The Lowest Frequency Observations of YSOs with the GMRT

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Abstract

We conducted a pathfinder project with the GMRT to detect low-mass YSOs at low frequencies, and **present for the first time observations of protostars at 325 and 610 MHz**. We detect the three target sources, T Tauri, L1551 and DG Tauri at both frequencies and present a catalogue of other sources identified within the primary beam of the GMRT. We present the SEDs associated with these objects, and search for evidence of non-thermal emission such as synchrotron or gyro-synchrotron emission. Non-thermal emission is known to arise for more evolved YSOs (Class III), but has only been detected in a handful of Class I and II YSOs, which constitute our target sample.

Background

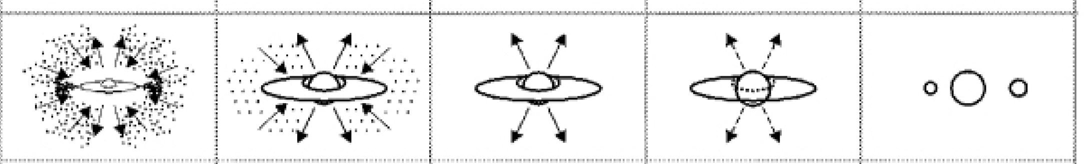
Properties	Infalling Protostar	Evolved Protostar	Classical T Tauri Star	Weak-lined T Tauri Star	Main Sequence Star
Sketch					
Age (years)	10^4	10^5	10^6 - 10^7	10^6 - 10^7	> 10^7
mm/Infrared Class	Class 0	Class I	Class II	Class III	(Class III)
Disk	Yes	Thick	Thick	Thin or Non-existent	Possible Planetary System
X-ray	?	Yes	Strong	Strong	Weak
Thermal Radio	Yes	Yes	Yes	No	No
Non-Thermal Radio	No	Yes	No ?	Yes	Yes

Figure 1: The stages of low-mass YSO evolution (Feigelson & Montmerle 1999).

Radio emission from YSOs is complex. Possible processes:

- Thermal bremsstrahlung, with spectral index $-0.1 < \alpha < 2$
- Synchrotron or gyro-synchrotron, with $\alpha < -0.1$

The emission from low-mass YSOs is typically believed to arise as free-free radiation from e.g. a partially ionised, collimated outflow (Reynolds 1986) or through shock ionisation as the outflow impacts on the surrounding envelope (Curiel, Canto, & Rodríguez 1987, Rodríguez & Reipurth 1996). It should be noted that non-thermal emission has been detected only for VERY FEW YSOs (e.g. Curiel et al. 1993; Ray et al. 1997). A possible mechanism for generating non-thermal emission is gyro-synchrotron radiation from relativistic electrons.

The GMRT

Figure 2: Antennas in the GMRT central array.

The GMRT

- The Giant Metrewave Radio Telescope, near Pune, India.
- Thirty 45 m dishes in an approximate 'Y'-configuration.
- Longest interferometric baseline ≈ 25 km.
- Operates at 50, 153, 233, 325, 610 and 1420 MHz.

The Obervations

- Made at 325 and 610 MHz with a total bandwidth of 32 MHz.
- Primary beam $\approx 81'$ at 325 MHz $\approx 43'$ at 610 MHz.
- PSF $\approx 11 \times 10''$ at 325 MHz $\approx 6 \times 5''$ at 610 MHz.

References

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Results

Source	Class	$S_{\mathrm{int},365}$ (mJy)	$\sigma_{\mathrm{rms},325}$ (μJy)	$S_{\mathrm{int},610}$ (mJy)	$\sigma_{\mathrm{rms},610}$ (μJy)	α_{325}^{610}	α'
T Tauri	II	3.38 ± 0.31	110	4.16 ± 0.23	50	0.13 ± 0.16	0.15 ± 0.02
L1551	I	1.19 ± 0.33	150	1.35 ± 0.13	50	0.23 ± 0.47	0.23 ± 0.02
DG Tauri	II	0.97 ± 0.38	150	0.48 ± 0.24	90	-1.10 ± 0.99	0.27 ± 0.01

Table 1: Column [1] target sources [2] protostellar evolutionary class [3] 325 MHz integrated flux density [4] rms noise of 325 MHz combined channel map [5] 610 MHz integrated flux density [6] rms noise of 610 MHz combined channel map [7] spectral index between GMRT data and [8] spectral index over wider dataset (see Fig. 3). Both α_{325}^{610} and α' are in agreement for T Tau and L1551 and are consistent with free-free emission. However, **at GMRT frequencies DG Tau has a spectral index indicative of non-thermal emission**.

