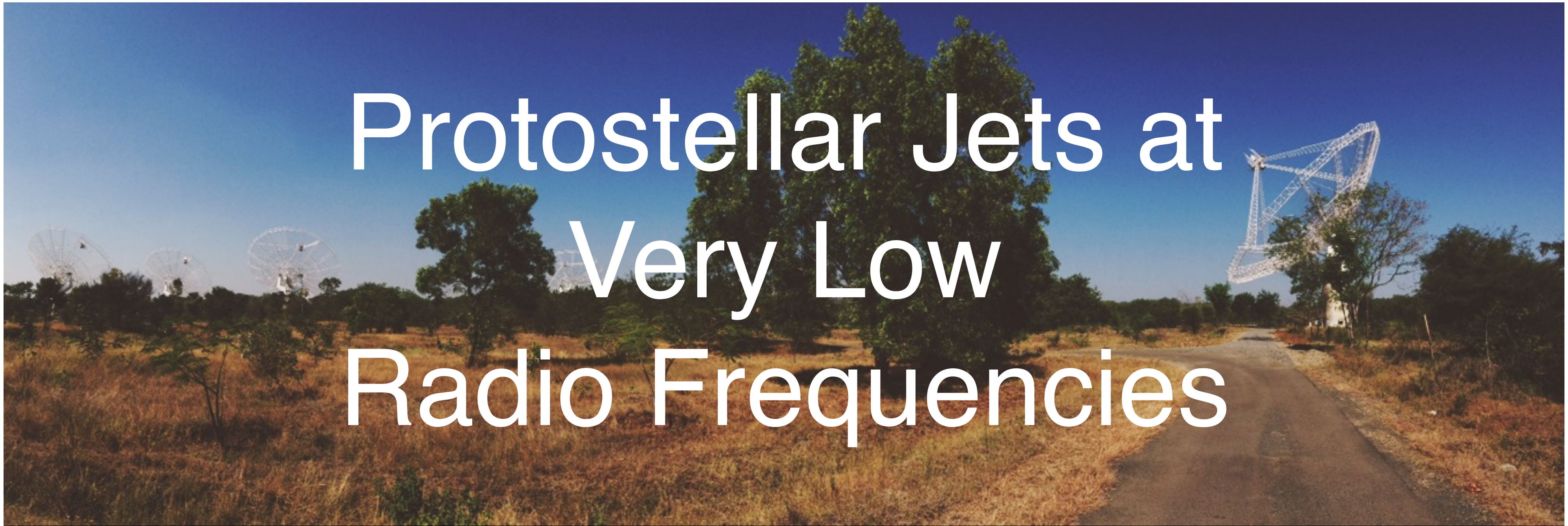

Protostellar Jets at Very Low Radio Frequencies

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Dublin Institute for Advanced Studies (DIAS)

