Compact Radio Sources in Regions of Massive Star Formation

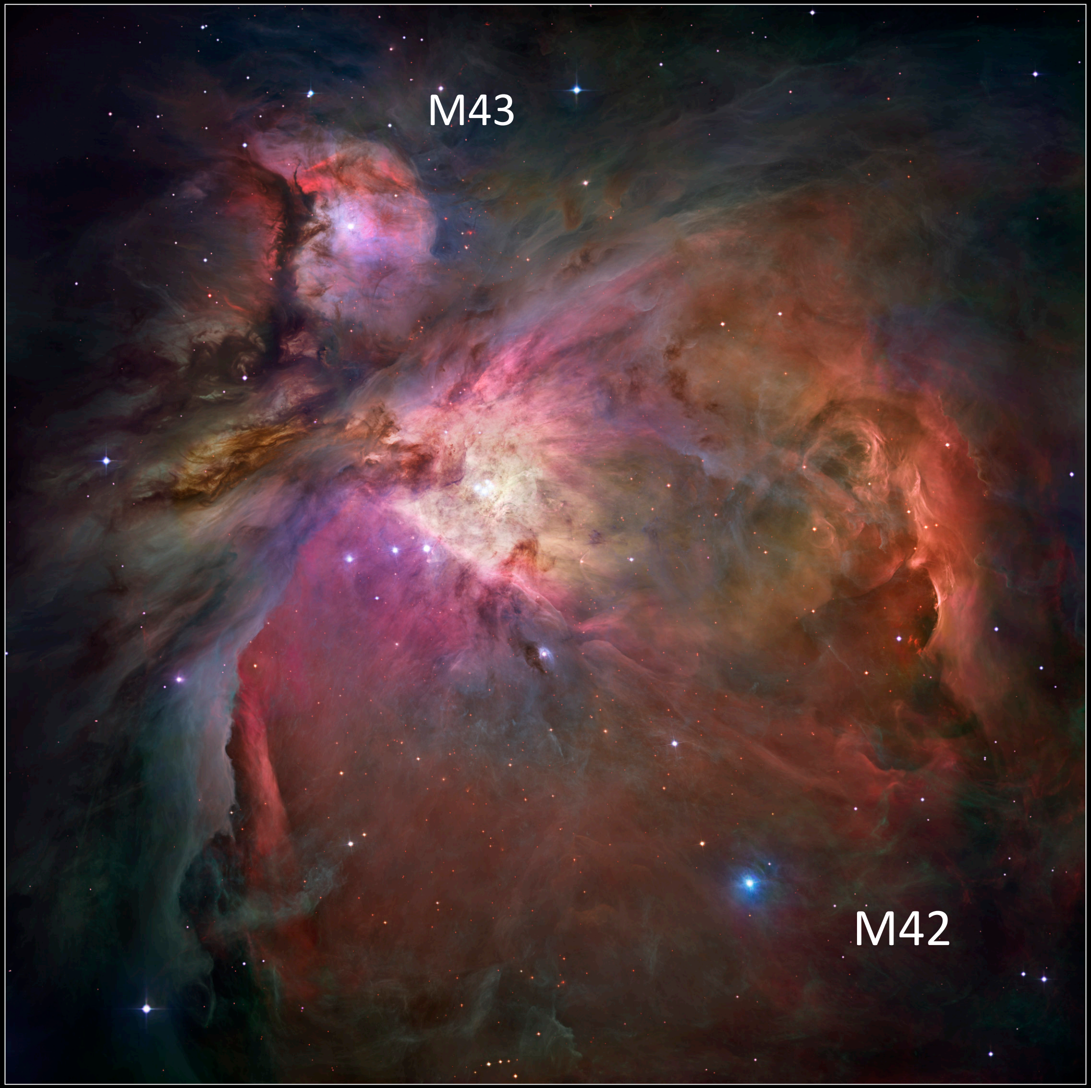
Luis F. Rodriguez

Centro de Radioastronomía y Astrofísica, UNAM

Three main continuum processes in centimeter radio astronomy:

- Free-free (thermal)
- Gyrosynchrotron (non-thermal)
- Synchrotron (non-thermal)

- Tomorrow we will see millimeter processes, mostly dust and molecular emissions.



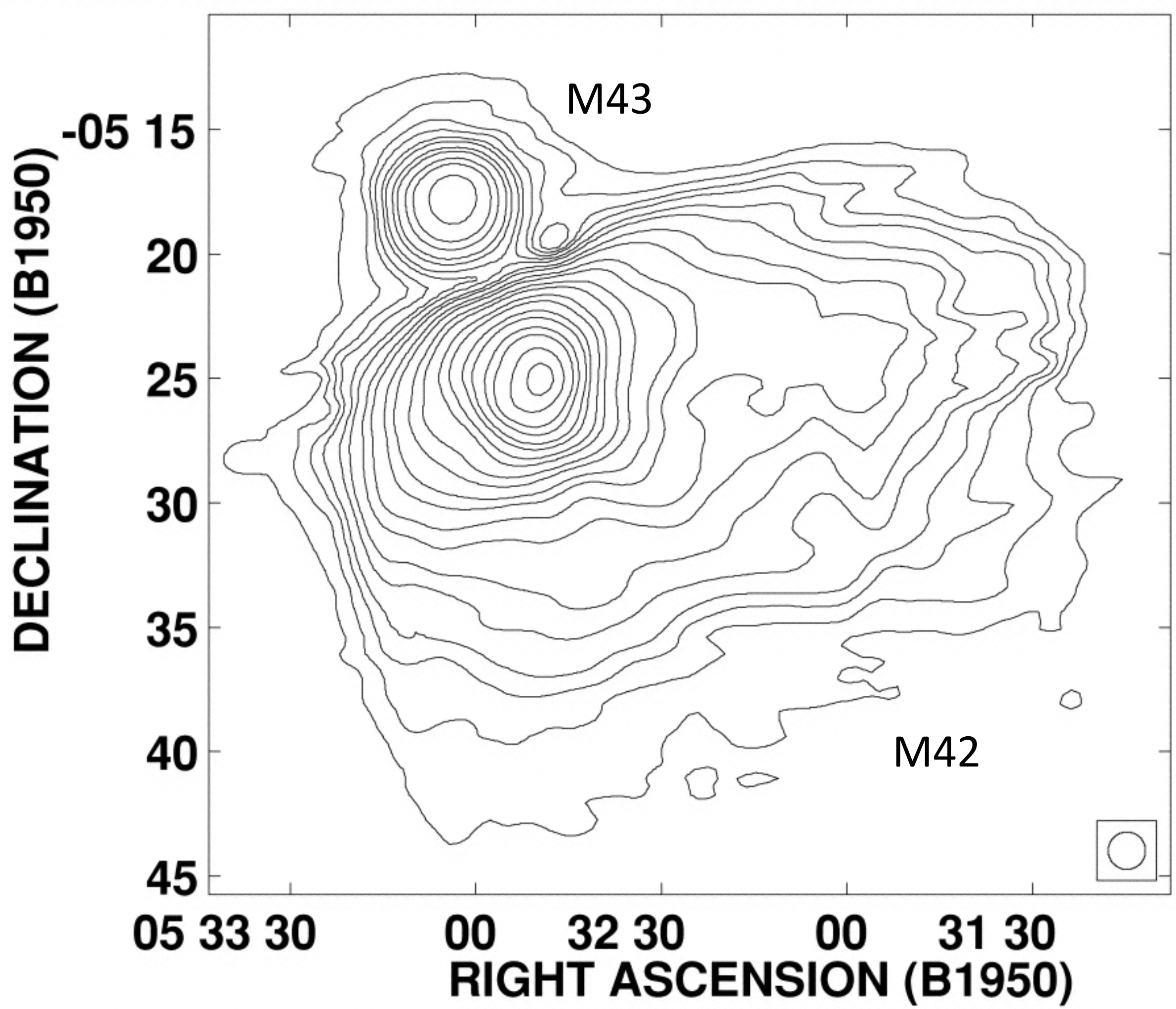
Orion Nebula ▪ M42

Hubble Space Telescope ▪ ACS/WFC

NASA, ESA, M. Robberto (STScI/ESA), and the HST Orion Treasury Project Team

STScI-PRC06-01a

Orion nebula at 10.55 GHz

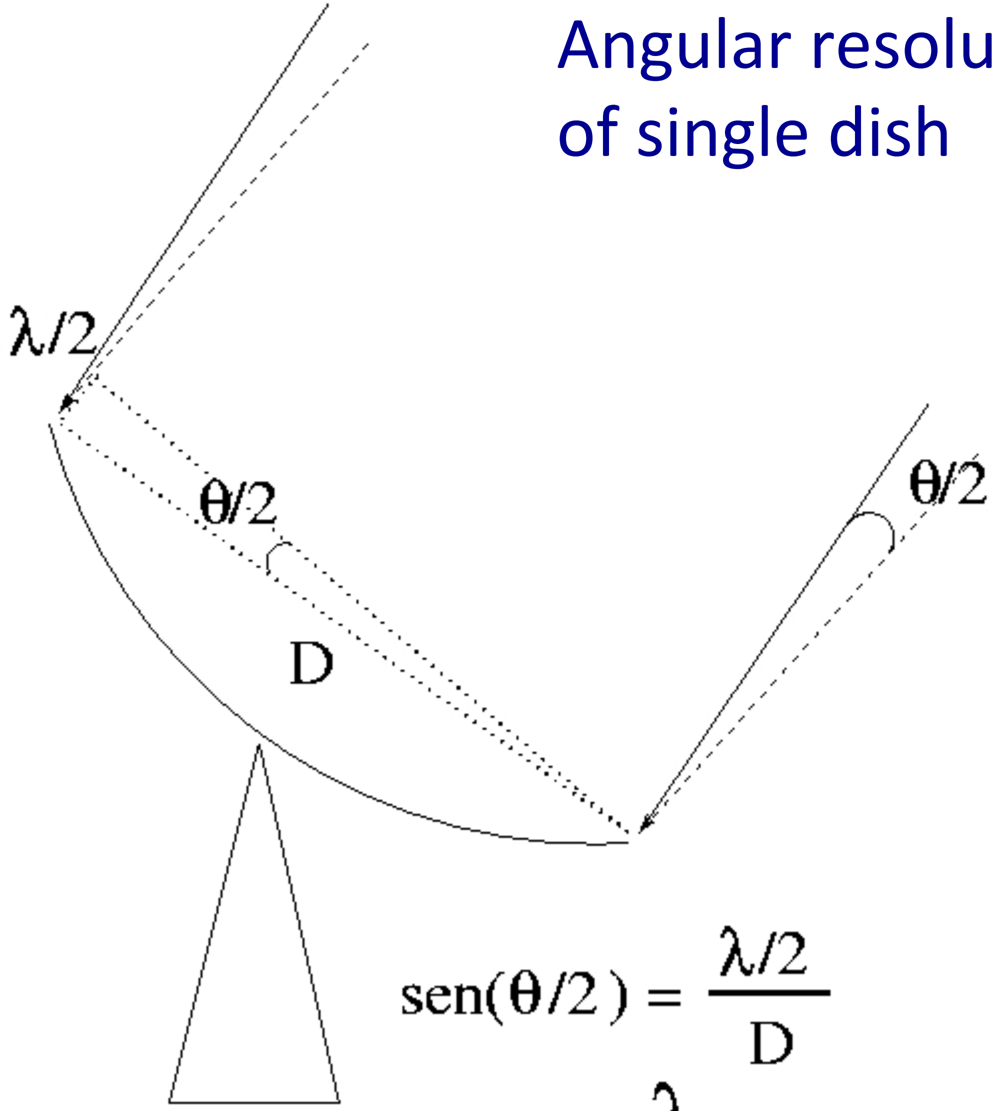


Single-dish (Effelsberg) observations with an angular resolution of 1.5′.

Extended free-free emission.

Subrahmanyan et al. (2001).

