A High-Resolution Radio Study of the L1551 IRS 5 binary jet

A. Feeney-Johansson[1,2], S. J. D. Purser[1], T. P. Ray[1], C. Carrasco-Gonzalez[3], A. Rodriguez-Kamenetzky[3]
1. Dublin Institute for Advanced Studies, Ireland. 2. The University of Tokyo, Japan 3. Universidad Nacional Autónoma de México (UNAM), Mexico.

Abstract

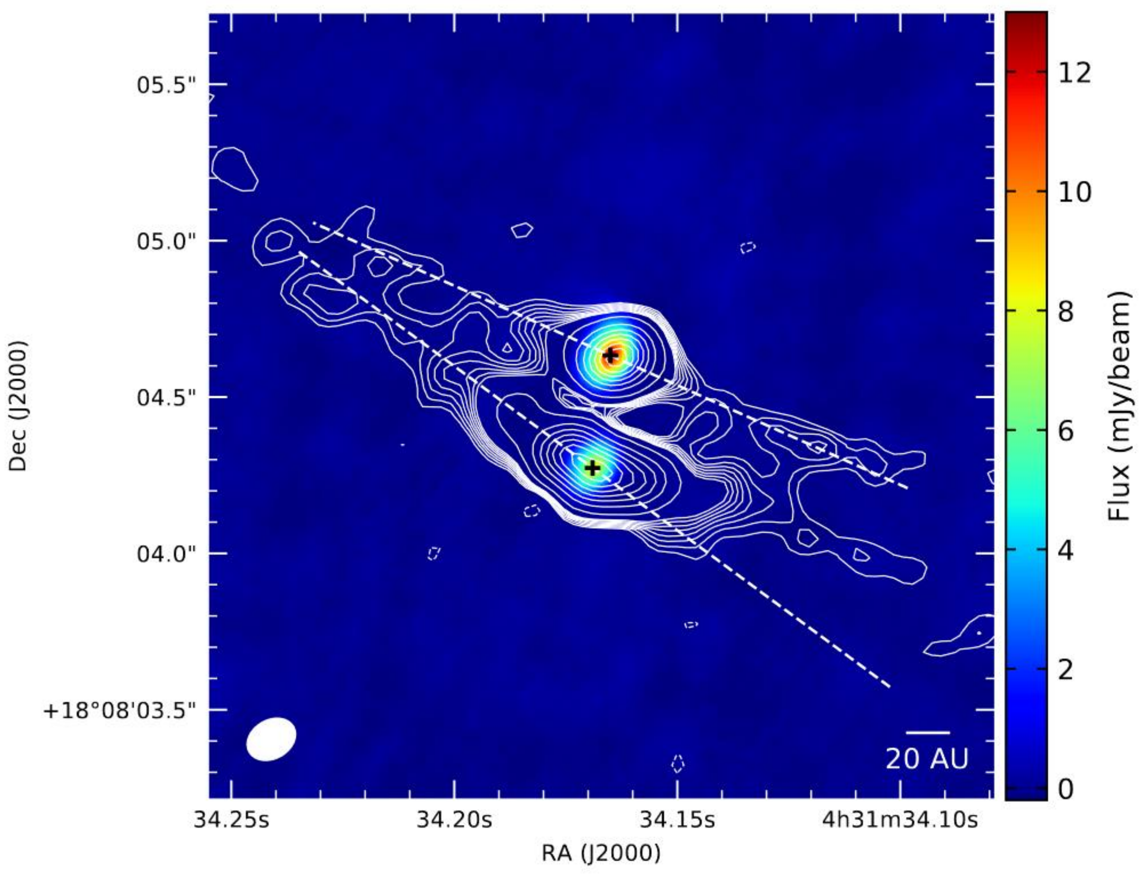
Protostellar jets and outflows play an important role in star formation, helping to extract mass and angular momentum from the system and are closely linked to the accretion processes taking place. However, much remains unknown about the launching and collimation mechanisms of these jets. Centimetre radio emission can play a key role in understanding this, as it can trace the ionized emission close base of the jet, where observations at optical and near-infrared wavelengths are difficult due to extinction. By combining VLA observations at several bands with high resolution observations using e-MERLIN at C band (6 GHz / 5 cm), we carried out a study of L1551 IRS 5, a binary protostellar system located in the Taurus Molecular Cloud, resolving emission down to scales of ~ 10 au. . Our results show a significant degree of variability in the flux density of the jet emission from the two sources in the system, as well as significant changes in the morphology of the two jets. We compared our data with archival data from ALMA to model the spectrum across a large range of frequencies, including the thermal free-free emission from the jet and the thermal dust emission from the disk. This showed that while the southern source contained both jet and dust emission, the northern source contained virtually only dust emission, implying that the radio jet previously seen from the northern source has almost disappeared over the last 20 years. By fitting the spectra of the sources, the ionized mass-loss rates of the jets are derived and it is shown that there is significant variability of up to a factor of ~6 on timescales of ~20 years.