The Accretion/Outflow Connection in YSOs Workshop
ESA/ESTEC - 28 October 2015

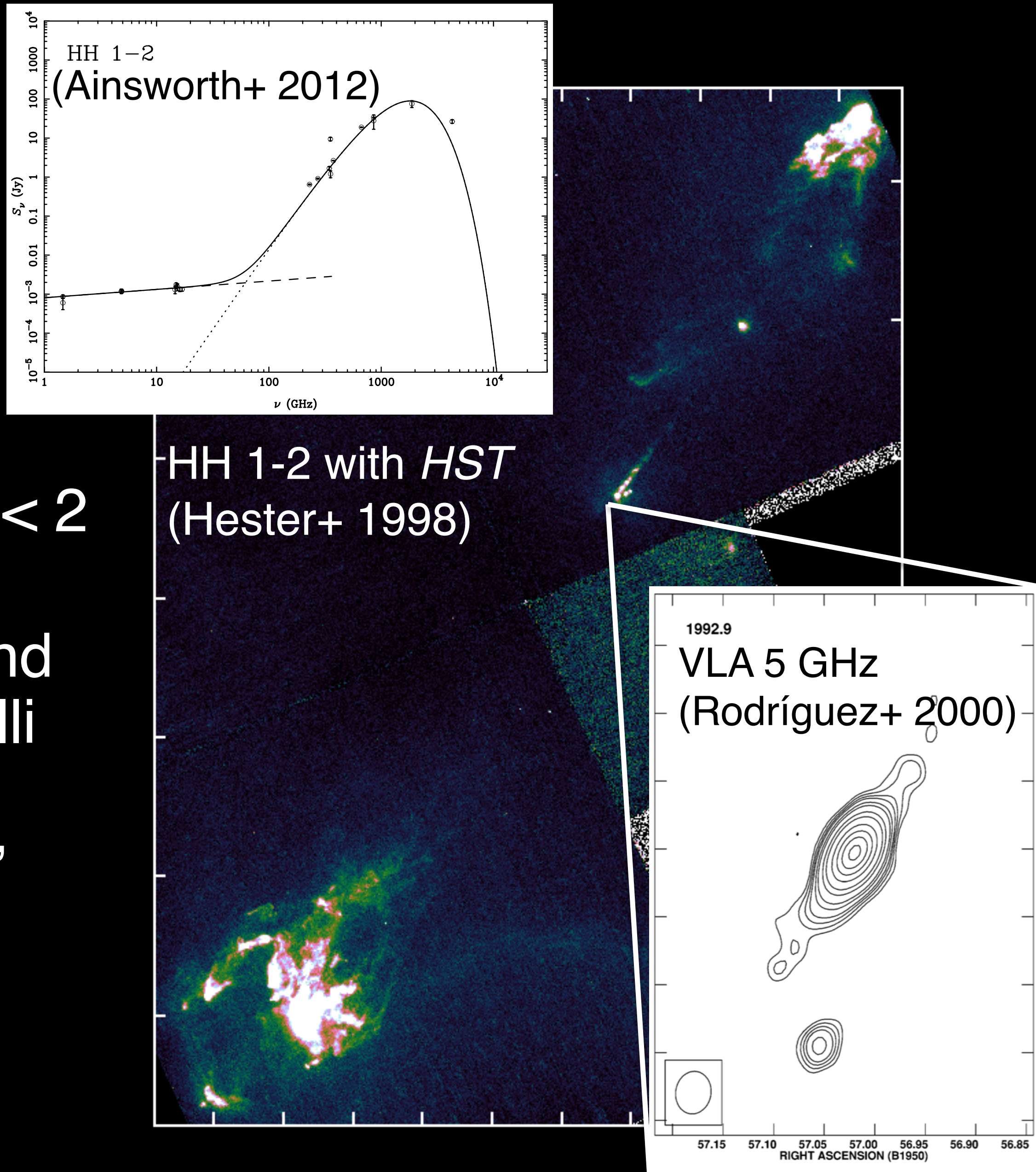
Collaborators: Tom Ray (DIAS), Anna Scaife (Manchester), Dave Green (Cambridge), Andrew Taylor (DIAS), Colm Coughlan (DIAS) & Jochen Eislöffel (TLS)

