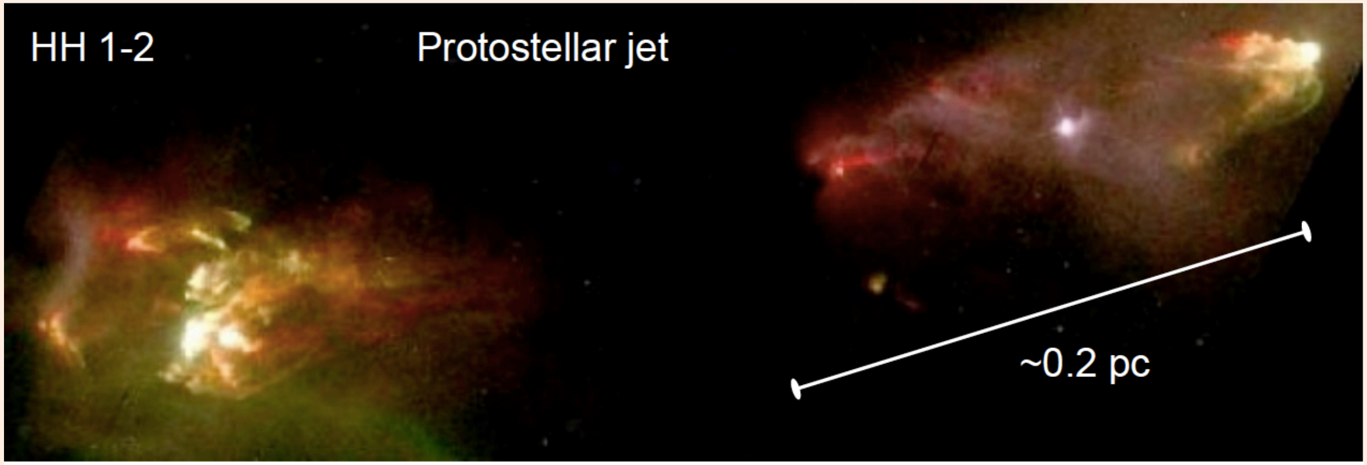
Protostellar Jets in the ngVLA Era

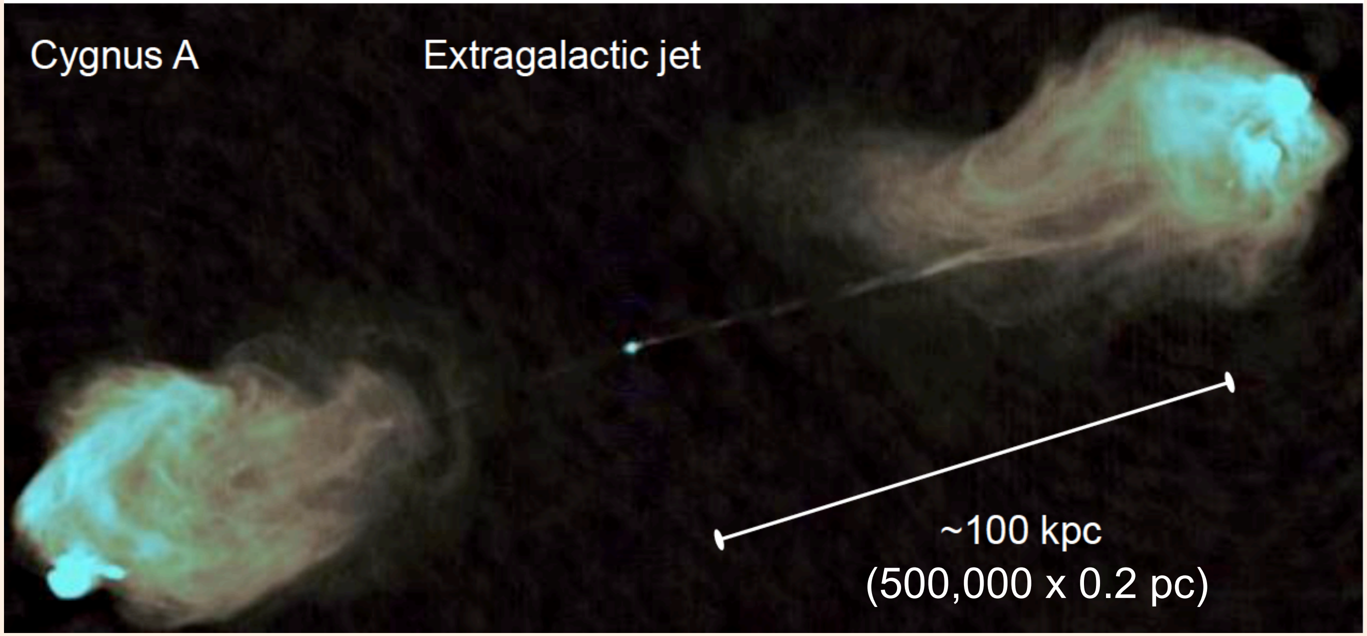
Luis F. Rodríguez (IRyA-UNAM, Mexico)

In collaboration with G. Anglada, C. Carrasco-González, L. Zapata, A. Palau, R. Galván-Madrid, C. Rodríguez-Kamenetzky, A. Araudo, J.M. Torrelles, J.M. Masqué, L. Loinard, S. Dzib, G. Pech, O. Morata, H.B. Liu, S. Curiel, J. Martí

Astrophysical Jets

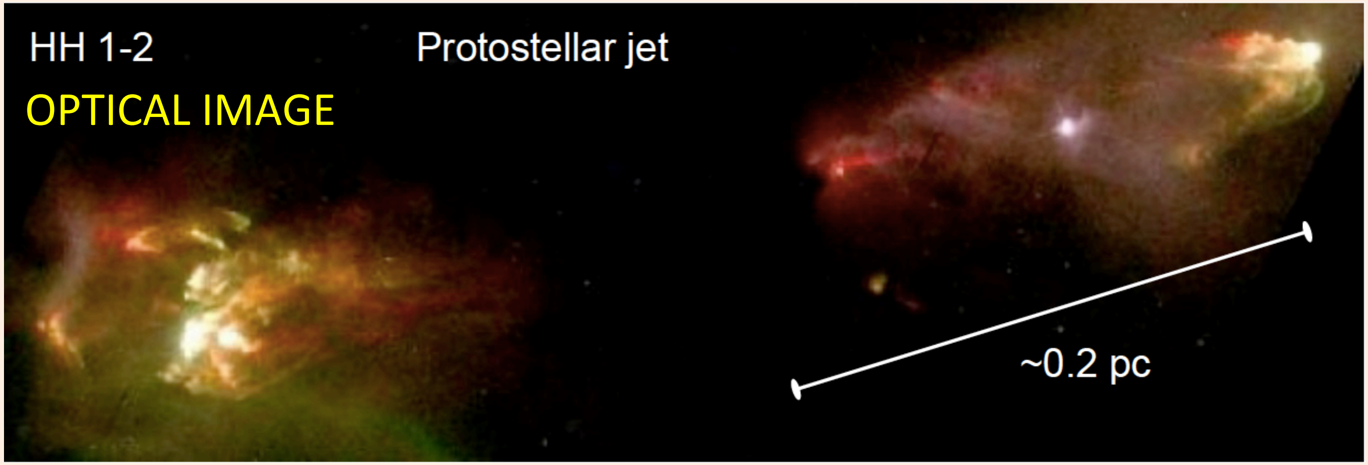
Jets are ubiquitous in Astrophysics (also seen in X-ray binaries, planetary nebulae, GRB supernovae)

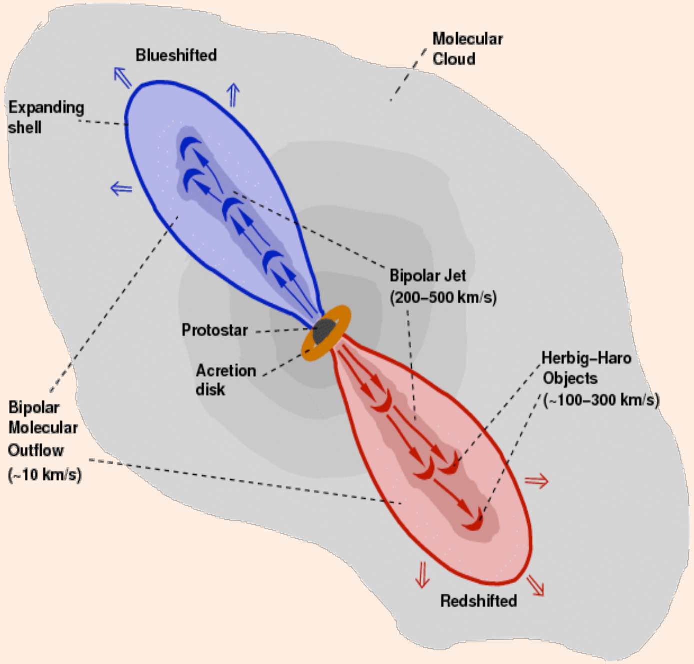




Jets in YSOs

Jets are intrinsically associated to the SF process.