L1551 IRS 5

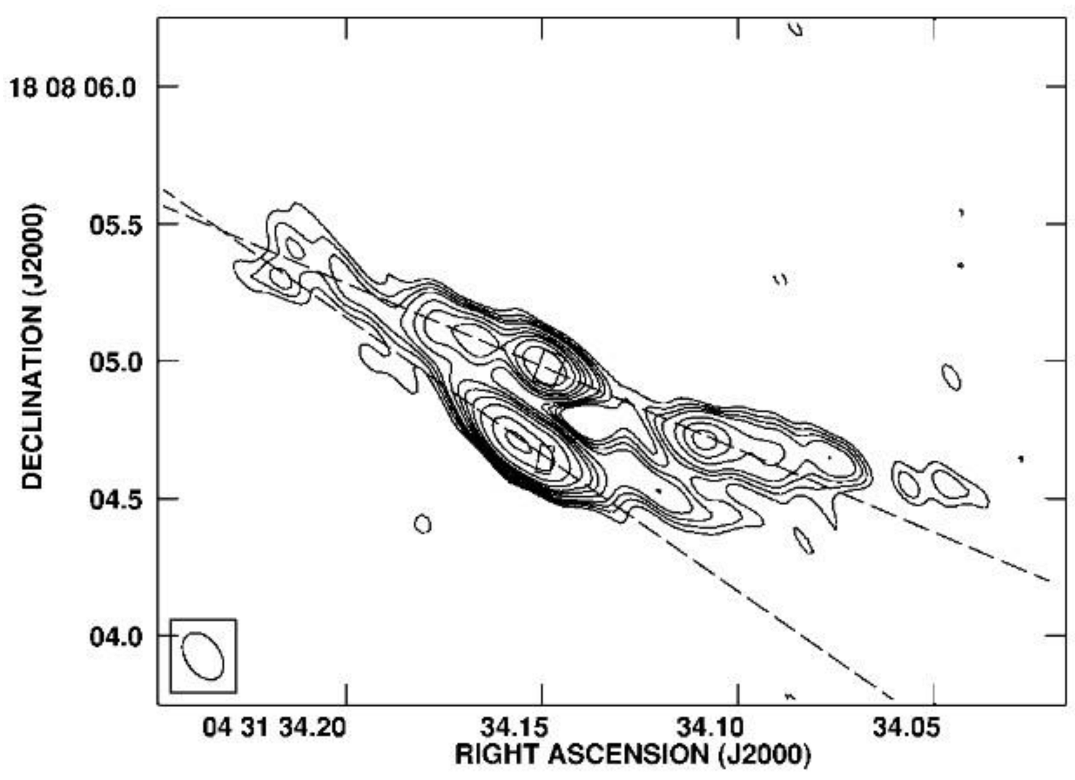
- Deeply embedded young system (~10^5 yr)
- Located in Taurus Molecular Cloud (~140 pc)
- Binary system
  - Northern source: (0.8 $M_\odot$)
  - Southern source (0.3 $M_\odot$)
  - Separation: ~ 0.36", 50 au
- Strong accretion rates (Liseau et al., 2005):
  - N: ~ 6 x 10^{-6} $M_\odot$ yr^{-1}
  - S: ~ 2 x 10^{-6} $M_\odot$ yr^{-1}
- Circumstellar disks seen around sources at mm-wavelengths along with circumbinary ring (Cruz-Sáenz de Miera, 2019; Takakuwa et al., 2020)
- Both sources previously show strong radio jets at cm-wavelengths (Rodríguez et al., 2003)

