Formation of Massive Stars

- With great advances achieved in our understanding of low mass star formation, it is tempting to think of high mass star formation simply as an extension of low mass star formation.
- However…

Problems with the study of massive star formation(1)

$$\tau_{K-H} \approx \frac{GM^2}{RL}$$ Kelvin-Helmholtz time

$$For\ M \geq 20\ M_{SUN};\ L \propto M^4\ and\ R \propto M$$

$$\frac{\tau_{K-H}}{yr} \approx 70{,}000 \left(\frac{M}{20\ M_{sun}} \right)^{-3}$$

=> The more massive the star, the less time it spends in the pre-main sequence…

Problems with the study of massive star formation(2)

$$\dot{N}(>M) \approx 0.003\left(\frac{M}{20\,M_{SUN}}\right)^{-3}$$

Rate of massive star formation in the Galaxy

$$N_{PMS}(>M) \approx \frac{\tau_{K-H}}{yr} \times \dot{N}(M > 20M_{SUN}$$

$$N_{PMS}(>M) \approx 200\left(\frac{M}{20\,M_{SUN}}\right)^{-6}$$

=> Massive, pre-main sequence stars are very rare…

Summary of past lecture

Model of accretion via disk and ejection via collimate outflows (jets) successful for formation of solar-type stars and even brown dwarfs.

Can this model be extended to high mass (>10 solar masses) stars?

Some problems with extending the picture of low-mass star formation to massive stars:

- Radiation pressure acting on dust grains can become large enough to reverse the infall of matter:
  - $F_{\mathrm{grav}} = GM_* m/r^2$
  - $F_{\mathrm{rad}} = L\sigma/4\pi r^2 c$
  - *Above 10 M_{sun} radiation pressure could reverse infall*

So, how do stars with $M_*>10M_\odot$ form?

- Accretion:
  - Need to reduce effective σ, e.g., by having very high M_{acc}
  - Reduce the effective luminosity by making the radiation field anisotropic
- Form massive stars through collisions of intermediate-mass stars in clusters
  - May be explained by observed cluster dynamics
  - Possible problem with cross section for coalescence
  - Observational consequences of such collisions?

Other differences between low- and high-mass star formation

- Physical properties of clouds undergoing low- and high-mass star formation are different:
  - Massive SF: clouds are warmer, larger, more massive, mainly located in spiral arms; high mass stars form in clusters and associations
  - Low-mass SF: form in a cooler population of clouds throughout the Galactic disk, as well as GMCs, not necessarily in clusters
- Massive protostars luminous but rare and remote
- Ionization phenomena associated with massive SF: UCHII regions
- Different environments observed has led to the suggestion that different mechanisms (or modes) apply to low- and high-mass SF

Still, one can think in 3 evolutionary stages:

- Massive, prestellar cold cores: Star has not formed yet, but molecular gas available (a few of these cores are known)
- Massive hot cores: Star has formed already, but accretion so strong that quenches ionization => no HII region (tens are known)
- Ultracompact HII region: Accretion has ceased and detectable HII region exists (many are known)

First, let´s consider massive, prestellar molecular cores

- Only a handful know...
- Are low mass stars already formed in them (before high mas stars do)?
- Should look like HMCs, only that cold.

TABLE 2

Derived Parameters

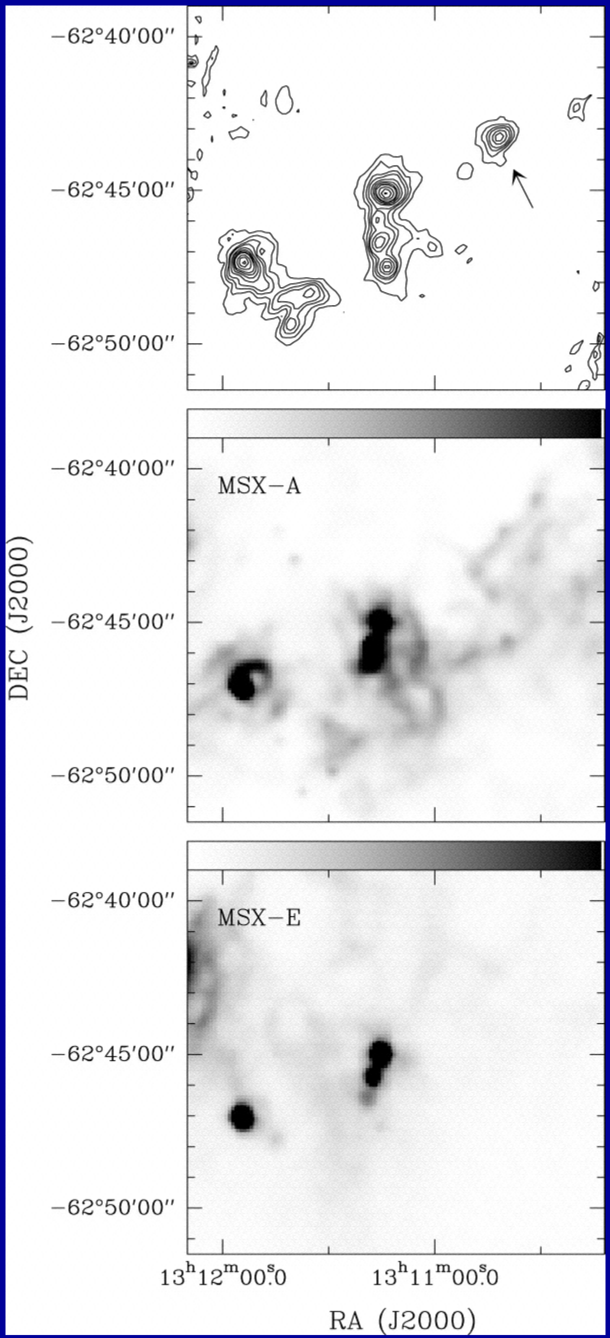
		1.2 mm				CS (2 → 1)		
SIMBA Source (1)	D (kpc) (2)	R (pc) (3)	T_d (K) (4)	M[a] ($M_\odot$) (5)	n[a] (cm^{-3}) (6)	R (pc) (7)	M_{vir} ($M_\odot$) (8)	n (cm^{-3}) (9)
G305.136+0.068	3.4	0.27	<16	1.1×10^3	2×10^5	0.30	1.1×10^3	2×10^5
G333.125−0.562.........	3.5	0.34	<17	2.3×10^3	2×10^5	0.68	2.2×10^3	3×10^4
G18.606−0.076...........	3.7	0.20	<15	4.0×10^2	2×10^5	...	...	...
G34.458+0.121	3.8	0.24	<17	7.8×10^2	2×10^5	0.64	1.5×10^3	2×10^4

[a] Lower limit.

Garay et al. (2004)

Massive but cold (and thus with low luminosity)

How are they found?



Garay et al (2004)

IRAS 13080-6229

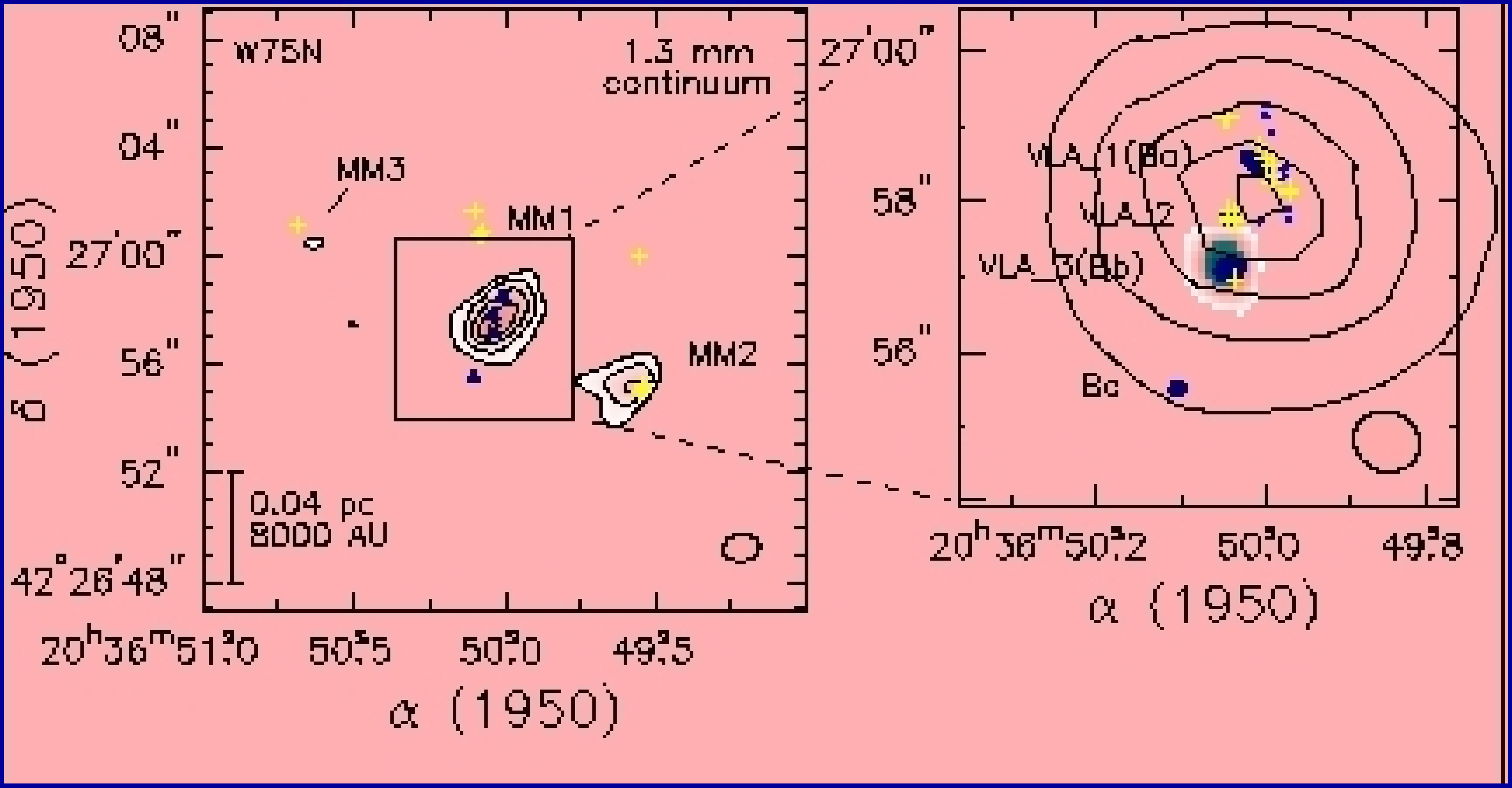
1.2 mm, 8.8-10.8 μm, and 18.2-25.1 μm observations

Non detection at 8.8-10.8 μm and 18.2-25.1 μm implies low temperature

PHYSICAL PARAMETERS OF HOT MOLECULAR CORES

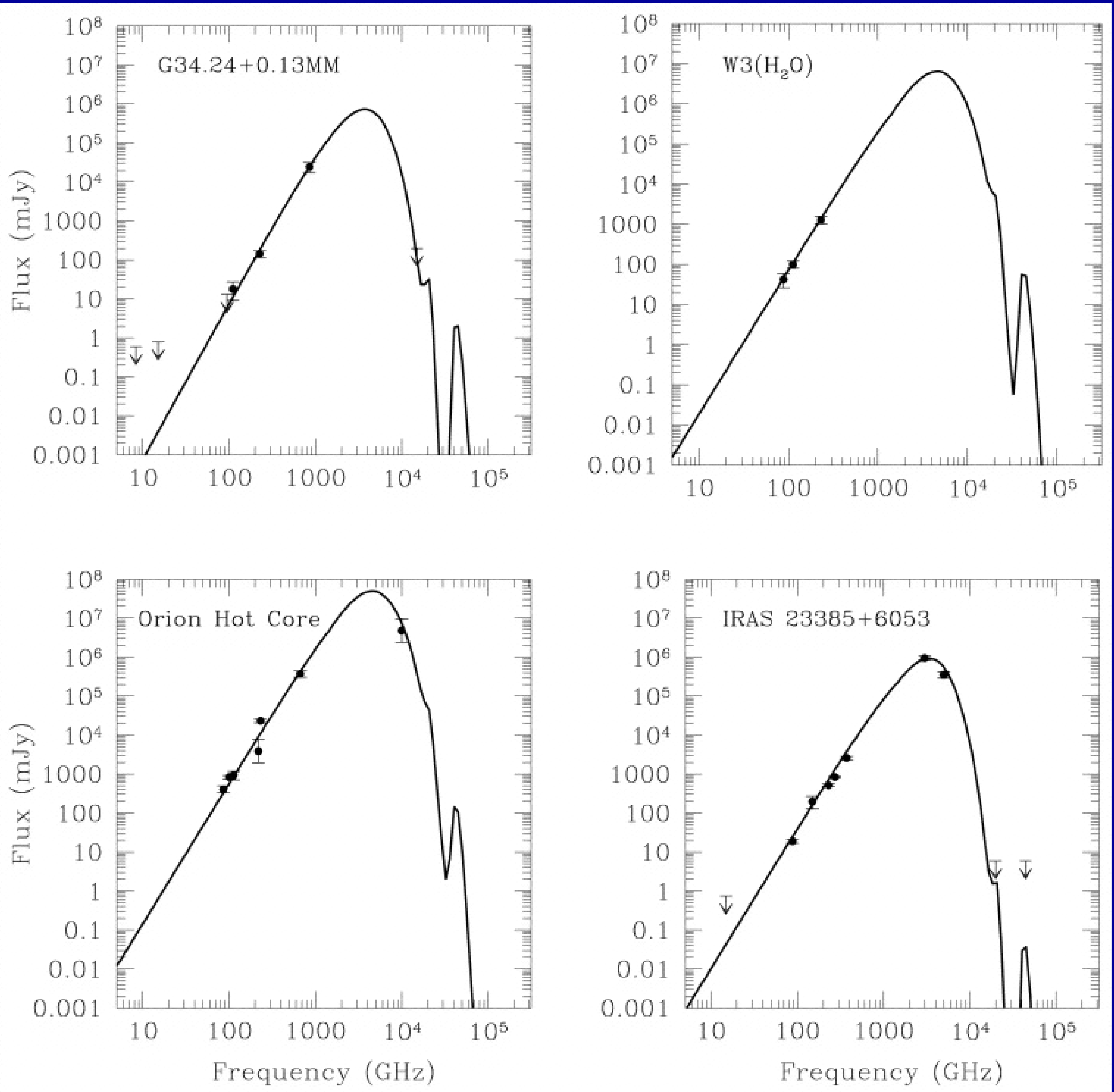
Diameter	$\lesssim 0.1$ pc
Mass	$10 - 10^4\ M_\odot$
Temperature	> 100 K
Density	$> 10^7\ cm^{-3}$

Also quite luminous, $L \geq 10^4\ L_{sun}$, since star already formed



W75N HMC, contours = NH_3, greyscale = continuum,

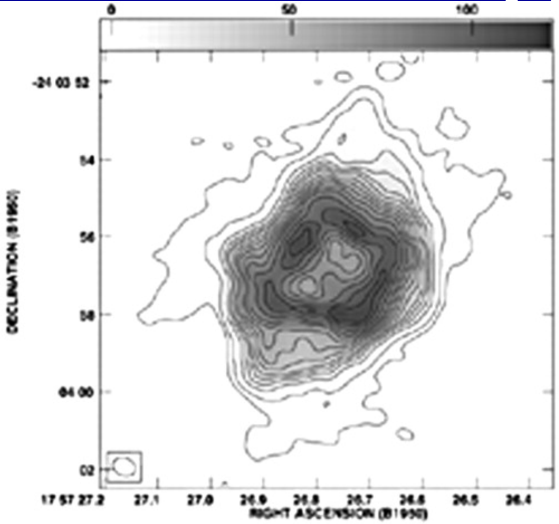
+ = H2O masers. Three star formation sites embedded in one HMC, another problem in the study of massive star formation.



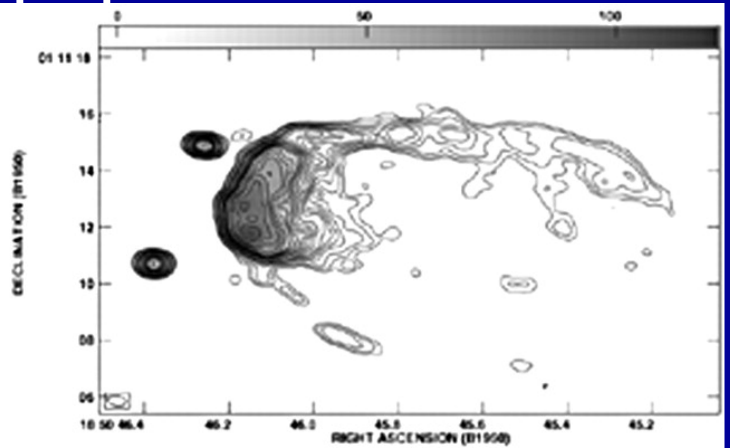
Osorio et al. (1999)

Models of continuum emission from HMCs

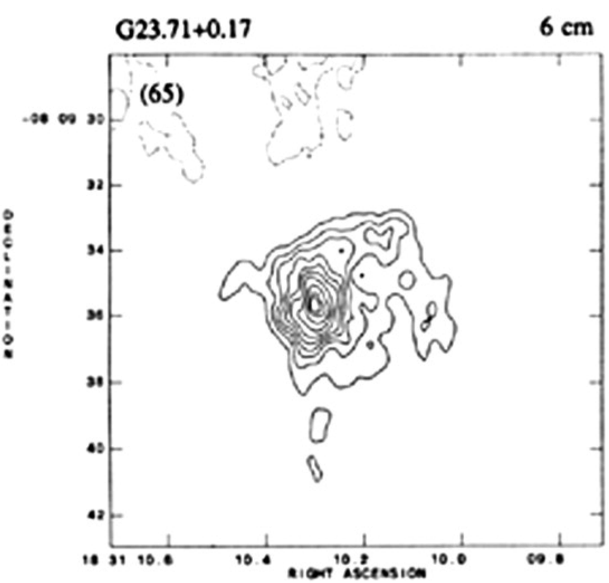
Ultracompact H II Regions



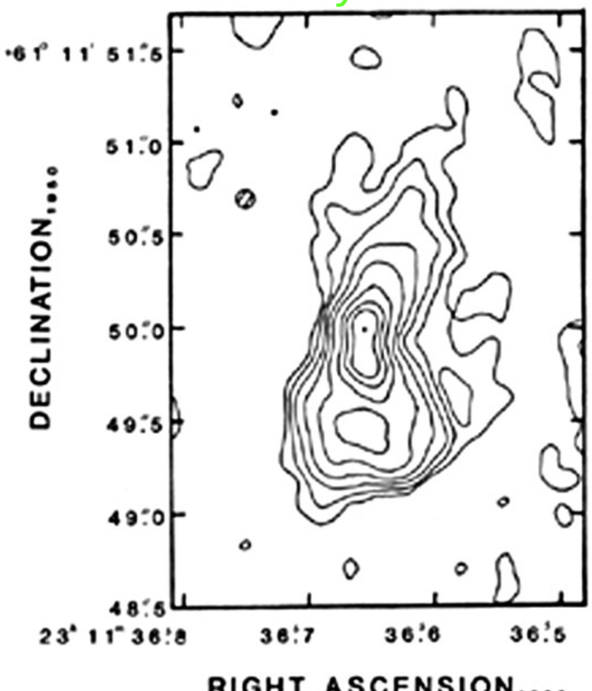
Shell-like



Cometary



Core-halo



Bipolar

…plus spherical, irregular, and unresolved morphologies (Churchwell 2002)

Disks and Jets in Young Massive Stars?

- Young, low mass stars are characterized by the simultaneous presence of disks and jets.
- Is this the case in young massive stars?
- To study this question, we have to center in the hot molecular core stage.