Disk-jet scenario probably valid in the formation of stars of all masses.

Gas entrained by the jet produces molecular outflows and HH objects.

I will concentrate on the compact, ionized jet component.

Jets in YSOs

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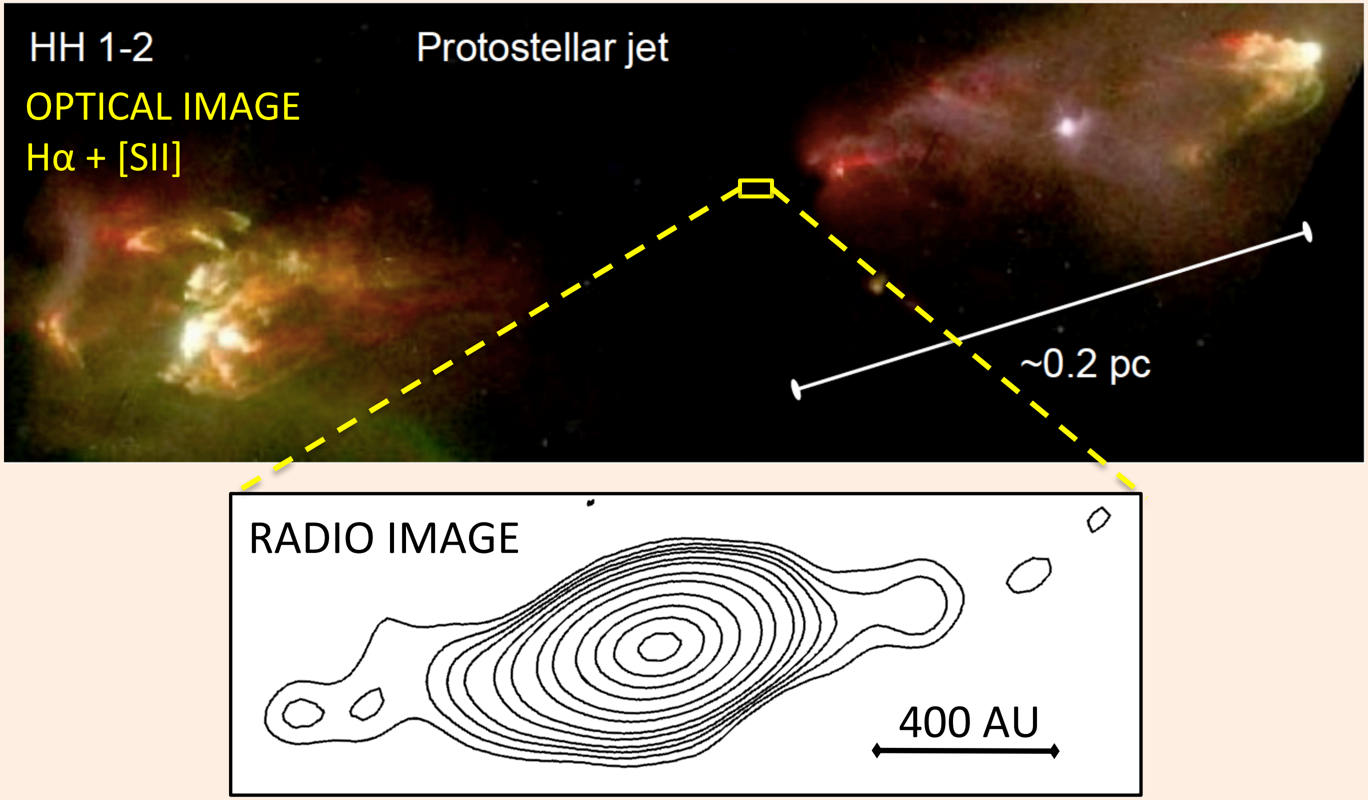
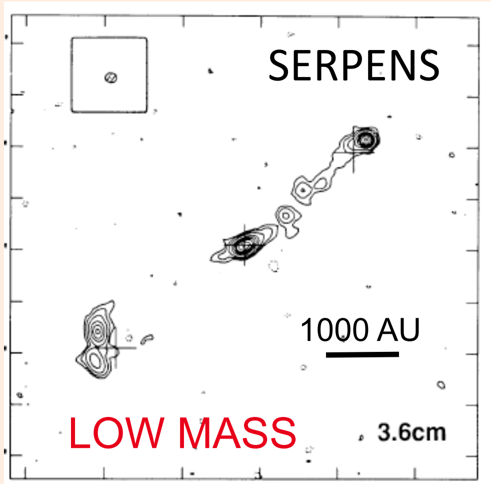
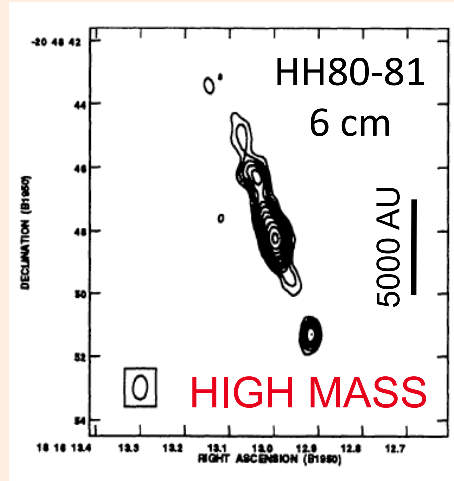


Radio emission from YSOs traces the "base" of the jets, which is usually obscured at other wavelengths.

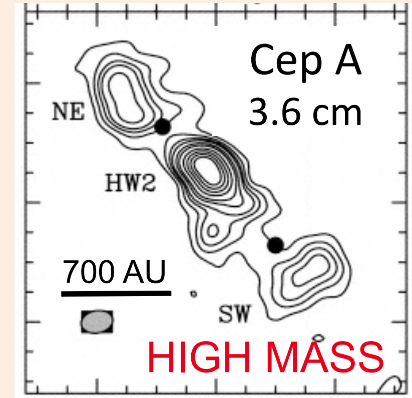
Examples of Radio Jets in YSOs



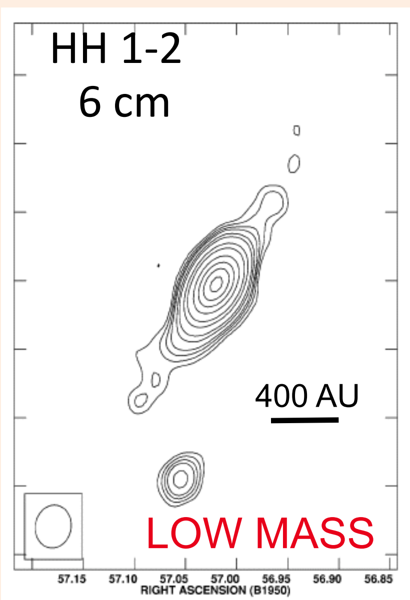
(Curiel et al. 1993)



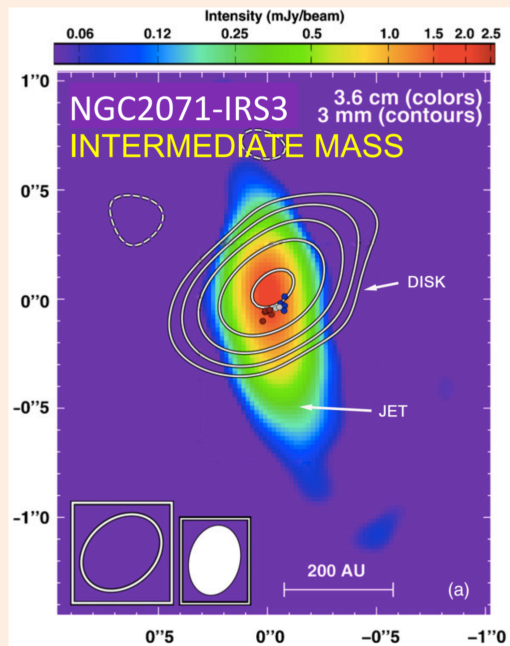
(Martí et al. 1993)