MANCHESTER 1824
The University of Manchester

CAVENDISH ASTROPHYSICS

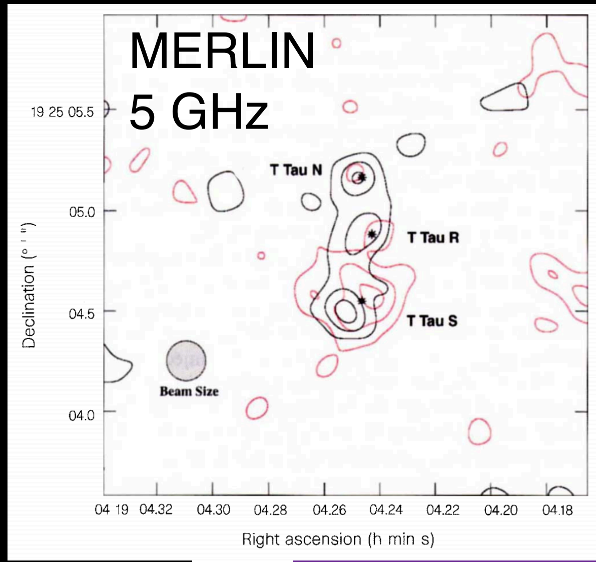
Radio Emission from YSOs

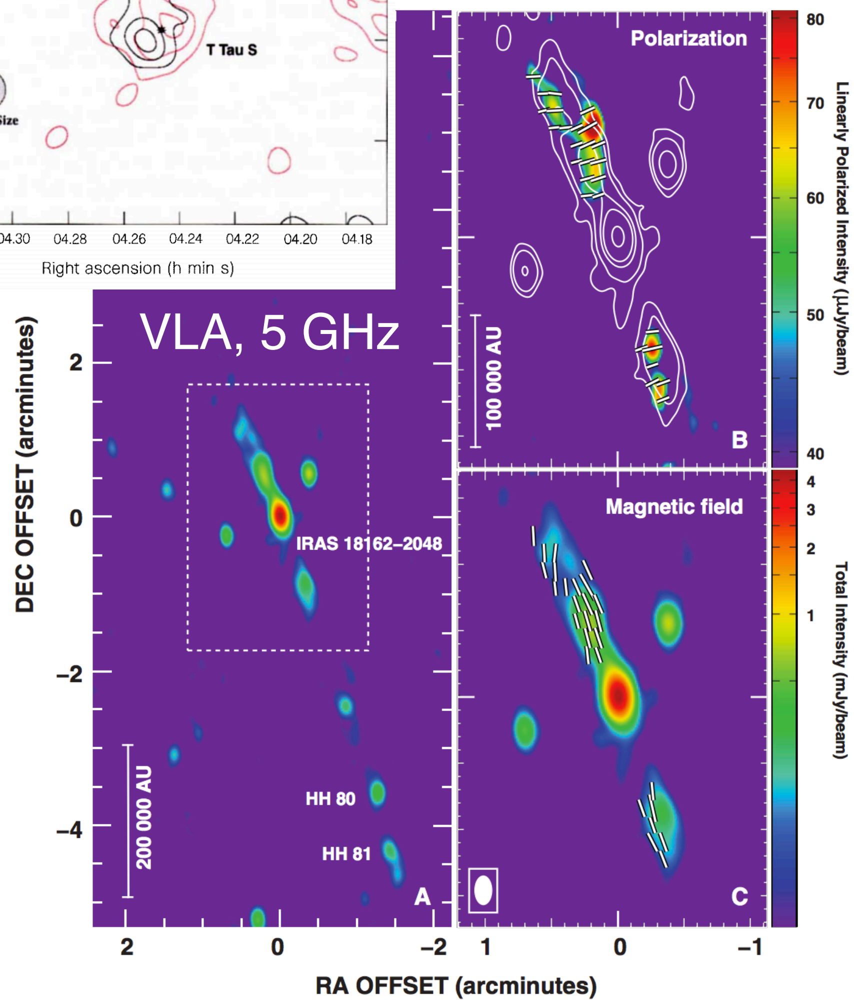
- Free-Free emission
  - $1 \leq \nu \leq 20$ GHz
  - Class 0-II YSO jets
  - Flux density ~ 1 mJy
  - Traces outflow
  - $S_\nu \propto \nu^\alpha$, where $-0.1<\alpha< 2$
    - $\alpha \approx 0.6$ "standard" spherical stellar wind (e.g. Panagia & Felli 1975)
    - $\alpha \approx 0.25$ "standard" collimated jet (Reynolds 1986)



Radio Emission from YSOs

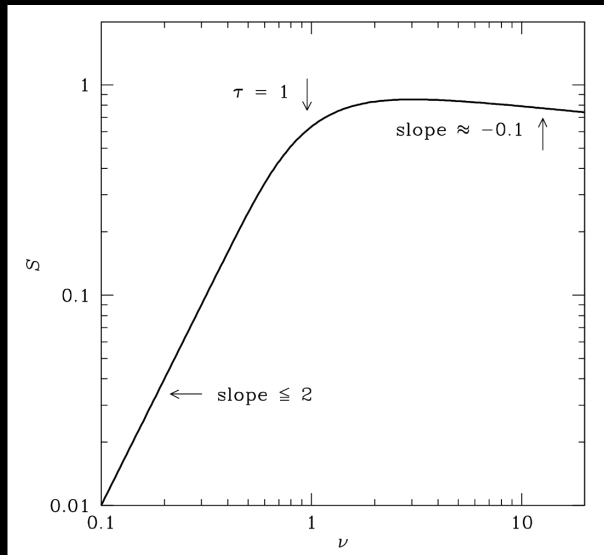
- Non-thermal emission
  - Class III
    - e.g. White+ 1992
  - Gyrosynchrotron from T Tau
    - Ray+ 1997
  - Synchrotron from a <u>high-mass</u> YSO (α ~ -0.7)
    - Carrasco-González+ 2010
  - VERY FEW <u>low-mass</u> C0-II have α < -0.1 indicative of non-thermal
    - e.g. Curiel+ 1993; Girart+ 2002