Angular resolution of single dish

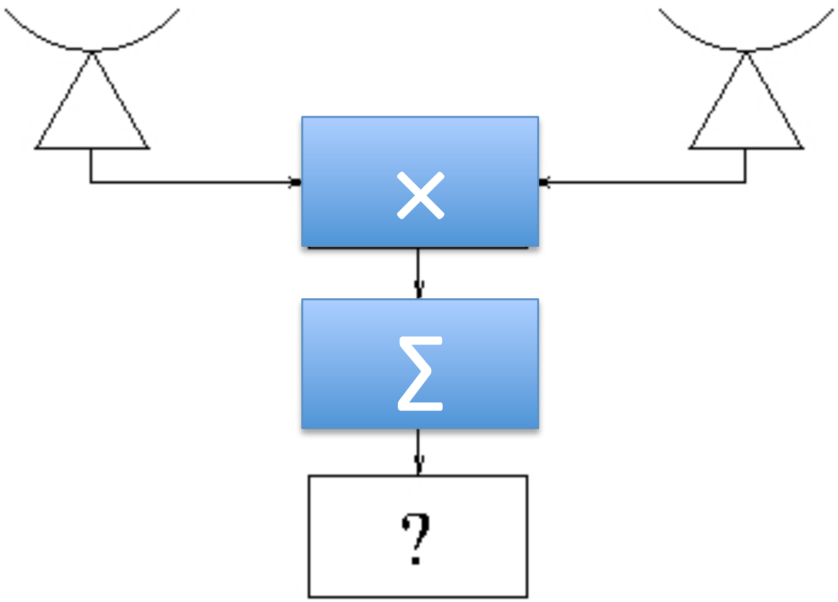


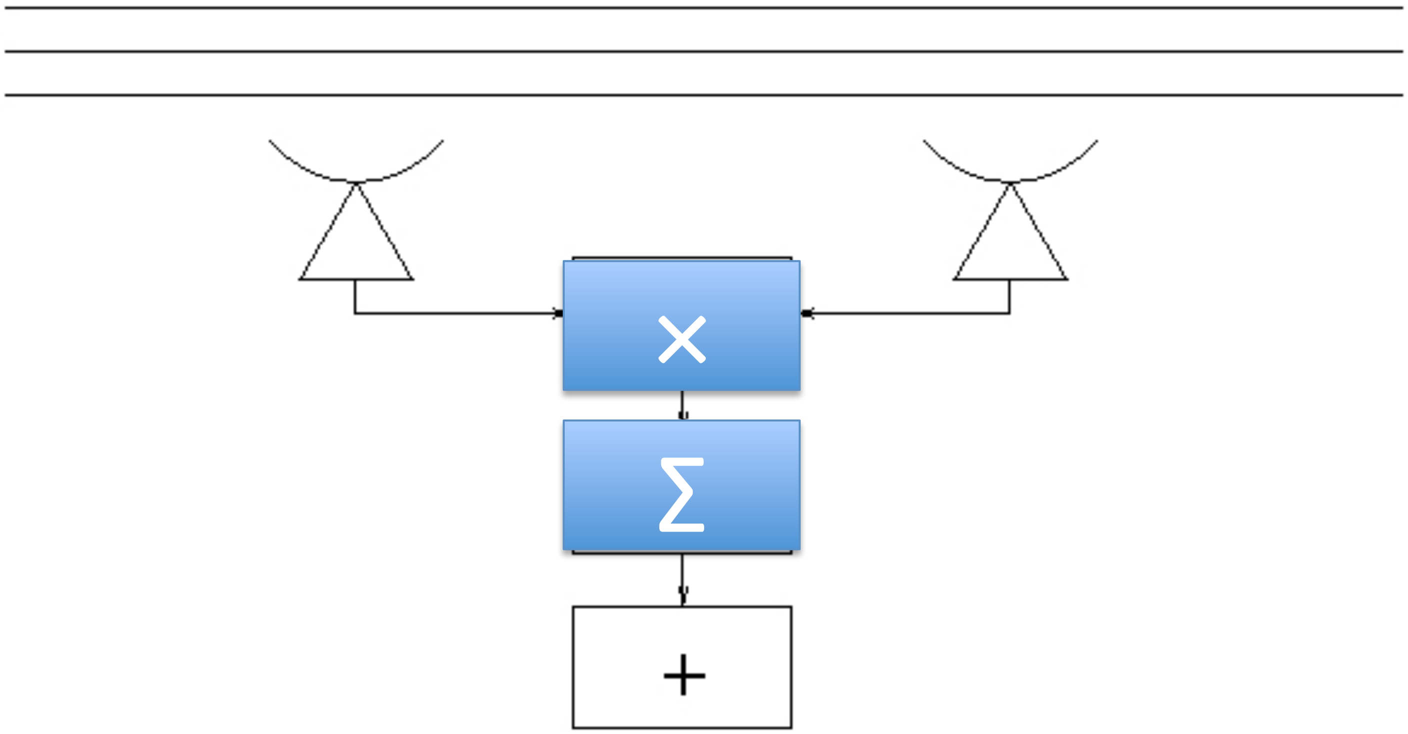
$$\text{sen}(\theta/2) = \frac{\lambda/2}{D}$$

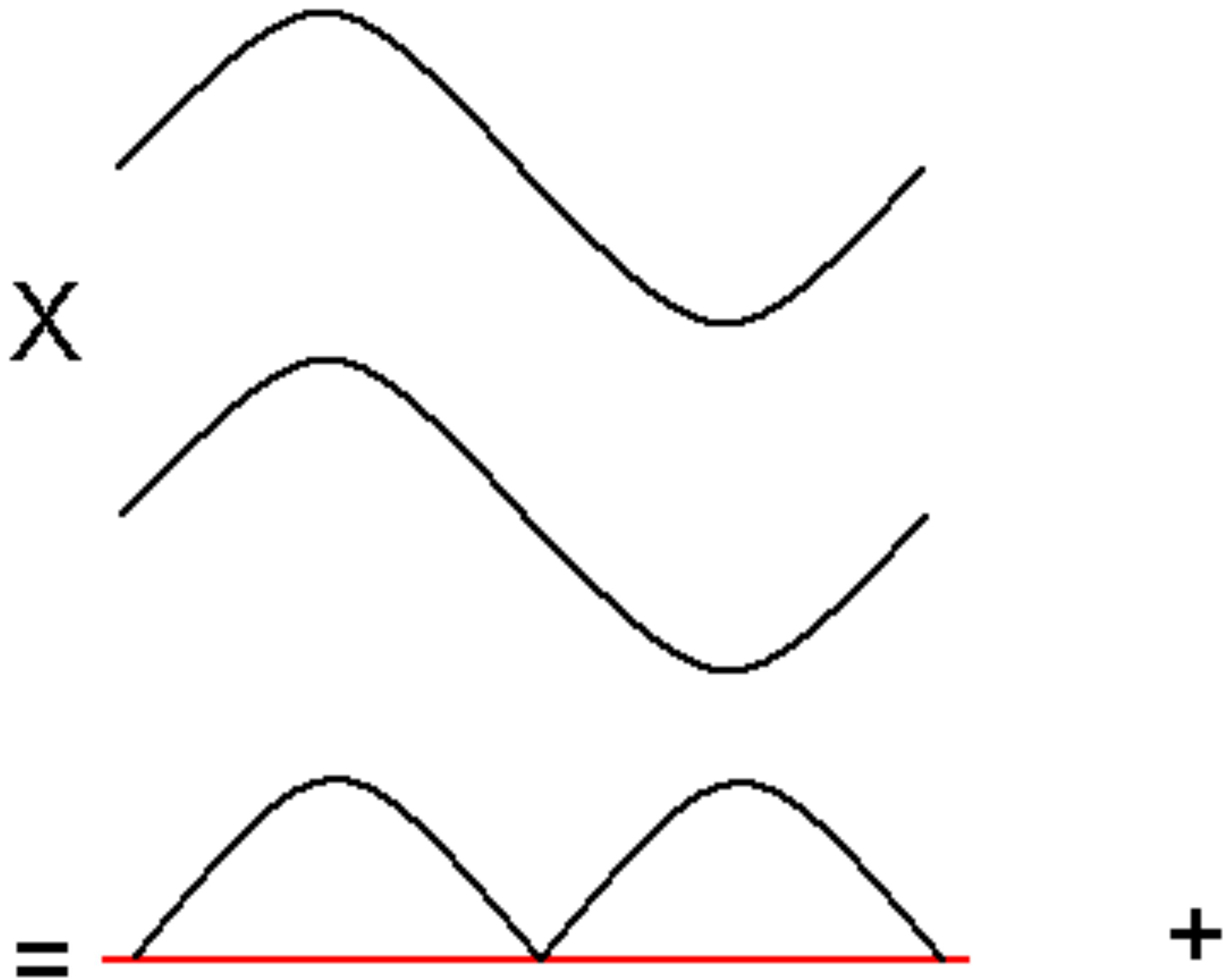
$$\theta = \frac{\lambda}{D}$$

Consider two-element interferometer.

The signal of each antenna pair is multiplied and product is integrated in time. What sign does the resulting number has?



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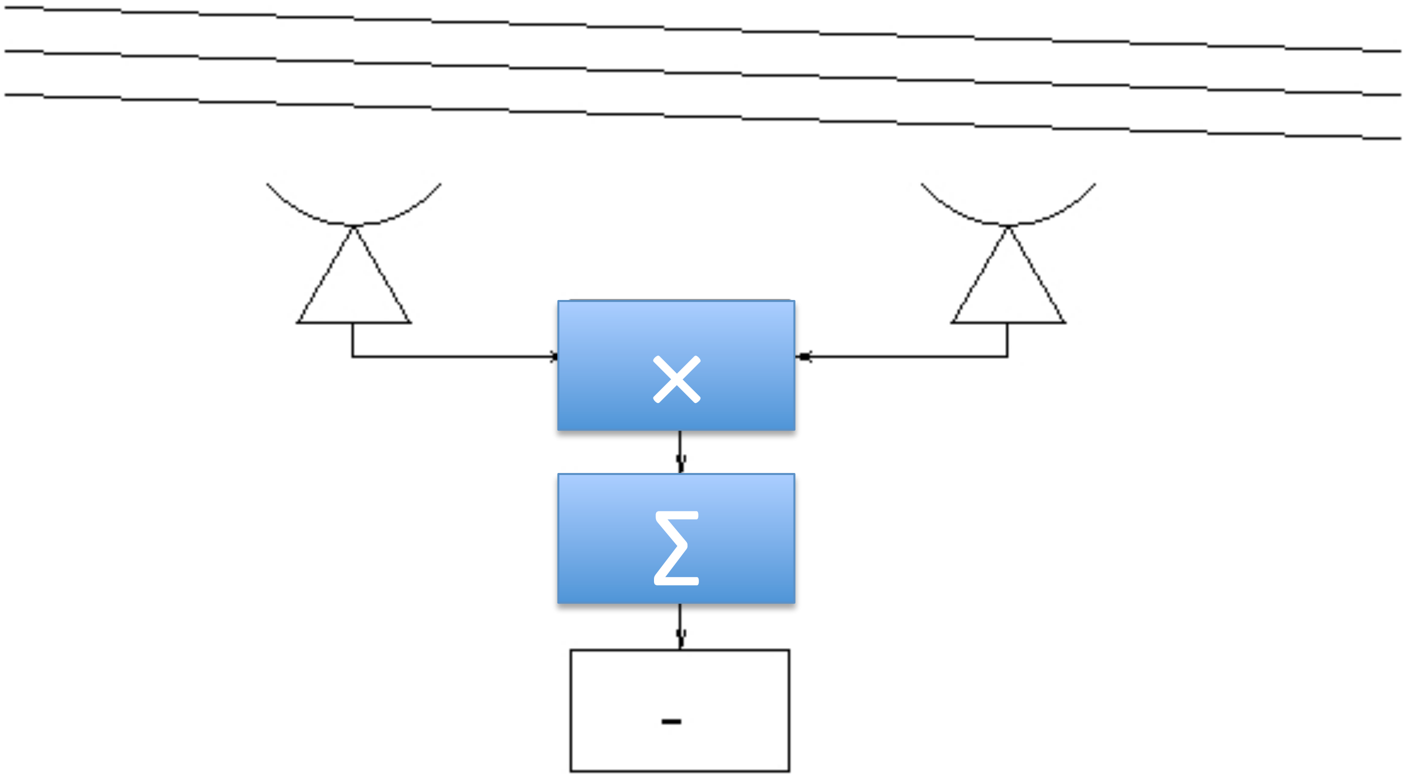
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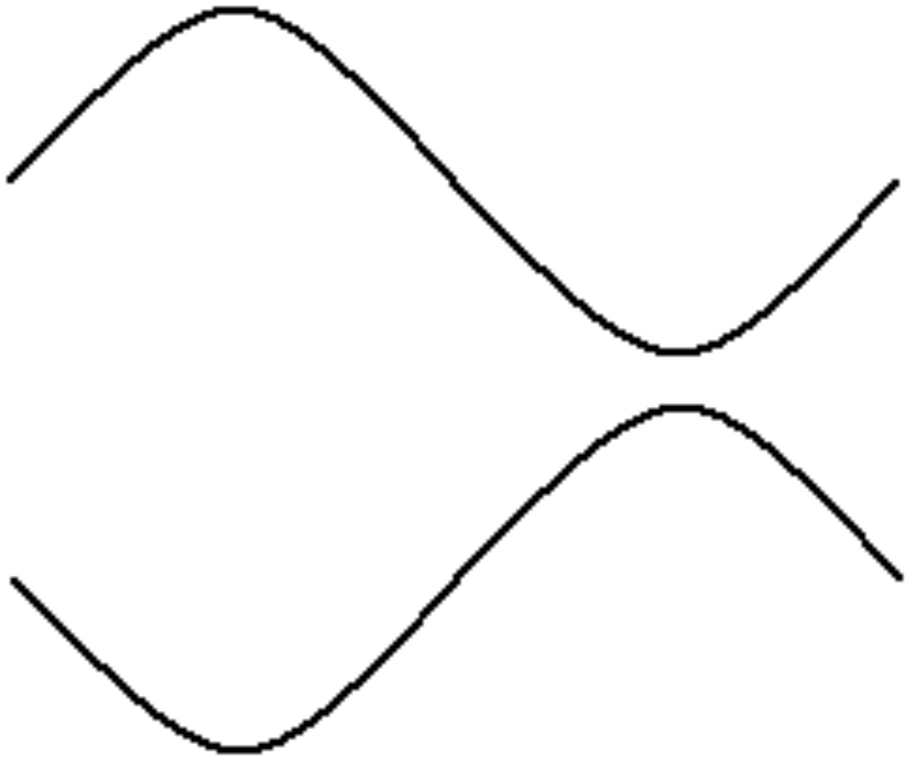