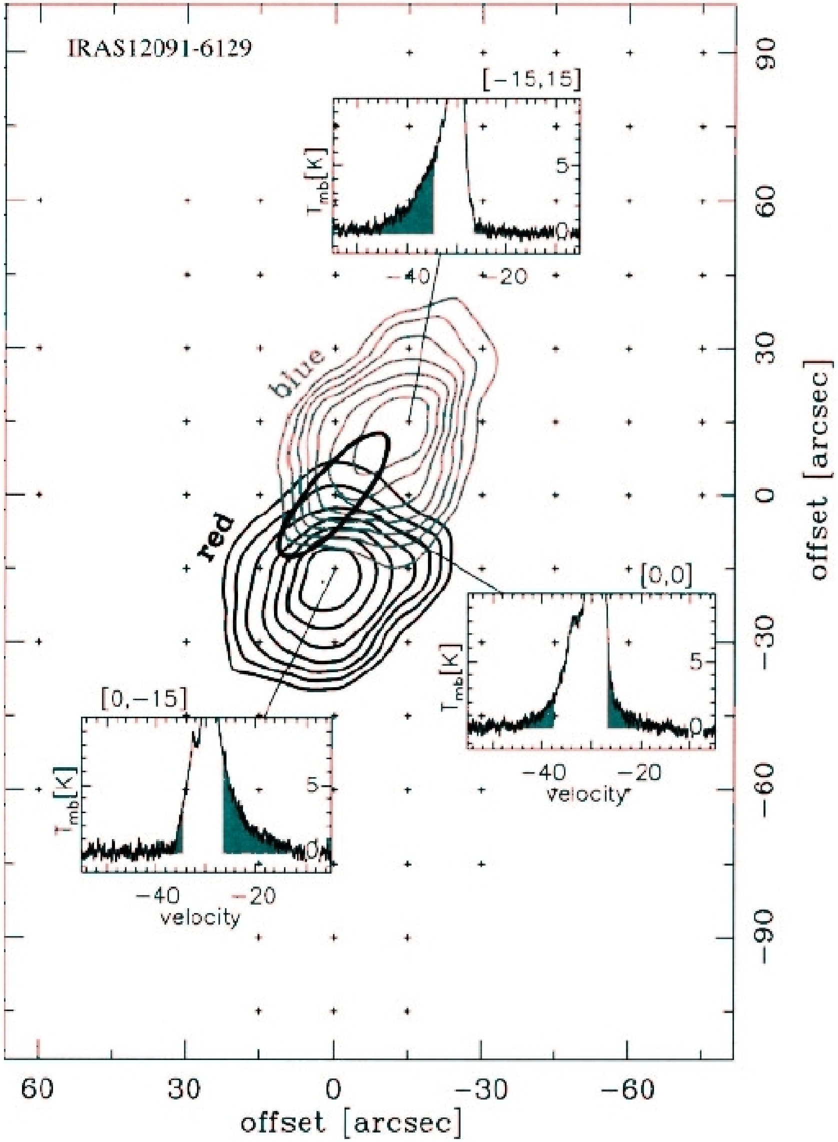


Figure 6 The CO outflow presumably driven by the FIR source IRAS12091-6129 from Henning et al. (2000). This figure illustrates three general properties of outflows driven by massive protostars: low outflow speeds, poor collimation, and large masses. The arbitrary cutoff velocities (shaded regions in the spectra) for the outflow also illustrate why outflow masses are uncertain and different authors disagree on the estimated masses.

In the HMC stage, it is frequent to find molecular outflows associates with the embedded stars. These outflows disappear by the UCHII stage.

Molecular outflows from massive protostars are believed to be more massive, but slower and less collimated than outflows from low mass stars. However, some sources well collimated.

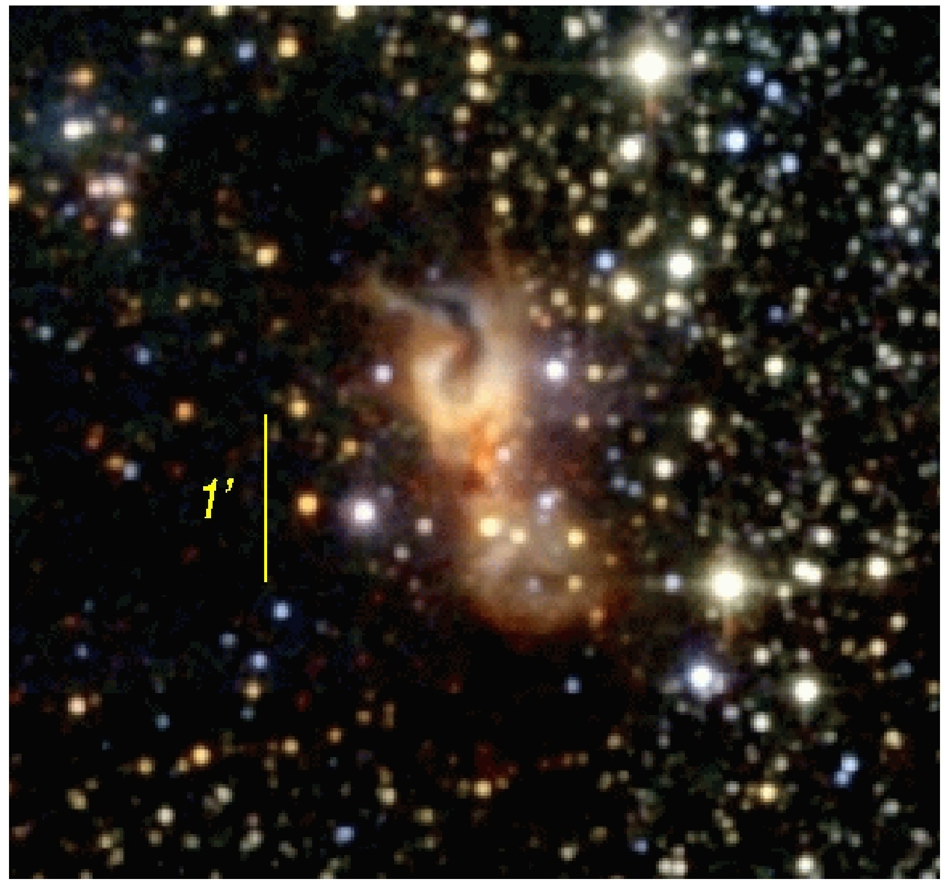
HH 80-81 (GGD27) in L291 dark cloud

Distance 1.7 kpc
(Rodríguez et al. 1980),

Luminosity: 2×10^4 L_{Sol}

Star: B0.5 ZAMS

Two Micron All Sky Survey



HH 80-81 also known as GGD 27 (Gyulbudaghian et al. 1978)

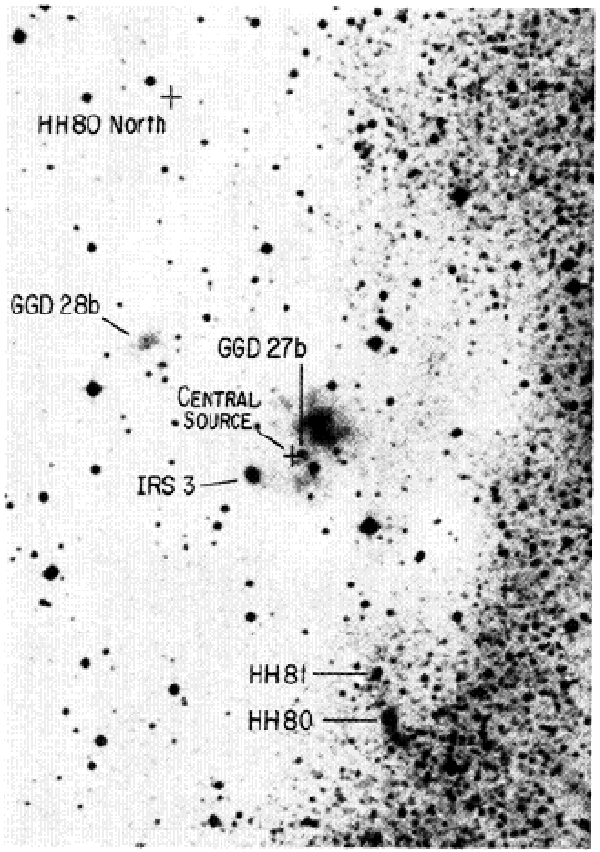


FIG. 1a

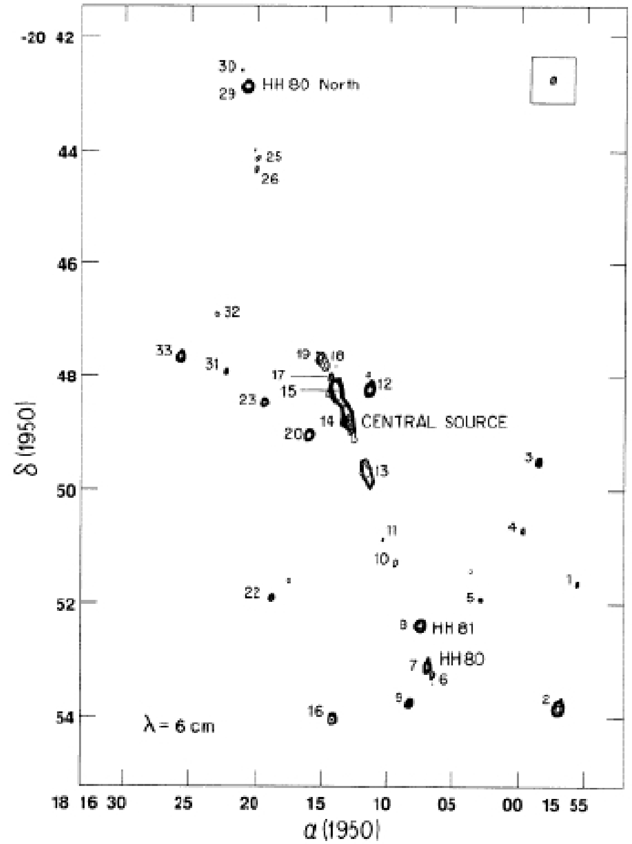


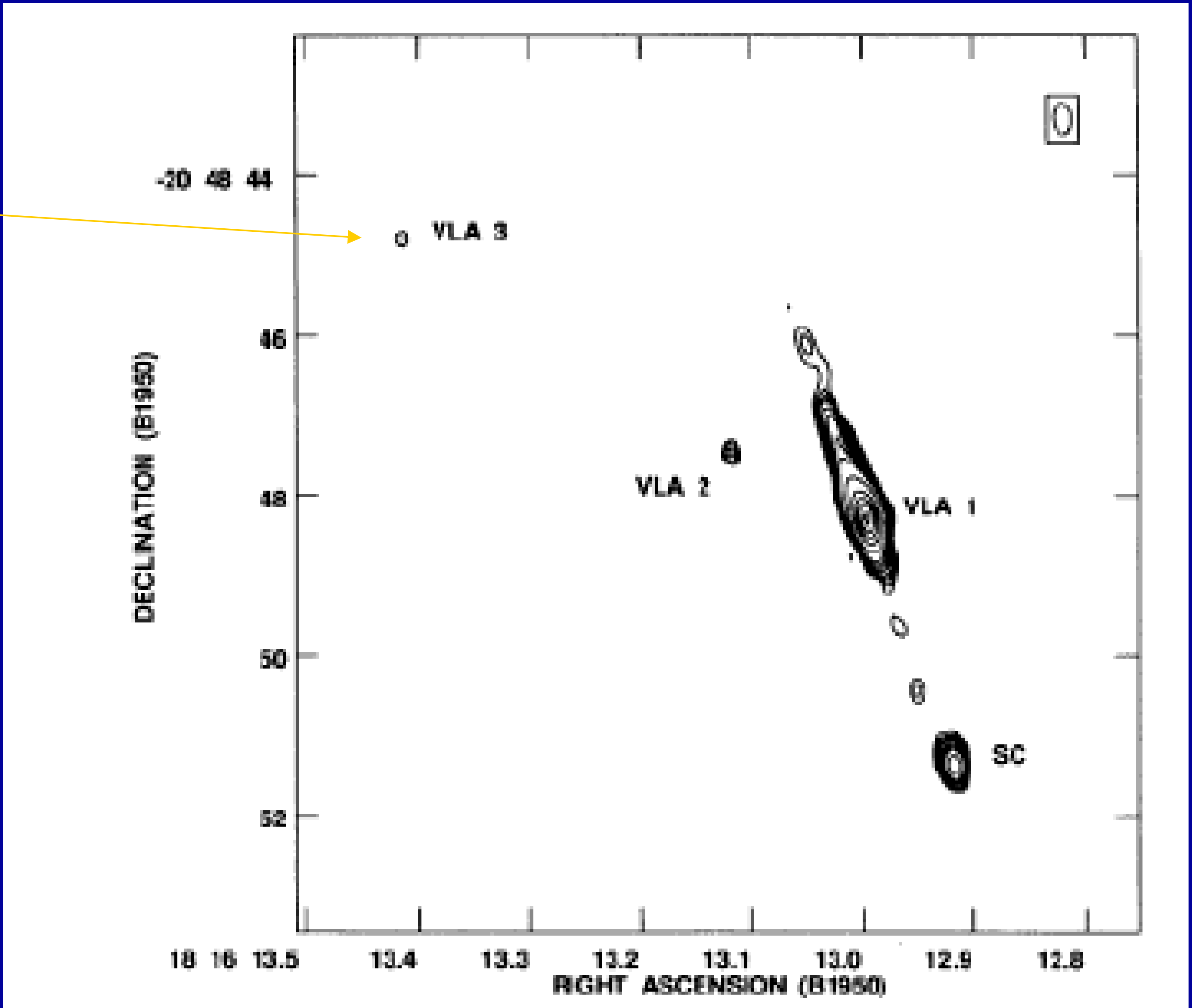
FIG. 1b

FIG. 1.—(a) The region of HH 80–81 and GGD 27–28 is seen in this figure from a deep red ESO Schmidt plate. The various objects in the region are identified. GGD 27b is a reflection nebula a few arcseconds from the central source. IRS 3 coincides with radio object 20. The crosses mark the positions of HH 80 North and the central exciting source, objects with no optical counterpart. North is up, and east is left. (b) Composite VLA 6 cm map of the HH 80–81 system made with natural weighting, showing the same region as (a). The two fields combined are not primary beam response-corrected. The northern counterpart of HH 80–81 is clearly visible at the top of the map. Note also the presence of small condensations between the central source and the HH objects following a slightly sinusoidal path. This can be interpreted as evidence of jet precession. Contours are −3, 3, 4, 5, 7, 10, 20, 50, and 100 times 20 μJy per beam, the rms noise of the individual maps. The beam size is 7.″0 × 4.″9 with position angle of −18°.

Highly collimated jet with extension of 5.3 pc (11´)

(Martí, Rodríguez & Reipurth 1993)

H_2O maser



Gómez et al. 1995

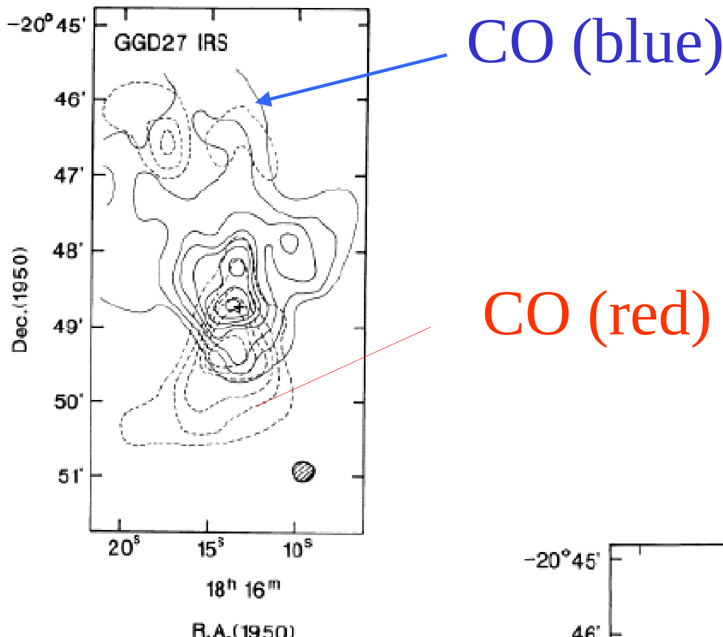
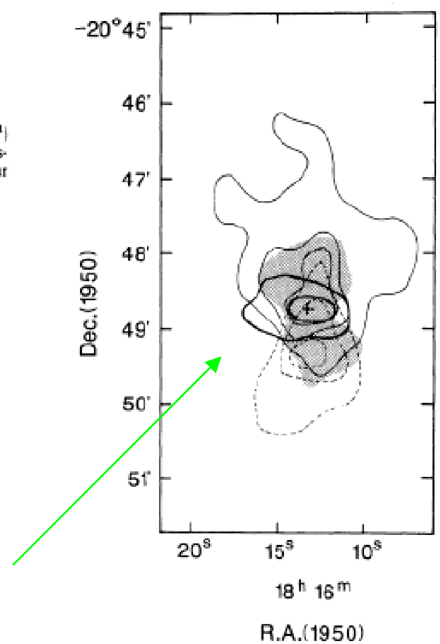


FIG. 2.—An angular distribution of the blueshifted (V_{LSR} = 6–10.5 km s^{-1}) and the redshifted (V_{LSR} = 14.5–19 km s^{-1}) wing components of the CO emission. The beam size is displayed in the right-hand lower corner. The contour interval is 2 K km s^{-1}.

(Yamashita et al. 1989)

CS (2-1) torus

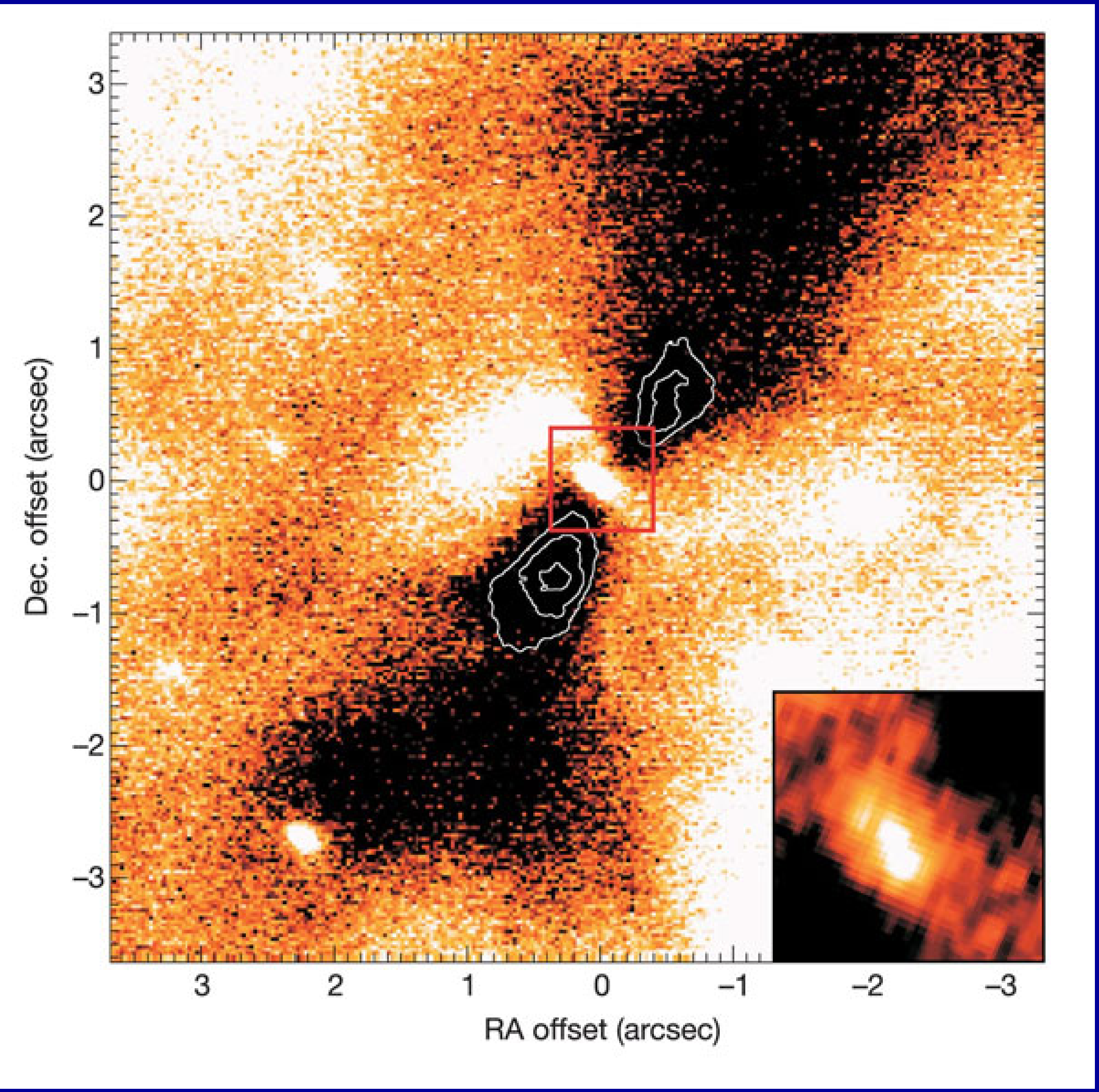
(Nobeyama 45m, 36" resolution)



NO clear evidence of a disk in HH 80-81

The search for disks aroung massive protostars is now a very active topic of research

- Let´s look at some possible examples.