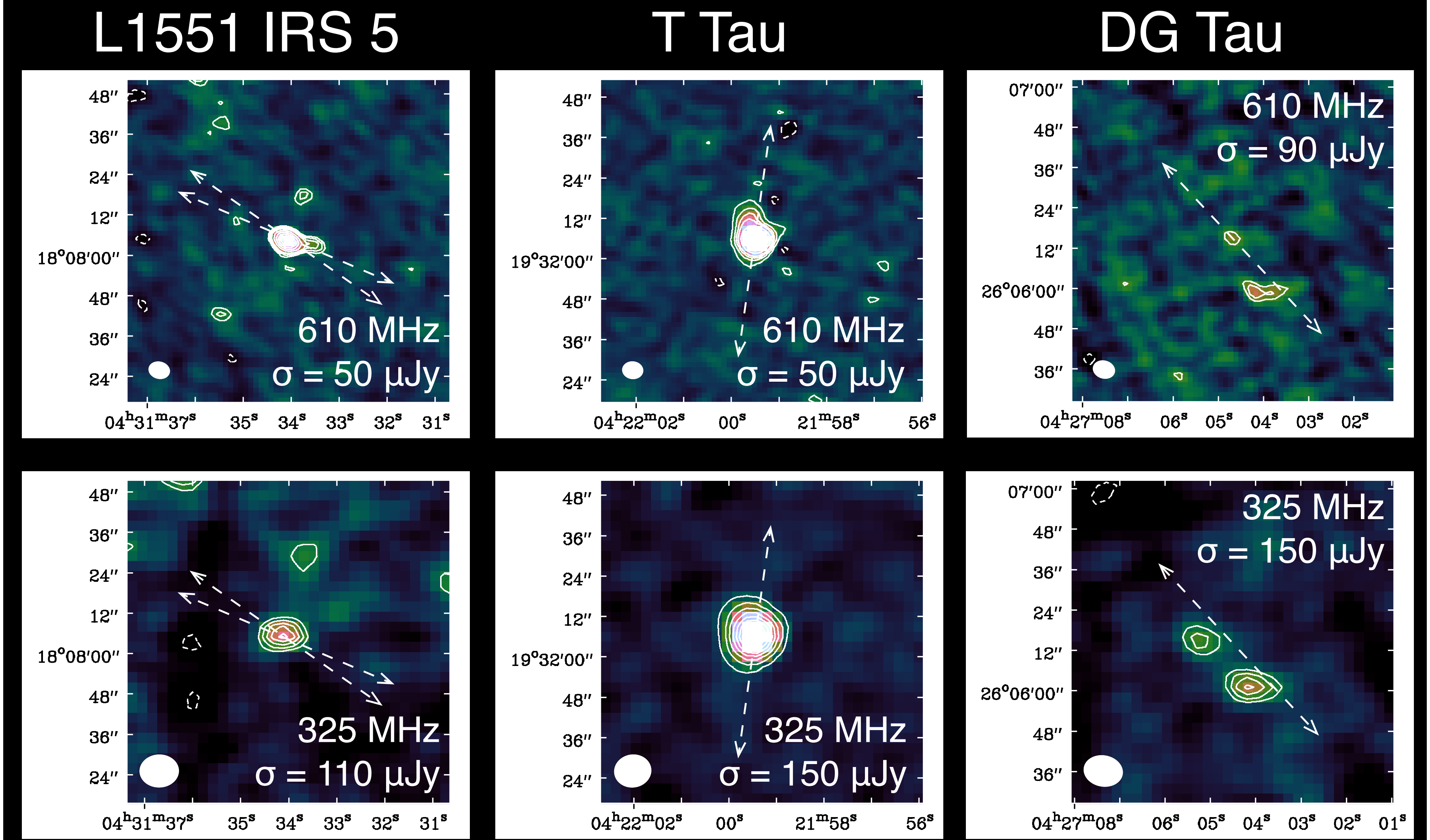


GMRT Observations

- Goal: to detect YSOs at 610 & 325 MHz to search for the transition frequency between optically thick & thin emission
- Target sample: L1551 IRS 5, T Tau & DG Tau



