Routine Estimation of Coronal Mass Ejection Magnetic Fields at Coronal Heights

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Abstract

The importance of measurement and modelling of the coronal magnetic fields has been appreciated for a long time, and in view of the fact that magnetic fields of Coronal Mass Ejections (CMEs) play a crucial role in determining their geo-effectiveness, this also has considerable societal impact. The coronal magnetic fields are, however, very hard to measure directly. Unlike those at play in X-ray, EUV and optical regimes, radio emission mechanisms are sensitive to the local magnetic fields and hence can potentially lead to their measurements. In practise, however, this potential has been hard to realize. To the best of our knowledge, in the past eighteen years, there have been only three published instances of radio detection of CME like structures. Only for two of these instances, it was possible to estimate coronal magnetic fields by fitting the measured spectra with gyrosynchrotron models. Using data from the Murchison Widefield Array (MWA), for two CMEs we have detected radio structures resembling the CME morphology. These structures are cospatial and cotemporal with the white light coronagraph images of the CME and we can convincingly demonstrate that this is not plasma emission. The maximum heliocentric distance where we can detect such emission is 4.74 solar radii, and the flux densities we measure are among the lowest reported. We note that these detections have been enabled by the confluence of the availability of data from the modern arrays like the MWA; and an automated interferometric solar radio imaging which we have developed. The MWA provides unprecedentedly dense sampling of Fourier (uv) plane, an essential pre-requisite for high imaging fidelity; and the imaging pipeline is tuned to extract the best imaging performance from these data. We present the hypothesis that gyrosynchrotron emission from CMEs intrinsically is not rare, it only appeared so because the dynamic range and imaging fidelity of available solar radio images was typically insufficient to convincingly detect this emission. If true, this then provides an exciting opportunity for routine estimation of the CME magnetic fields at coronal heights and a host of other coronal diagnostics, uniquely associated with gyrosynchrotron emissions.

Measuring the magnetic field of a CME at high coronal heights using low frequency radio observation

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Coronal Mass Ejections (CMEs)

- Orientation of magnetic field of CME determines its 'geo-effectiveness'.
- Very important to measure the magnetic field of CME; but also very difficult and no standard technique available yet.
- Various emission mechanisms which emit in radio bands are sensitive to the local magnetic field.
- Magnetic field can be estimated by modelling gyrosynchrotron emission from the CME plasma; expected to peak at metre wavelengths.
- Low frequency radio observations: a powerful remote sensing tool to measure the CME magnetic field.
- As the gyrosynchrotron emission is expected to be much weaker than even the quiescent solar radio emission, this is very challenging.
- Bastian et al. (2001): first to estimate the CME magnetic field using spectroscopic imaging at coronal heights of ~2.8 $R_\odot$
- Only 2 such imaging studies have followed (Maia et al. 2007, Demoulin et al. 2012).
- We use data from the Murchison Widefield Array (MWA) to estimate the magnetic field using high dynamic range multi-frequency images.
- MWA: radio interferometer consisting of 128 tiles; operates from 80-300 MHz.
- Located in exquisitely radio quiet western Australia, it is a precursor of the Square Kilometre Array (SKA).
- Array geometry makes it the best radio interferometer available for monochromatic snapshot imaging in the low frequency radio bands.