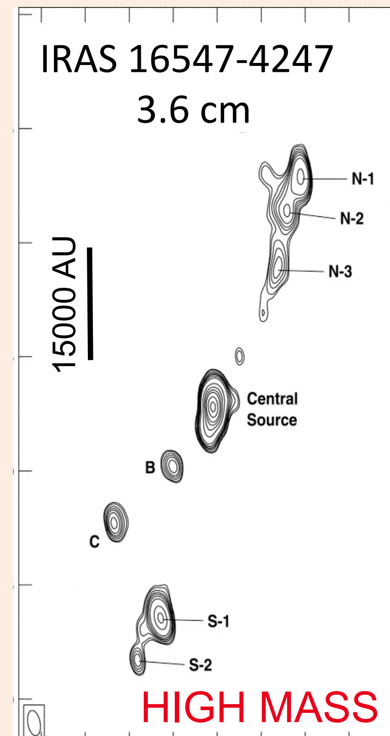
(Curiel et al. 2006)



(Rodríguez et al. 2000)



(Carrasco-González et al. 2012)



(Rodríguez et al. 2008)

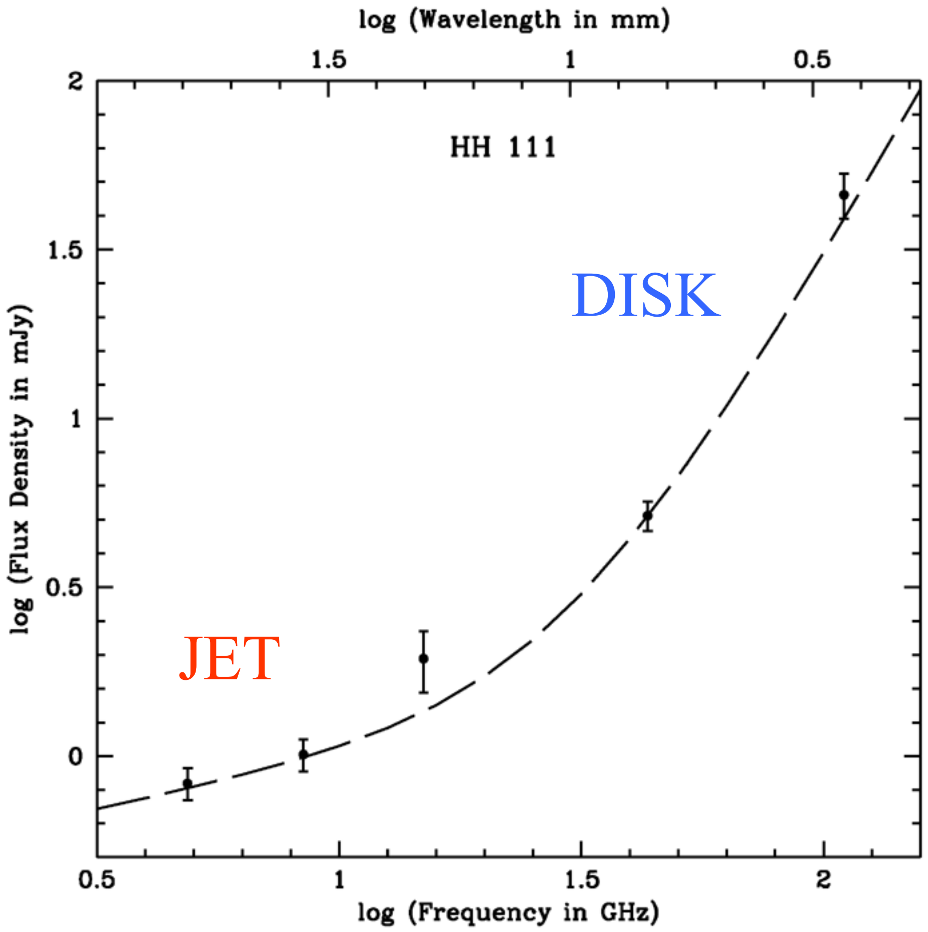
Table 1: Properties of Selected Angularly Resolved Radio Jets in YSOs

Source	$L_{\rm bol}$ ($L_\odot$)	$M_\star$ ($M_\odot$)	d (kpc)	S_ν (mJy)	α	θ_0 (deg)	Size (AU)	V_j (km s^{-1})	$t_{\rm dyn}$ (yr)	ε	$\dot{M}_i$ ($M_\odot$ yr^{-1})	r_0 (AU)	Refs.
HH 1-2 VLA1	20	$\sim$1	0.4	1	0.3	19	200	270	2	0.7	1×10^{-8}	$\leq$11	1, 2, 3, 4
NGC 2071-IRS3	$\sim$500	4	0.4	3	0.6	40	200	400[a]	3	1	2×10^{-7}	$\leq$18	5, 6, 2, 7
Cep A HW2	1×10^4	15	0.7	10	0.7	14	400	460	3	0.9	5×10^{-7}	$\leq$60	8, 9, 10, 11, 12
HH 80-81	2×10^4	15	1.7	5	0.2	34	1500	1000	7	0.6	1×10^{-6}	$\leq$25	13, 14, 15, 16, 17, 18

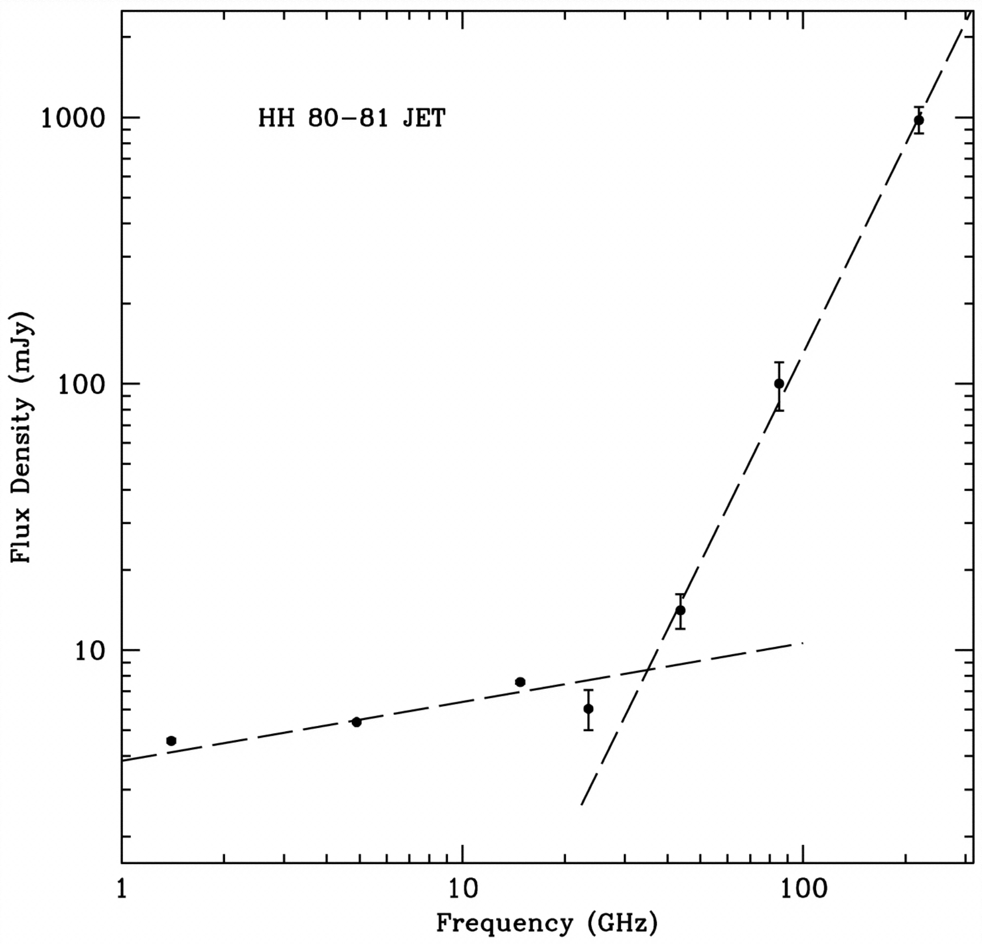
[a]Assumed.