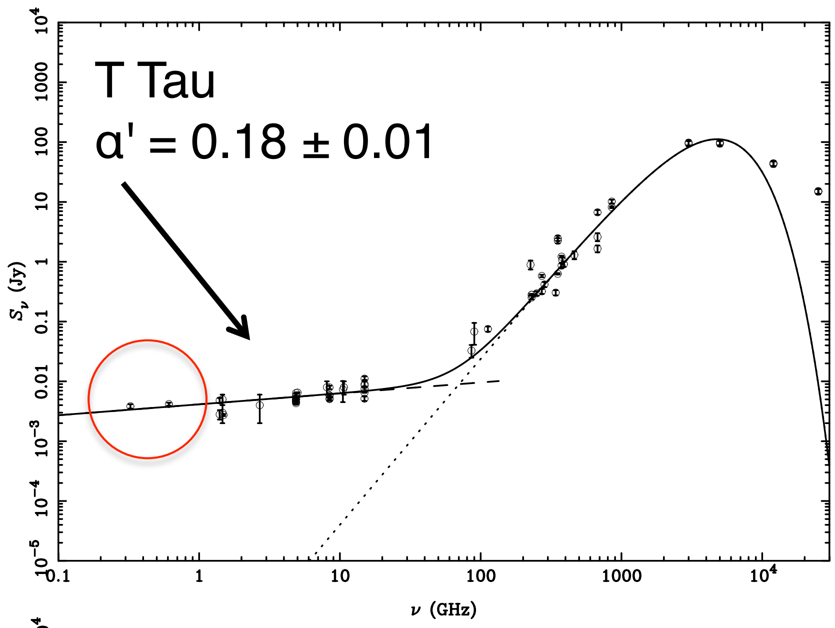
GMRT Maps

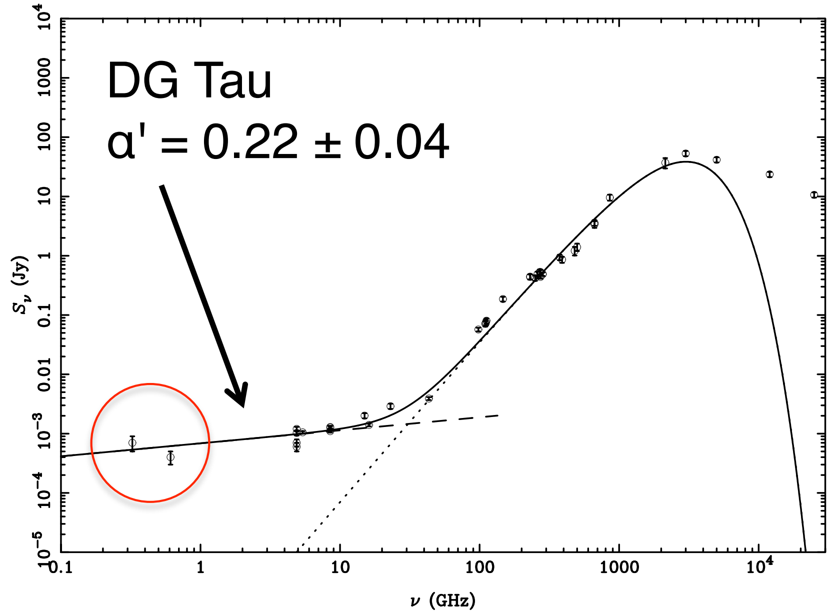


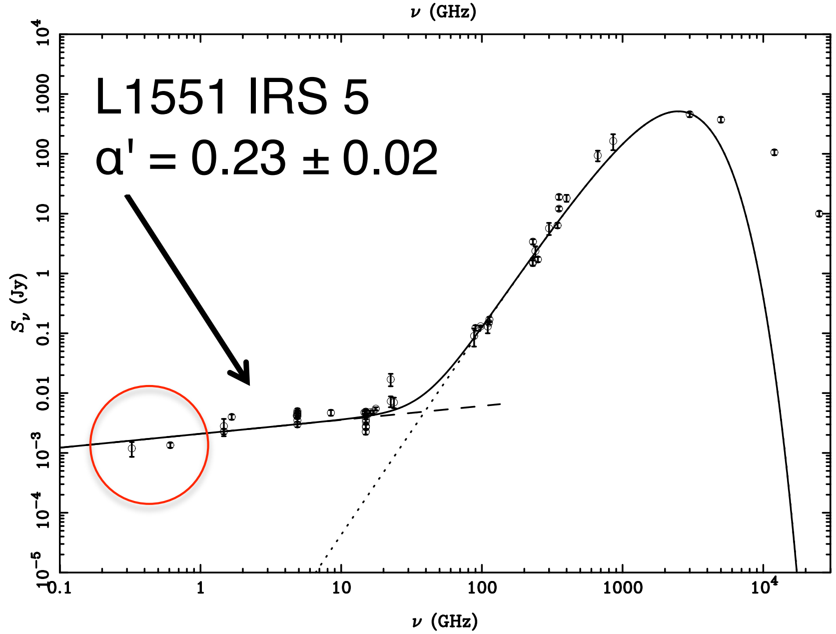
σ = rms noise

Epoch 2012.95

Spectral Energy Distributions