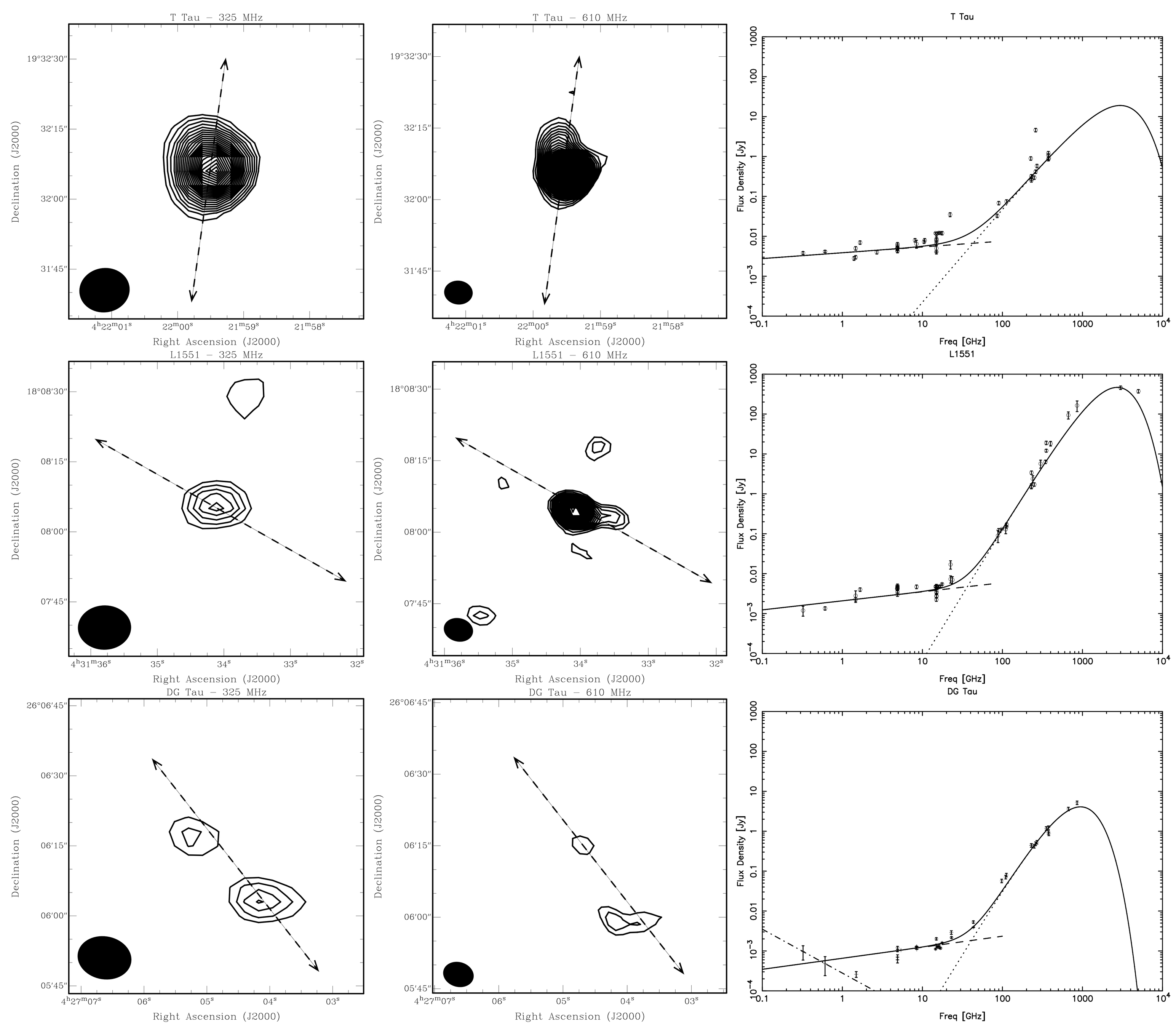
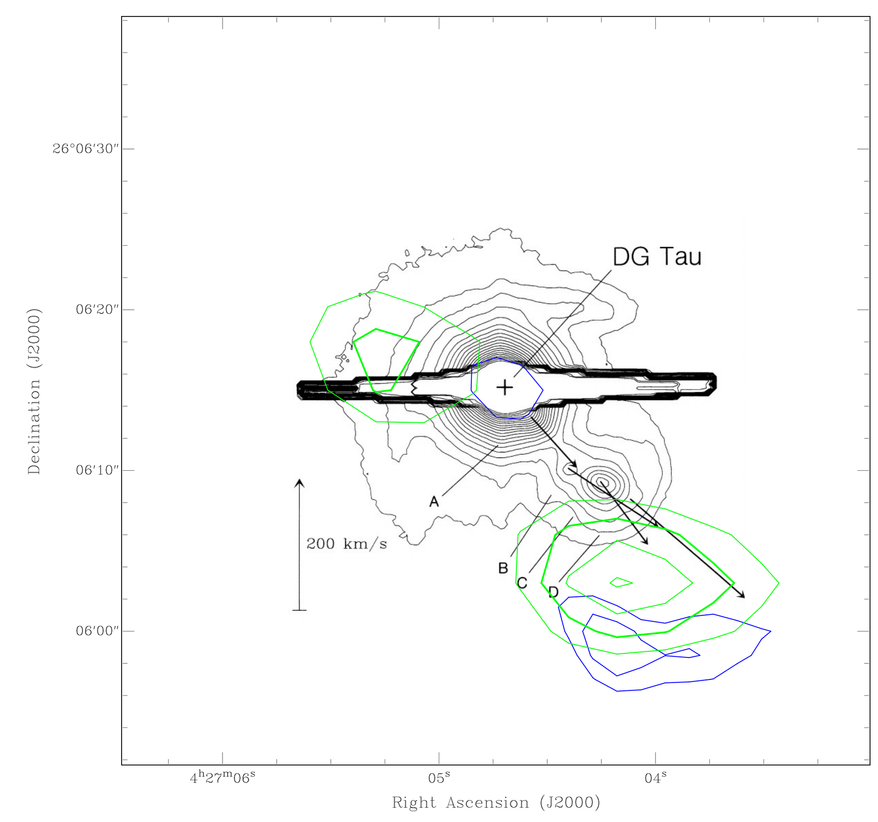