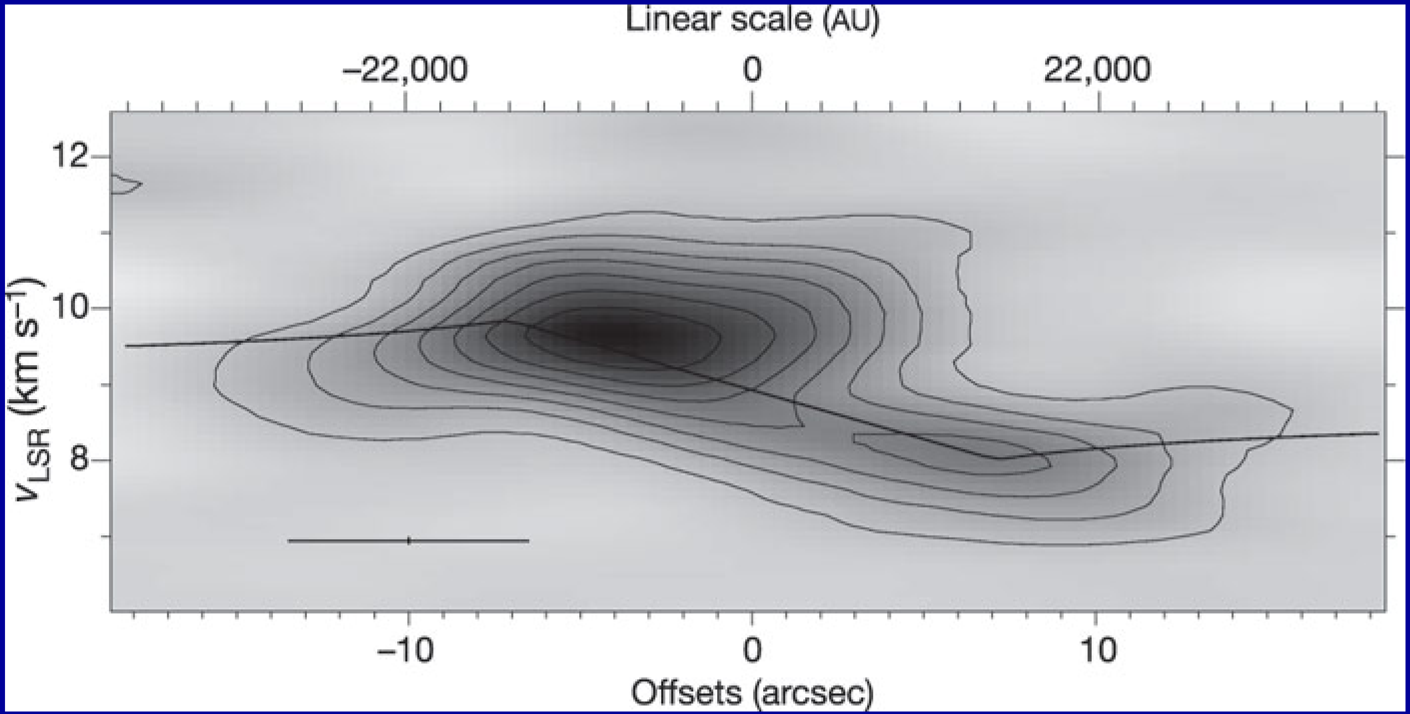


Chini et al. (2004) report at 2.2 microns a silhouette of a possible accretion disk in M17.

The proposed disk has a diameter of 20,000 AU, much larger than disks around solar-type young stars.

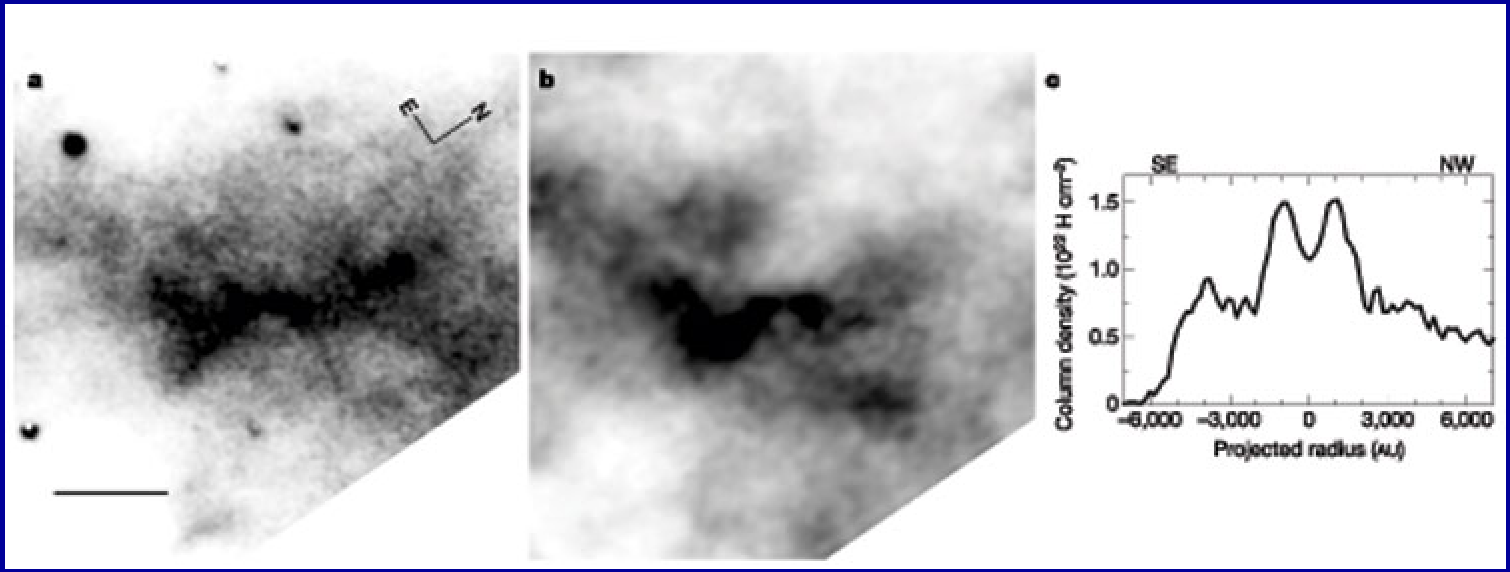
Emission at center is taken to trace central, massive star.

NAOS-CONICA at VLT



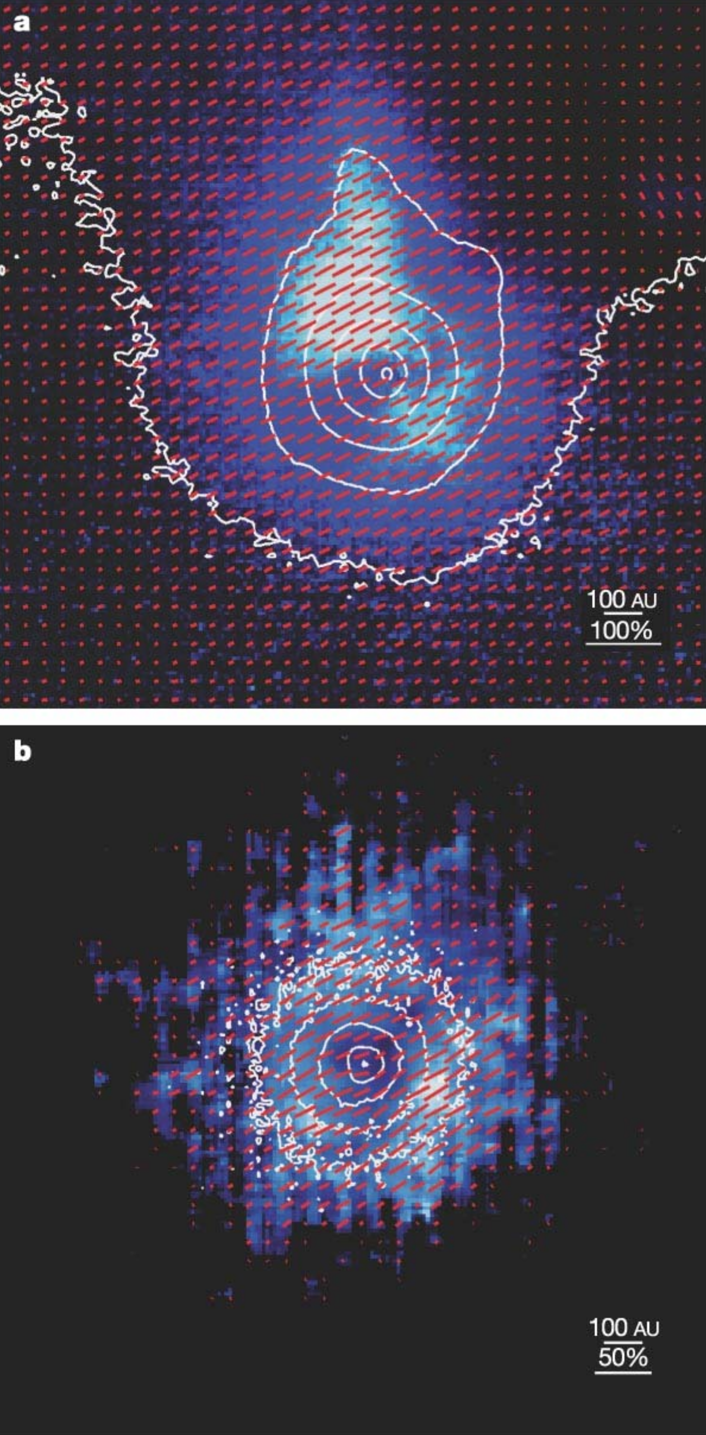
Velocity gradient in ^{13}CO implies total mass of 15 solar masses, assuming Keplerian rotation.

IRAM interferometer



However, Jiang et al. (2005) obtained Brγ and 12.8 μm images where the central compact object seen in H and K' is not seen.They interpret these results to imply that the central star is less massive than 8 solar masses and thus an intermediate-mass young star and not a true high mass star.

Subaru 8.2 m data with adative optics cameras.

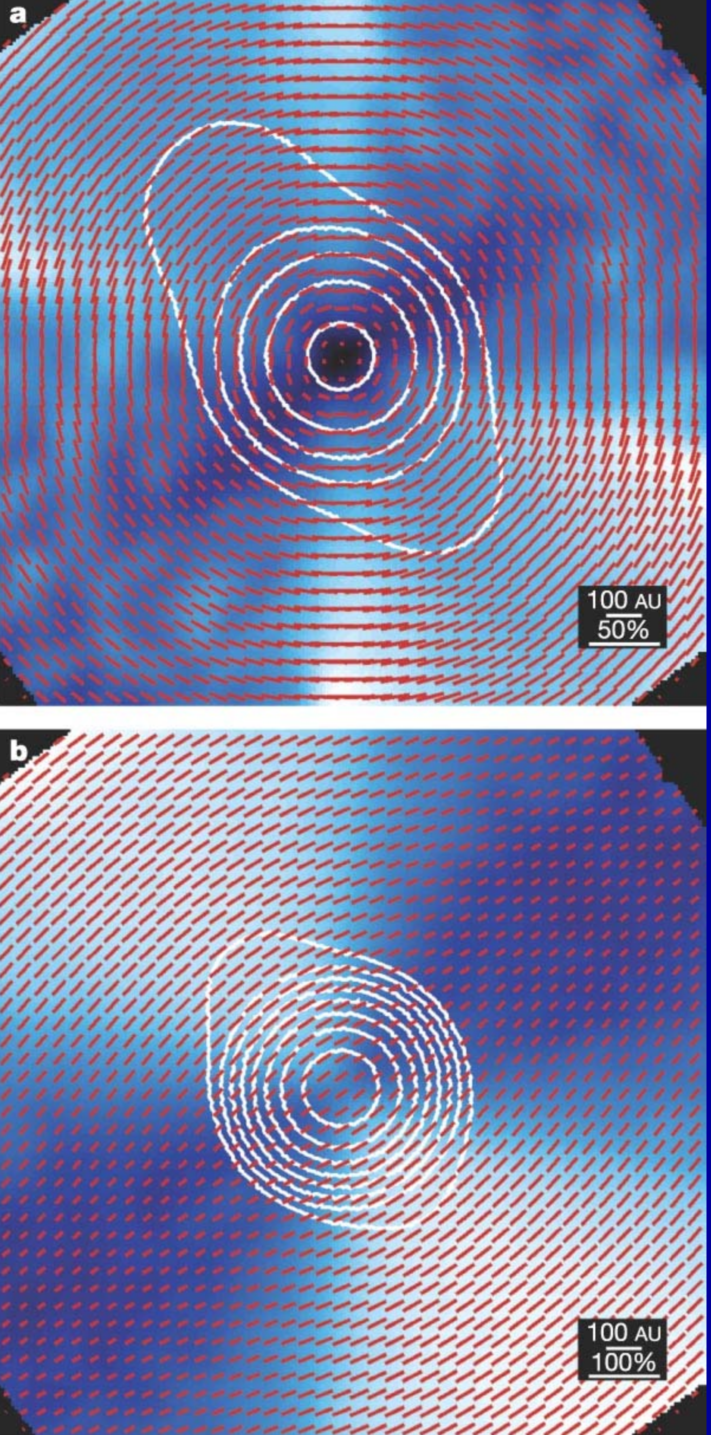


Disk associated with the BN object in Orion (Jiang et al. 2005)

H = 1.65 micras

Images taken with Subaru´s Polarimetric Camera with adaptive optics and an anular resolution of 0.1 arcsec

K = 2.2 micras



Just radiation scattering form dust grains

Monte Carlo models of the near-infrared emission

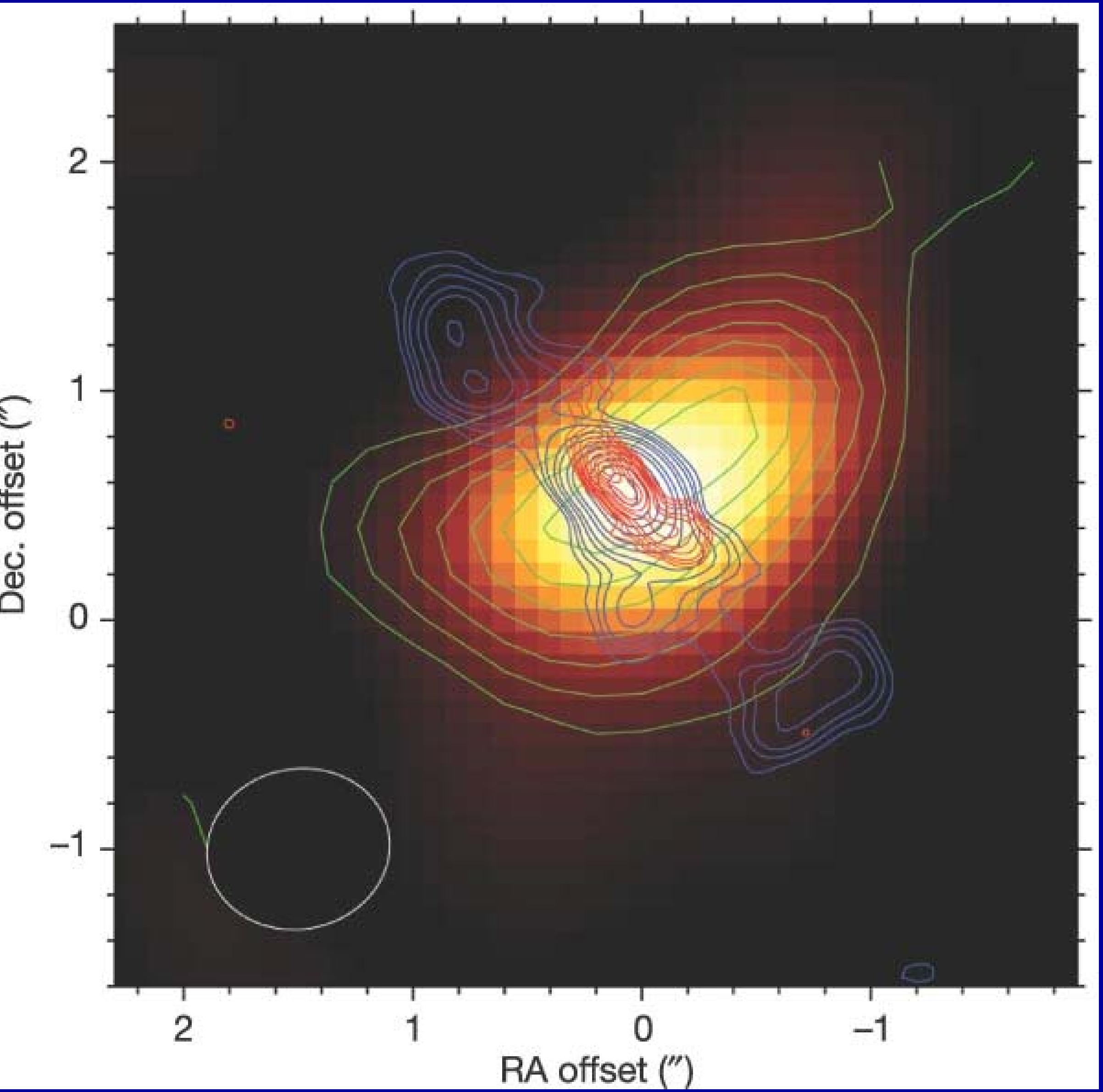
Scattering from dust grains plus dichroic extinction (assuming dust grains are elongated and abosrb more in one polarization direction

Their conclusions:

- The BN object is known to have a mass between 7 and 20 solar masses.
- The proposed disk would have a radius of 800 AU

Some concerns:

- No kinematic information
- Even when the region has been observed in several molecular lines, there is no detection (all you see is a compact HII region)
- No evidence of an outflow in the expected angle
- BN is a runaway object (more on this later)



One of the best cases is Cep A HW2 (Patel et al. 2005)

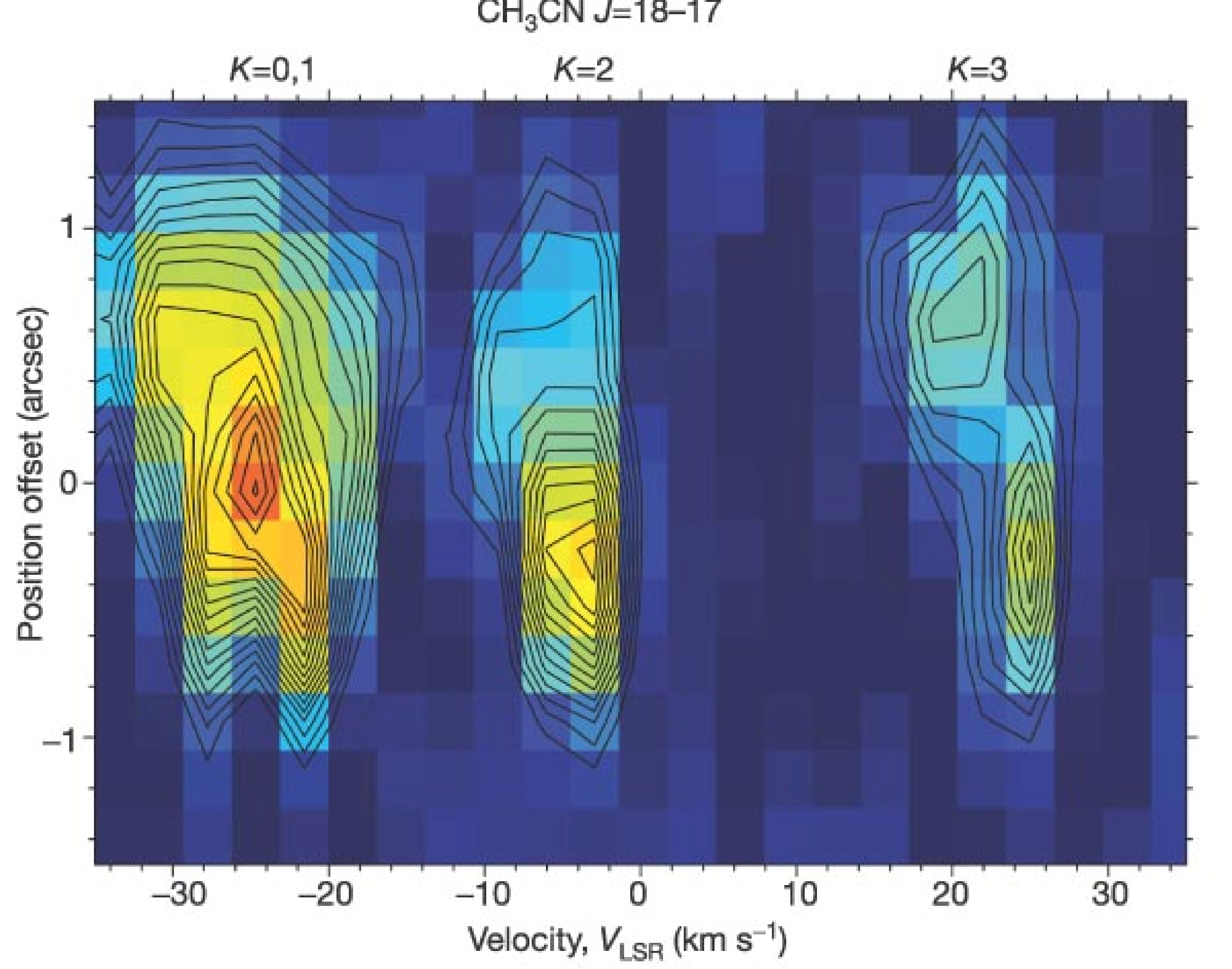
Dust and molecular emissions perpendicular to bipolar jet.