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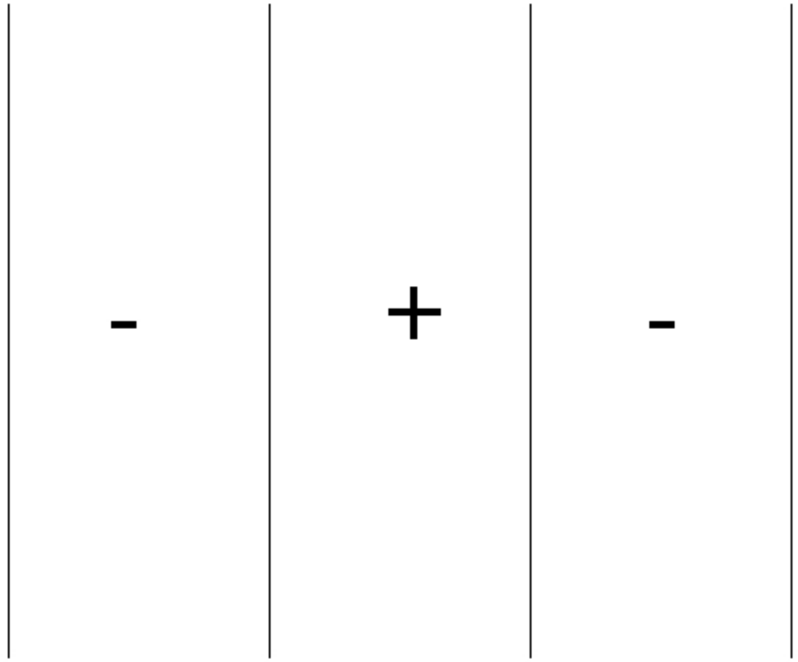
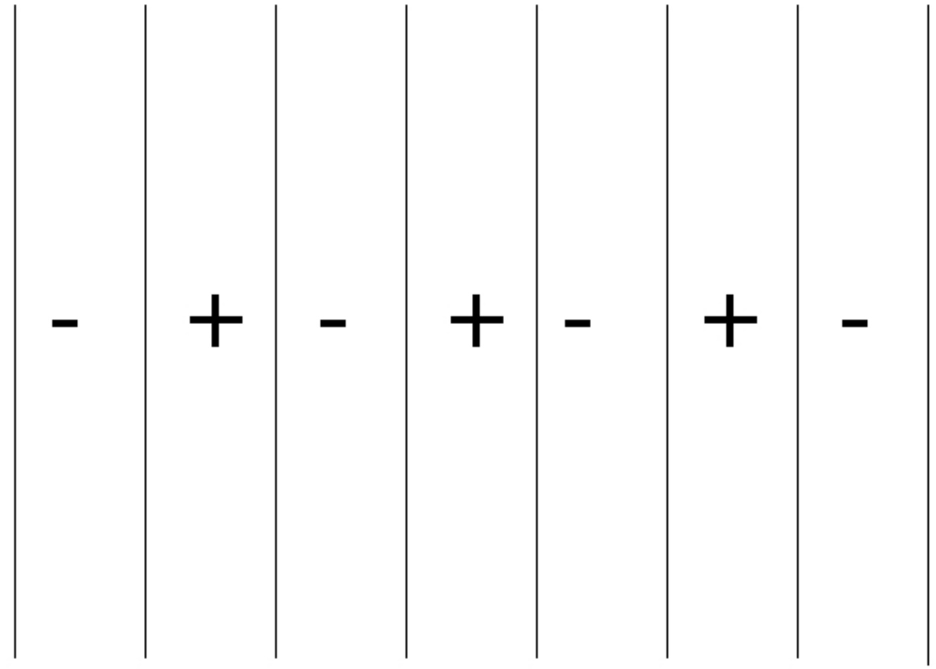
Sinusoidal response in plane of sky



Sinusoidal response in plane of sky

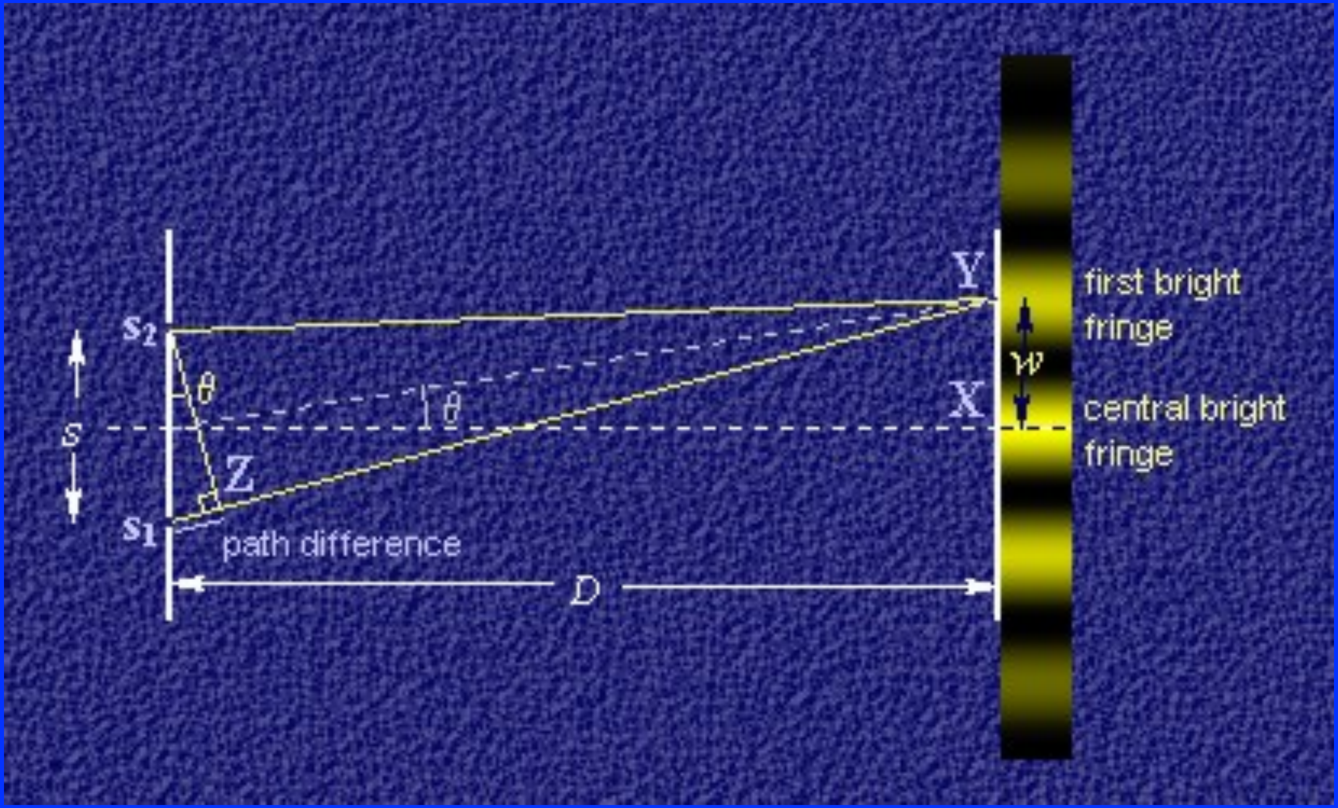


The more distant the two radio telescopes, the closer the fringes…
Now angular resolution is

$$\theta \approx \frac{\lambda}{B}$$

More graphically…

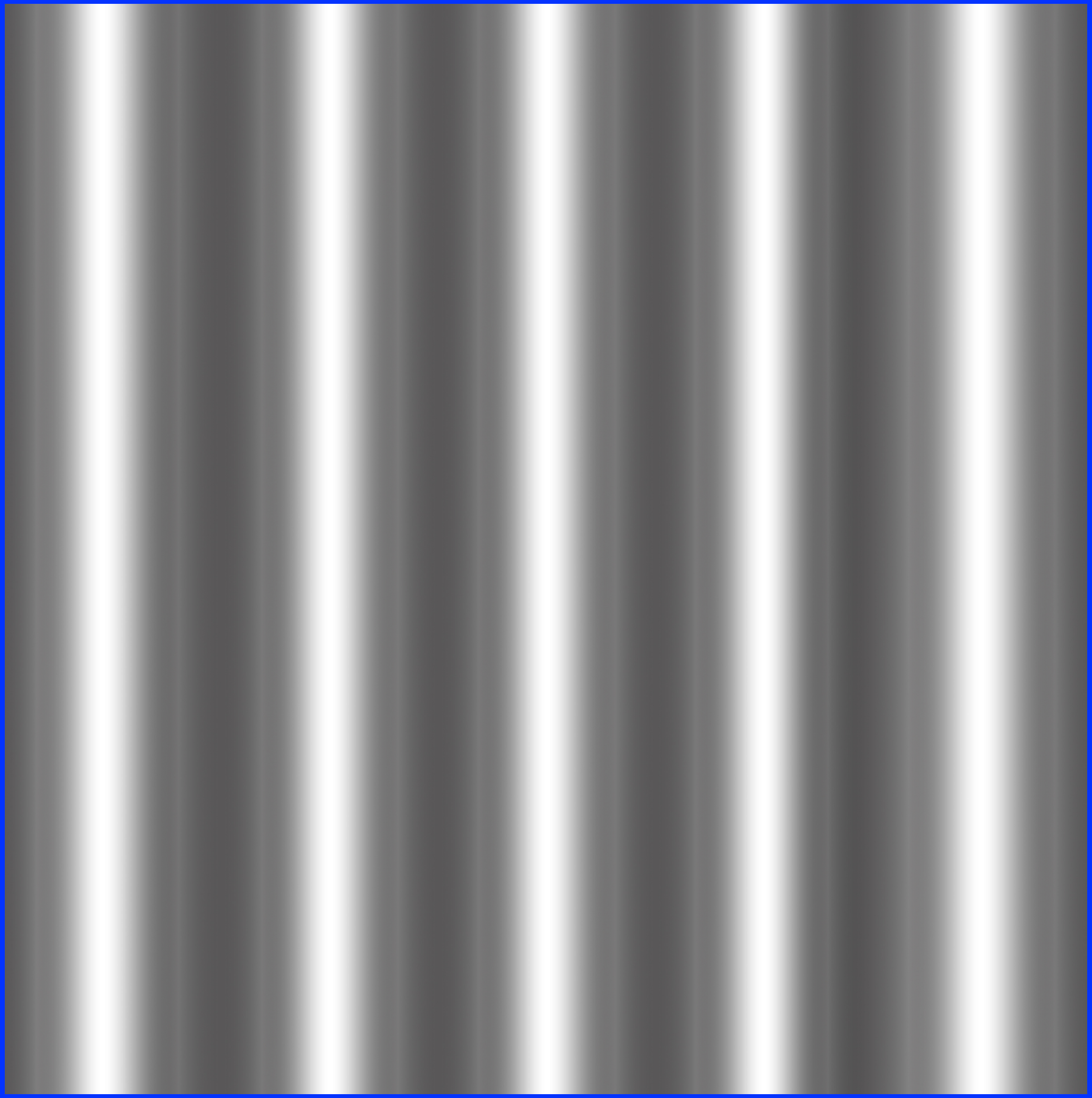
Young's double slit experiment: constructive interference occurs when path difference is an integer number of wavelengths.