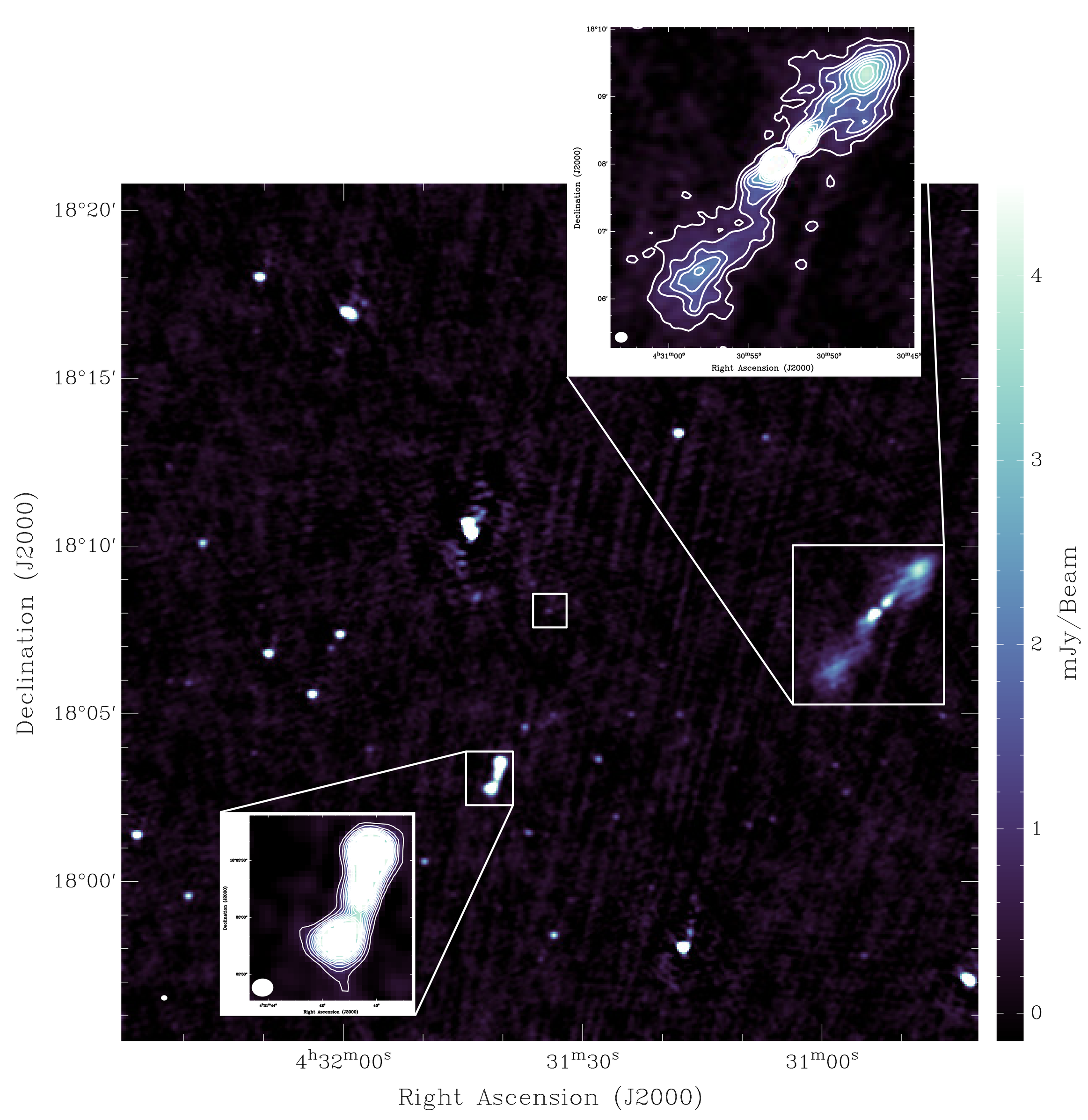
Figure 3: [Left Column] GMRT combined channels maps at 325 MHz and [Centre Column] 610 MHz, with contours at 3, 4, 5, 6 σ_{rms}, etc. (see Table 1), and the PSF is a filled ellipse. The known outflow axes for T Tau (Reipurth, Bally, & Devine 1997), L1551 (Hartigan et al. 2000) and DG Tau (Eislöffel & Mundt 1998) are denoted by dashed lines. Right Column: Spectral energy distributions fit with a combined power-law (α', see Table 1; dashed line) and modified blackbody model (dotted line). In the case of DG Tau, we plot the GMRT spectral index $\alpha_{325}^{610} = -1.10$ (dot-dash line) as it is inconsistent with α' and suggests non-thermal emission. The SEDs are constructed using archival data from the literature along with our GMRT flux densities, see Table 1).