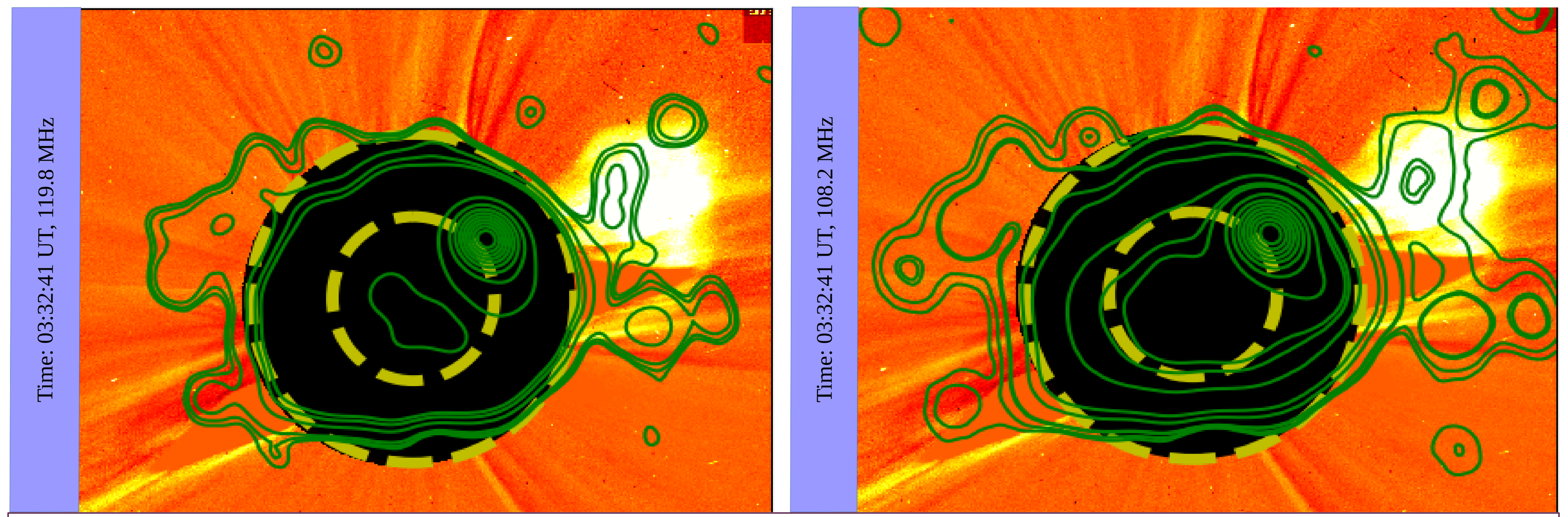


Fig 1: Radio contours from MWA data overlaid on the LASCO C2 base difference image. The LASCO C2 image nearest to the time of the radio map was chosen. The radio contours match well with the white light images of the CME. The flux density on the CME is about 100 times fainter than the quiet sun disk and 800 times fainter than the active region on the west limb.

Overview of this work

- CDAW catalogue reported CMEs at 02:12:04, 04:00:04 and 04:12:04 UT on 04/11/2015.
- Chose a MWA observation between the first & the second CME.
- Data from 03:18:41-03:38:40 were imaged at one minute cadence at multiple frequencies.
- Chose two time slices: *03:32:41.0 & 03:33:26.0* based on the features we were interested in.
- Two example images for the time 03:32:41.0 are shown in Fig. 1.
- Obtained the spectra of multiple regions *(on the CME and on a streamer)* near the west limb.