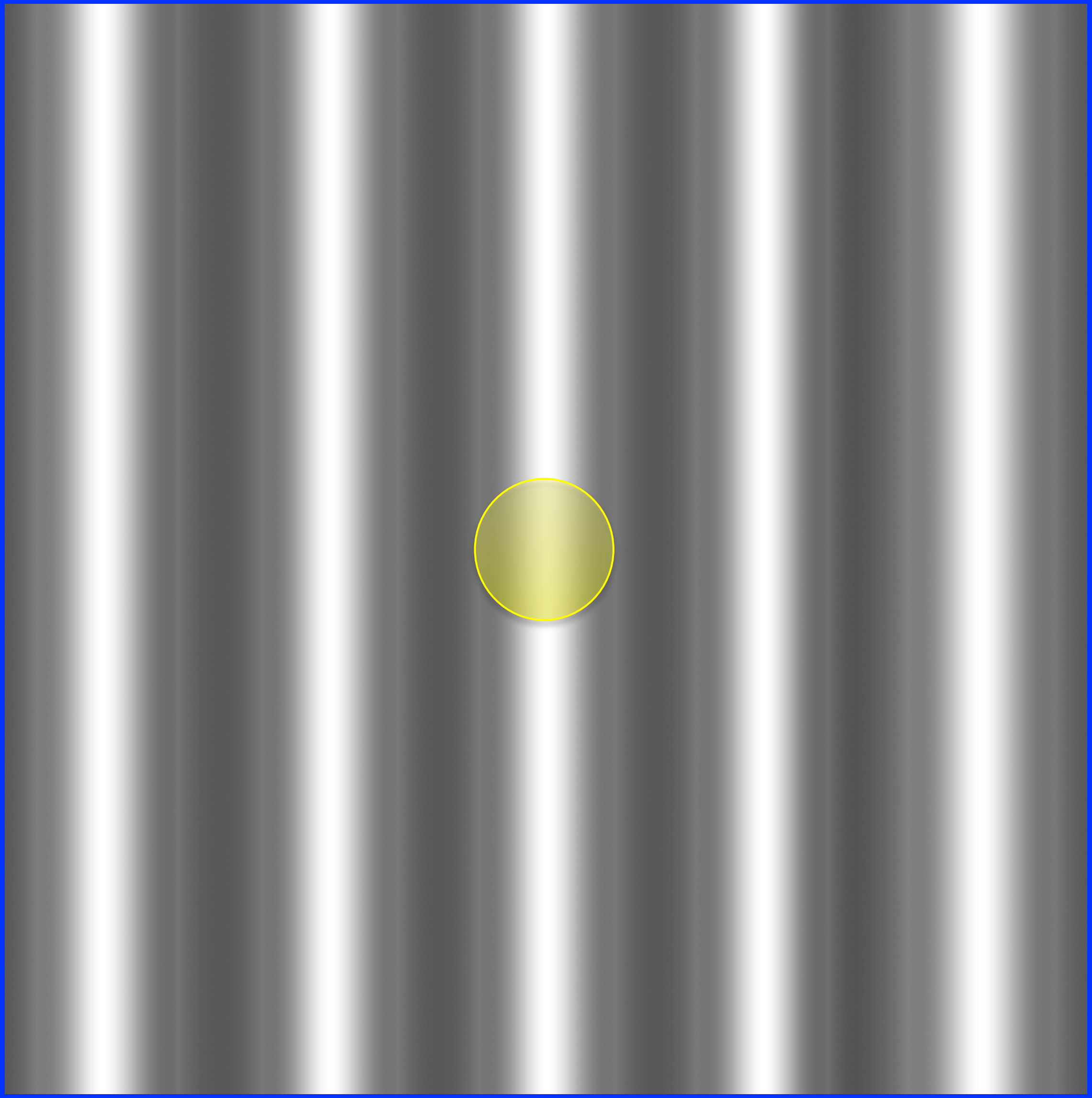
from Dave McConnell

Interferometer response in sky

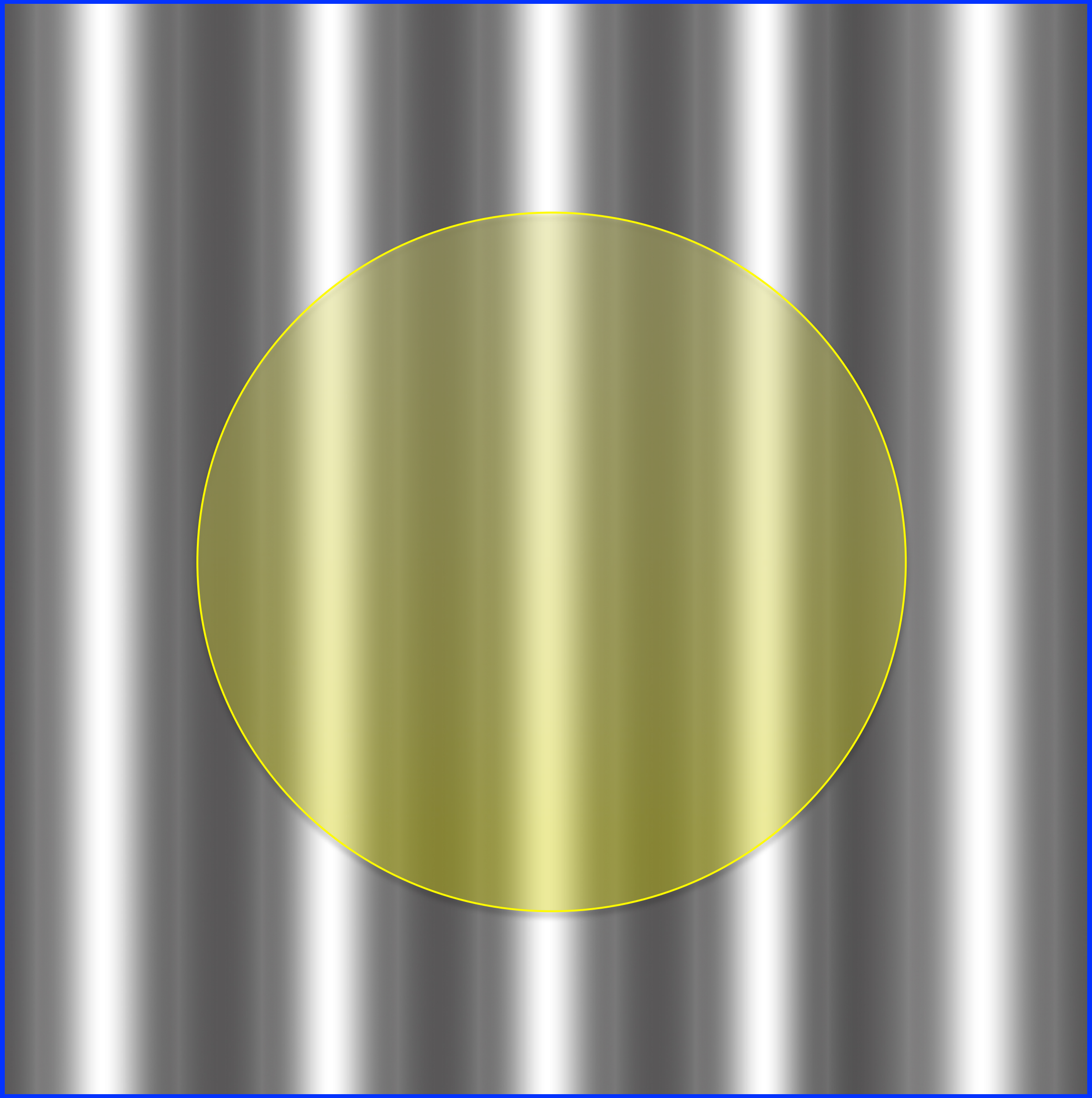
$$\theta = \frac{\lambda}{B}$$

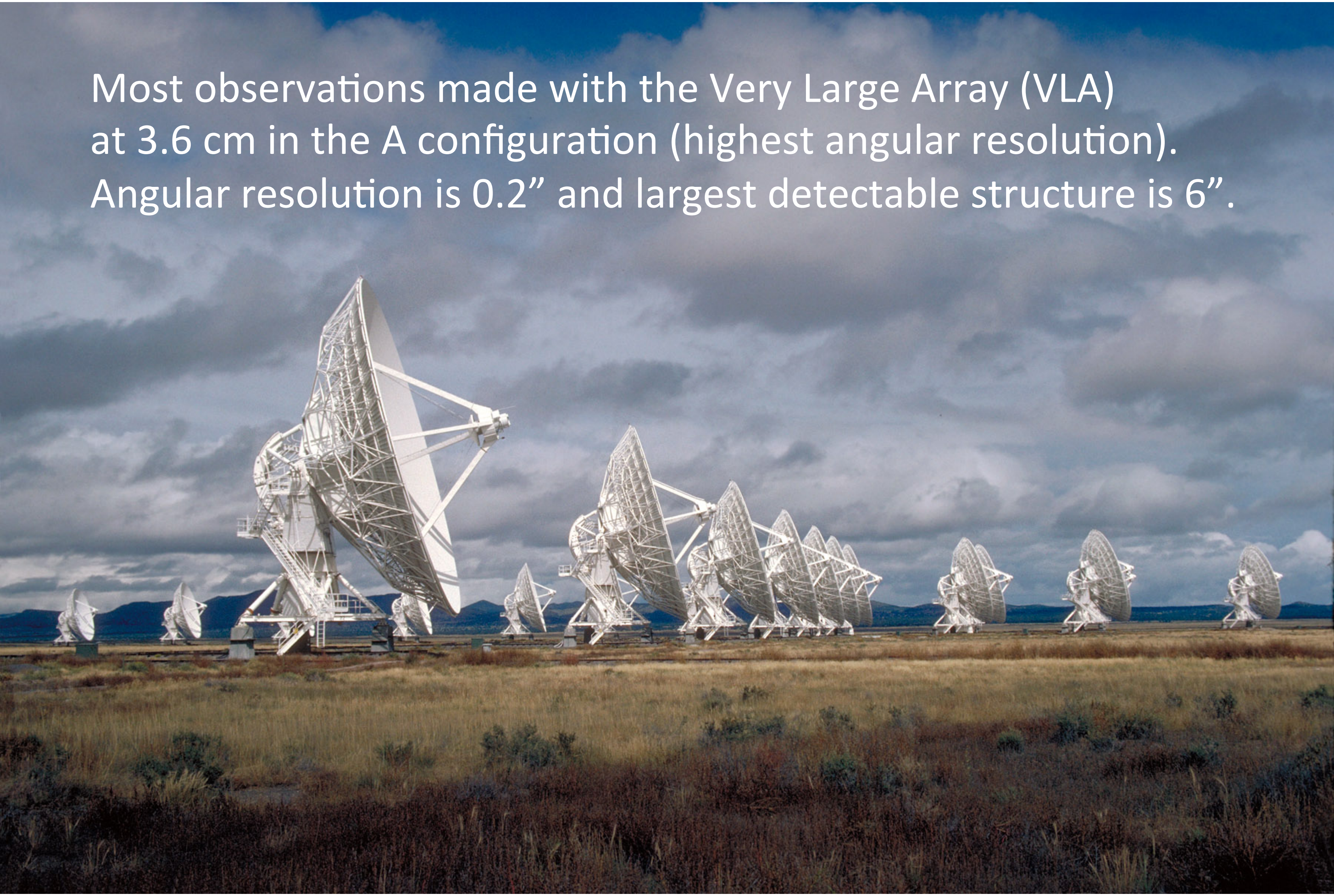


Compact source



Extended source




Most observations made with the Very Large Array (VLA)
at 3.6 cm in the A configuration (highest angular resolution).
Angular resolution is 0.2” and largest detectable structure is 6”.

What types of sources do we expect to detect (cm wavelengths)?

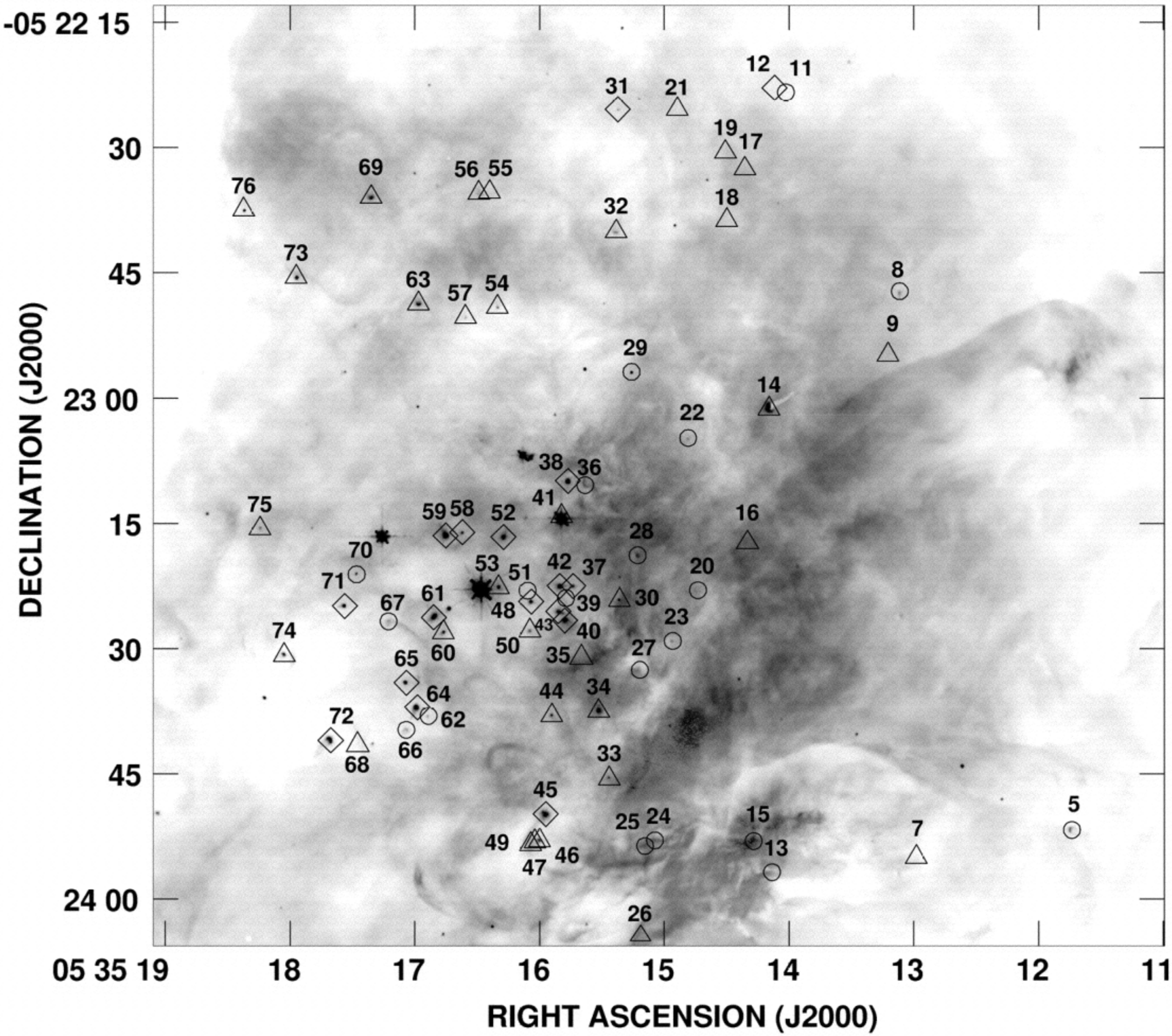
Table 1
Characteristics of Compact Radio Continuum Sources in H II Regions