Characteristics of Thermal Radio Jets

- Elongated morphology, indicating collimation at small scales (< 100 AU).
- Association with both high- and low-luminosity objects.
- Alignment within a few degrees with the large-scale outflow.
- Weak sources, with typical flux densities 0.01-1 mJy.
- Velocities of a few 100 km/s to a few 1000 km/s.
- Dynamical time scales of only a few years (extremely young material).
- Ionization starts at r_0<10 AU.
- Positive or flat spectral indices. Well described by thermal free-free jet models of Reynolds (1986): $S_\nu \propto \nu^{1.3-0.7/\epsilon}$, $\theta_\nu \propto \nu^{-0.7/\epsilon}$ ($w \propto r^\epsilon$, ϵ=1 for a conical jet)



Rodriguez et al. (2008)

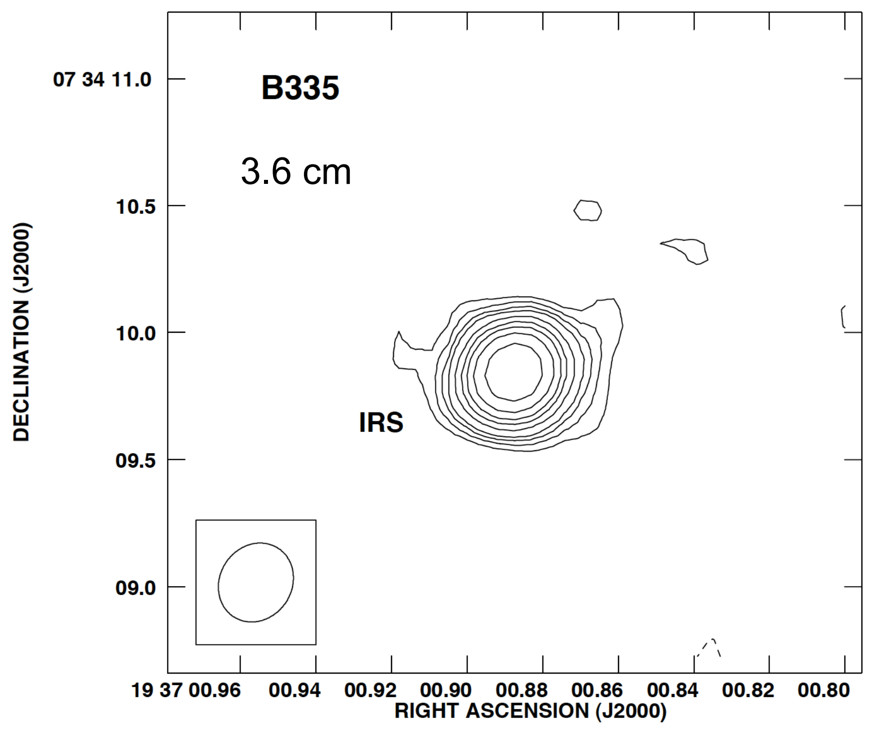


Gómez et al. (2003)

Continuum observations at several frequencies reveal characteristic spectrum of jet+disk.

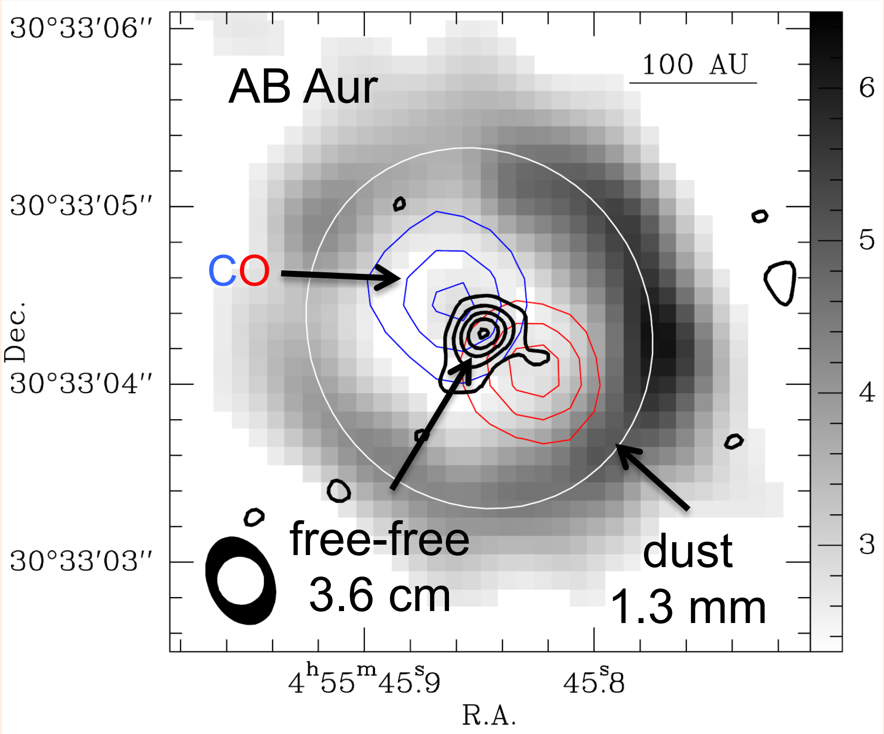
Jets in All Phases of Stellar Formation

CLASS 0 OBJECT



(Reipurth et al. 2002)

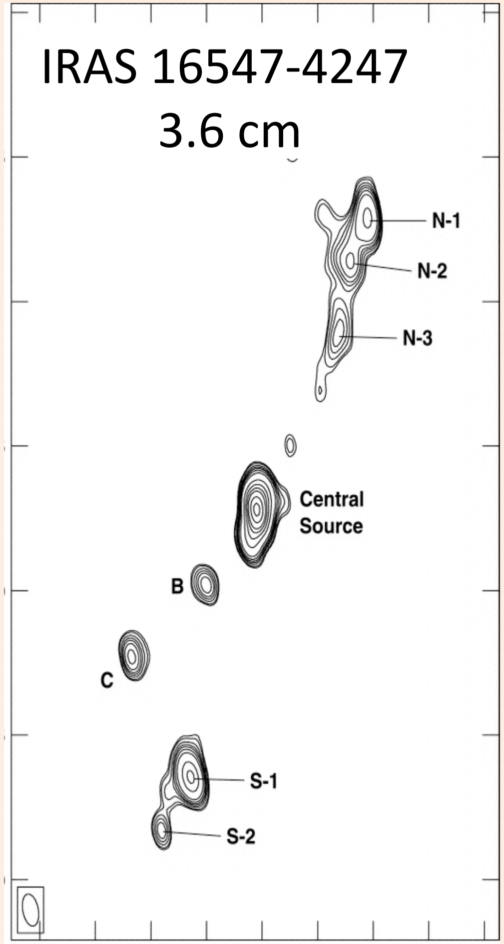
TRANSITIONAL DISK



(Rodríguez et al. 2007, Tang et al. 2012)

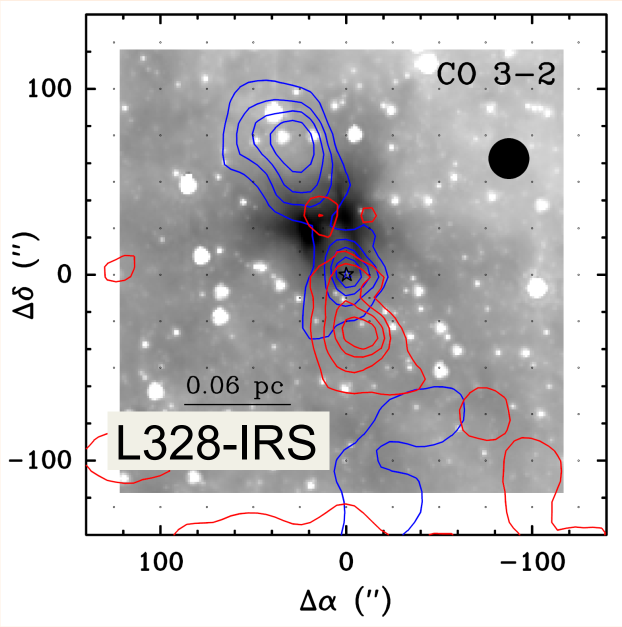
Jets Across the Stellar Mass Spectrum

JETS IN HIGH MASS PROTOSTARS

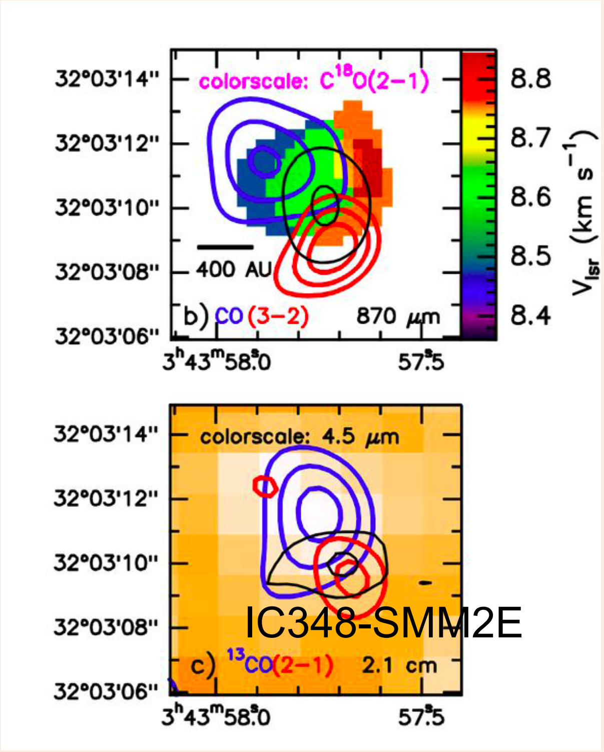


(Rodríguez et al. 2008)