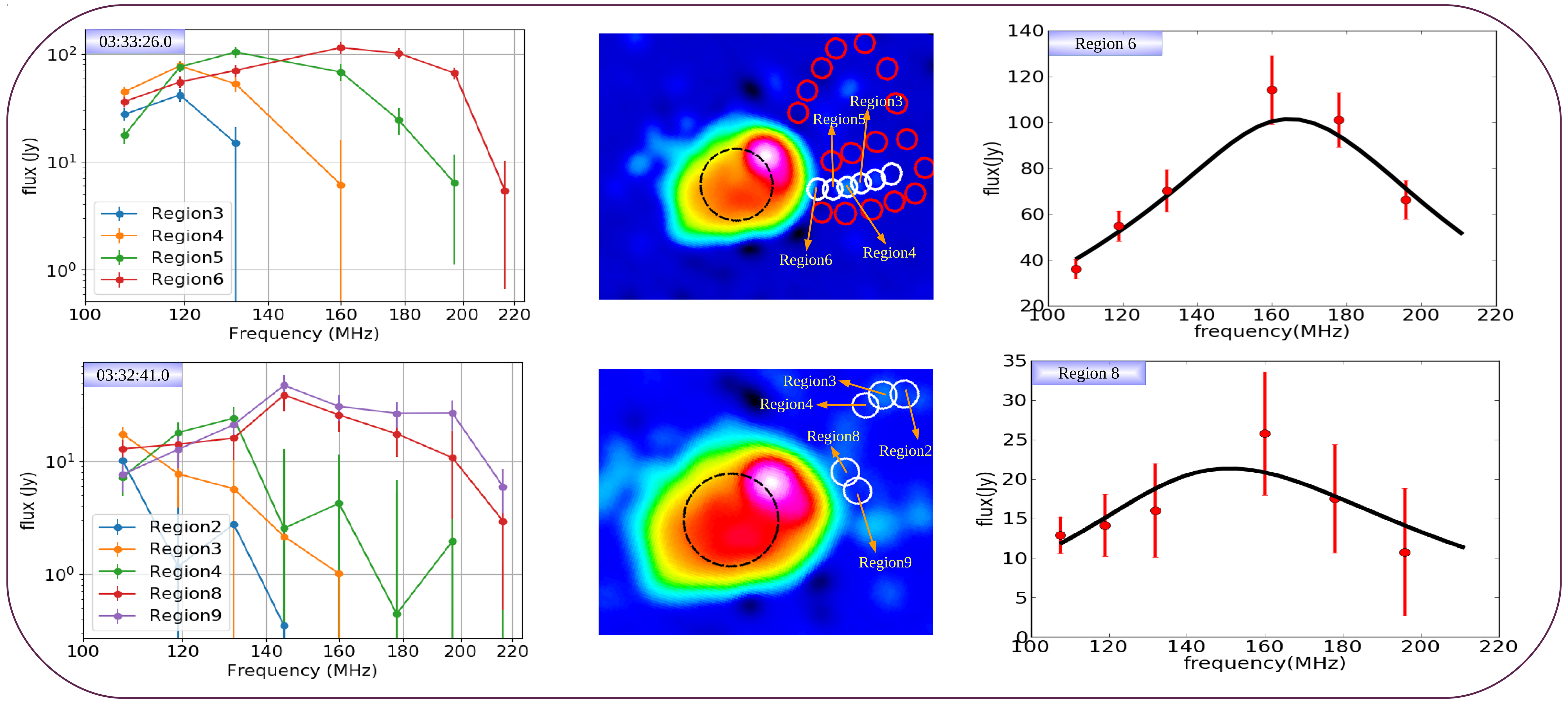


Fig 2: Upper panel: 03:33:26.0 UT, Lower panel: 03:32:41.0 UT; Left panel: Radio spectra at different locations. *Middle panel*: Radio images, black dashed circle shows the solar optical disc. Regions for extracting the spectra are marked with white circles. Red circles mark the regions which are used to estimate errorbars on the flux values. *Right panel*: Fitted radio spectra at two different regions.

Modelling the spectra

- We model the spectra using gyrosynchrotron code from Fleishman et al. (2010).
- Many free parameters; assigned physically motivated values where possible.
- Thermal electron density is obtained from LASCO C2 polarised brightness map.
- Spectra with maximum data points chosen for fitting.
- ***Power-law parameters of the electron energy distribution, magnetic field*** were derived (Fig. 2, upper panel).
- ***Magnetic field and lower energy cut-off*** were derived keeping other parameters fixed (Fig. 2, lower panel).

	E_{min} (MeV)	E_{max} (MeV)	δ	B (G)	n_b (cm^{-3})	Distance ($R_\odot$)
Maia et al. 2007	>1	~10	1.5-3.5	0.3-7	-	1.9
Carley et al. 2017	0.009	6.6	3.2	4.4	10^6	1.3
Bastian et al. 2001	0.1	10	3.5	0.3-1.4	200	1.4-2.8
Tun et al. 2013	0.001	0.1	3	5-15	~10^6	2
Region6	**0.2**	**0.9**	**5.9**	**1.4**	**30000**	**2.3**
Region8	**0.6**	**10**	**7.6**	**0.8**	**6000**	**2.7**

Table 1: Parameter estimates from this work (bottom two panels, highlighted in dark bold blue) are compared with previous works. E_{min} and E_{max}: lower and upper energy cutoffs, δ: power-law index, n_b : non-thermal electron density, B: magnetic field, distance: heliocentric distance of feature.