Observations

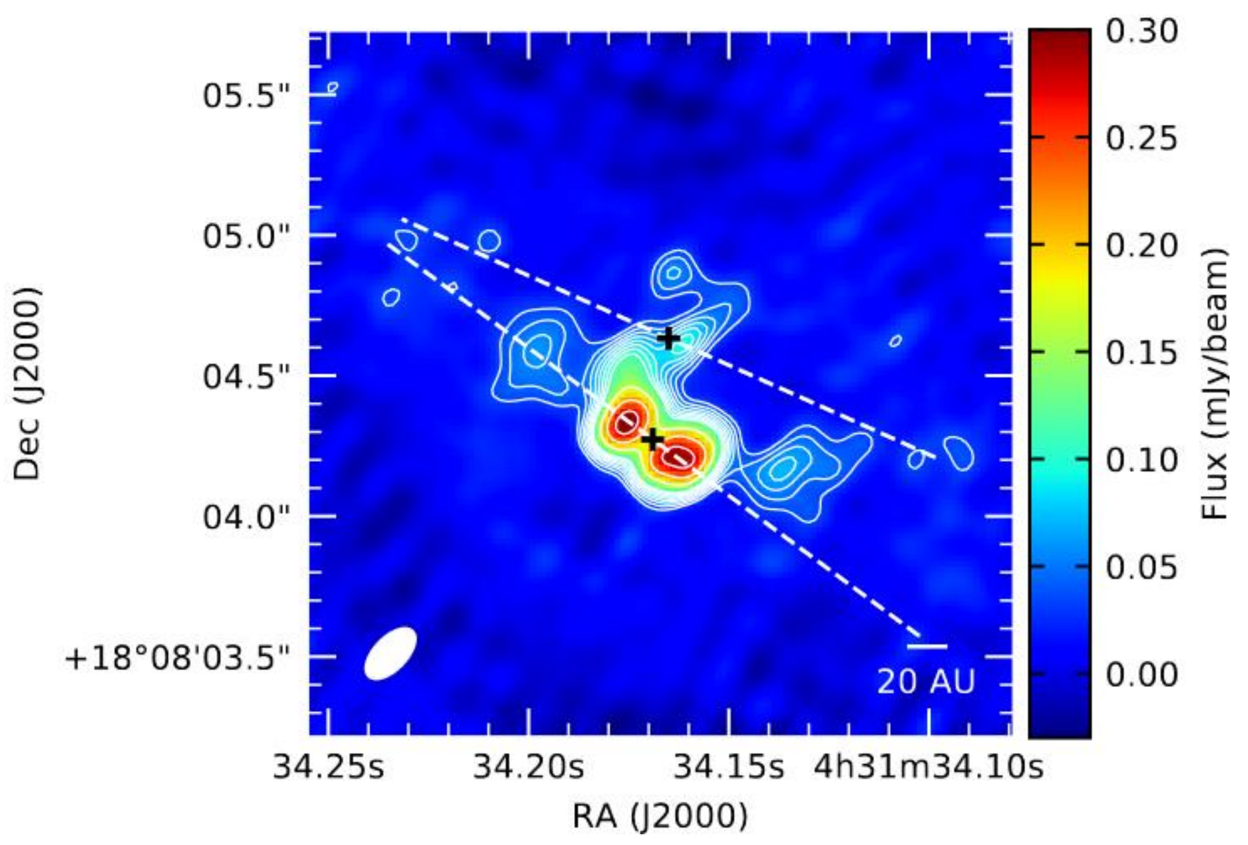
- Very Large Array (VLA):
  - Date: January 2021
  - Bands: K Band (22 GHz, 1.4 cm), Ku Band (15 GHz, 2 cm), X Band (10 GHz, 3 cm), C Band (5 GHz, 6 cm)
- E-Merlin:
  - Date: January 2020
  - Band: C Band (5 GHz, 6 cm)
- ALMA:
  - Archival data
  - Date: Jul – Nov 2017
  - Bands: Band 3 (93 GHz, 3.2 mm), Band 4 (153 GHz, 2 mm), Band 6 (225 GHz; 1.3 mm), Band 7 (336 GHz, 0.9 mm)
- In C Band, the VLA and E-Merlin observations were combined to achieve greater uv-coverage and lower noise