Class of Source	Emission Mechanism	Spectral Index	Polarization	Time Variability	Morphology	Excitation
HC H II region	Free–free	~ 1	No	No	Various	Internal
Ionized globule	Free–free	~ -0.1	No	No	Cometary	External
Proplyds	Free–free	~ -0.1	No	No	Cometary	External
Jet	Free–free	~ 0.6	No	Yes	Elongated	Internal
Spherical wind	Free–free	~ 0.6	No	No	Unresolved	Internal
Low-mass protostars	Gyrosynchrotron	$-2 - +2$	Circular	Yes	Unresolved	Internal
Massive binary stars	Synchrotron	~ -0.7	Linear	Yes	Cometary	Internal

We are extending with the JVLA the pioneering work made by the groups of Felli, Garay and Churchwell with the VLA.

It is possible to identify the nature of the source with the characteristics listed in the table.

As we will see, in addition to these types of sources, we have recently detected two other types…



Four different epochs.

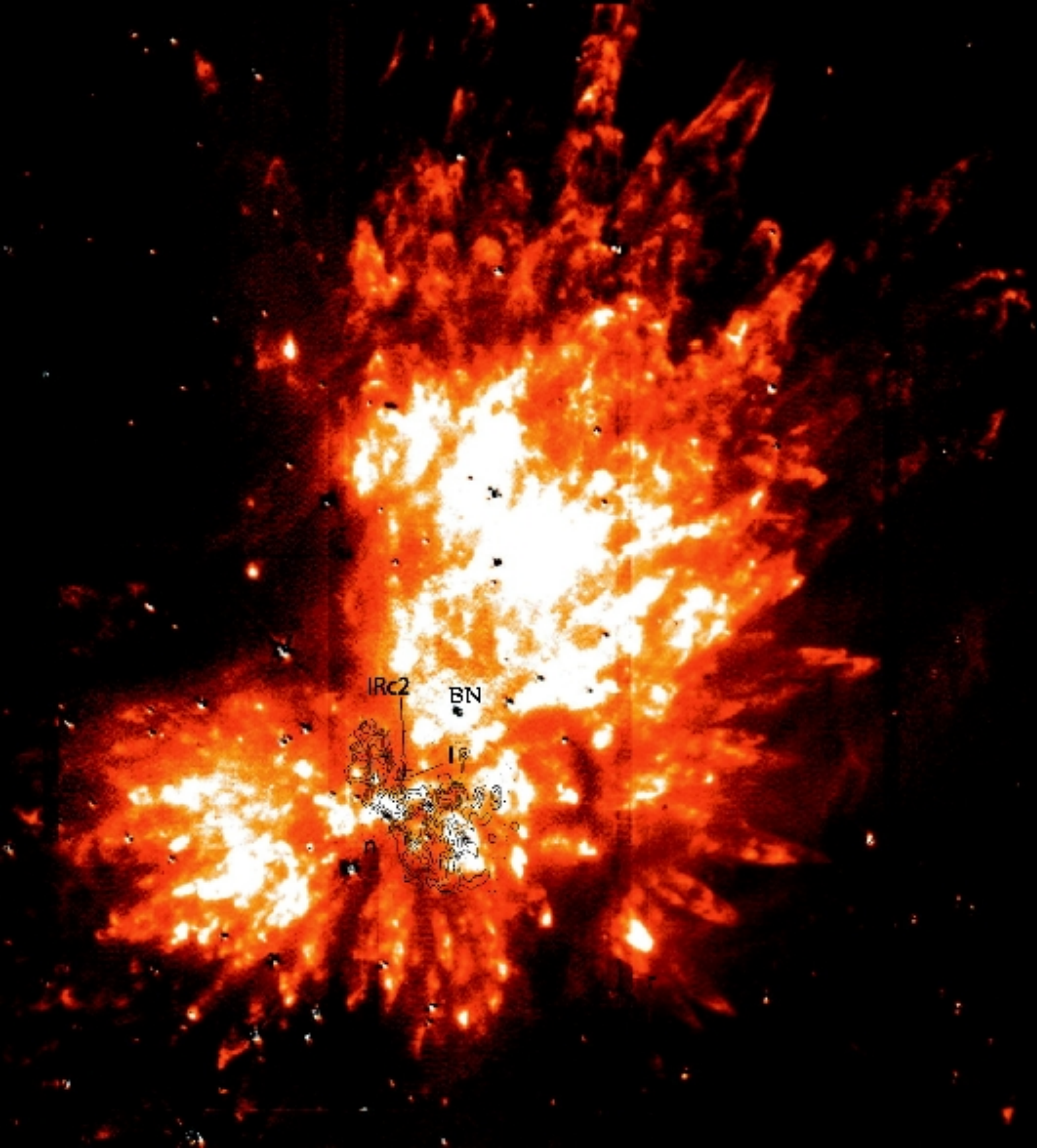
77 compact sources, most with counterparts.

Triangles = Time variable

Diamonds = Non-variable

Circles = Faint, detected only on average image.

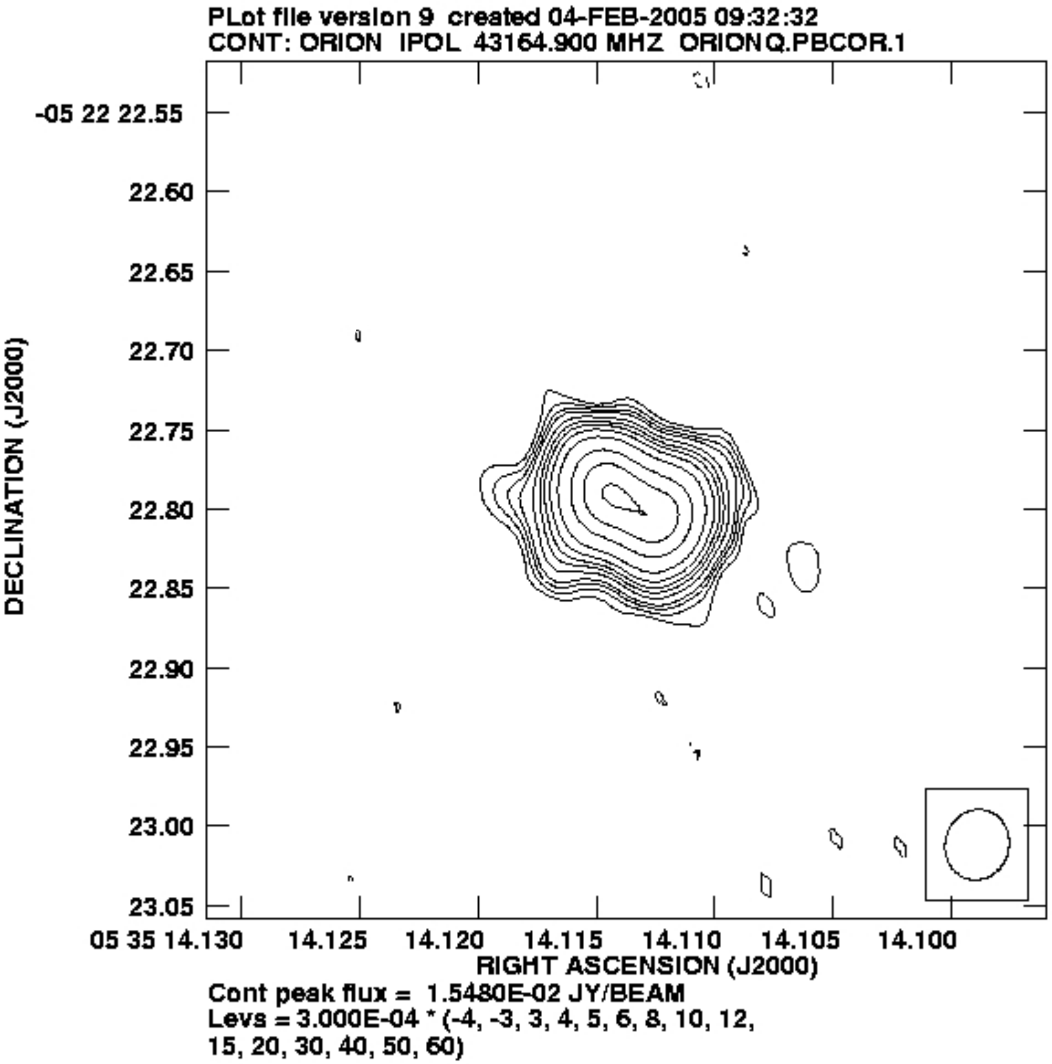
Zapata et al. (2004) on Hα image of O´Dell & Wong (1996)



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

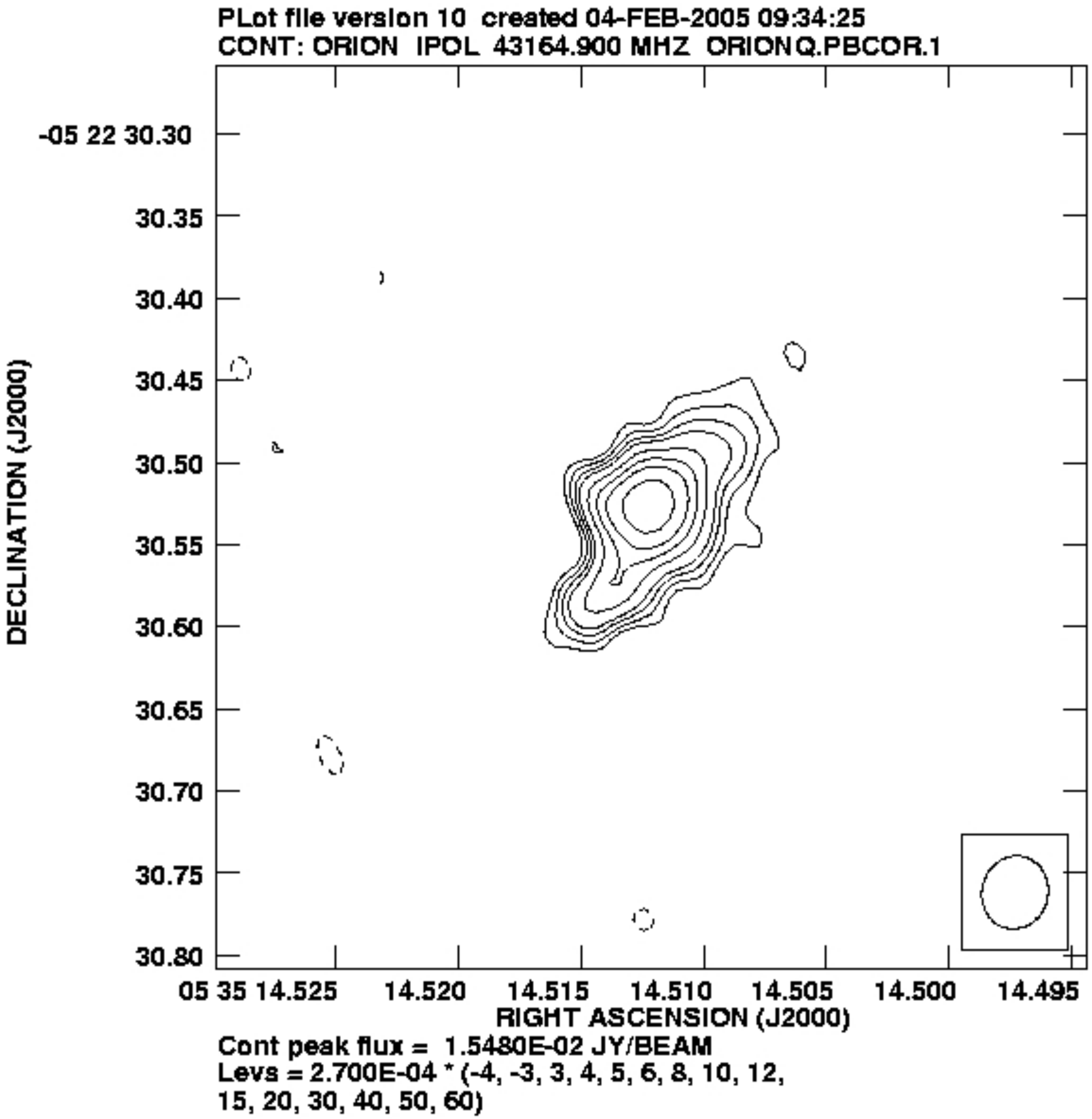
H2 image with NH3 contours (Shuping et al. 2004; Wilson et al. 2000)