Comparison with past works

- Most previous works suffer from poor spectral sampling, especially close to the peak of the spectrum.
- Leads to poorly constrained parameters.
- We have good sampling close to the peak → **better constraint on parameters (Fig. 3).**
- Detected much lower fluxes → **possibility of characterising CMEs routinely (Fig. 3).**
- Our detections extend to about 1.5 hrs after the CME entered the LASCO C2 field of view → **Information about late time evolution.**

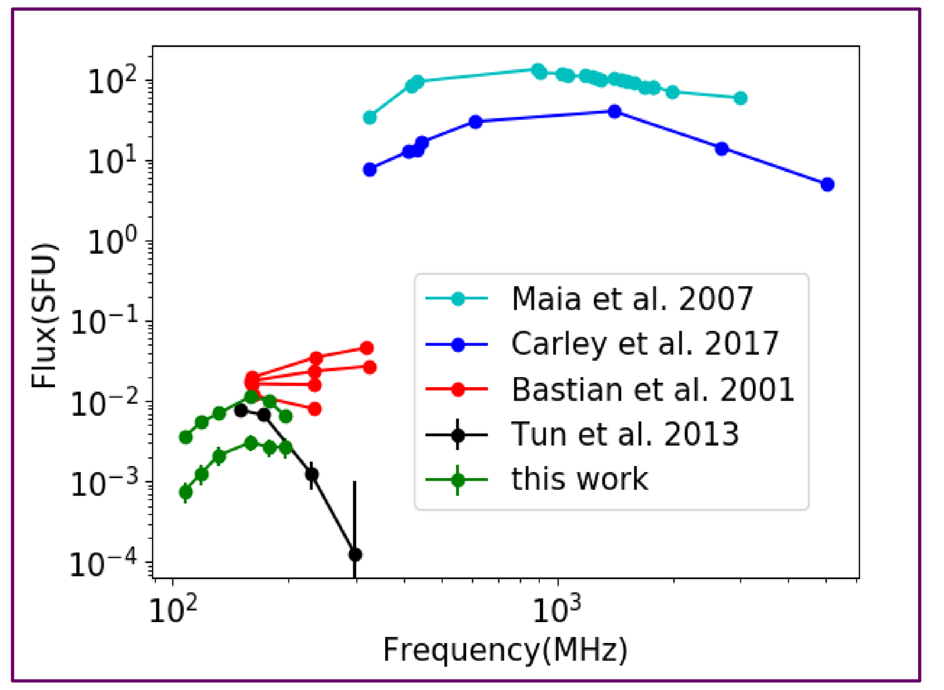
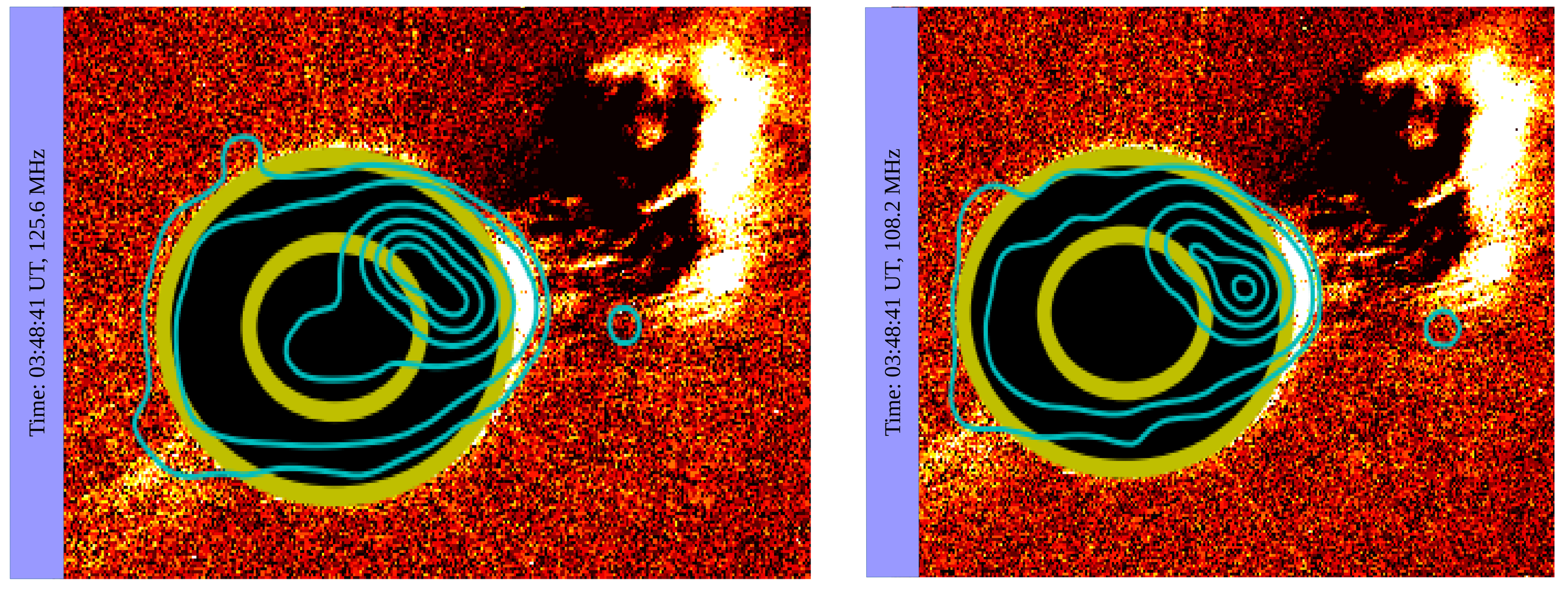