Radius of disk = 330 AU

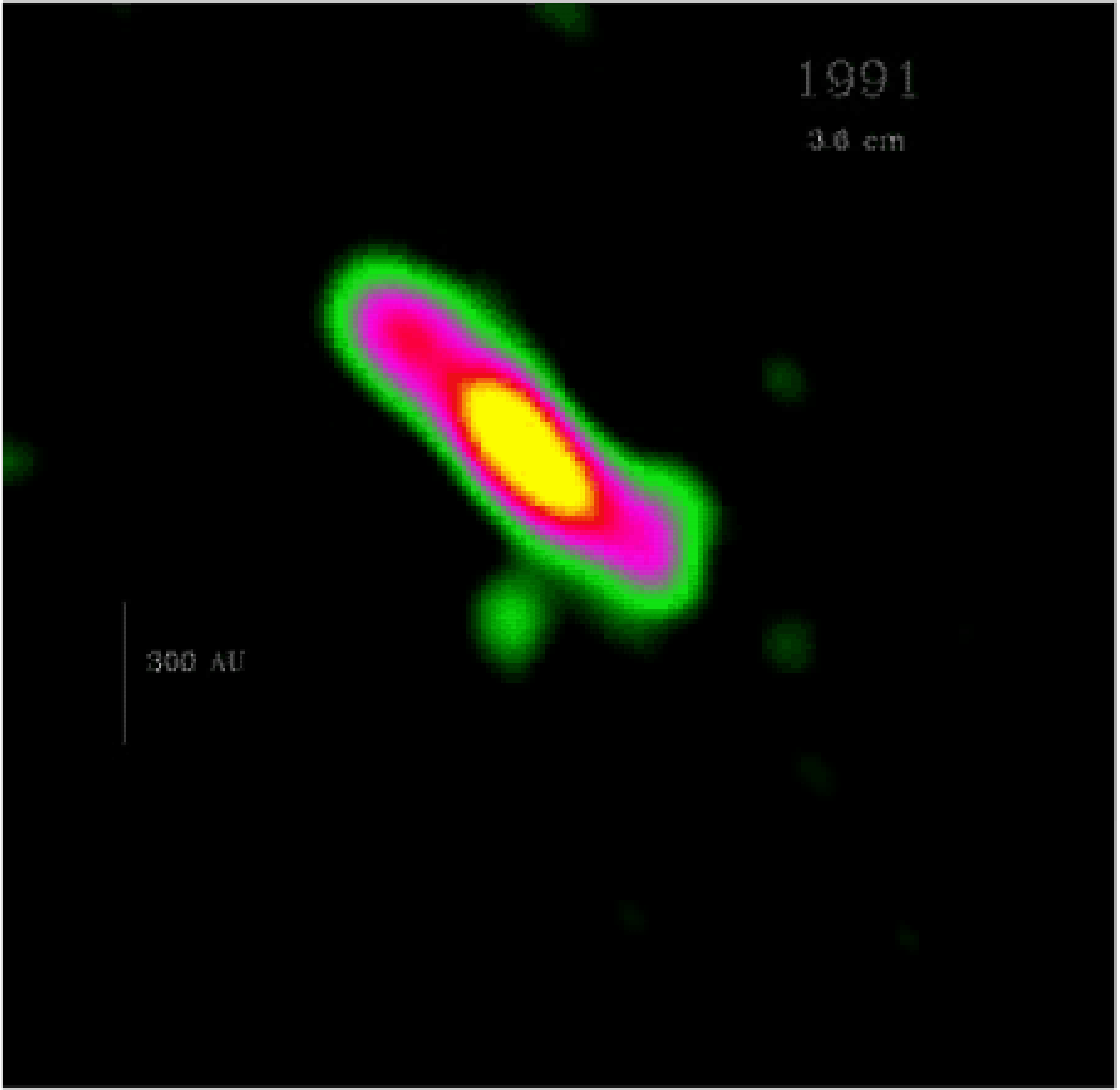
Mass of disk = 1-8 M_{SUN}

Mass of star = 15 M_{SUN}

SMA and VLA data



Position-velocity map across major axis of disk implies $M = 19 \pm 5\ M_{SUN}$

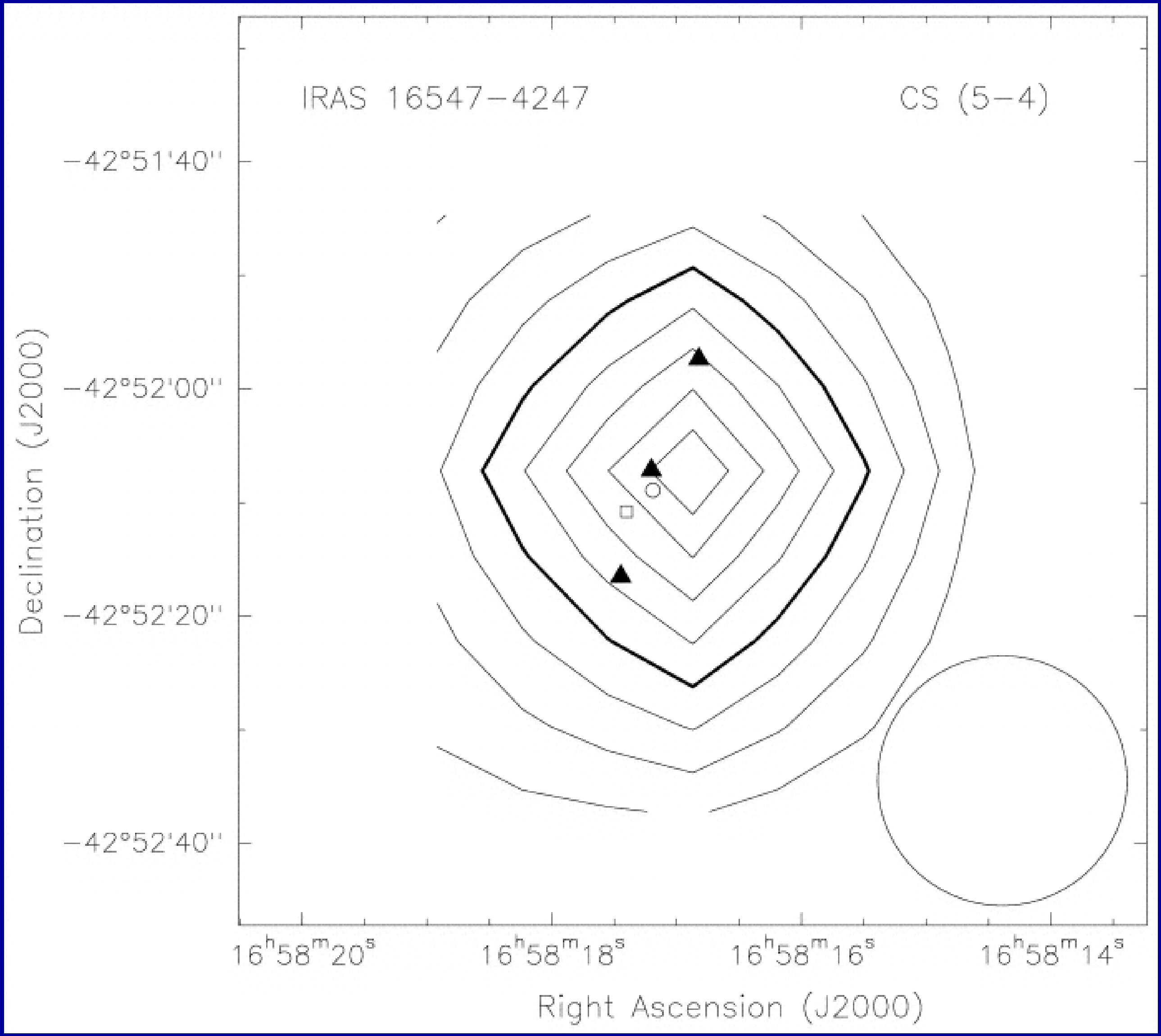

1991
3.6 cm
300 AU

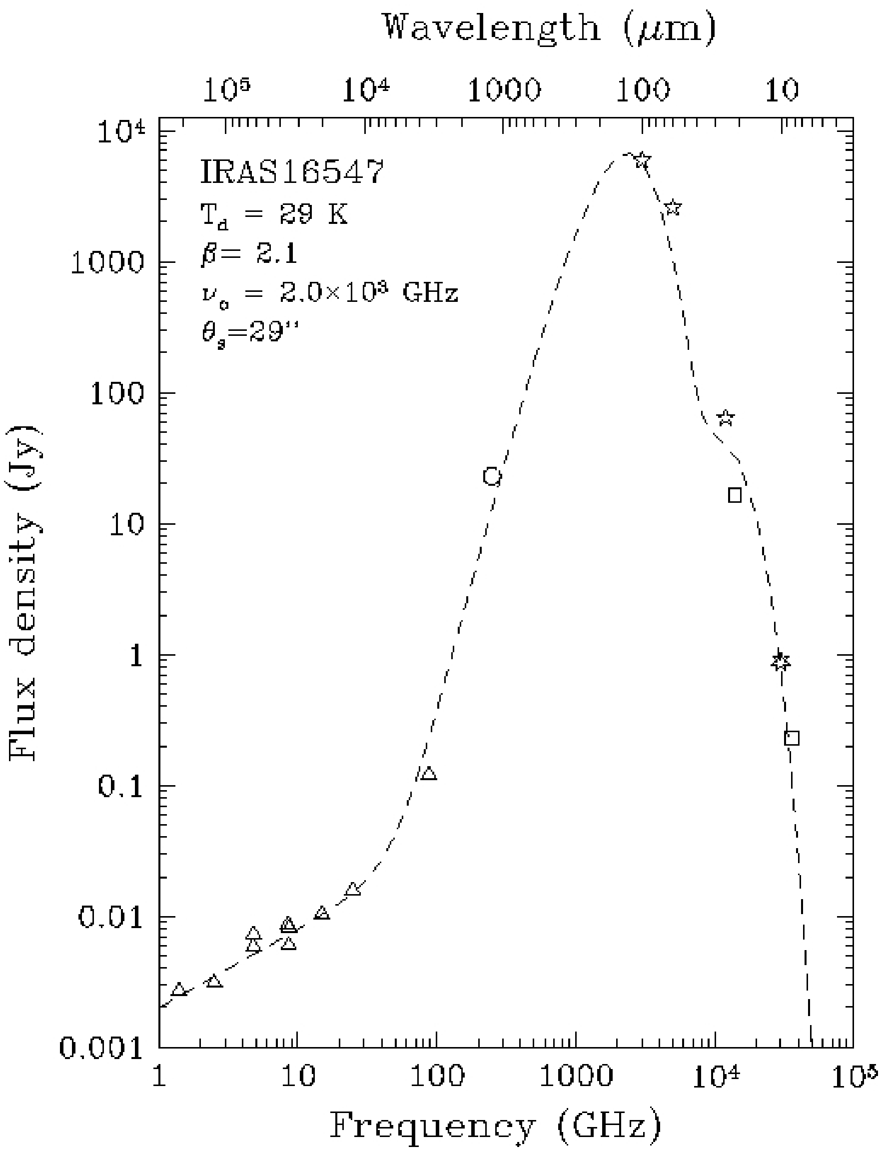
- Are there other less massive stars embedded in the disk?
- Up to now, the cases are associated with B type stars. Is there any case associated with a more luminous, O-type protostar?

O STARS

- IRAS 16547-4247

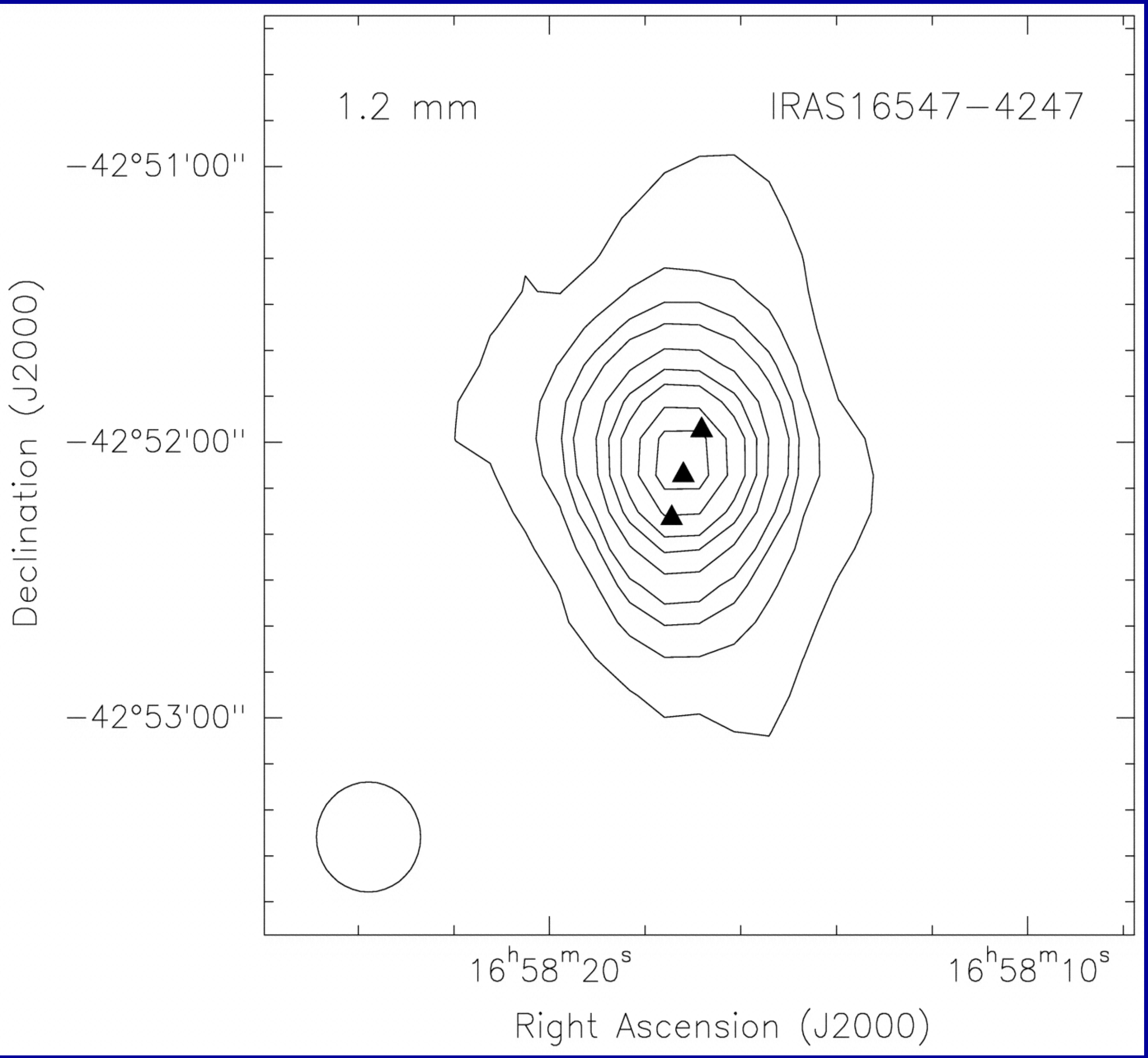
(Garay et al. 2003)





IRAS 16457-4742

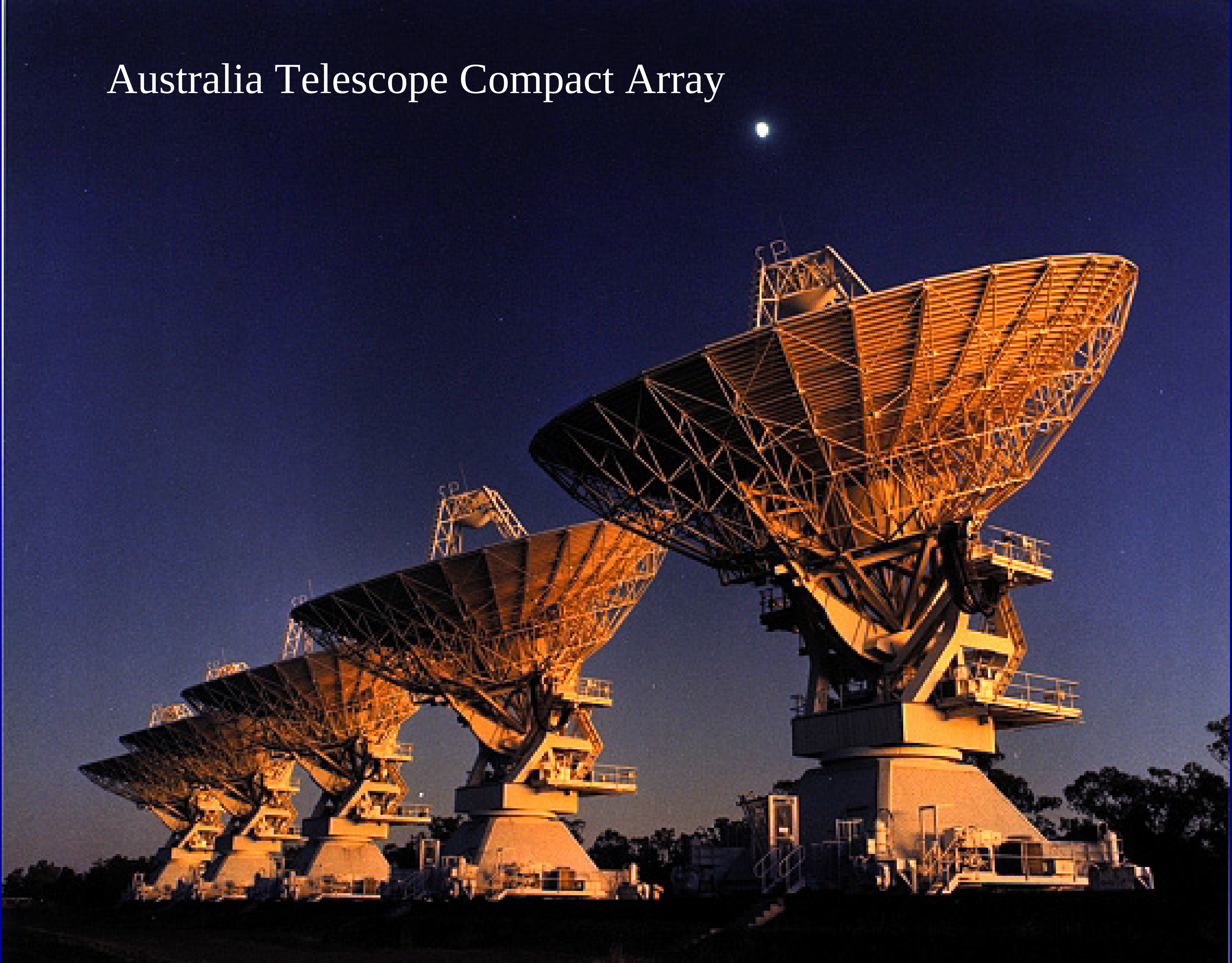
At a distance of 2.9 kpc, it has a bolometric luminosity of 62,000 solar luminosities, equivalent to an O8 ZAMS star.