The BN object, a "moving" UCHII region…



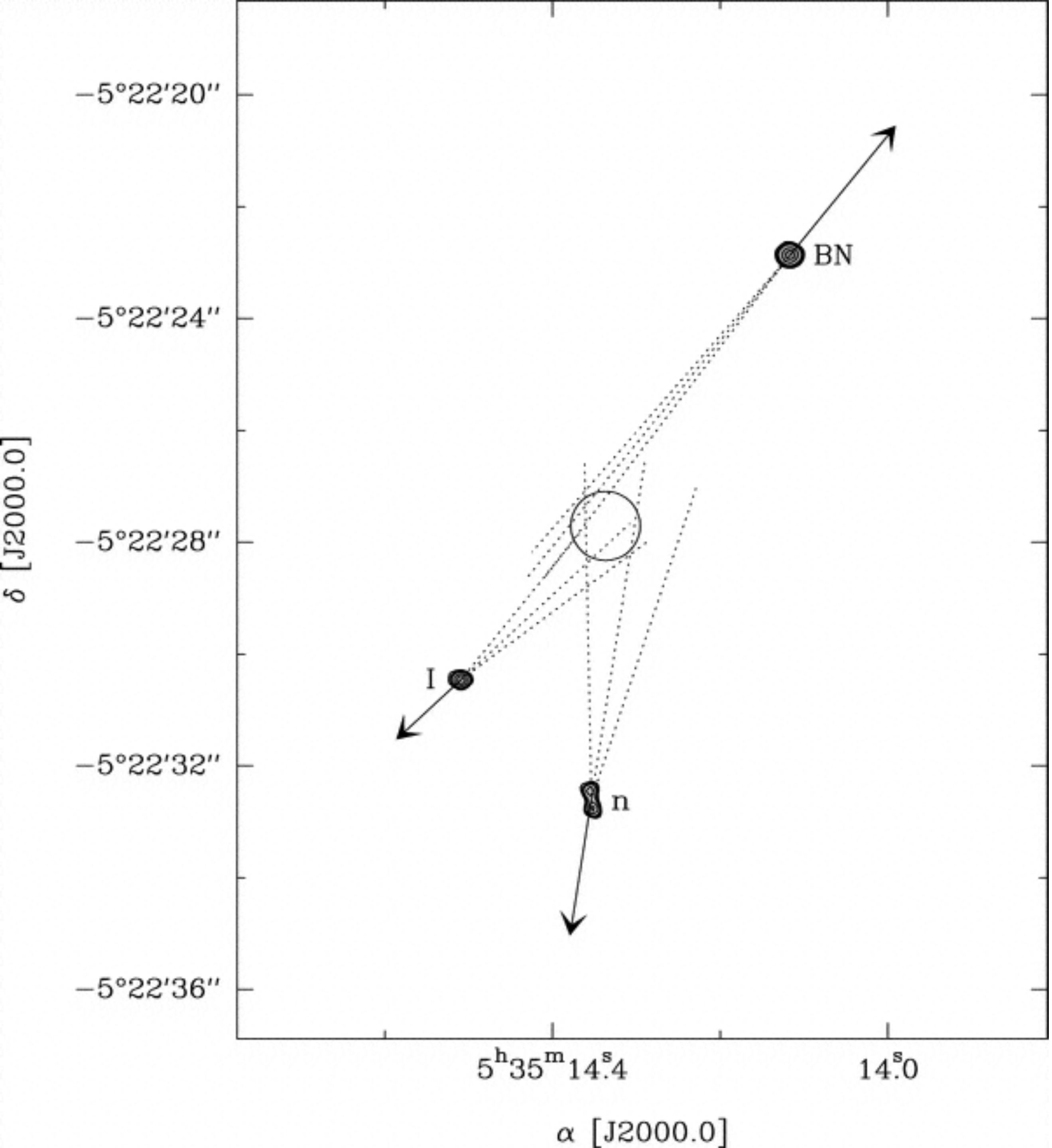
In the radio, the BN object in the Orion BN/KL region is detected as an UCHII region ionized by a B-type star.

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



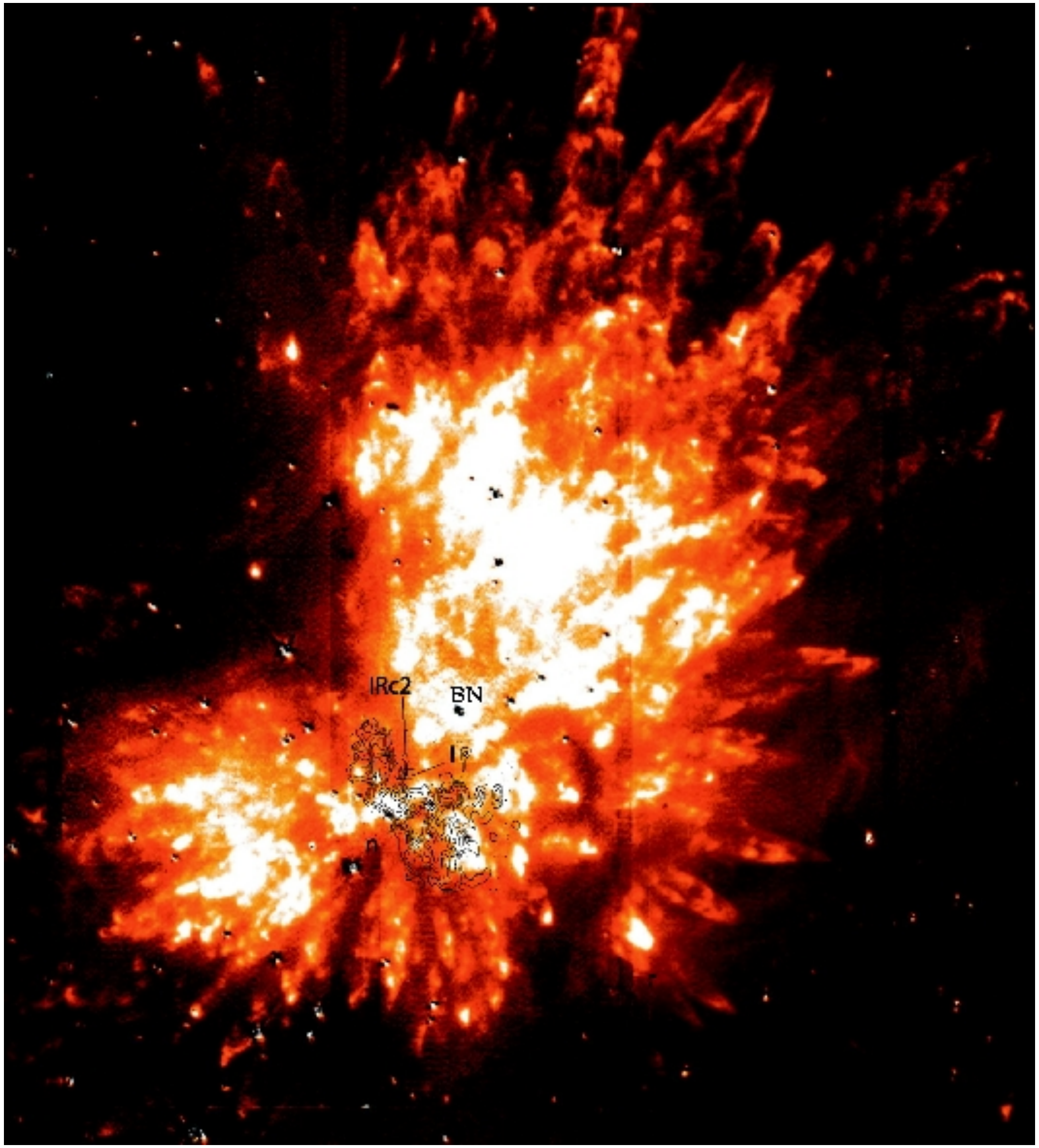
The Radio Source I is also moving in the sky, to the SE.

Controversial nature: thermal jet or ionized disk? Recent evidence favors ionized disk.



BN, I and possiby (n) are all moving away from the same point (Gomez et al. 2005, 2007).

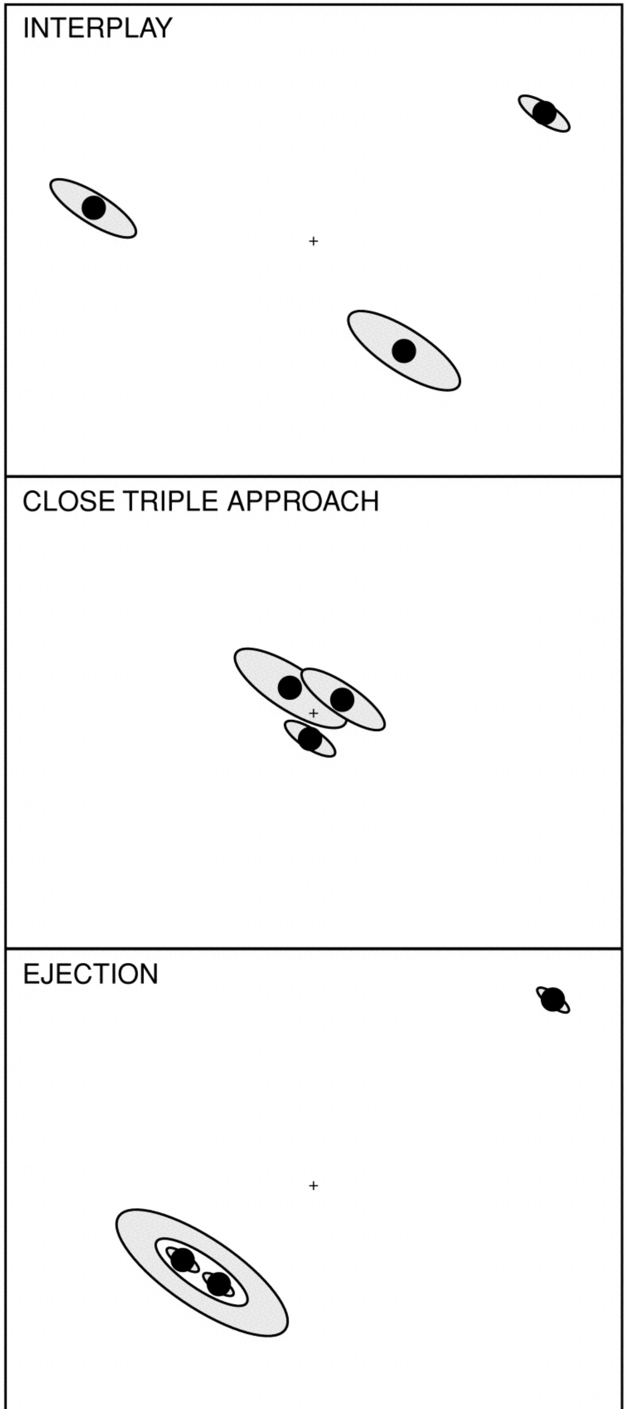
Age of outflow about 500 years.



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.