VLA Ku Band (15 GHz, 2 cm) of L1551 IRS 5 (contours) on ALMA Band 4 (153 GHz, 2 mm) image (colourscale) with peak of 2 mm emission (black cross) and jet position angle (white dotted line) indicated



3.6 cm (8.3 GHz) VLA image of L1551 IRS 5 from Rodríguez et al. (2003) . Synthesized beam of 0.18" x 0.12", PA=35°



Combined VLA+E-Merlin C Band (5 GHz, 6 cm) of L1551 IRS 5 (contours + colourscale) with peak of 2 mm ALMA emission (black cross) and jet position angle (white dotted line) indicated. Synthesized beam of 0.22" x 0.11", PA=-43°

Results

Resolution of ~0.11" achieved in VLA+E-Merlin image

Emission seen at ~0.1" from disk center, implying collimation occurs at <10 au from source

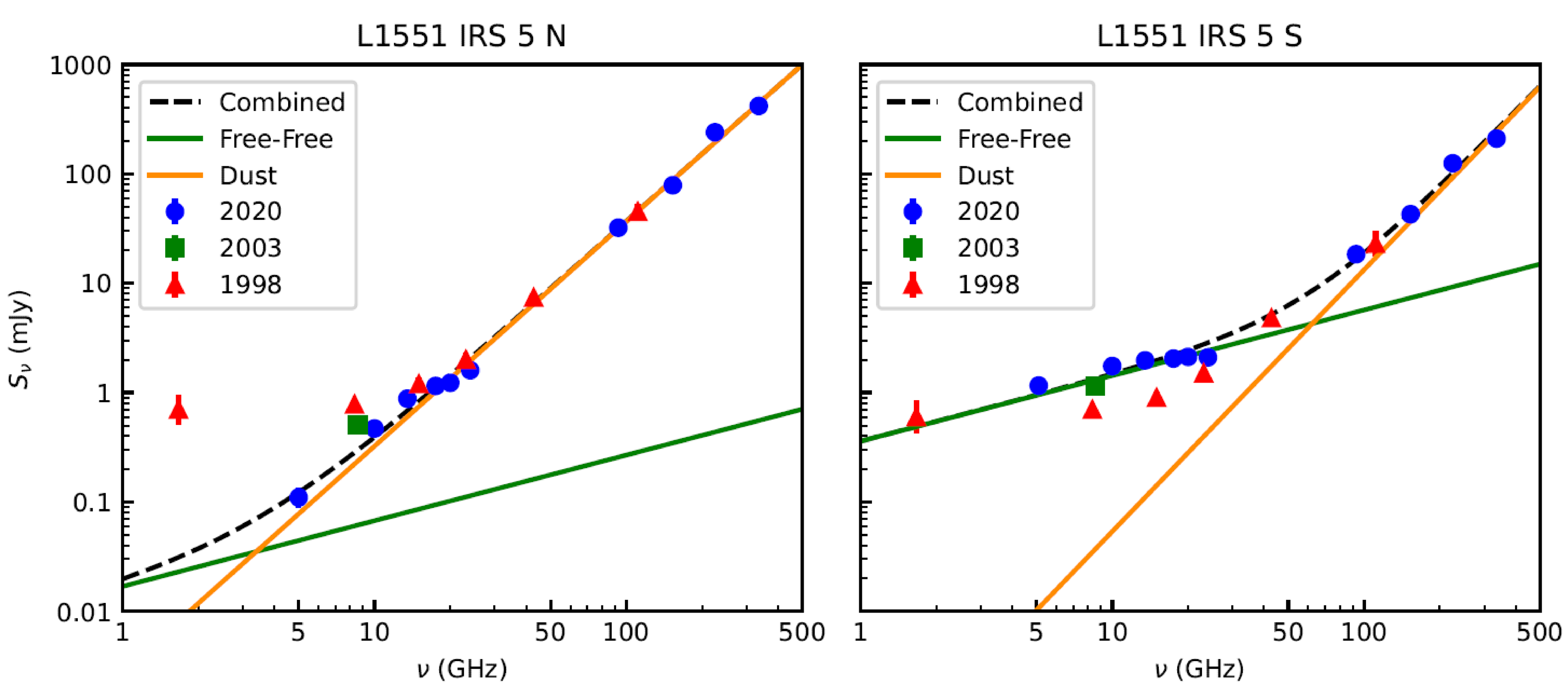
Jets in both sources show a high degree of variability in flux density as well as significant changes in morphology compared to Rodríguez et al. (1998) and Rodríguez et al. (2003)