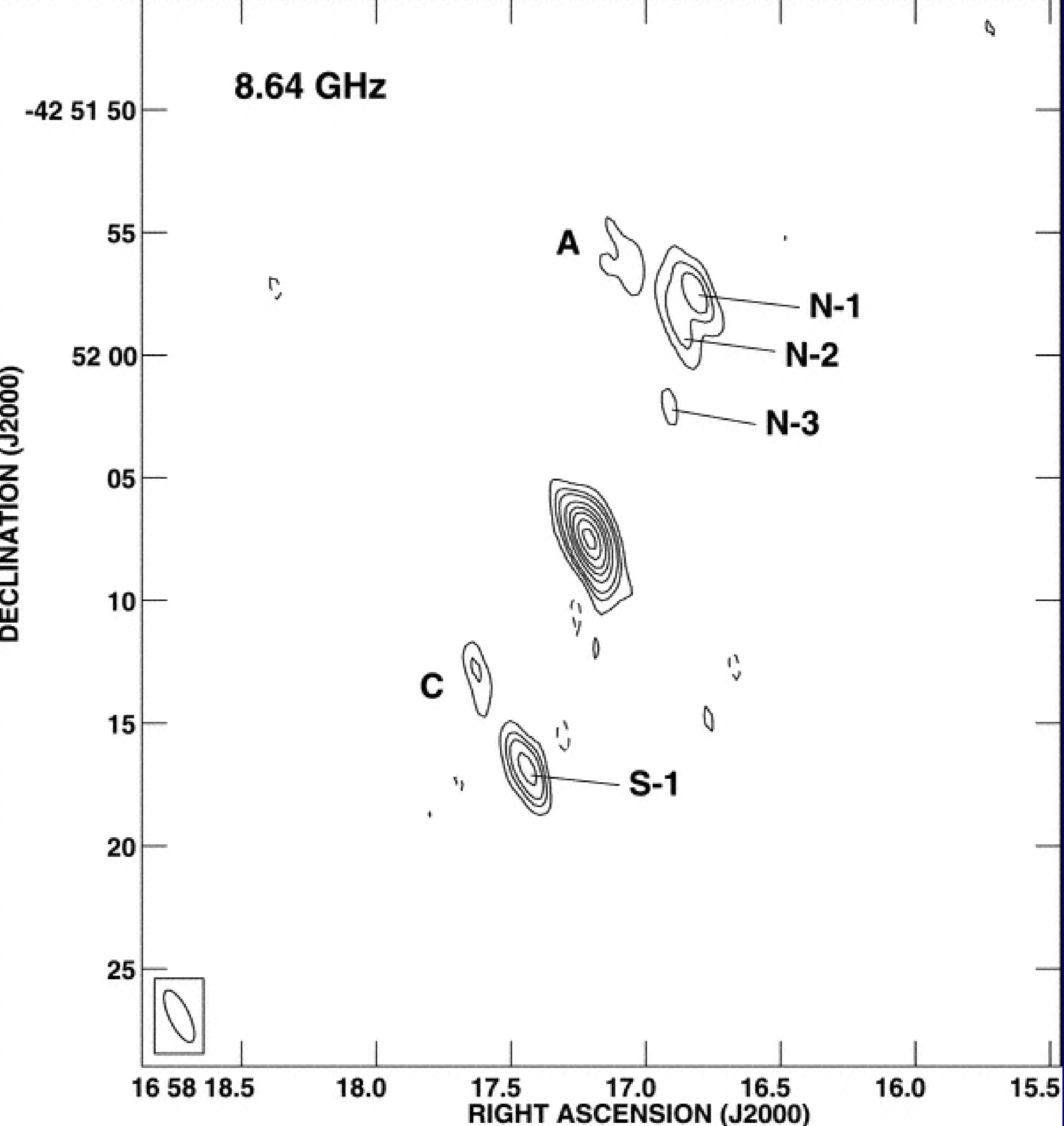


Garay et al. (2003) found millimeter continuum emission (dust) and a triple source in the centimeter range.

Core has 1,000 solar masses.

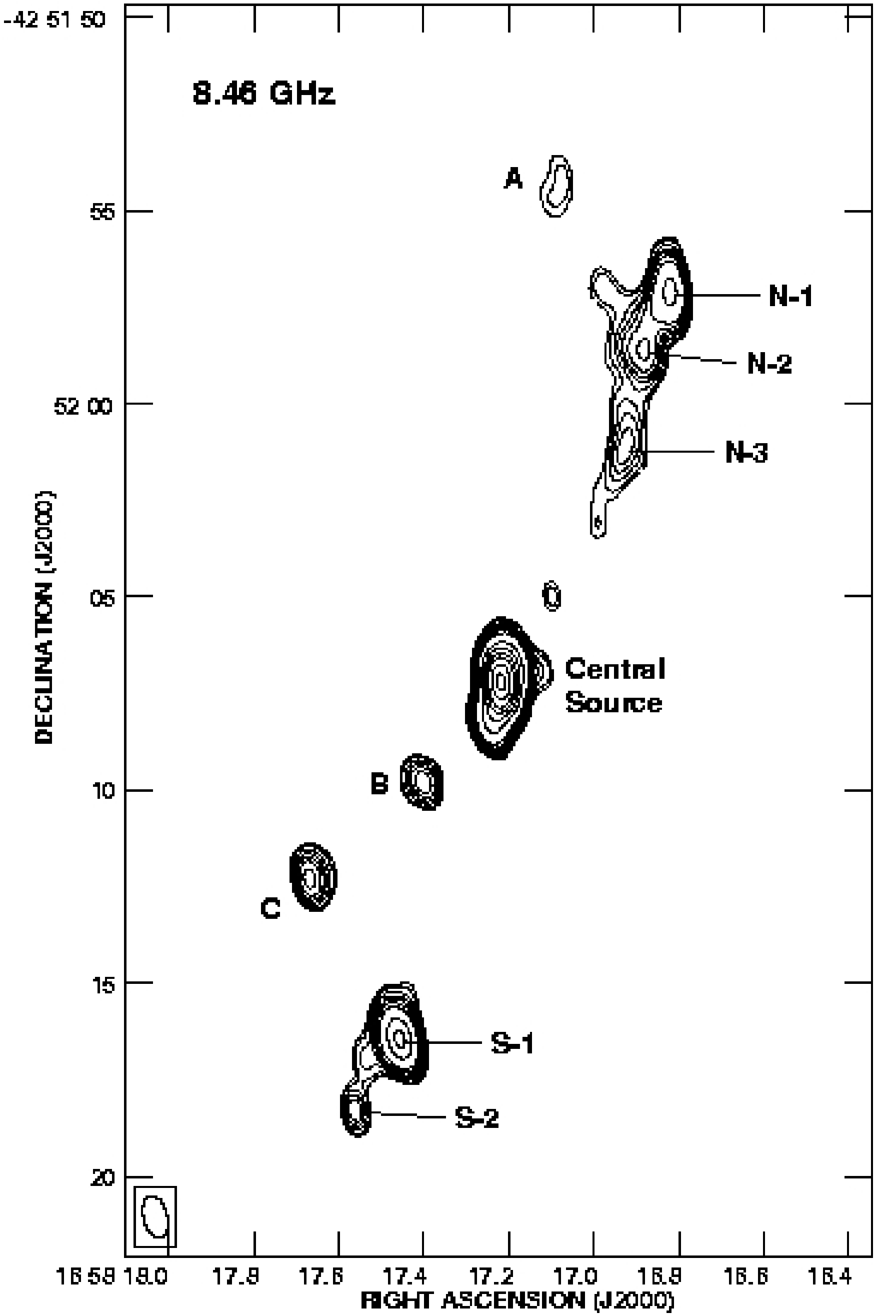
Data from SEST (mm) and ATCA (cm)

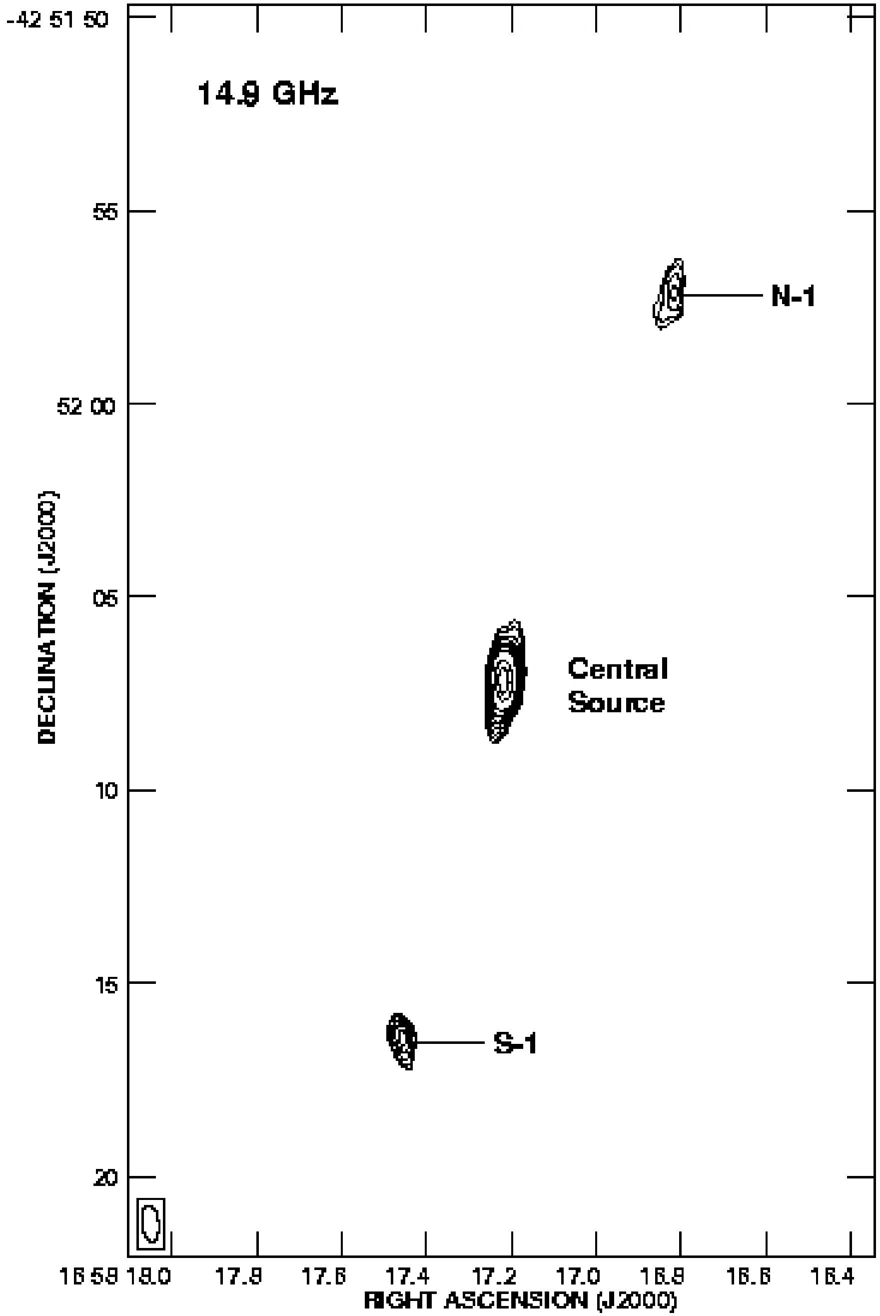

Australia Telescope Compact Array

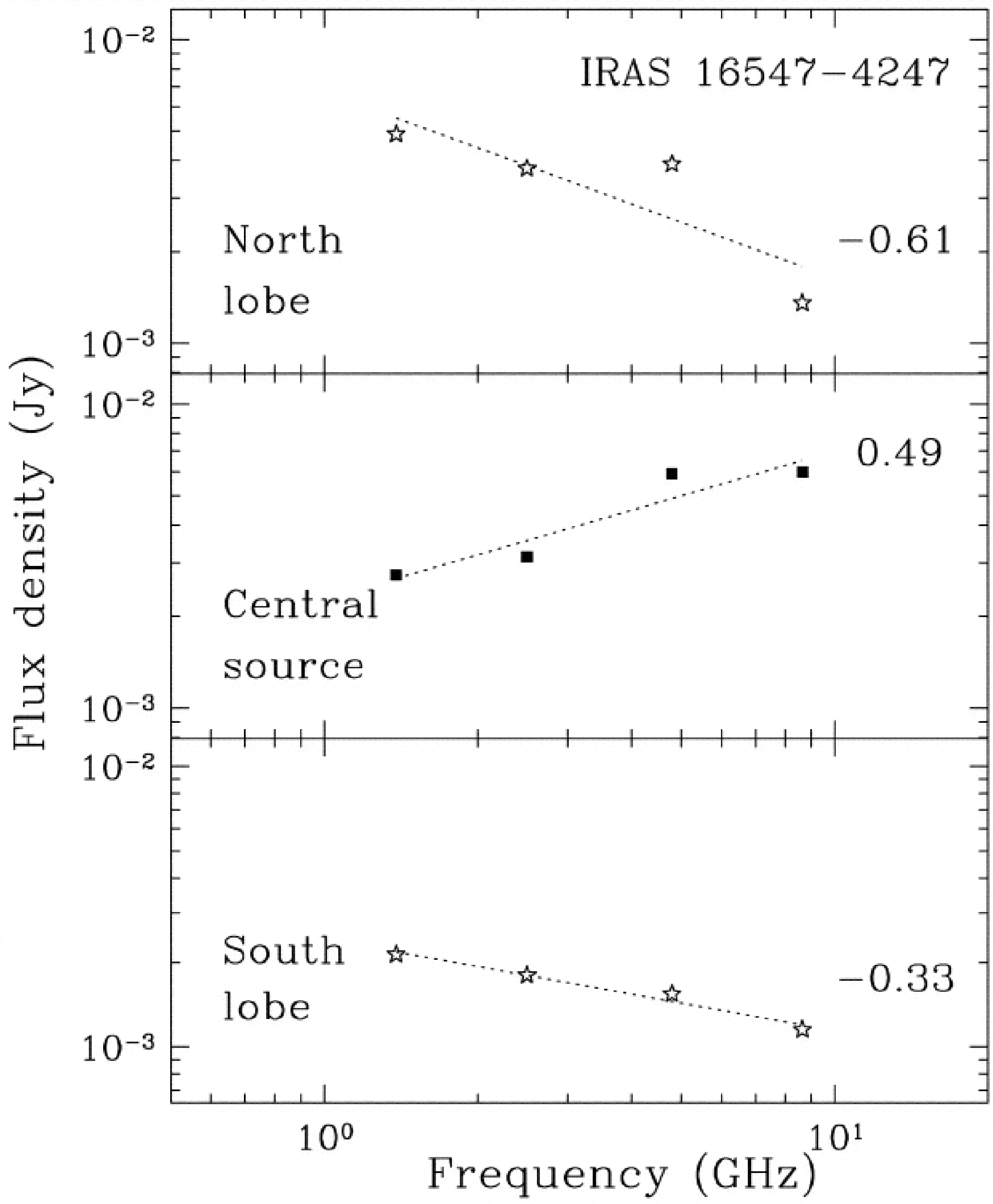


Data from ATCA, the components are not clearly resolved.

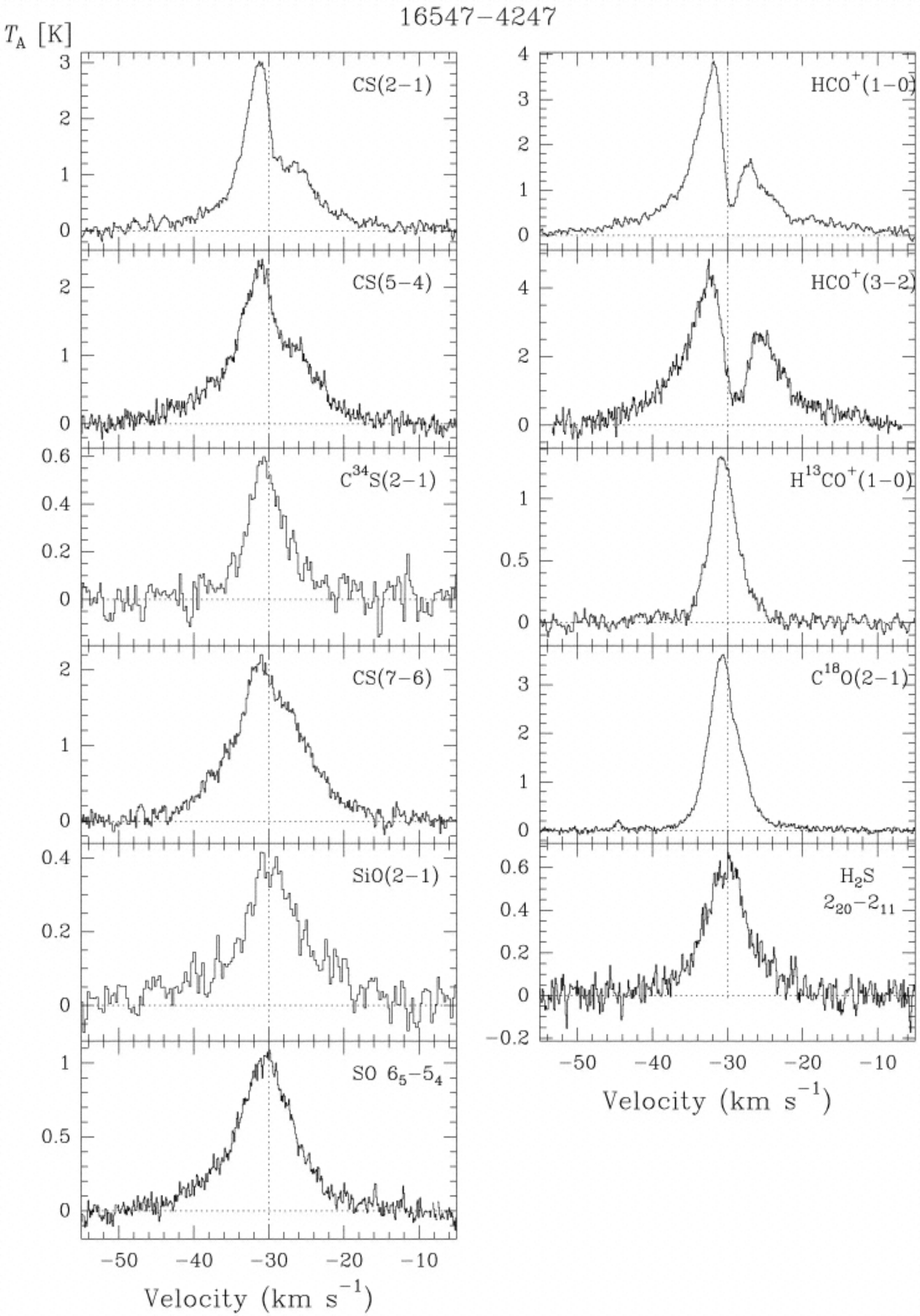
VLA images of IRAS 16547-4247







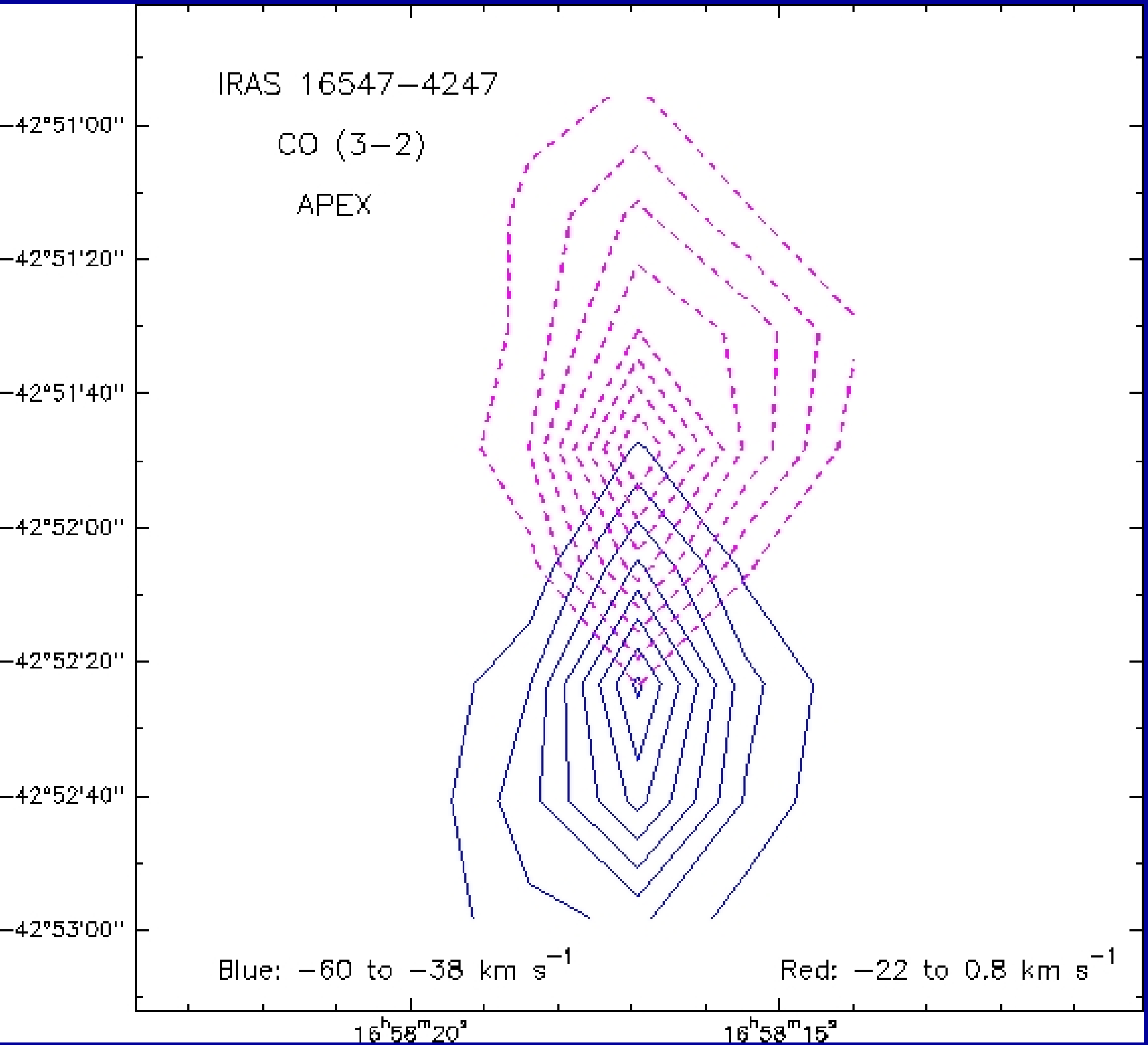
Las componentes de la fuente triple muestran índices espectrales que sugieren se trata de un chorro asociado con una estrella joven masiva.