OUTFLOWS IN PROTO-BROWN DWARFS

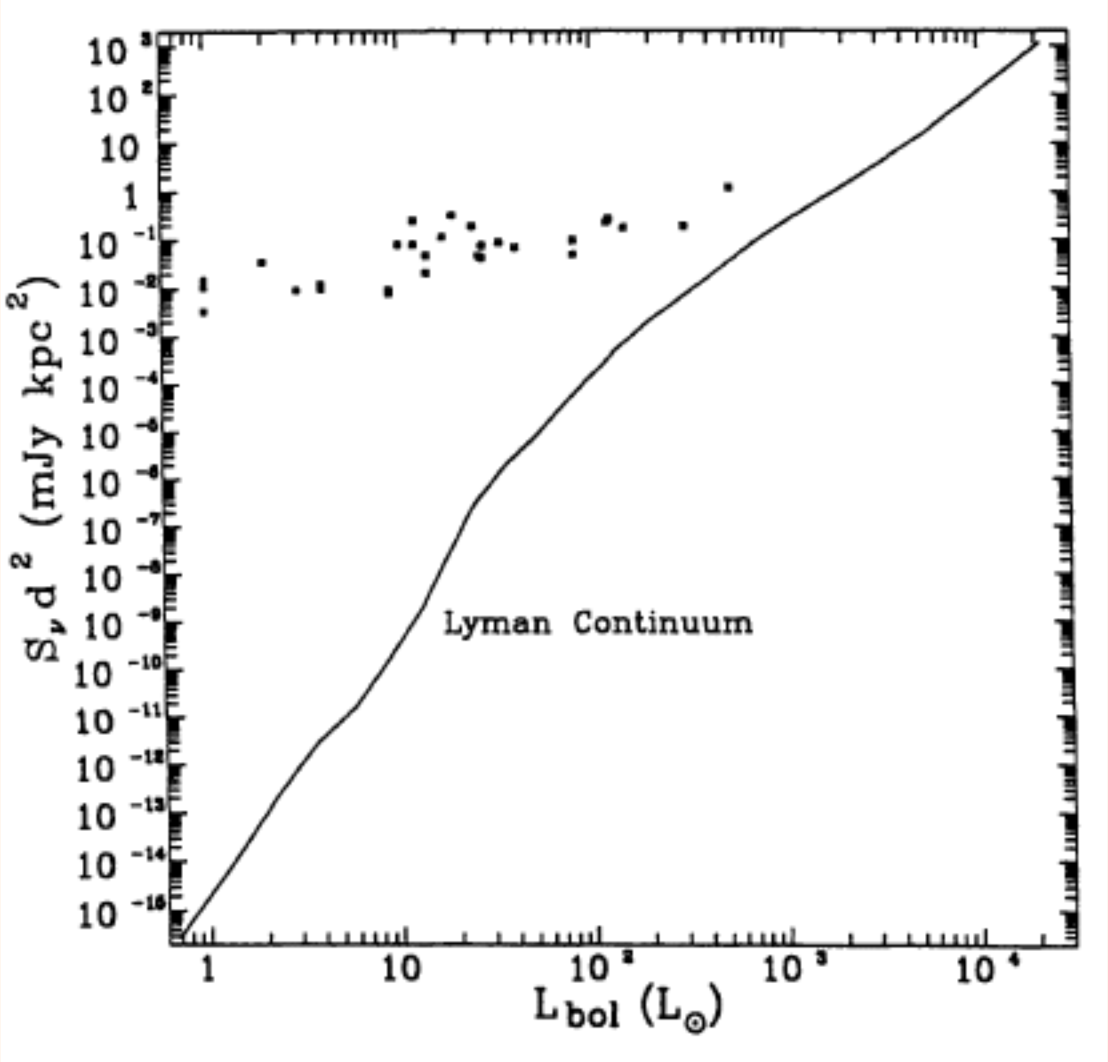


(Lee et al. 2013)



(Palau et al. 2014)

Nature of the cm Emission of Jets

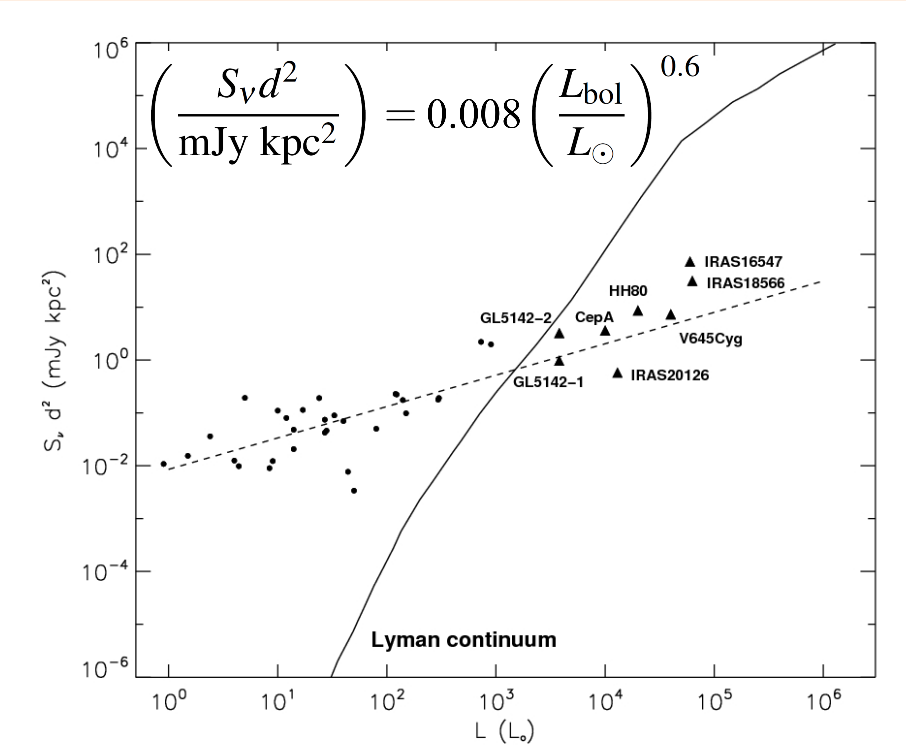


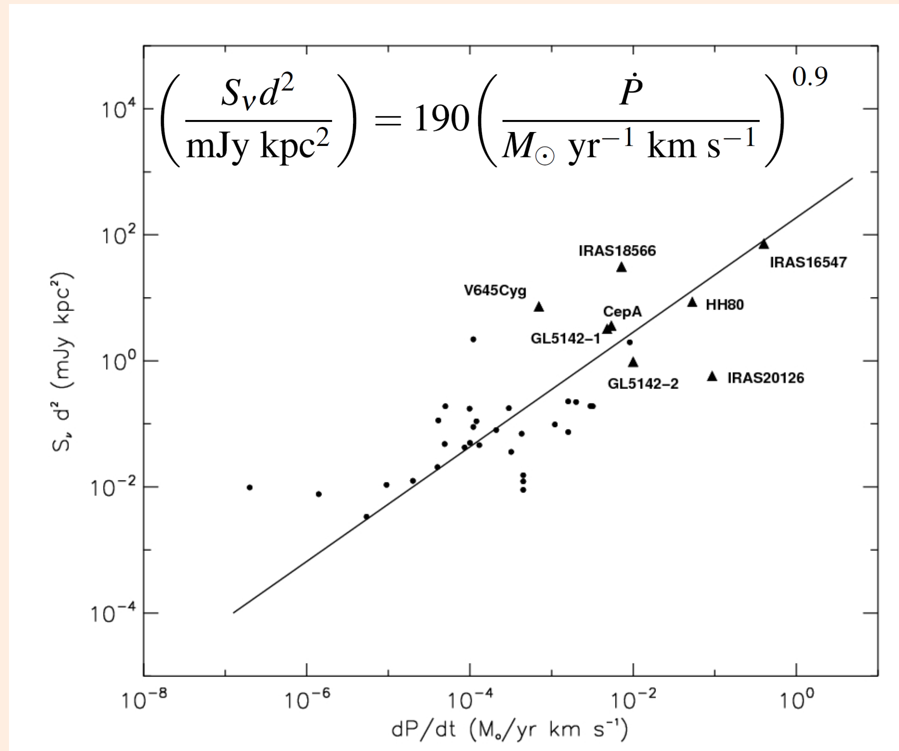
(Anglada 1995)

Emission from YSO radio jets is thermal free-free emission from partially ionized material.