- Partially due to proper motion of knots in jet

N source

- Much weaker at low frequencies than previously
- Jet emission decreased drastically
- Several knots seen in Rodríguez et al. (2003) along jet axis, virtually none in new image
- Traces of jet still seen in Ku band image

- S source
  - Jet emission much stronger
  - Two emission lobes clearly seen either side of centre of disk emission



Spectrum of N source (left) and S source (right) from E-Merlin, VLA, and ALMA data from this work (blue circles). Also plotted are the data from Rodríguez et al. (1998) (red triangles) and from Rodríguez et al. (2003) (green squares). The combined spectral fit is indicated by the dashed black line with the free-free component shown by the green line and the dust emission component shown by the orange line.

Nature of Emission

- Spectra of both sources modelled including:
  - Thermal free-free emission (α ~ 0 - 1)
    - Associated with jets
  - Dust emission (α ~ 2 - 4)
    - Associated with disk
- Jet emission of both sources varies a lot while dust emission has not varied at all
- N source
  - Very little jet emission
  - Almost entirely dust emission
  - Factor of ~ 6 decrease in flux density compared to Rodriguez et al. (1998)
- S source
  - Opt. thick and opt. thin free-free emission clearly seen
  - Factor of ~2 increase in flux density at 5 GHz compared to Rodriguez et al. (1998)

Mass-Loss Rate

- Ionized Mass Loss rates derived
  - N source: $(0.8 \pm 0.5) \times 10^{-9}$ $M_\odot$ yr^{-1}
  - S source: $(6.0 \pm 0.5) \times 10^{-9}$ $M_\odot$ yr^{-1}
- Can compare with total mass-loss rate
  - $4.9 – 5.4 \times 10^{-7}$ $M_\odot$ yr^{-1} (Sperling et al., 2021)
  - Implies ionization fraction of ~ 1% in jet

Conclusions

- Both sources show high degree of variability in jet emission in both morphology and flux density
- Radio jet from N source has almost completely disappeared in last 20 years
- In contrast, radio jet from S source has increased significantly in same time period

References

Coughlan et al., 2017, ApJ, 834, 206
Cruz-Sáenz de Miera, 2019, ApJL, 882, L4
Liseau et al., 2005, ApJ, 619, 959
Rodríguez et al., 1998, Nature, 395, 355
Rodríguez et al., 2003, ApJ, 586, L137-L139
Sperling et al., 2021, A&A, 650, A173
Takakuwa et al., 2020, ApJ, 898, 10