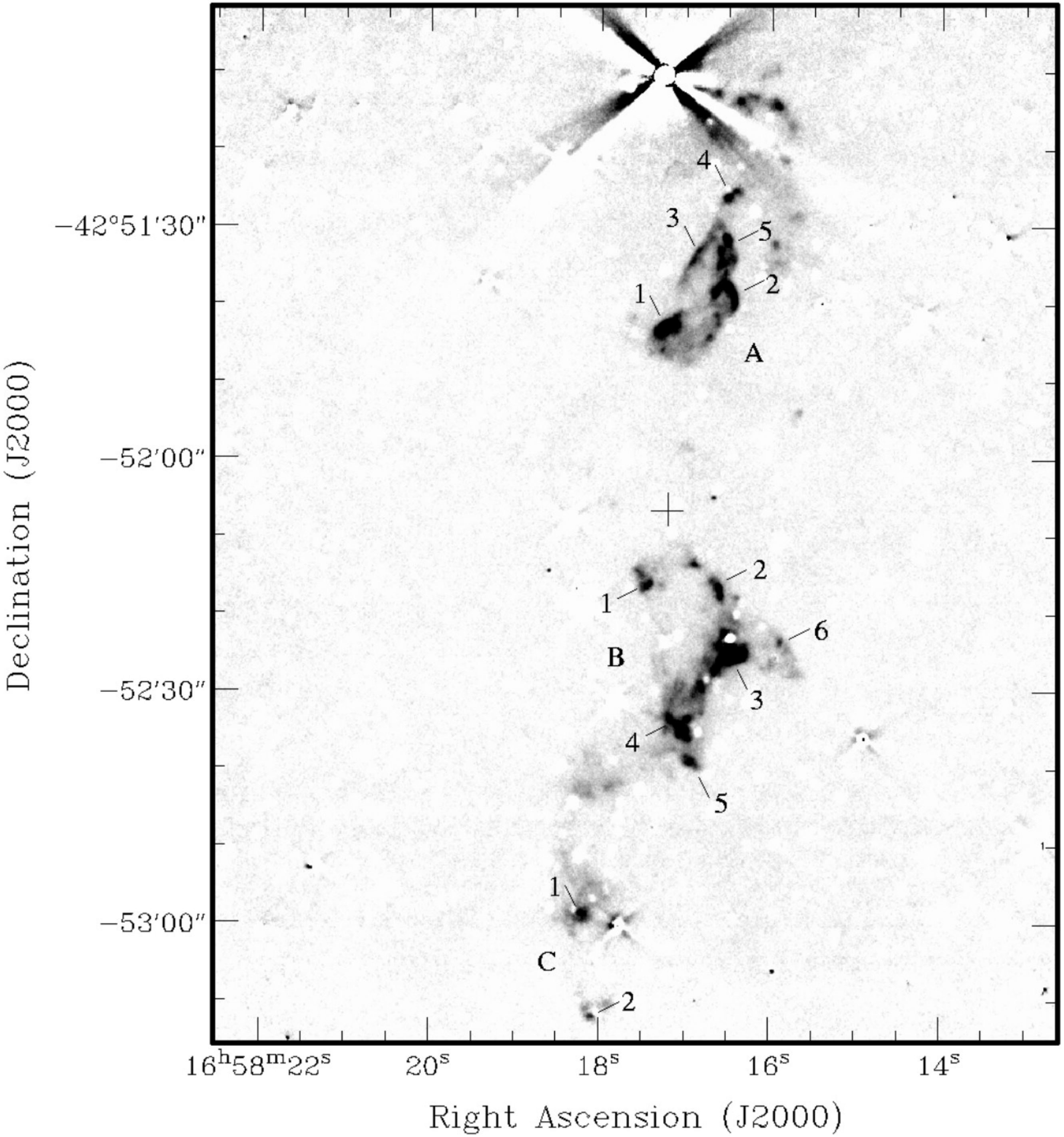
The wide wings in the molecular lines suggest the presence of high velocity gas in a bipolar outflow.

This has been recently confirmed.

Data from SEST

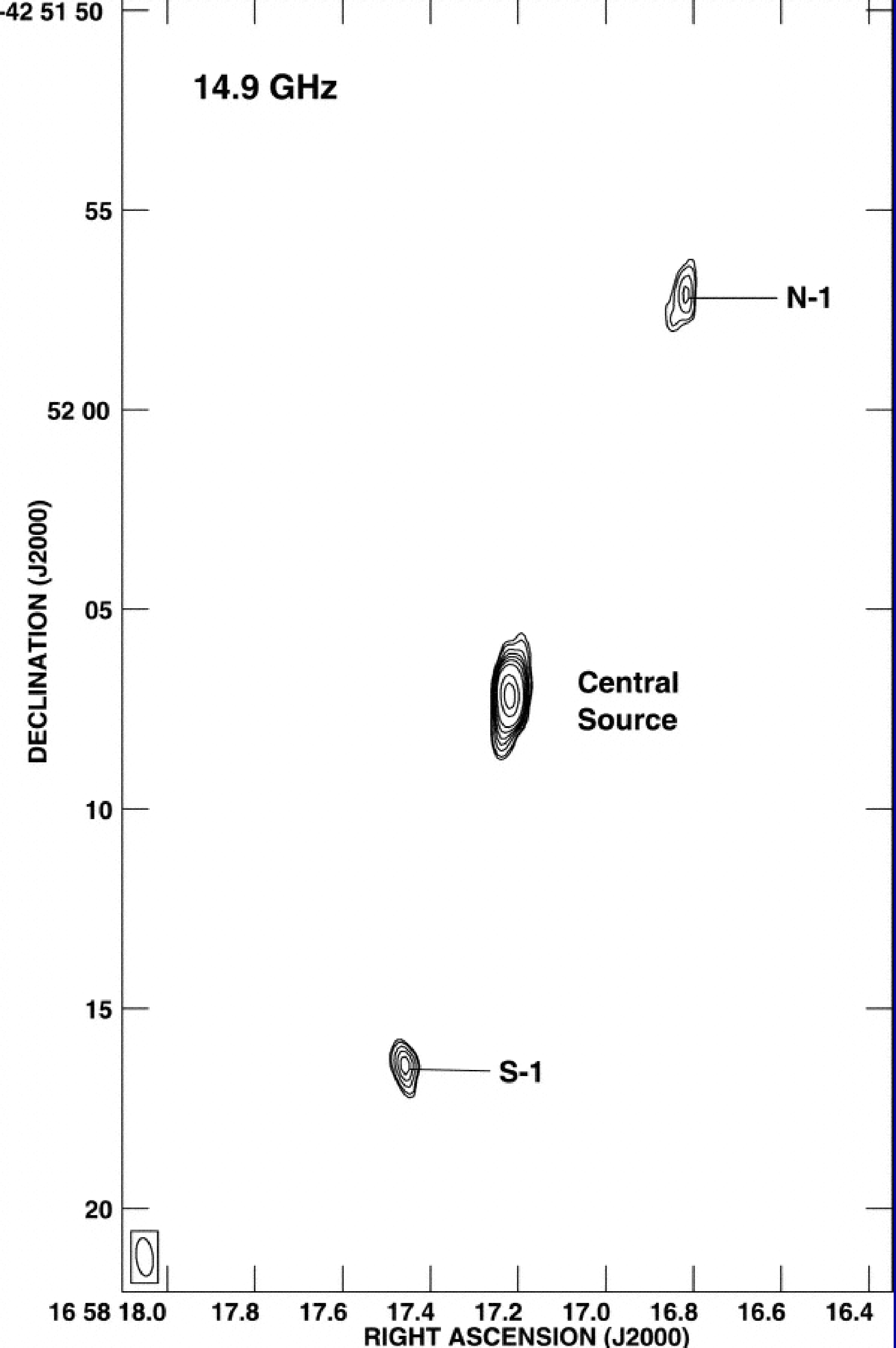


The outflow carries about 100 solar masses of gas (most from ambient cloud) and has characteristics of being driven by a very luminous object.



Molecular hydrogen (2.12 micronss) tracing the bipolar outflow (Brooks et al. 2003)

Data from ISAAC in the VLT

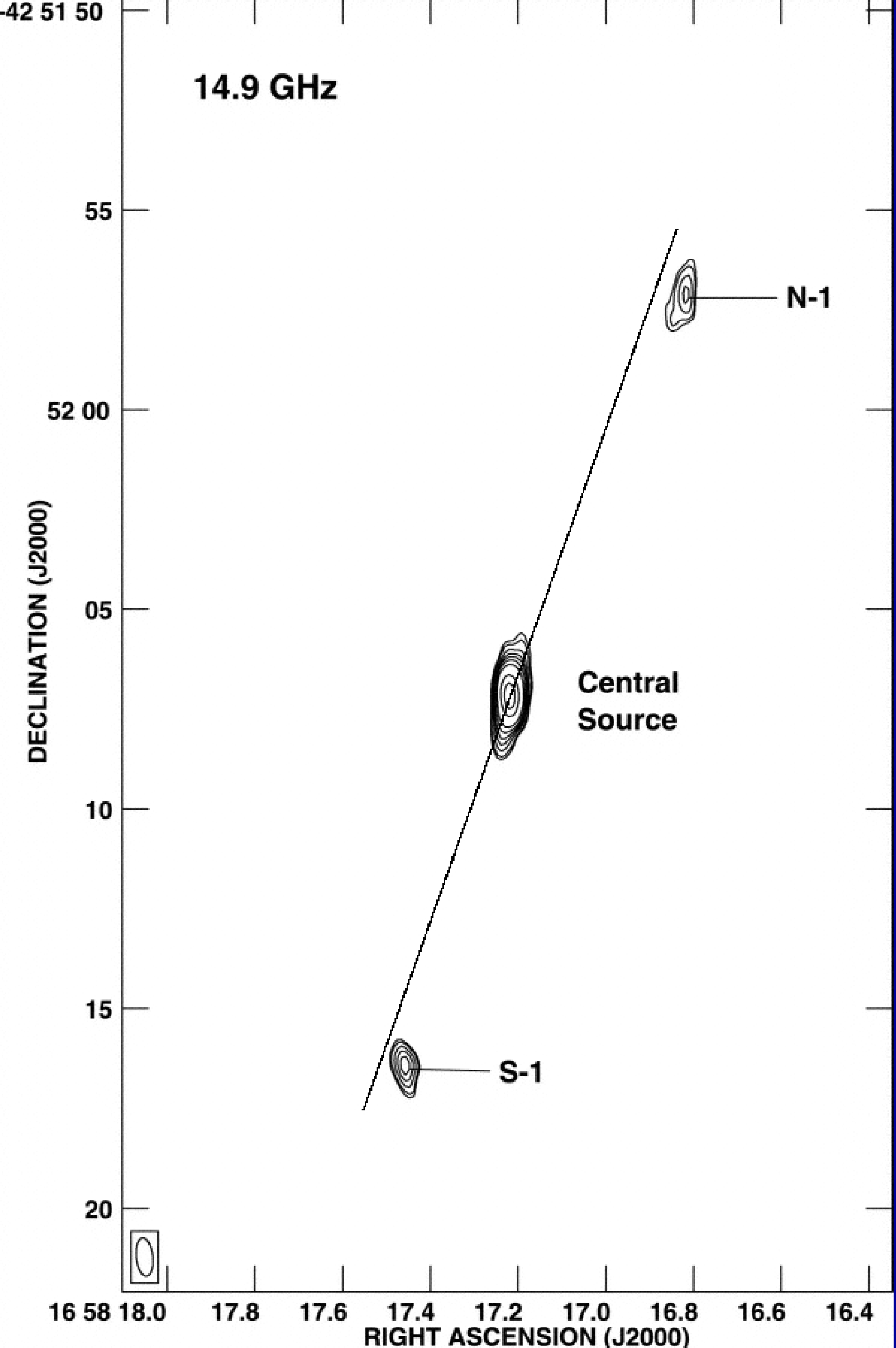


VLA data at 2 cm

The central source is resolved as an elongated object

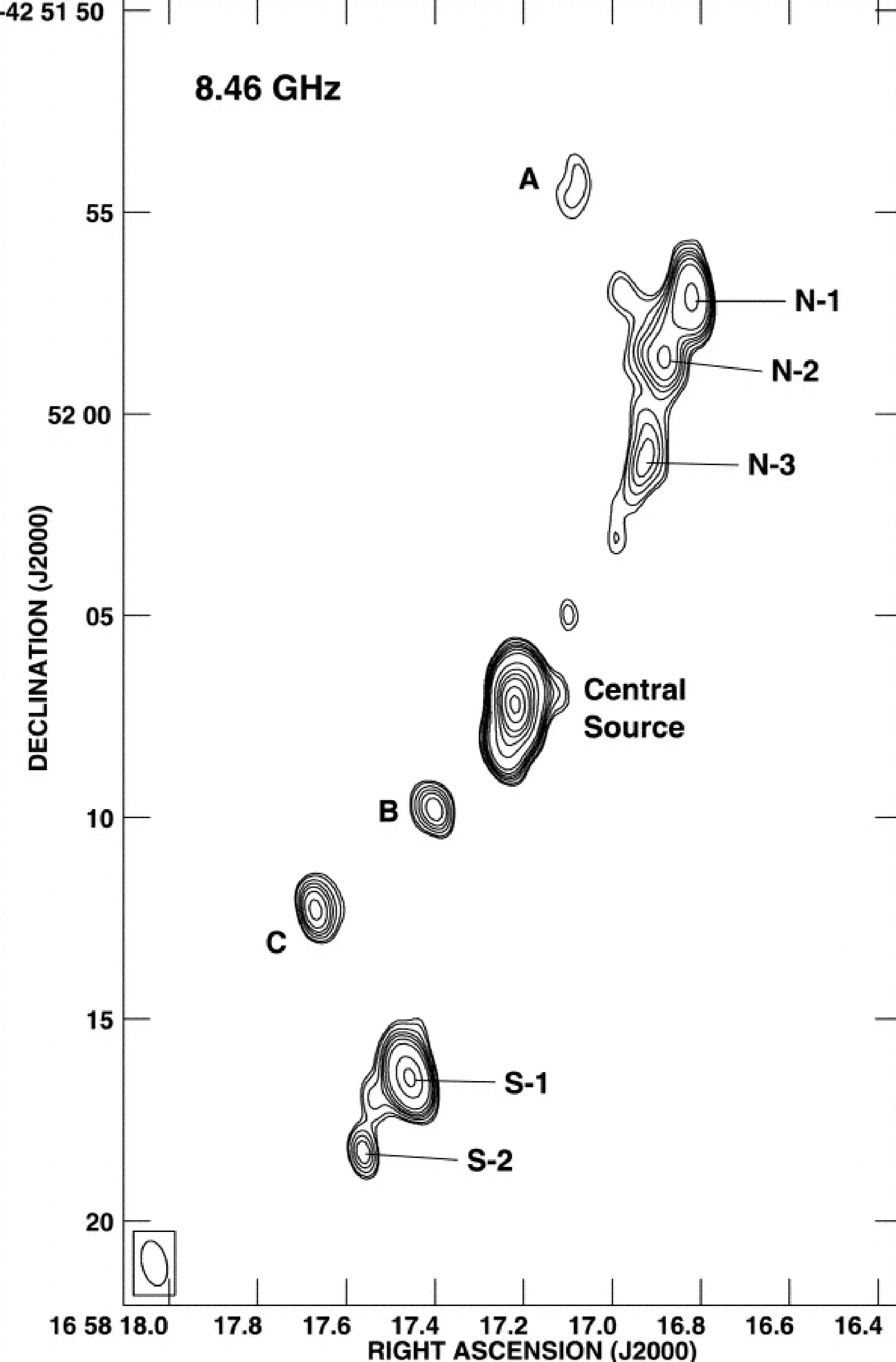
In particular, the position angle of 165 +- 2 degrees aligns well with the lobes.

We observe a dependence of angular size with frequency characteristic of ionized outflows.



However, the axis of the jet misses the lobes.

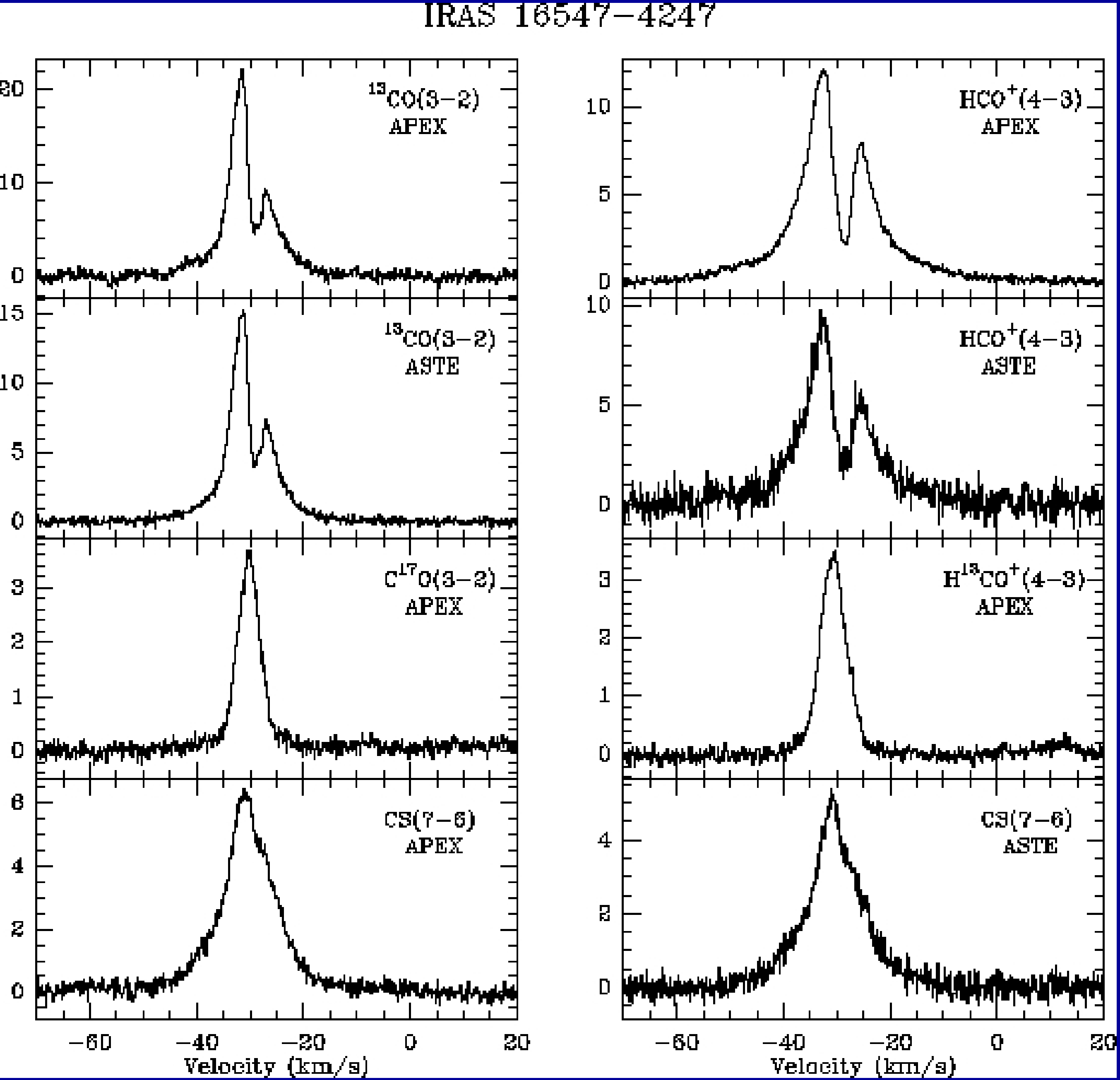
We are investigating this problem (common in triple sources of this type).