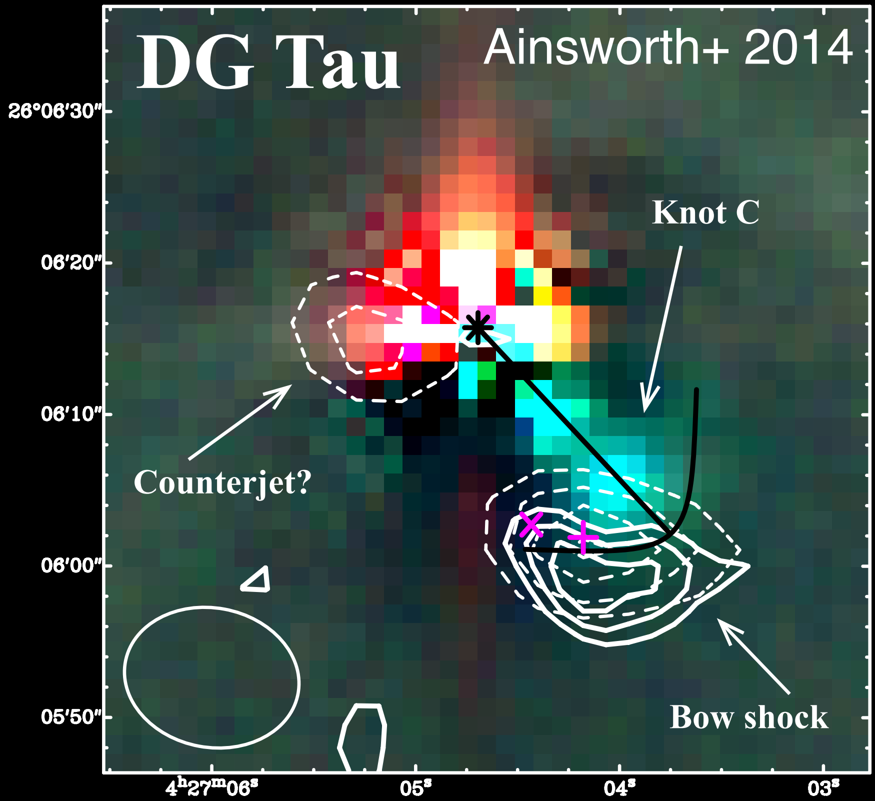




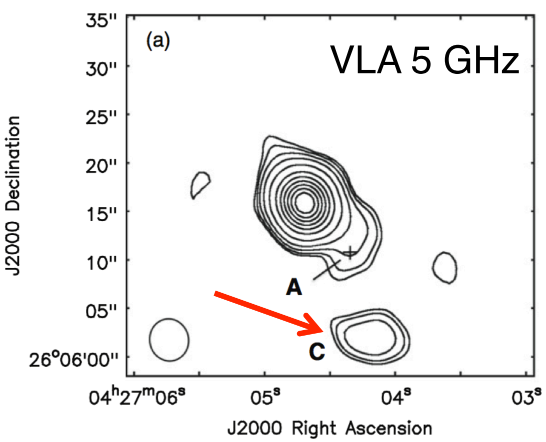


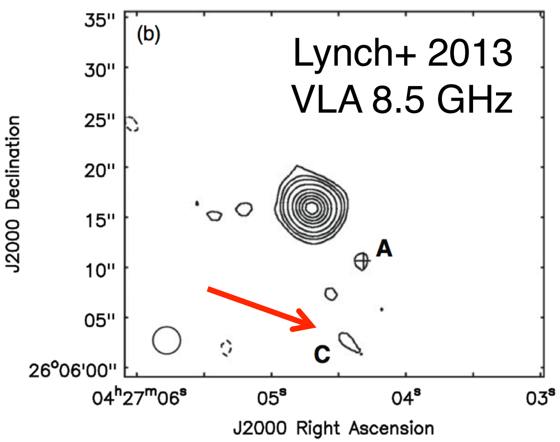
GMRT data for all 3 targets show a continuation of their free-free spectra to 610 and 325 MHz

