Low frequency GMRT observations of ultra-cool dwarfs

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1. What is the nature of low-frequency radio emission of Ultra-Cool dwarfs?

2. Can we use this to place tighter constraints on their coronal properties?

3. What does this tell us about the physical mechanisms operating in their magnetosphere?
What are Ultra-Cool Dwarfs?

Spectral class $> M7$

Span the gap between low-mass stars and high-mass planets

Fully convective
$\rightarrow$ early dynamo theory predicted weak magnetic fields
(e.g. Durney et al. 1993)
UCDs break trends

UCDs exhibit a sharp decline in Hα & X-ray luminosity

→ inability of UCDs to sustain hot corona
→ transition to cold neutral atmosphere

Güdel-Benz Relation: $L_X \sim L_{\nu,R}^{0.73}$

→ For UCDs: decline in $L_X$ → negligible $L_{\nu,R}$

Berger et al. (2001): detection of strong non-thermal radio emission:

– Bursty, flare-like
– Steady, persistent
Radio emission mechanisms

Gyrosynchrotron radiation:
- Broadband, polarised
- Likely to be responsible for quiescent emission

Electron cyclotron maser instability (ECMI):
- Bursty, flare-like emission
- Emits close to local cyclotron frequency:
  \[ \Omega_e = \frac{eB}{cm_e} \approx 2.8 \times 10^6 B \]
- Could be source of quiescent emission?
Key questions

Presence of non-thermal radio emission indicates presence of strong magnetic fields (up to several kG)
  - Unexpected, given early theoretical considerations & observed decline of activity tracers

How are these strong magnetic fields generated in UCDs? What is their topology, and does this evolve?

How is the stellar magnetosphere populated with non-thermal electrons responsible for radio emission?
Degeneracies, and how to break them

Gyrosynchrotron emission can be used to constrain coronal electron density and magnetic field strength ($N_e$ & $B$)

Problem: $N_e$ and $B$ are degenerate*

Low frequency observations break degeneracy:
Probe optically thick emission → locate spectral turnover

Spectral turnover depends on $N_e$ & $B$:

$$\nu_{\text{peak}} \approx 10^{3.41+0.27\delta(N_e/L)^{0.32-0.03\delta}B^{0.68+0.03\delta}}$$

*(see e.g. Lynch et al. 2015; Ravi et al. 2011; Osten et al. 2006) Dulk (1985)
Probing UCD magnetospheres with the GMRT

Observed 9 UCDs with the Giant Metrewave Radio Telescope (GMRT) at ~610 & 1300 MHz, to:

1. Determine location of spectral turnover

2. Determine existence of low-frequency counterpart to bursty emission observed at higher frequencies
  (spoiler: detected no flares above ~few mJy threshold)

First observations of UCDs at these frequencies to be published in the literature (Zic et al., in prep.)
### Detections... and non-detections

| Name           | $S_{610}$ (μJy) | $S_{1300}$ (μJy) | $T_{B,610}$ (10$^{10}$K) | $T_{B,1300}$ (10$^{10}$K) |
|----------------|-----------------|-----------------|----------------------|---------------------|
| J1314+1320     | 390 ± 26        | 908 ± 65        | 19 ± 1               | 8.8 ± 0.6           |
| TVLM 513-46    | $<$ 148 a       | $<$ 194 b       | $<$ 2.8 a            | $<$ 0.85 b          |
|                | $<$ 201 c       | $<$ 6.7         | $<$ 0.76 c           |
| 2M 0314+16     | $<$ 200         | $<$ 728         | $<$ 5.4              |
| 2M 0746+20     | 319 ± 58        | 355 ± 65        | 8.0 ± 1.5            | 2.0 ± 0.4           |
| 2M 0828-13     | $<$ 160         | $<$ 165         | $<$ 3.5              | $<$ 0.8             |
| 2M 0036+18     | $<$ 800         | $<$ 1040        | $<$ 10               | $<$ 3.0             |
| 2M 0034+05     | $<$ 245         | $<$ 243         | $<$ 3.8              | $<$ 0.83            |
| 2M 0355+11     | $<$ 184         | $<$ 1020        | $<$ 2.0              | $<$ 2.5             |
| 2M 0423-04     | $<$ 150         | $<$ 1360        | $<$ 5.9              | $<$ 12              |

Table 3. Notes: (a): Epoch 2016-08-18; (b): Epoch 2008-01-19; (c): Epoch 2016-09-25

Zic et al. (in prep.)
Modelling coronal parameters

Variability + non-simultaneous observations = uncertainty in SED shape

Model corona as homogeneous population of power-law electrons contained within uniform magnetic field