The VLA image at 3.6 cm is very sensitive and shows structure connecting the central source with the northern lobe, as well as other sources in the field (possibly other young stars)

OK, so we have a jet

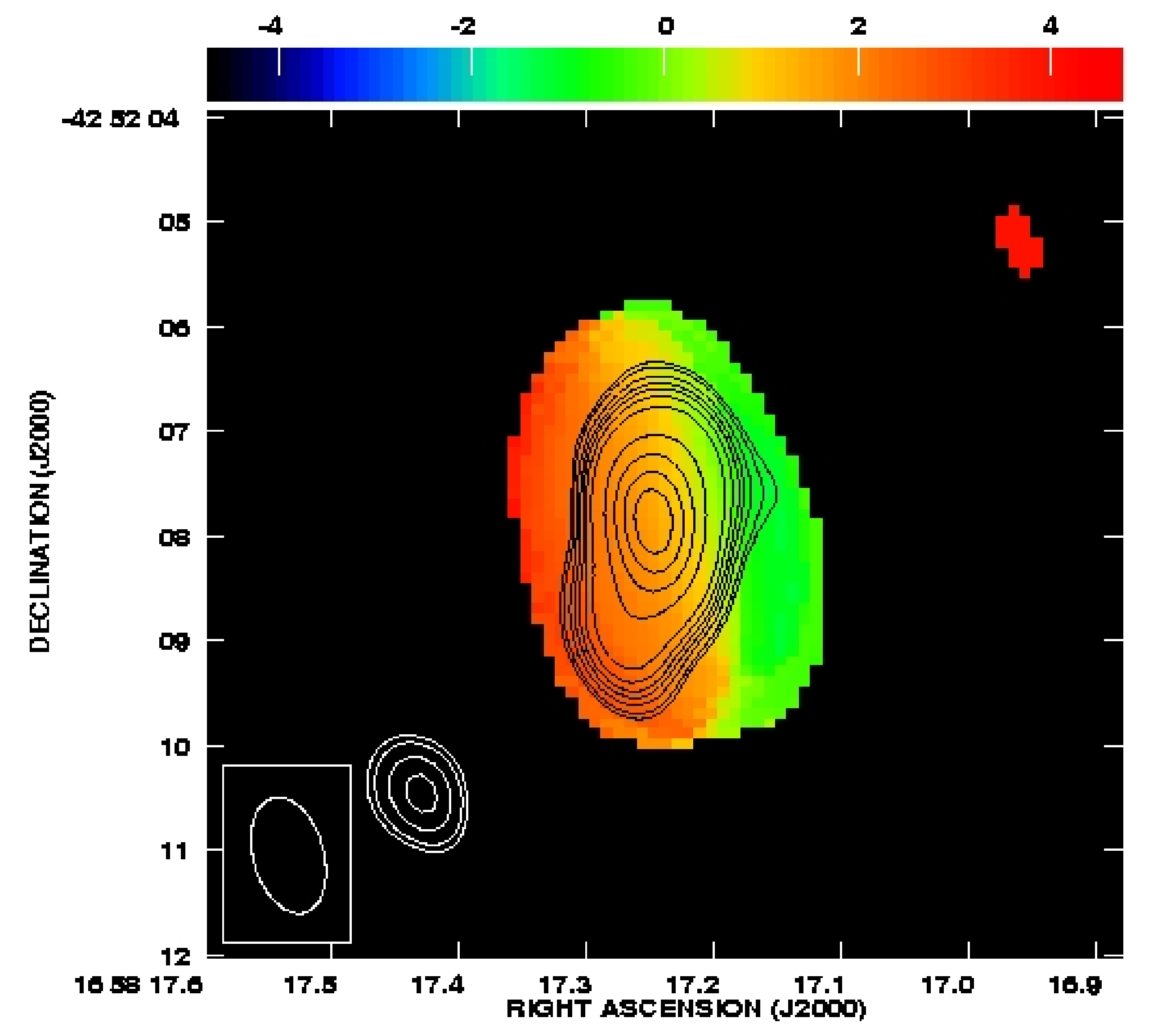
- What about infalling gas and in particular, a disk?



Some of the line emission from single dish (20”) observations show profiles characteristic of large scale infall.

You need much larger angular resolution to detect a disk.

The SubMillimeter Array

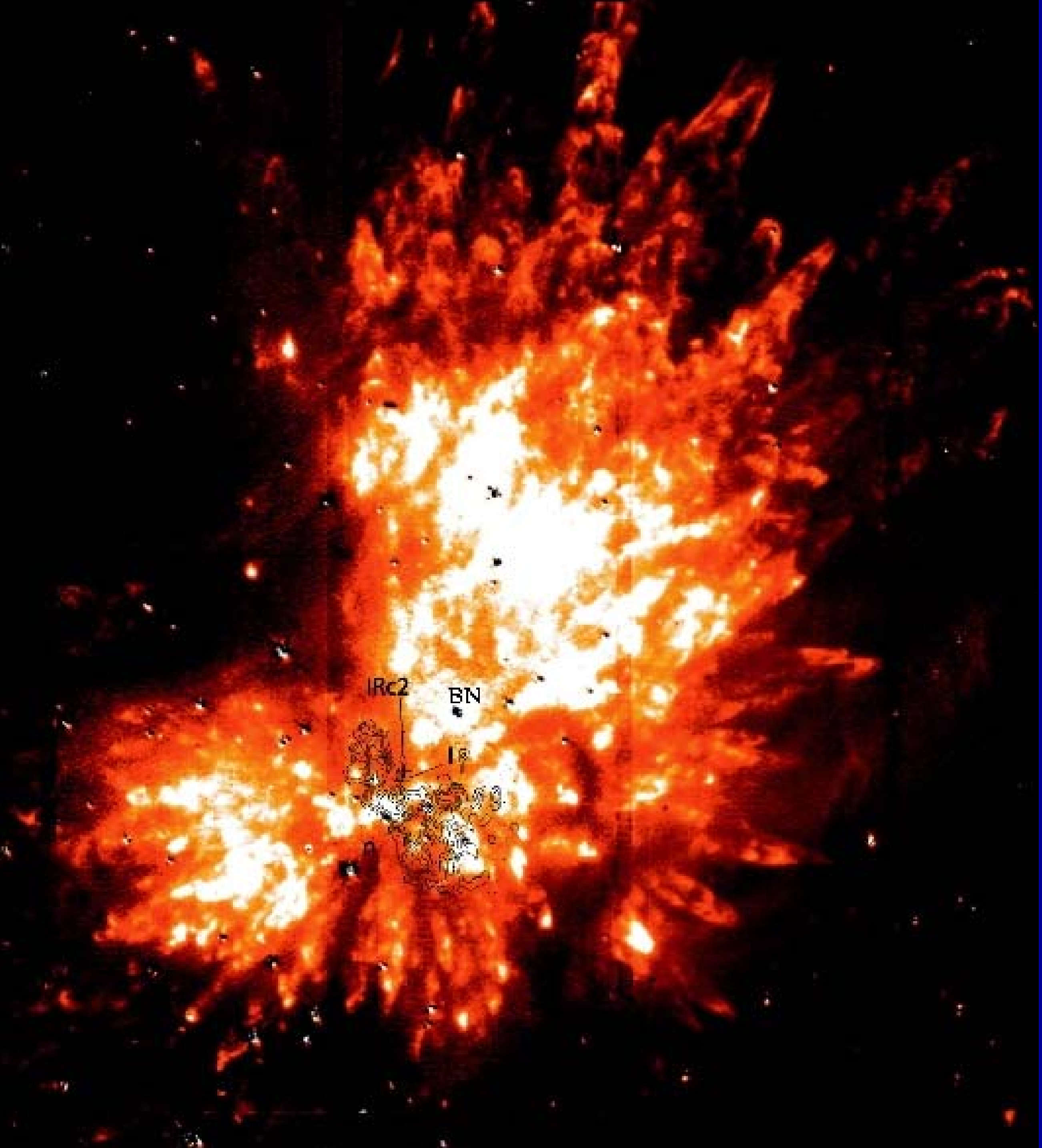


Velocity gradient in SO2 (colors) suggests total mass of 20 to 40 solar masses and a radius of 1,000 AU for the disk.

Most massive young star with jets, disk, and large scale infall.

Do we need merging?

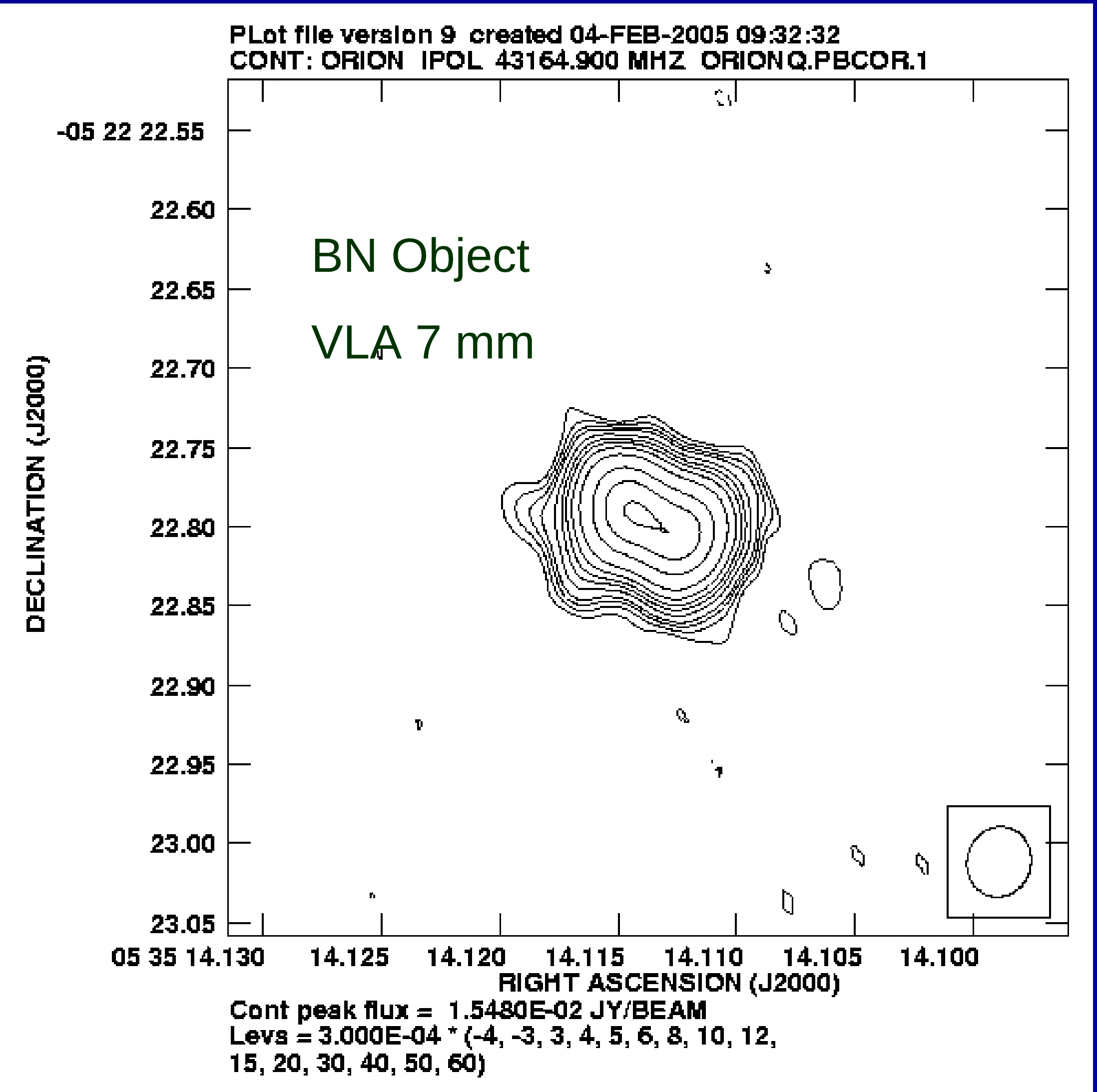
- Evidence for collimated outflows from massive young stars is relatively firm. Collimated outflows not expected after merging.
- Evidence for disks is scarce, but is being searched for vigorously. Some good cases.
- There is, however, the case of Orion BN/KL.



In the Orion BN/KL region there is an example of a powerful, uncollimated outflow. At its center there are several young sources.

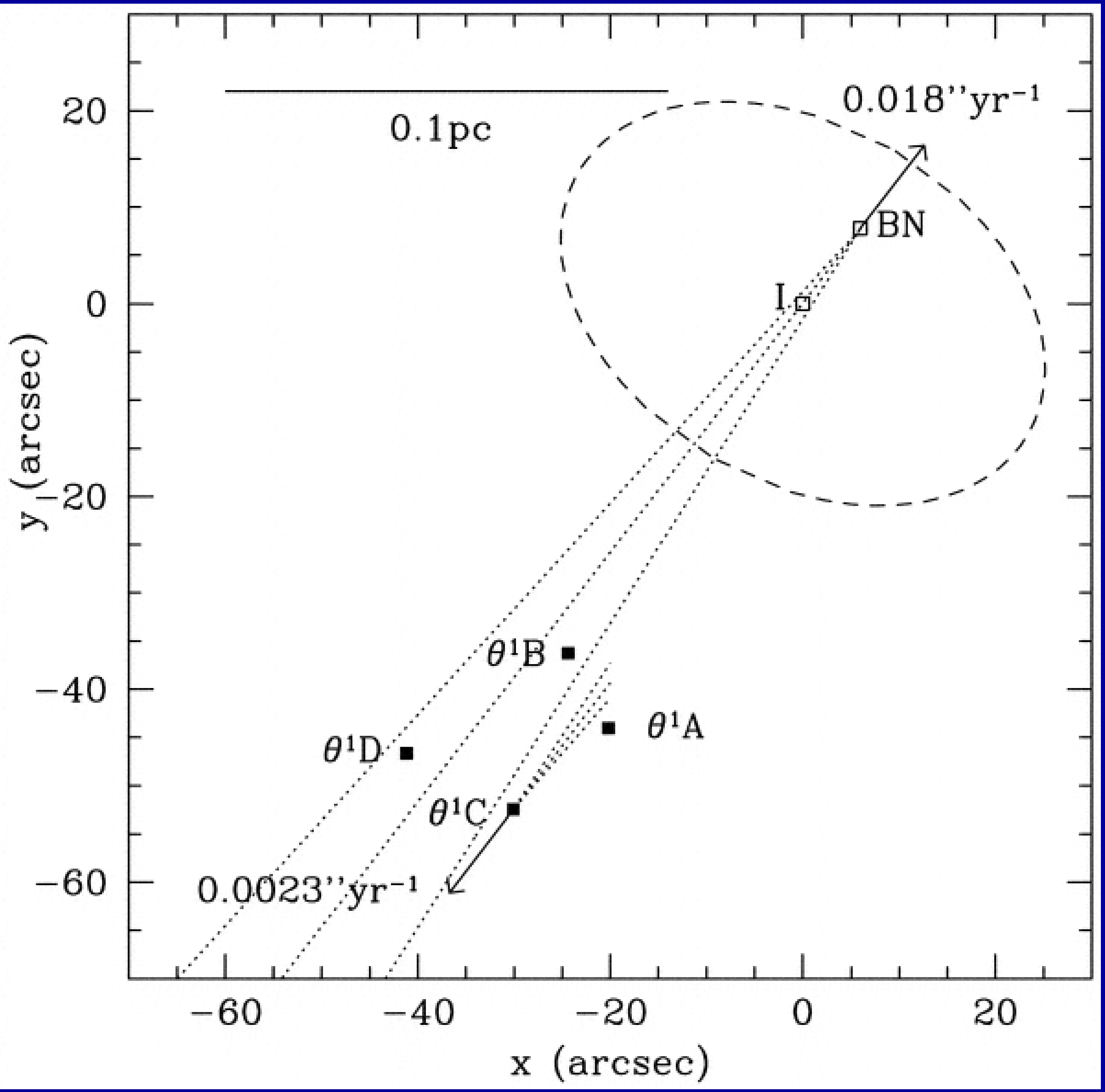
H2 image with NH3 contours (Shuping et al. 2004; Wilson et al. 2000)

The BN object, a "moving" UCHII region…

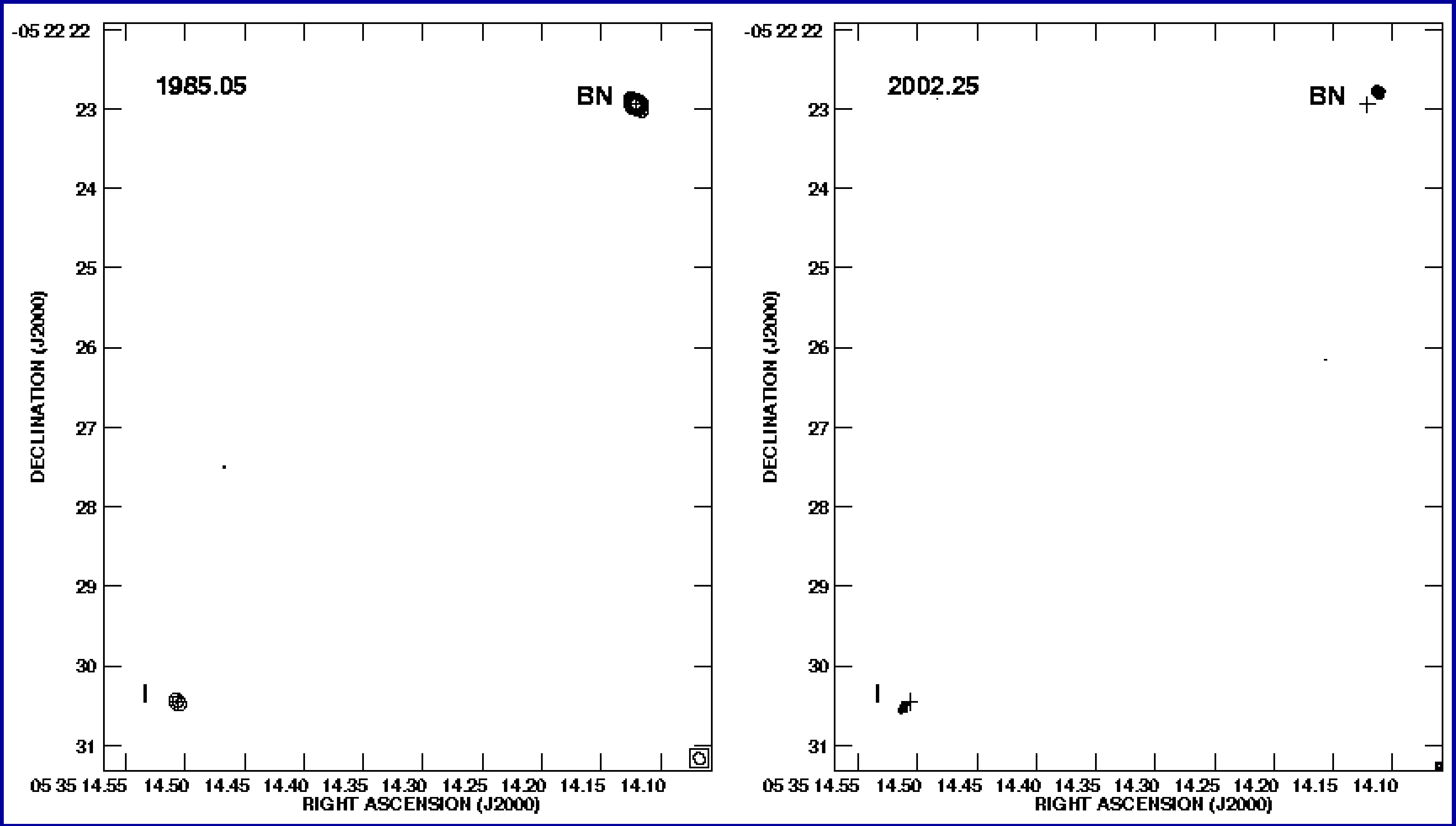


In the radio, the BN object in the Orion BN/KL region is detected as an UCHII region ionized by a B-type star.