Unlike HII regions, photoionization is not a viable ionizing mechanism, at least for objects of low bolometric luminosity.

Bolometric Luminosity, Outflow, and Radio Continuum Correlations





- These correlations (Anglada 1995, 1996) are consistent with the predictions of a simple model of **SHOCK IONIZATION** (Curiel et al. 1987, 1989).
- Correlations hold for jets of both LOW (very low?) and HIGH LUMINOSIY objects.
- Can be used to discriminate between jets (earlier stage), that should fall on the correlations, and UCHII regions (later stage) that should fall near the Lyman line.

Radio Recombination Lines

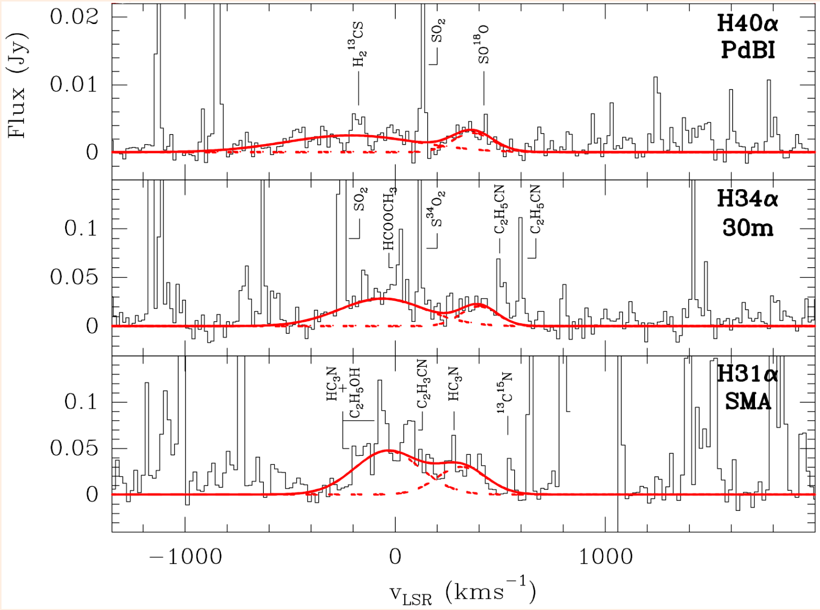
Radio jets are expected to show radio recombination lines (RRLs). In combination with proper motions should provide **3D kinematics**.

Assuming LTE and a standard biconical jet, at cm wavelengths, it can be shown that the expected line to continuum flux ratio is:

$$\frac{S_L}{S_C} = 0.19\left(\frac{\nu_L}{\text{GHz}}\right)^{1.1}\left(\frac{T}{10^4\ \text{K}}\right)^{-1.1}\left(\frac{\Delta V}{\text{km s}^{-1}}\right)^{-1}(1+Y^+)^{-1}$$

($Y^+ = He^+/H^+$)

RRLs from a jet are expected to be wide (~100 km/s), and therefore weak at cm wavelengths (S_L/S_C ~ 0.02).



So far, there are no detections of RRLs in jets at the expected LTE level. Broad radio recombination maser lines (flux density ~5 larger than LTE) have been detected toward the Cep A HW2 jet (Jiménez-Serra et al. 2011).

More sensitive observations are needed to start using RRLs as tools to study jet kinematics.

What can the ngVLA do for jets from young stars?

Combination of higher sensitivity and angular resolution will impact:

-Understanding of jet acceleration and collimation mechanisms.

-Disentangle multiplicity.

-Follow-up of discrete ejecta to determine velocity in plane of the sky.

-Observations of radio recombination lines will give radial velocity, 3-D kinematics

-Core of jet is usually thermal, but lobes can be non-thermal. Acceleration of electrons to relativistic velocities.

-Relation of “fresh” gas seen in thermal jets with older ejecta in bipolar outflows and HH objects.

-Larger sample of sources is needed to understand correlations of radio emission with bolometric luminosity, rate of momentum and age.

-To understand disks, you need to understand jets and to understand jets you need to understand disks.

-Jet acceleration and collimation mechanisms.