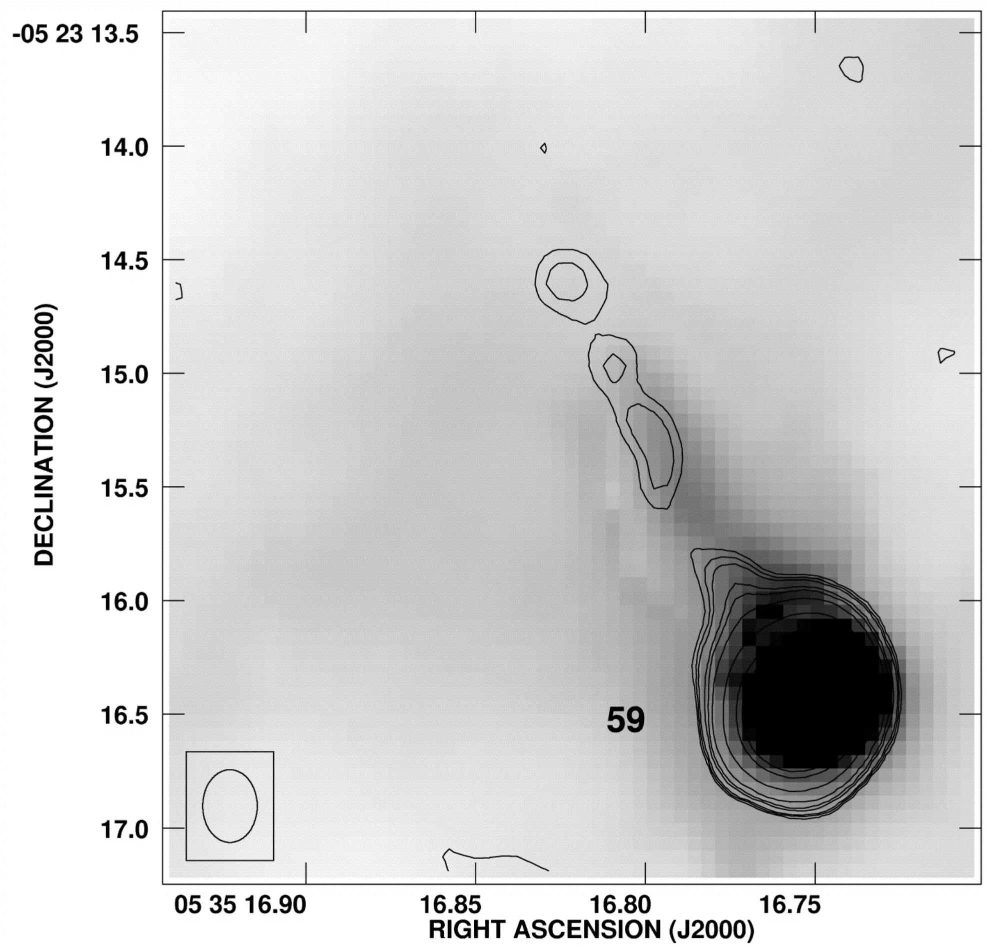
Energy in outflow is of order $4X10^{47}$ ergs, perhaps produced by release of energy from the formation of close binary or merger.



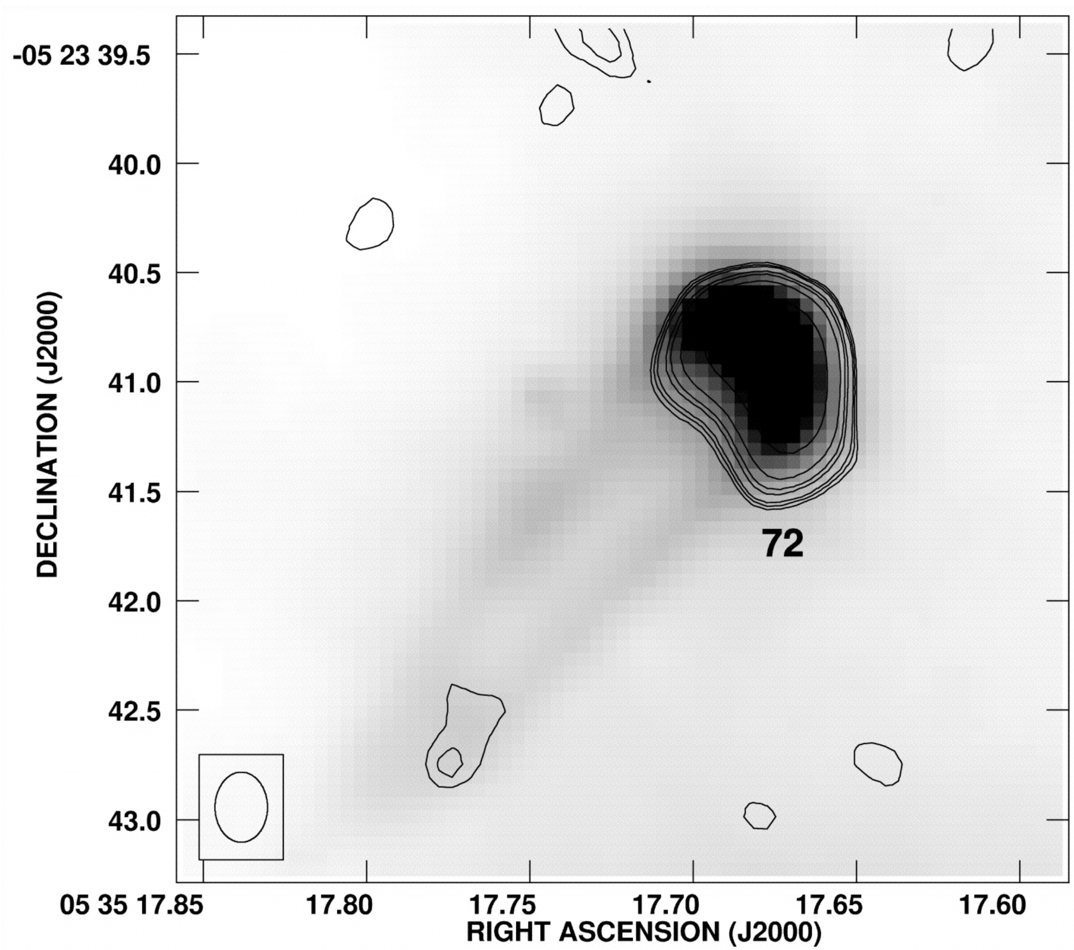
Encounters in multiple stellar systems can lead to the formation of close binaries or even mergers with eruptive outflows (Bally & Zinnecker 2005).

Reipurth (2000)