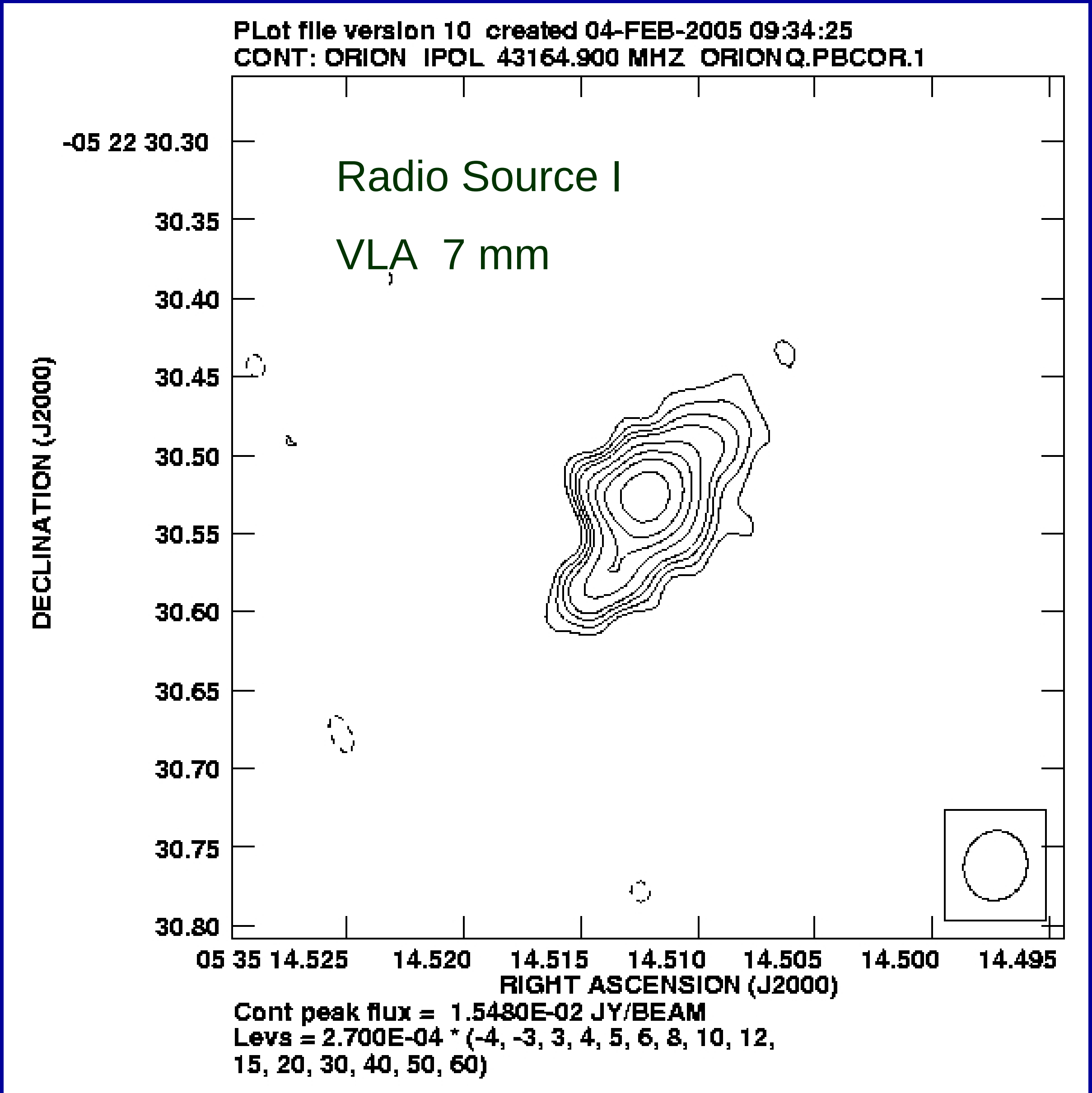
Since 1995, Plambeck et al. reported large proper motions (tens of km s^{-1}) to the NW.



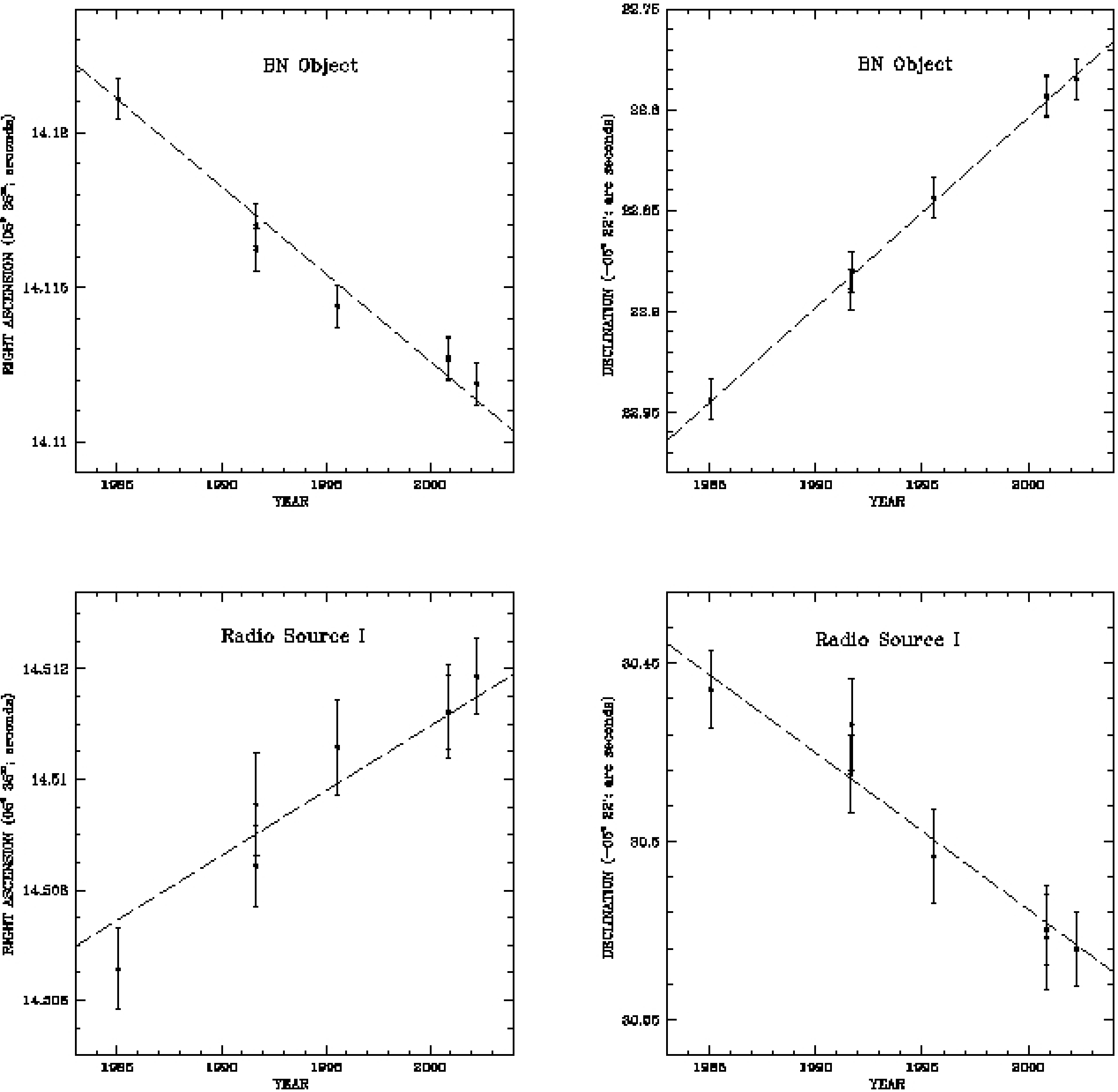
In a recent analysis of the data, Tan (2004) proposed that the BN object was ejected some 4,000 years ago by interactions in a multiple system located at θ^1C Ori, the brightest star of the Orion Trapezium.



However, an analysis of VLA data taken over the last two decades suggests that the radio source I (apparently a thermal jet), is also moving in the sky, receding from a point between it and the BN object.

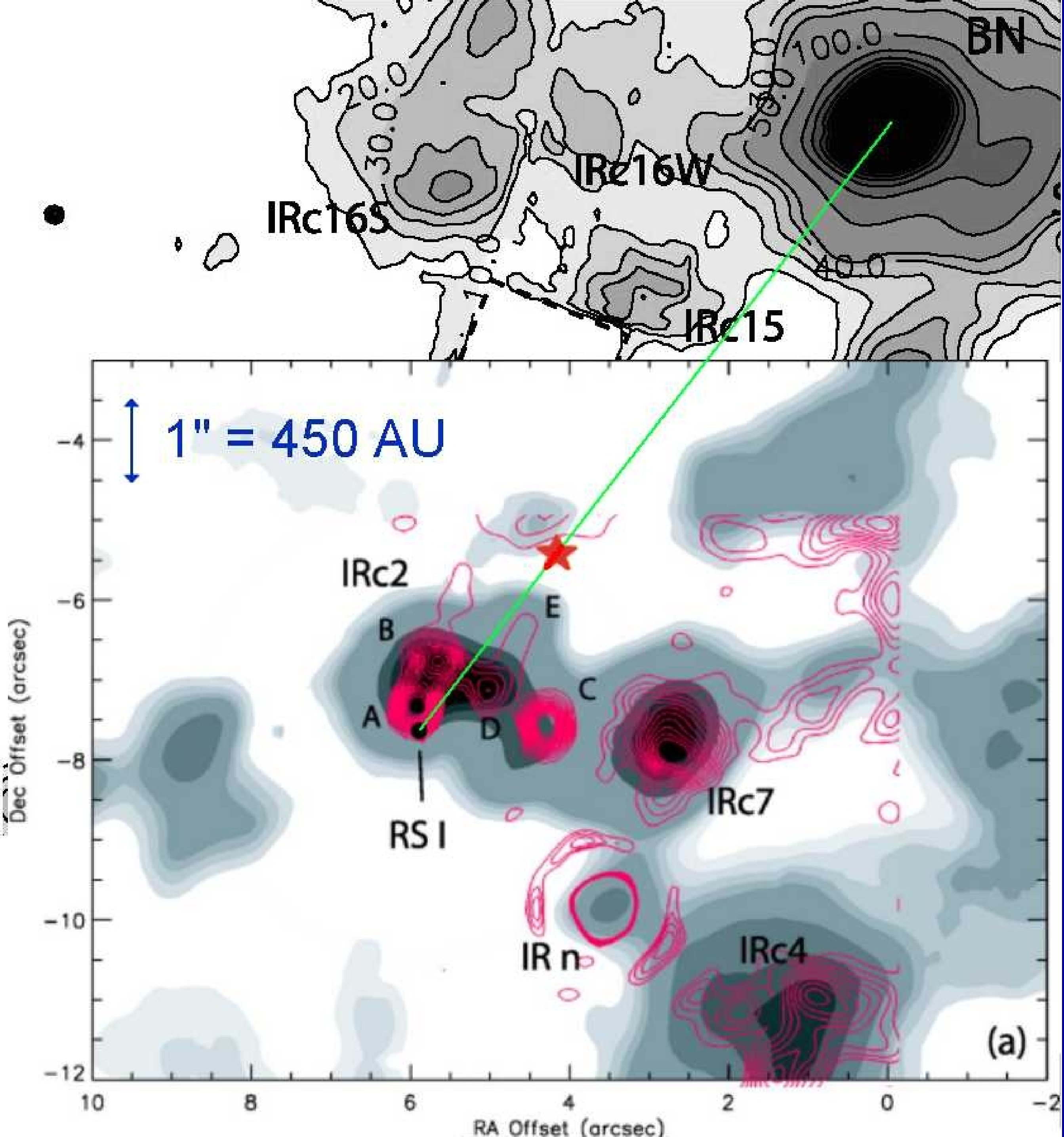


The Radio Source I is also moving in the sky.



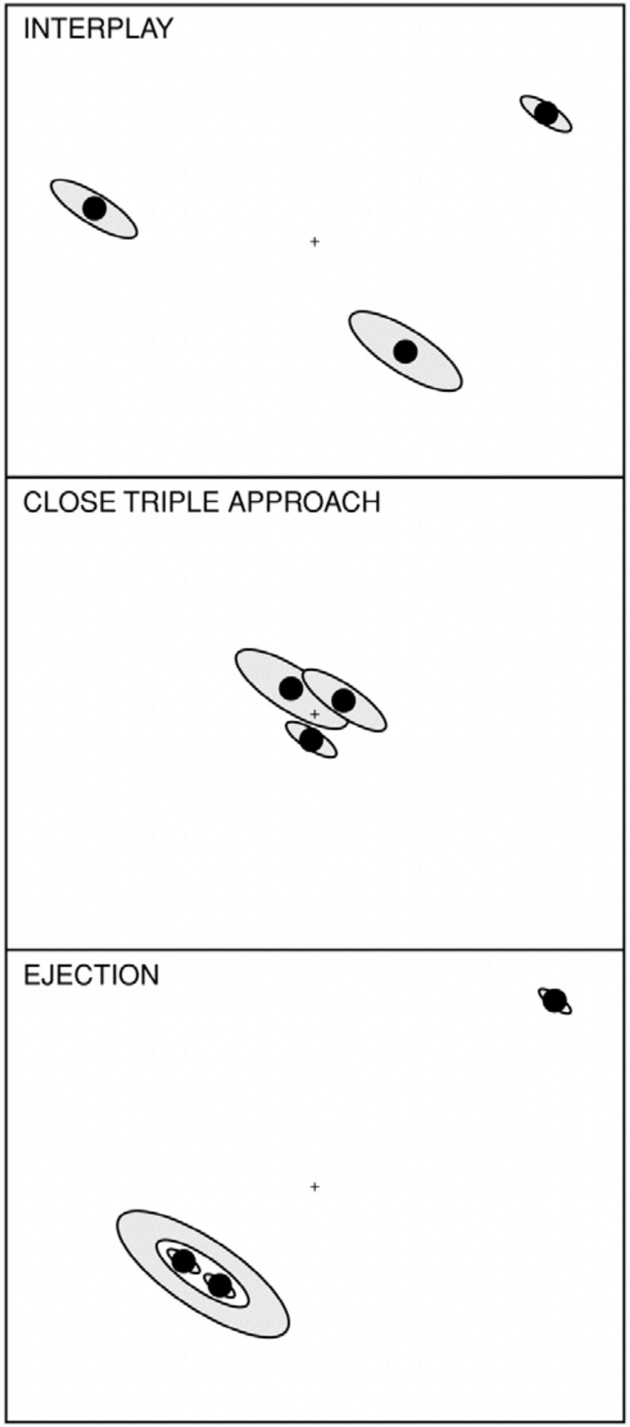
BN moves to the NW at 27+-1 km s^{-1}.

I moves to the SE at 12+-2 km s^{-1}.



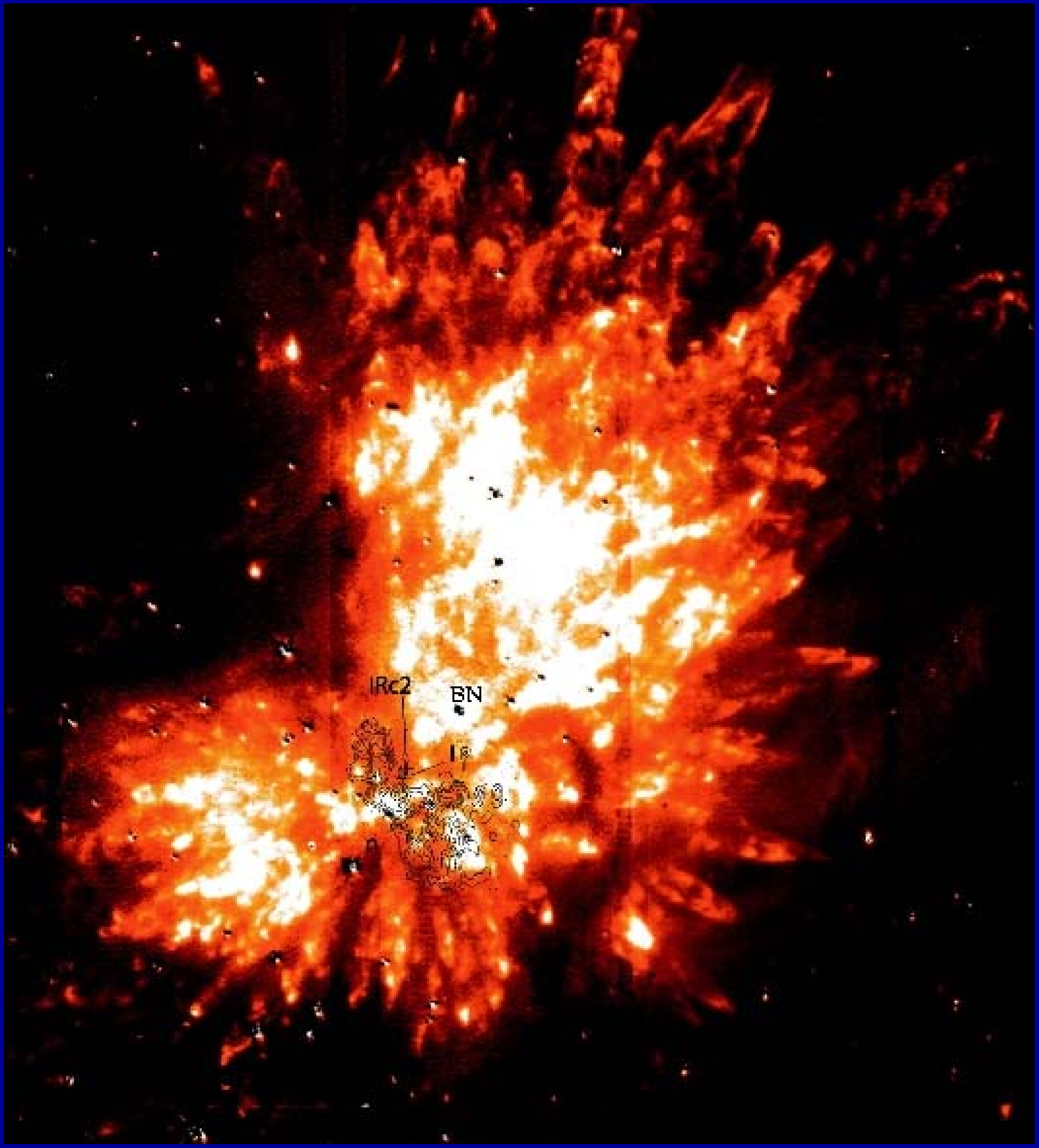
The data suggest that some 500 years ago, a multiple stellar system, formed at least by BN and I had a close encounter and the stars were expeled in antiparallel directions

BN or I have to be close binary systems for this scenario to work



Encounters in multiple stellar systems can lead to the formation of close binaries or even mergers with eruptive outflows (Bally & Zinnecker 2005).

Reipurth (2000)



Indeed, around the BN/KL region there is the well known outflow with an age of about 1000 years.

It is possible that the outflow and the ejection of BN and I were result of the same phenomenon.

Energy in outflow is of order $4X10^{47}$ ergs, perhaps produced by formation of close binary or merger.

Still many open questions in massive star formation...

- Are disks and jets always present?
- Accretion seems needed given collimated outflows
- Are mergers playing a role?