DG Tau Bow Shock

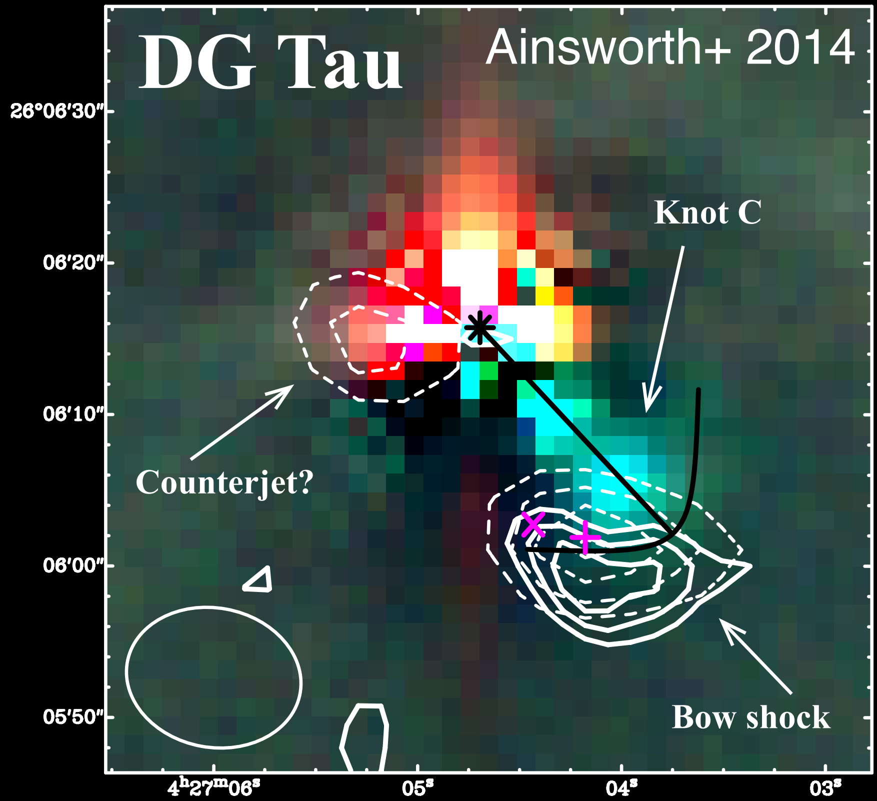


Dashed contours = 325 MHz with GMRT
Solid contours = 610 MHz with GMRT
Black ★ = optical stellar position
Overlaid on optical image: R = I, G = Hα; B = [SII]
(B. Stecklum, priv. com.)
Magenta x and + = VLA positions





DG Tau Bow Shock



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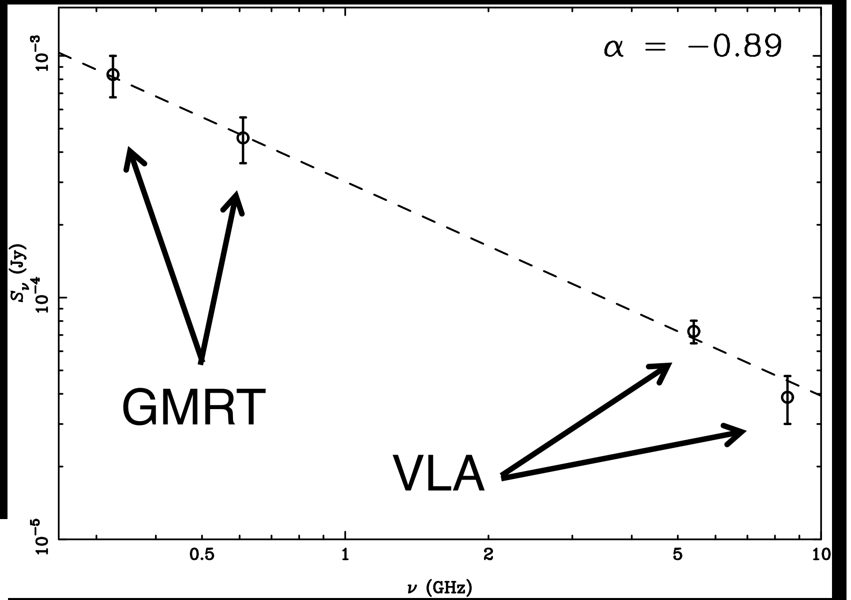