Goal: perform radiative transfer modelling with gyrosynchrotron emission/absorption coefficients from Robinson & Melrose (1984):

Obtain flux density, optical depth as function of \((\nu, N_e, B, \theta)\)

Look for regions of parameter space where:

1. Emission becomes optically thick at measured turnover frequency
2. Modelled Stokes I flux densities match optically-thin measurements
J1314+1320: measuring the turnover frequency

\[ \alpha_{\text{thick}} = 1.0 \pm 0.1 \]

\[ \alpha_{\text{thin}} = -0.17 \pm 0.02 \]

\[ \nu_{\text{br}} = 2.2 \pm 0.2 \text{ GHz} \]

- McLean et al. (2011)
- Metodieva et al. (2017)
- VLA FIRST
- Williams et al. (2015)
- Zic et al. (in prep.)
J1314+1320: getting coronal parameter estimates

Radiative transfer modelling is a work in progress

For preliminary estimates, use expressions from Dulk (1985)

\[ r_c \approx 1.26 \times 10^{0.035 \delta} 10^{-0.071 \cos \theta} \left( \frac{v}{v_B} \right)^{-0.782 + 0.545 \cos \theta} \quad (\tau_v \ll 1) \]

\[ \nu_{\text{peak}} \approx 2.72 \times 10^3 10^{0.27 \delta} \left( \sin \theta \right)^{0.41 + 0.03 \delta} (NL)^{0.32 - 0.03 \delta} \]
\[ \times B^{0.68 + 0.03 \delta}. \]

Assume \( \delta \sim 1.5 \), \( r_c = 0.1 \) (from Williams+ 2015), \( \theta = 60^\circ \)

**Magnetic field:** \( B \sim 20 \text{ G} \); **Electron density:** \( N_e \sim 10^7 \text{ cm}^{-3} \)
Summary

Constraining spectral turnover frequency can lead to accurate estimates of coronal parameters of UCDs.

Report lowest-frequency detection of non-thermal radio emission from J1314+1320 & 2M0746+20 to date.

J1314+1320: consistent with optically-thick gyrosynchrotron radiation, with a spectral turnover at ~2.3 GHz.

Use this to obtain $B \sim 20$ G, $N_e \sim 10^7$ cm$^{-3}$.

First step in precisely determining coronal parameters for UCDs.
Where to next?

Long-term variability adds significant uncertainty to the spectral shape and therefore coronal properties of UCDs. Simultaneous observations with the GMRT and VLA/ATCA → more accurate coronal constraints.

Millimetre observations can help disambiguate emission mechanisms (e.g. Williams et al., 2015).

Broadband optical, Hα, and X-ray also provide complimentary information on the chromospheric and coronal activity of UCDs.
Additional Slides
Modelling coronal parameters

Use expressions for gyrosynchrotron absorption and emission coefficients for power-law electrons from Robinson & Melrose (1984):

\[
\begin{align*}
J(\omega, \theta) & = \frac{N(\delta-1)\sqrt{3}}{8} \frac{A}{1+T^2} \frac{\Omega_e}{\omega^2} \sin^3 \theta \left( 1 + \frac{1}{\gamma_0} \right) \\
\Gamma(\omega, \theta) & = \frac{N(\delta-1)\sqrt{3}}{8} \frac{A}{1+T^2} \frac{\Omega_e}{\omega^2} \sin^3 \theta \left( 1 + \frac{1}{\gamma_0} \right) \\
& \times \left\{ \left( 1 + \frac{T \cot \theta}{\gamma_0} \right)^2 + \frac{2T^2}{3(a+b+2)} \right\} \\
& \times \left( \frac{\gamma_0-1}{\varepsilon_c} \right)^{1-\delta} Z^{2s} \left\{ \frac{1}{(2\pi)^3} \frac{\delta+2}{\varepsilon_c} \left( \frac{\gamma_0-1}{\varepsilon_c} \right)^{-1} \frac{\gamma_0}{1+\gamma_0} \right\}.
\end{align*}
\]
Flux Density (mJy)

10^0

10^-1

Frequency (GHz)

10^0

10^1

Zic et al. (in prep.)

31/07/2018

Cool Stars 20
2M0746+20 spectral shape is not so clear

Variable on long timescales

No clear turnover

610 MHz polarisation fraction > 46%

Zic et al. (in prep.)
Giant Metrewave Radio Telescope

Location: Maharashtra, India
Antennas: 30
Bandwidth: 32 MHz*
**Frequency range: 150-1400 MHz**
Max baseline: 25 km
Antenna diameter: 45 m

*now 300 MHz with upgraded correlators