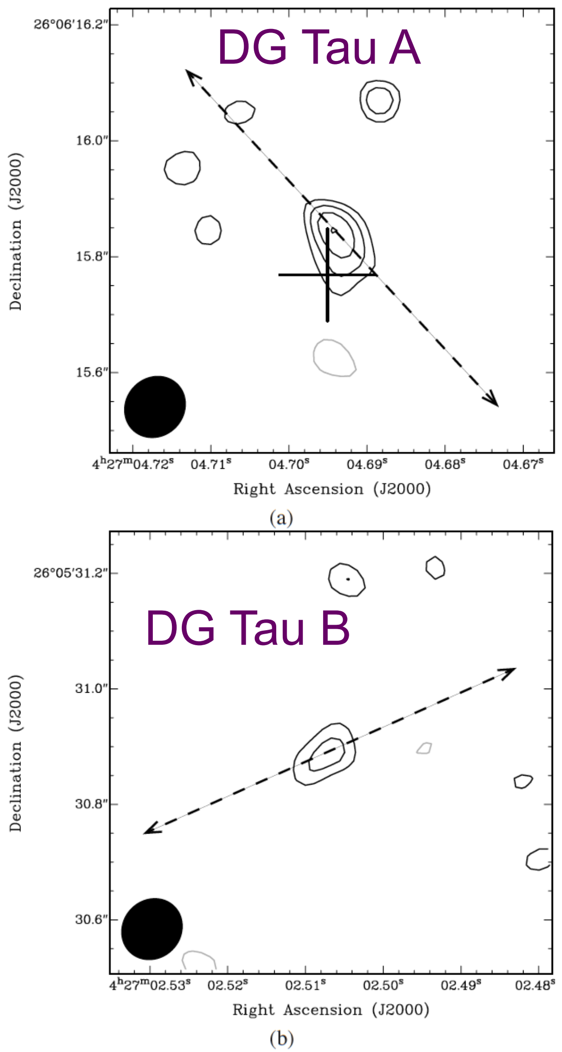


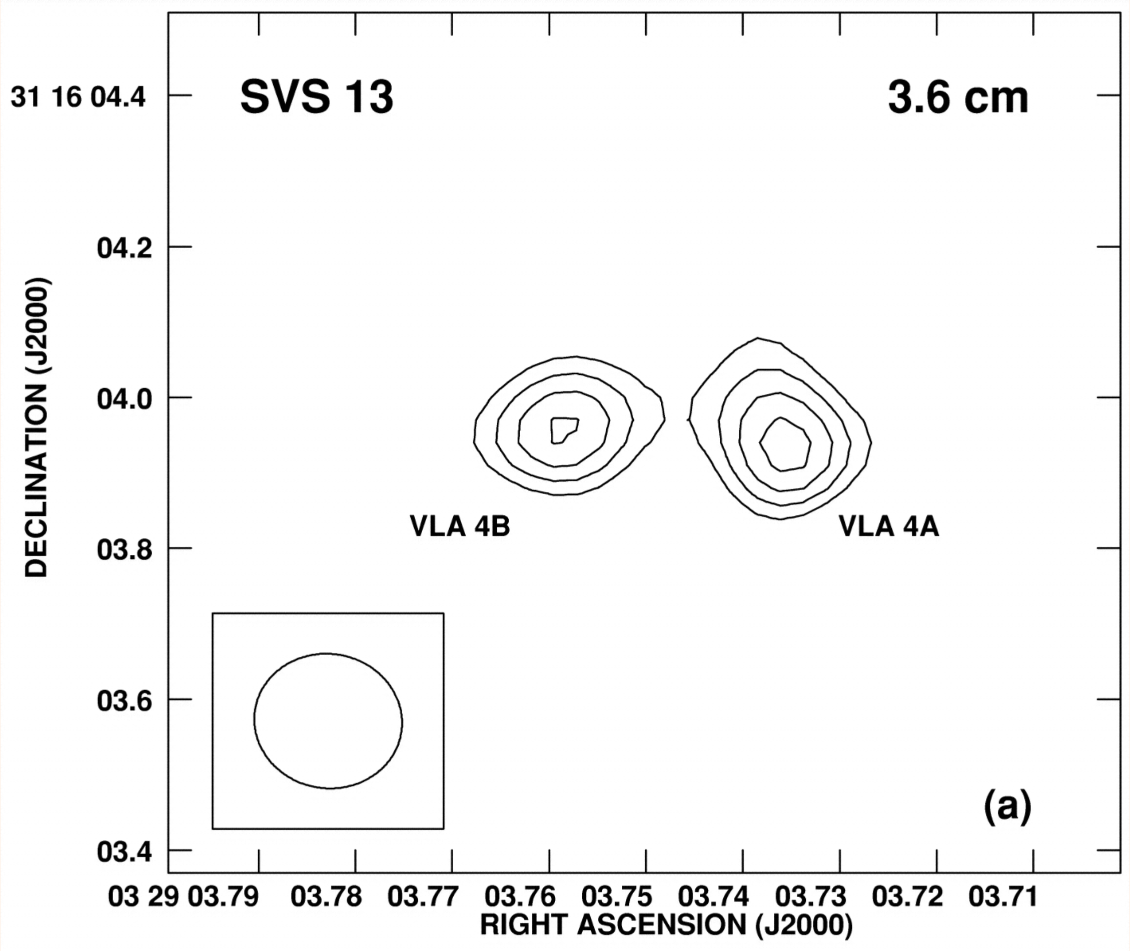
Figure 1. e-MERLIN maps at 5 GHz for (a) DG Tau A and (b) DG Tau B with contours at -3 (grey), 3, 4, 5, and 6 σ_{rms}, where $\sigma_{rms} = 24\,\mu$Jy beam^{-1} for DG Tau A and 25 μJy beam^{-1} for DG Tau B. The known outflow direction in both cases is shown as a dashed line, and the optical position for DG Tau A is shown as a cross (see Section 3).

Very important unsolved problem, since jets are a very common astrophysical phenomenon.

Extraordinary angular resolution and sensitivity are needed. For example, jets only marginally detected with e-MERLIN (Ainsworth et al. 2013). Collimation present inside a few AU.

Evidence for lower velocity, lower collimation outflow components in molecular emission.

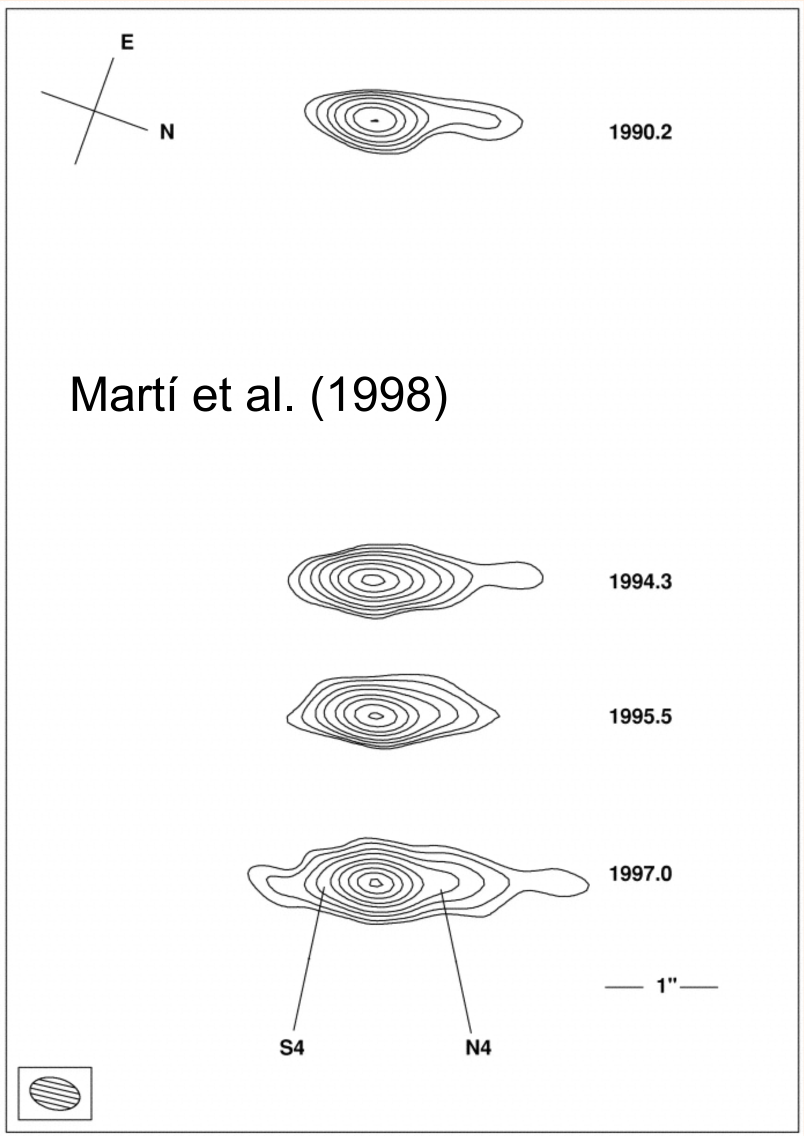
Binarity and Multiplicity

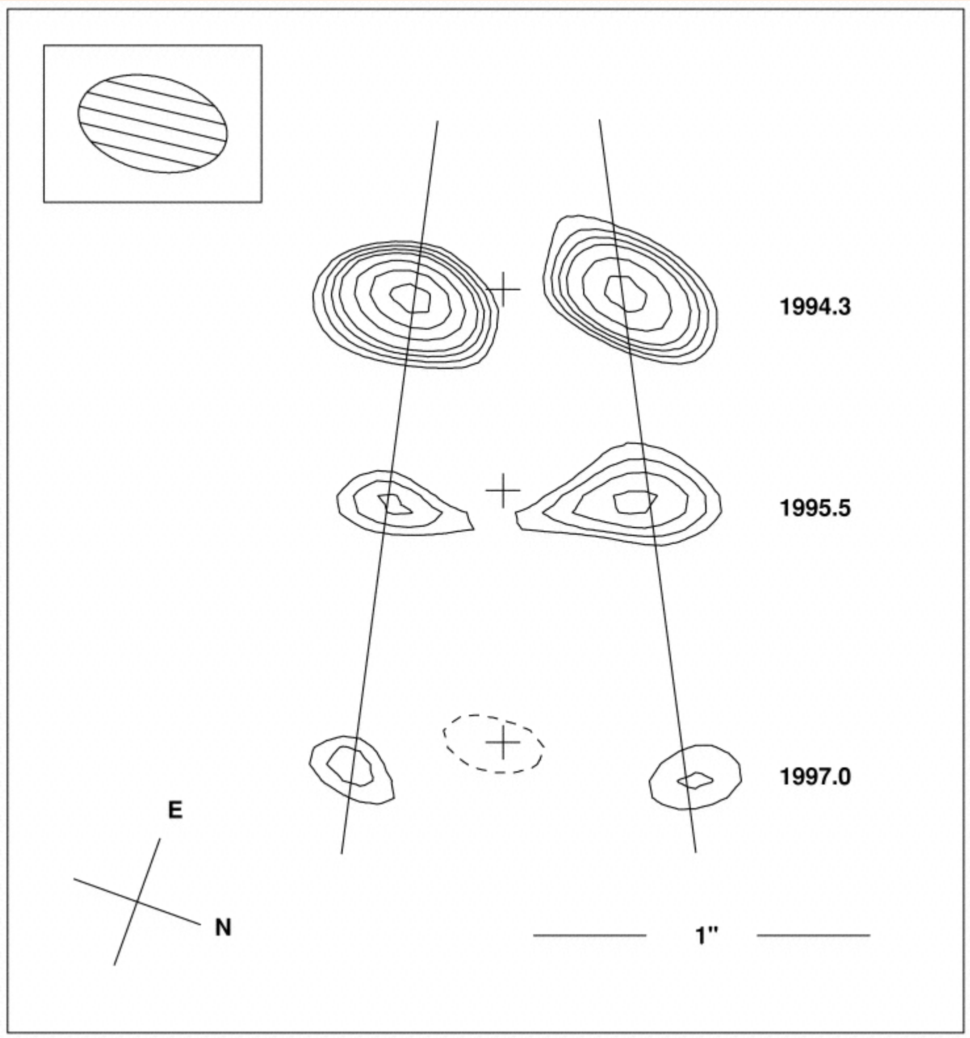


When observed with high angular resolution many sources turn out to be binaries and in the case of massive protostars even multiples.