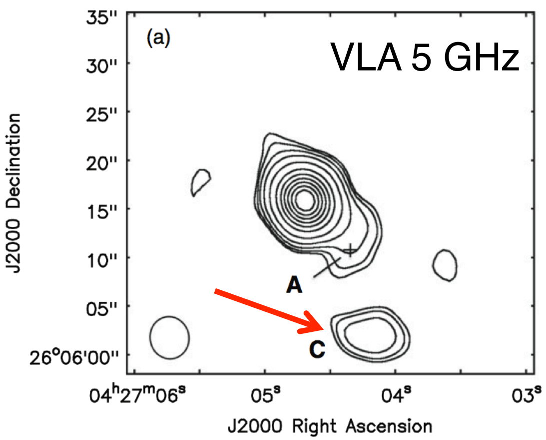

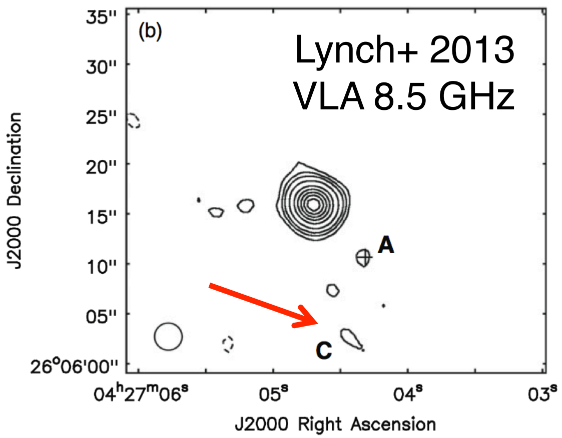

NOT free-free emission!
➔ Synchrotron
➔ Diffusive shock acceleration?

Equipartition Magnetic Field Strength and Minimum Energy

$$B_{\min} = \left[\frac{3\mu_0}{2}\frac{G(\alpha)(1+k)L_\nu}{Vf}\right]^{2/7}$$

$$\simeq \boxed{0.11\,\mathrm{mG}}$$

$$E_{\min} = \frac{7}{6\mu_0}(Vf)^{3/7}\left[\frac{3\mu_0}{2}G(\alpha)(1+k)L_\nu\right]^{4/7}$$

$$\simeq \boxed{4\times 10^{40}\,\mathrm{erg}}$$

(Longair 2011)

➔ These values of $B_{\min}$ and $E_{\min}$ are needed to account for the observed radio luminosity.

➔ Consistent with magnetic field values obtained from Zeeman observations toward star-forming cores (Crutcher 1999).

Cosmic rays from the young Sun?

- Observations
  - Synchrotron emission from jets of high mass (e.g. Carrasco-González+ 2010) and low mass (e.g. Ainsworth+ 2014) YSO systems
  - *Herschel* observations reveal the necessity of energetic particles to produce the chemistry observed in young protostellar systems (e.g. Ceccarelli+ 2014, Podio+ 2014)
- Theory
  - Jet shocks are possible accelerators of particles that can be easily boosted up to relativistic energies through diffusive shock acceleration (Padovani+ 2015)

Summary of GMRT Results

- Presented the lowest frequency investigations of YSOs to date using the GMRT
- Continuation of thermal jet spectrum to low frequencies from emission close to the source
- Detected the DG Tau bow shock
  - Provides tentative evidence for cosmic rays being generated in the jet of a young Sun-like star
  - Sheds light on the last unknown characteristic of jets from YSOs: the magnetic field strength
- Ainsworth et al. 2014, ApJ, 792, L18

Current and future work

- Characterise YSOs at very low radio frequencies (< 1 GHz)
  - Observations of more YSOs with GMRT
    - C0 sources: L1448, L723, Serpens FIR1, HH 1-2
    - Blind survey of NGC 1333
  - Observations of T Tau and DG Tau with LOFAR HBA (150 MHz)
    - Measure jet opening close to the source with international baselines
    - Insight into the magnetic collimation of the jets