DG Tauri

- Shown to the right are the optical results of Eislöffel & Mundt (their Fig. 3, including annotations and proper motion vectors; 1998) overlaid with our GMRT results to show that we detect the bow shock associated with DG Tau at low frequencies.
  - Green contours: 325 MHz
  - Blue contours: 610 MHz
  - Black contours: [SII]
- We find $\alpha = -0.99 \pm 0.05$ for the emission associated with the bow shock when including flux densities found in the literature, suggesting synchrotron or gyro-synchrotron emission.
- The offset of the emission at 325 MHz could be due to the difference in resolution, or we could be detecting the DG Tau counter-jet.



Catalogue



- Source Extractor (SExtractor, Bertin & Arnouts 1996) was used to identify other radio sources within our fields.
  - Six initial catalogues were created, one for each target field at 325 and 610 MHz, and the final catalogue will be presented in Ainsworth et al. (in prep).
  - We cross-reference our detections with existing catalogues, such as the *Spitzer* c2d survey, to search for other protostellar sources within the fields.
- Shown to the left is the centre of the L1551 target field at 325 MHz to illustrate the quality of the data.
  - Two example field sources are highlighted (contours at 3, 6, 9 $\sigma_{\mathrm{rms},325}$ etc, where $\sigma_{\mathrm{rms},325} = 150\,\mu$Jy).
  - The PSF is the filled ellipse in the bottom left corner of each region and the colour scheme is from Green (2011).
  - The centre box outlines the region in Fig. 3 for the target protostar, L1551.