Anglada et al. (2004)

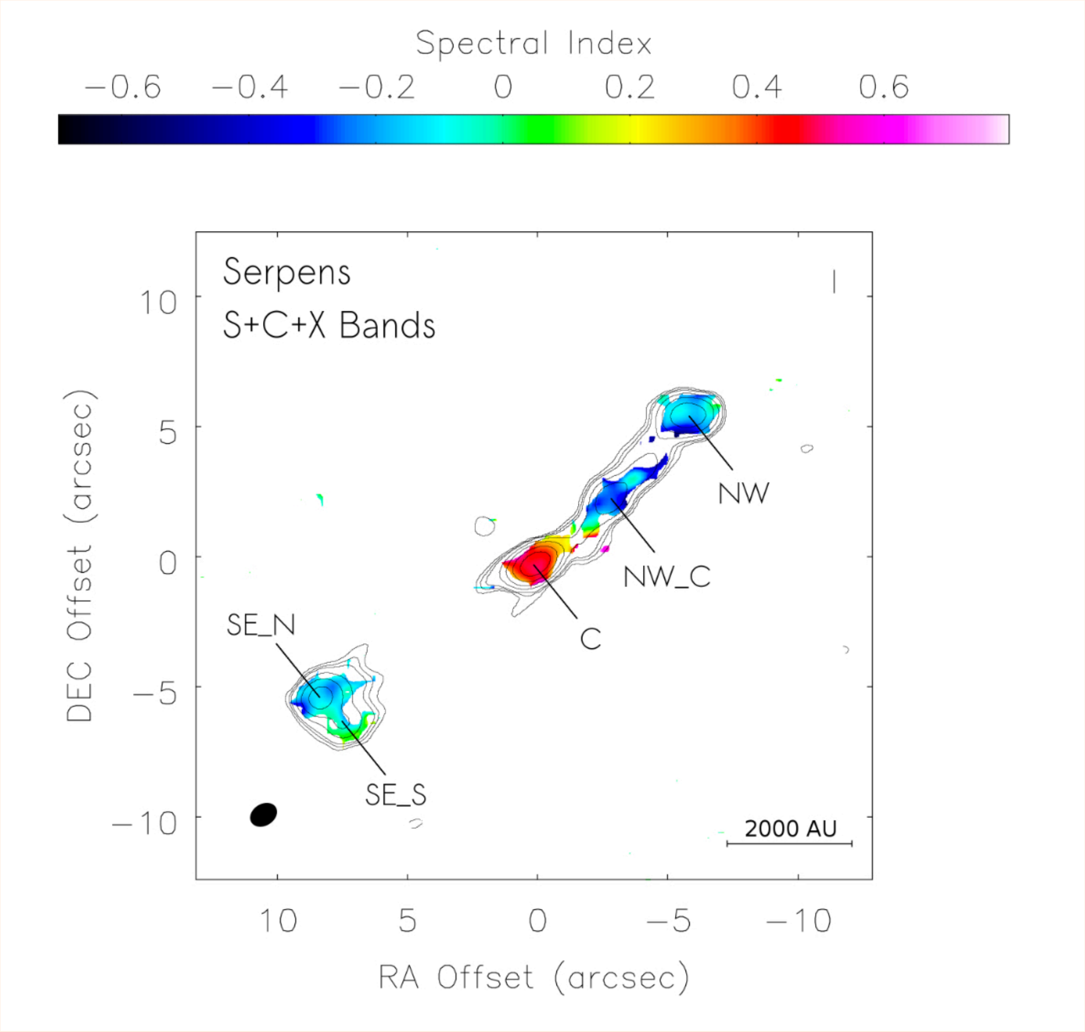
Proper motions of knots: Now feasible only in a handful of sources





…with RRLs you can get 3-D kinematics. Many-line stacking with the ngVLA.

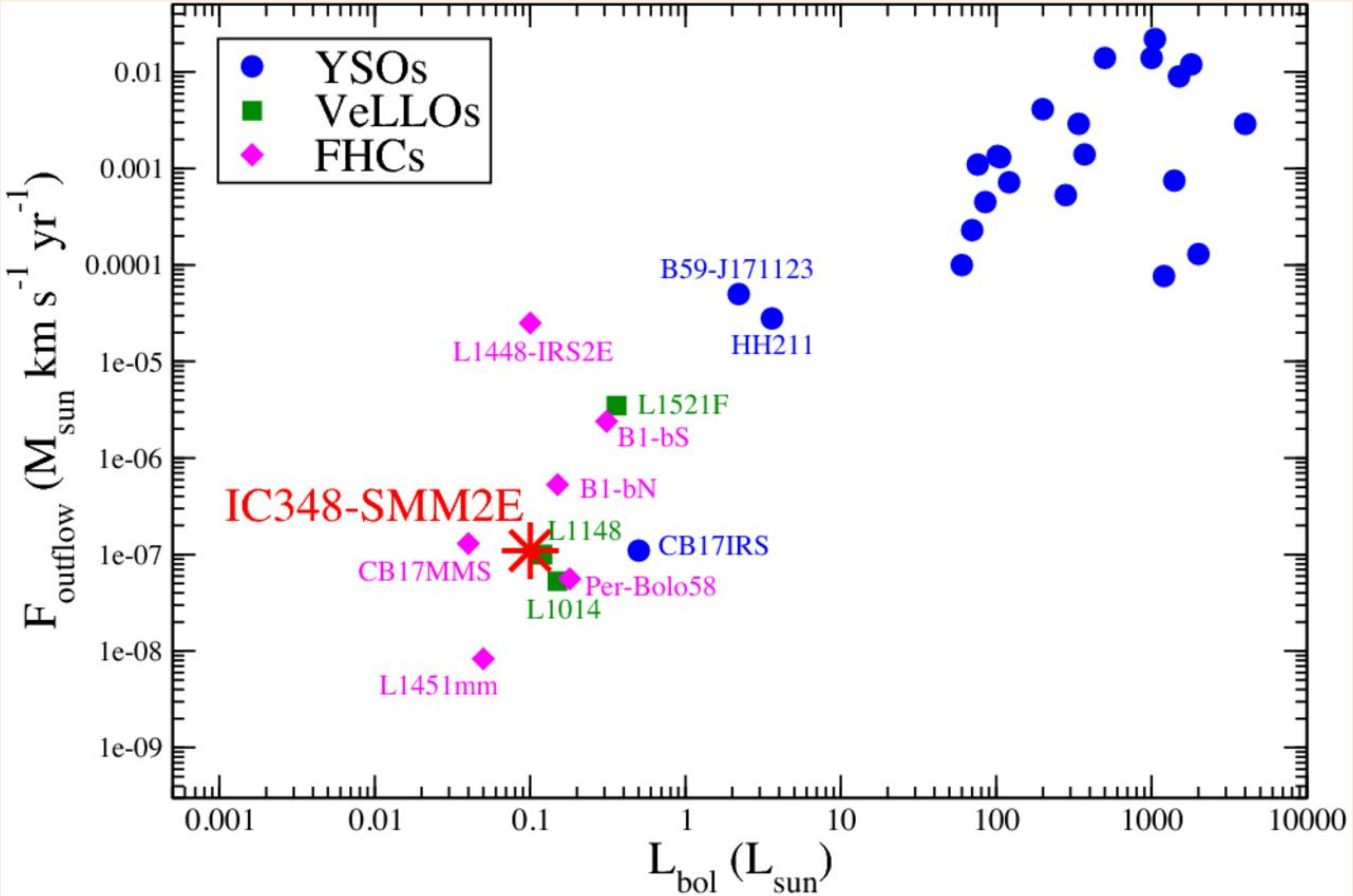
Non-thermal component



-Core of jet is usually thermal, but lobes can be non-thermal. Acceleration of electrons to relativistic velocities in our backyard. Relation of fresh with old ejecta.

Rodriguez-Kamenetzky et al. (2016)

Outflow-luminosity-age correlations (we need many sources)



Jets ↔ Disks

- Inside inner few AUs emission from jet and disk will be present. We will have to understand both components.
- To understand disks, you need to understand jets and to understand jets you need to understand disks.

Thank you