Fig 3: Radio fluxes reported by earlier authors and those from this work. The flux we report is the lowest reported so far.

Making such measurements routine: AIRCARS

- The high dynamic range (DR) images used were obtained using **Automated Imaging Routine for Compact Arrays for Radio Sun (AIRCARS;** Mondal et al. 2018**).**
- Traditional radio interferometric imaging is very human effort intensive.
- Automation essential to use solar radio interferometric data effectively.
- AIRCARS is a fully automated imaging pipeline, based on CASA.
- Has been designed to work with future instruments like the SKA1-Low & Mid.
- Improves the state-of-the-art in imaging DR by one to two orders of magnitude.
- **Can be routinely used to generate high DR images required for a similar study.**

Fig 4 (Right figure): Multi-frequency radio detection of another white light CME using AIRCARS on MWA data. We show images at two frequencies as example. The radio contours are overlaid on LASCO C2 base difference image. This was the frame where this CME first appeared in LASCO C2. Direct correspondence between this CME and the radio contours is evident.



Conclusion

- ✔ *Successfully detected and modelled gyrosynchrotron emission from a CME at multiple locations (Table 1 and Fig. 2)*
- ✔ *Better sampling of the spectra than previous works at similar heights; parameters are better constrained.*
- ✔ *Historically, radio counterparts for very few white light CMEs have been detected. Using AIRCARS on MWA data, we detected radio emissions from both the CMEs where we have attempted this so far.*
- ✔ *Flux densities we measure are lower than previous reported values:*
  - ✔ *Radio CMEs may not be as rare as suggested in literature; detection limited by imaging fidelity and DR.*
  - ✔ *Enables study of late time evolution of CME plasma.*
- ✔ *Data from a few tens of CMEs are available in the MWA solar archive. Effort under way to pursue similar studies for these CMEs.*
- ✔ *Polarisation calibration ongoing. This will add more constraints leading to better parameter estimation.*
- ✔ *Together, they can help realize the promise of low frequency radio interferometry in estimating the CME magnetic field.*