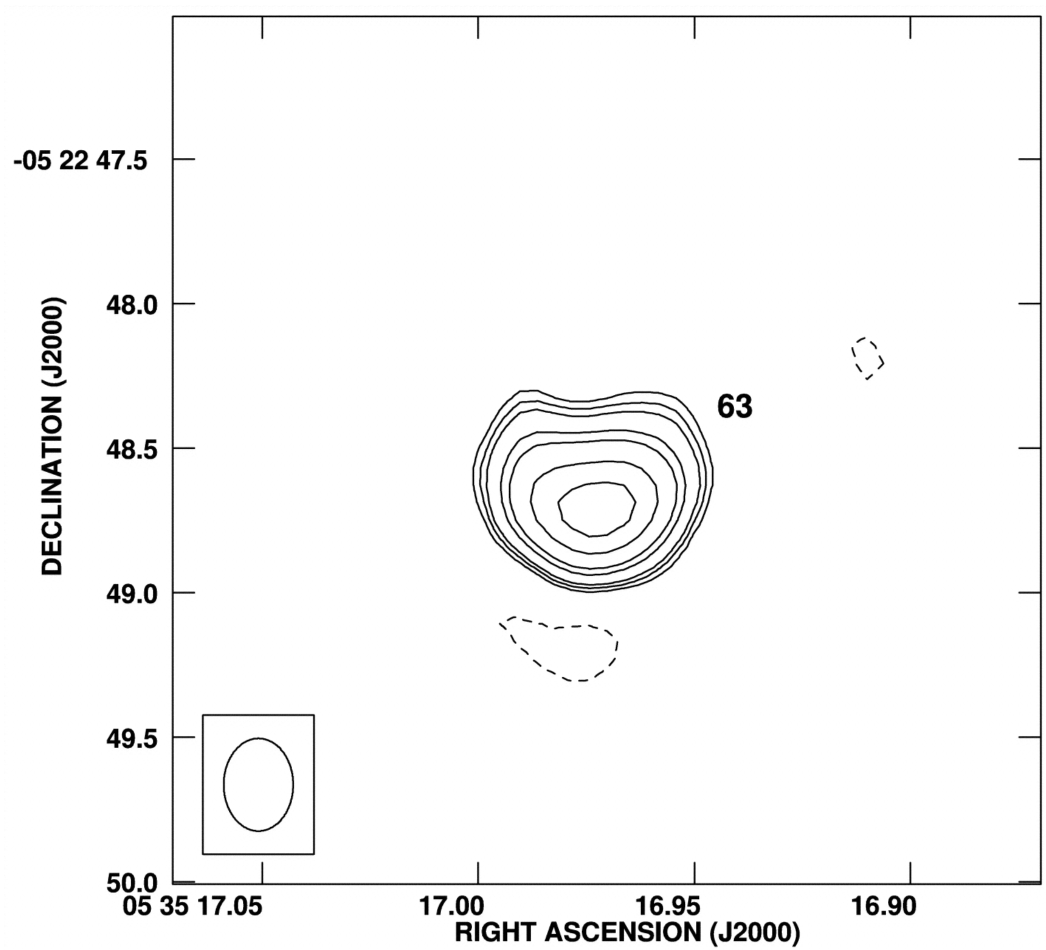
Proplyds in Orion



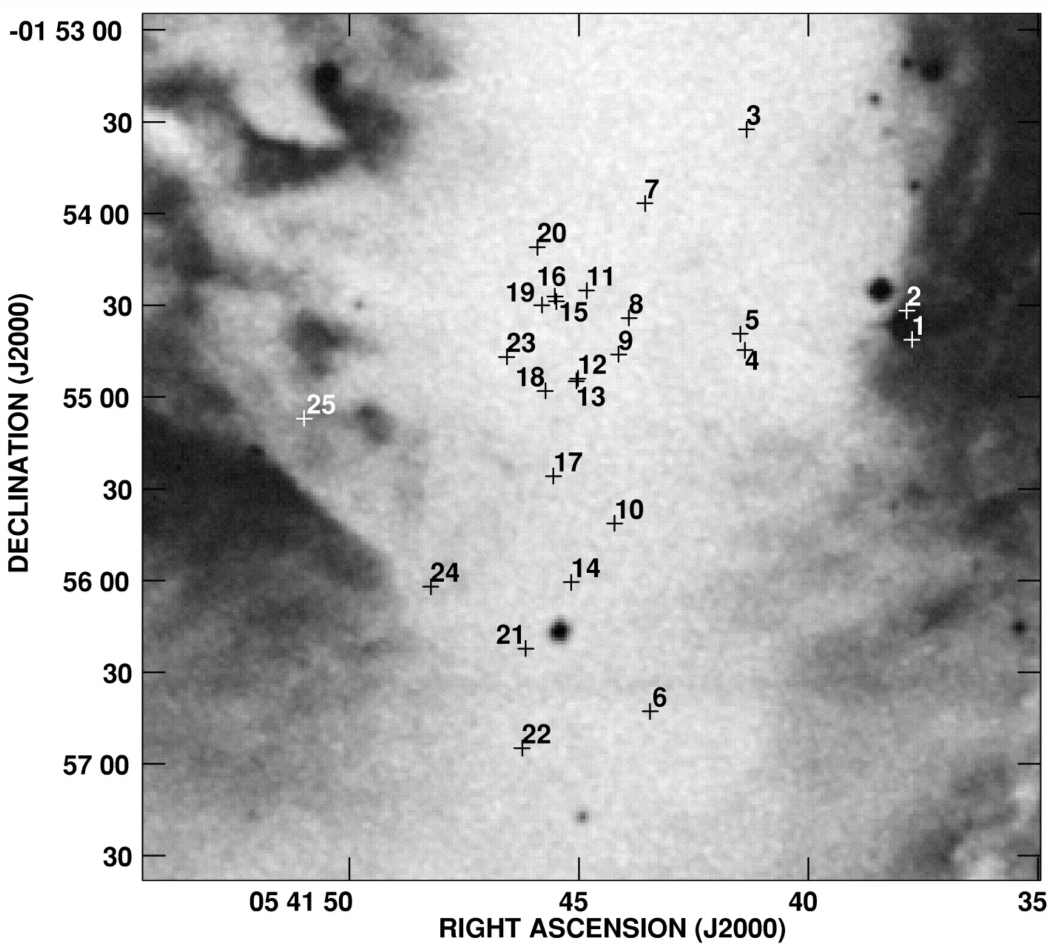
Proplyds in Orion



Obscured proplyd in Orion

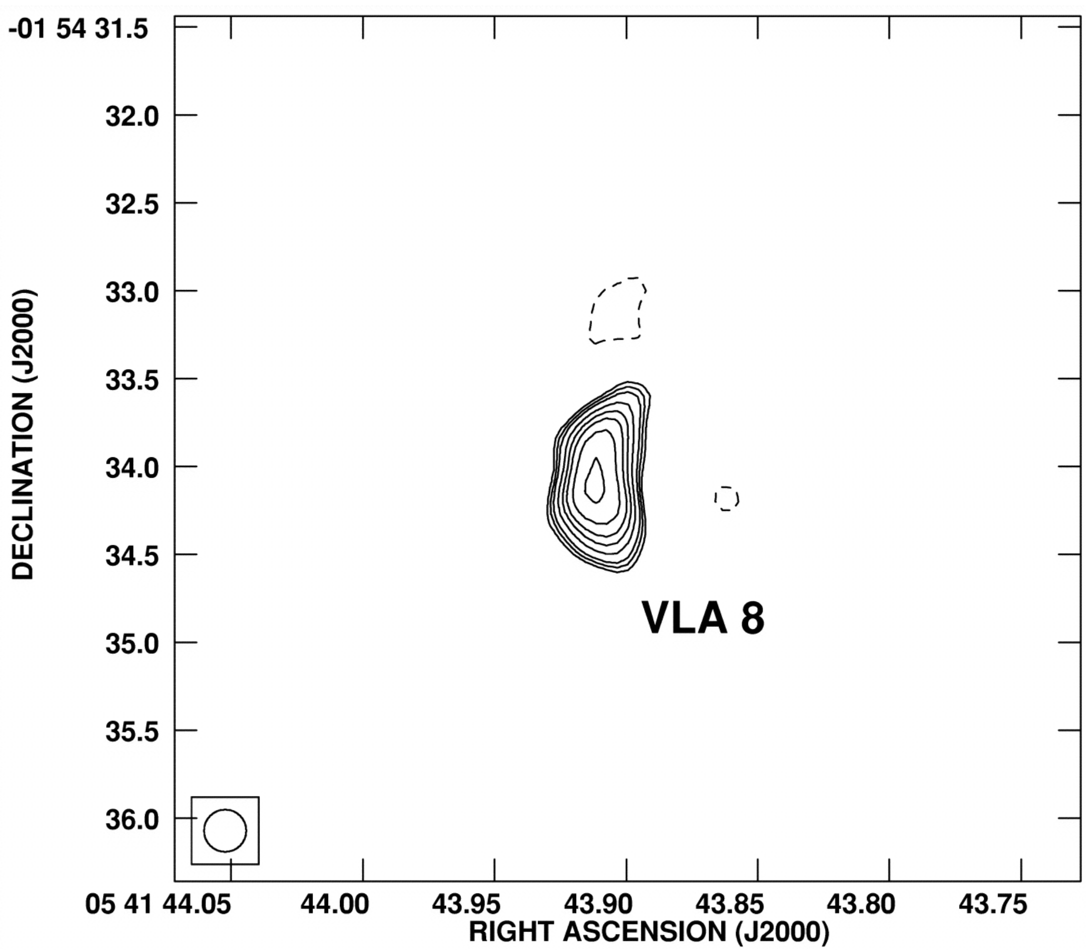


Orion B: Another region of massive star formation

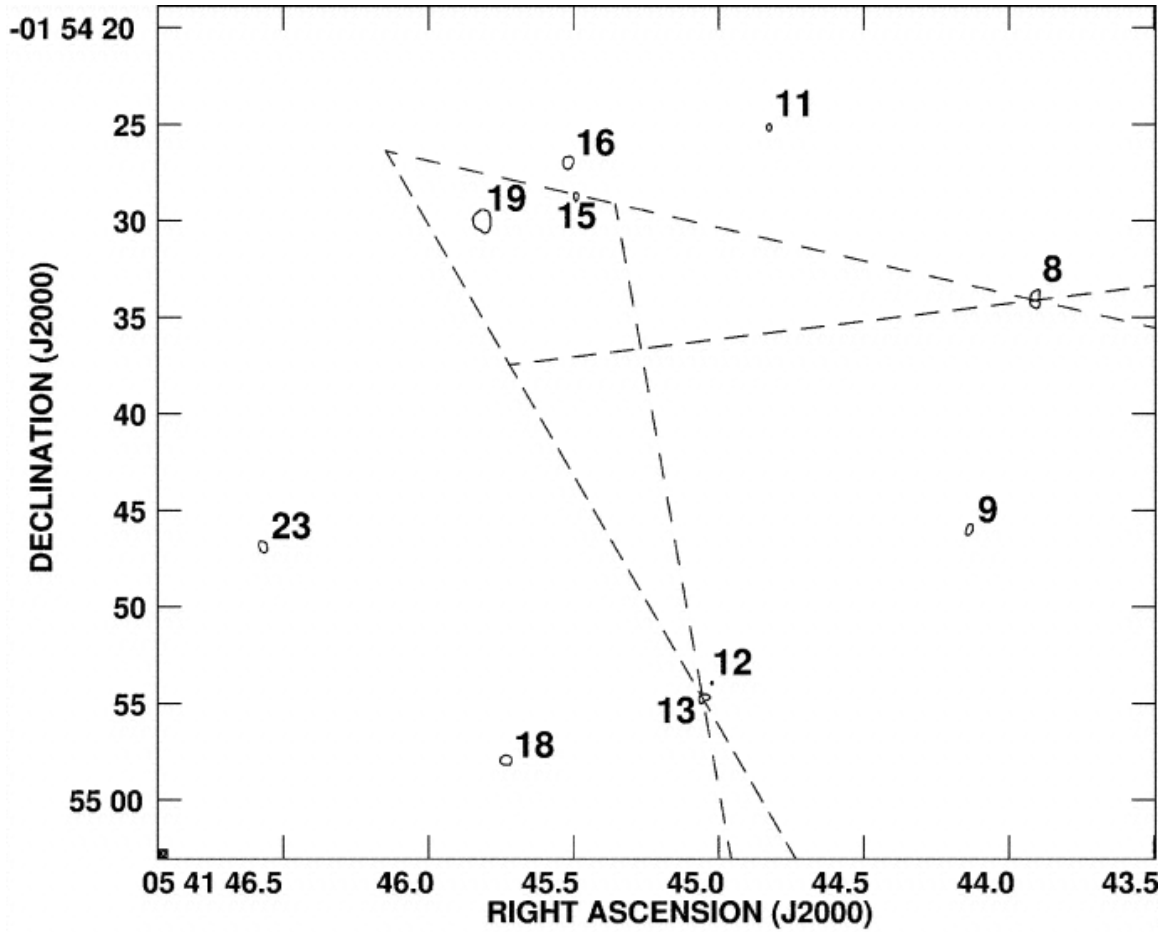


Radio sources on Red DSS image.

Obscured proplyd



Locating the exciting source



M17

39 compact sources (Rodriguez et al. 2012)

M17 UC1

Massive binary system CEN 1 (exciting source of region)

Classification HII regions

Table 3. Physical Parameters of HII Regions

Class of Region	Size (pc)	Density (cm^{-3})	Emis. Meas. ($pc\ cm^{-6}$)	Ionized Mass ($M_\odot$)
Hypercompact	$\lesssim 0.03$	$\gtrsim 10^6$	$\gtrsim 10^{10}$	$\sim 10^{-3}$
Ultracompact	$\lesssim 0.1$	$\gtrsim 10^4$	$\gtrsim 10^7$	$\sim 10^{-2}$
Compact	$\lesssim 0.5$	$\gtrsim 5 \times 10^3$	$\gtrsim 10^7$	~ 1
Classical	~ 10	~ 100	$\sim 10^2$	$\sim 10^5$
Giant	~ 100	~ 30	$\sim 5 \times 10^5$	10^3–10^6
Supergiant	>100	~ 10	$\sim 10^5$	10^6–10^8

Kurtz (2005)

Spectrum of homogeneous HII region

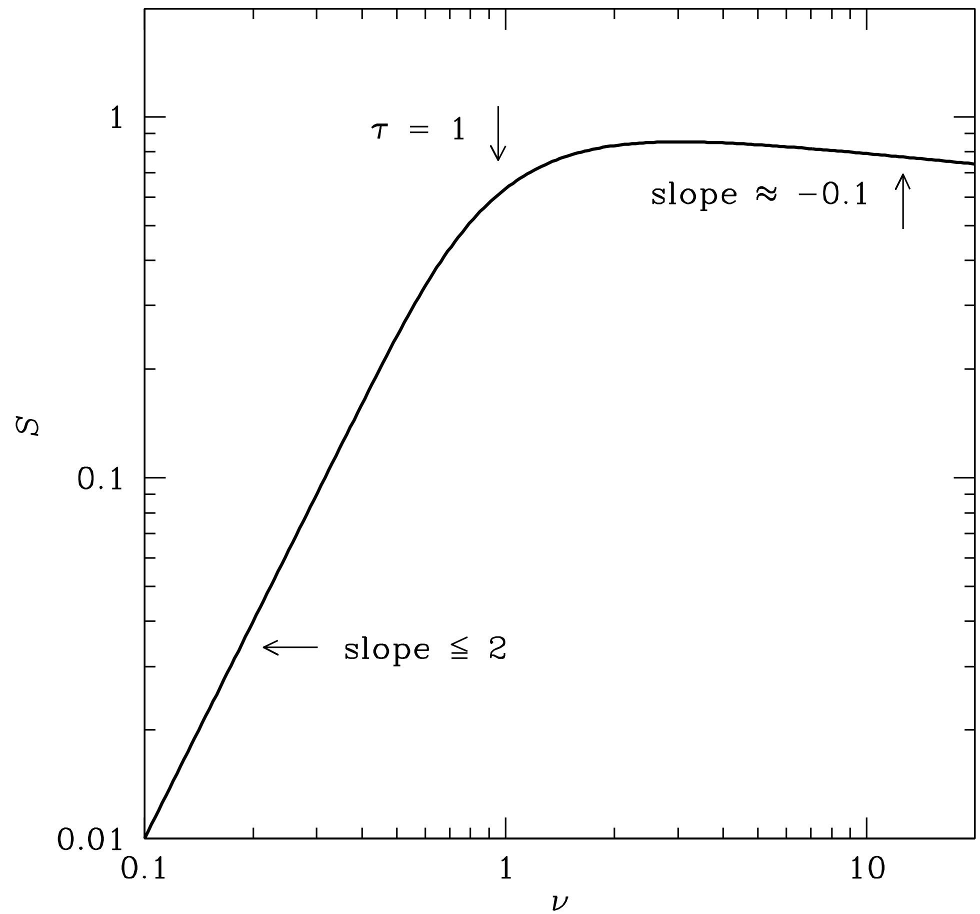
Free-free process:

$$\tau_\nu \propto \nu^{-2.1}$$

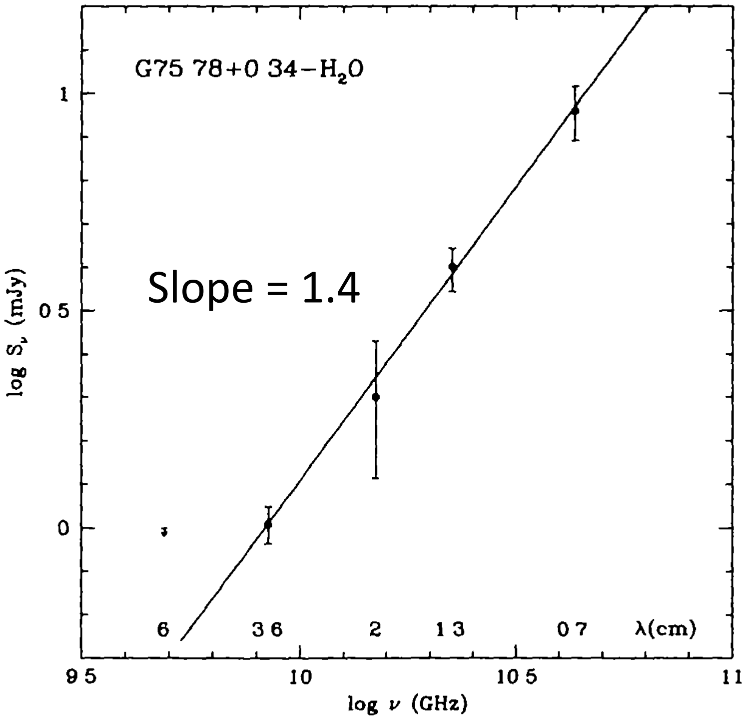
$$I_\nu = \frac{2kT_e\nu^2}{c^2}(1-e^{-\tau_\nu})$$

$$if\ \tau_\nu >> 1 \quad \Rightarrow \quad I_\nu \propto \nu^2$$

$$if\ \tau_\nu << 1 \quad \Rightarrow \quad I_\nu \propto \nu^{-0.1}$$



However, in HCHII regions:



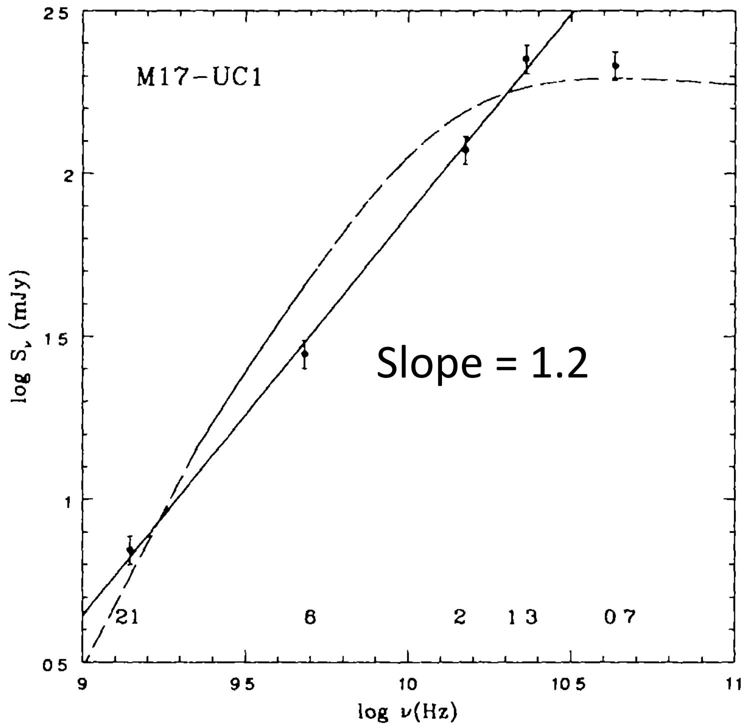
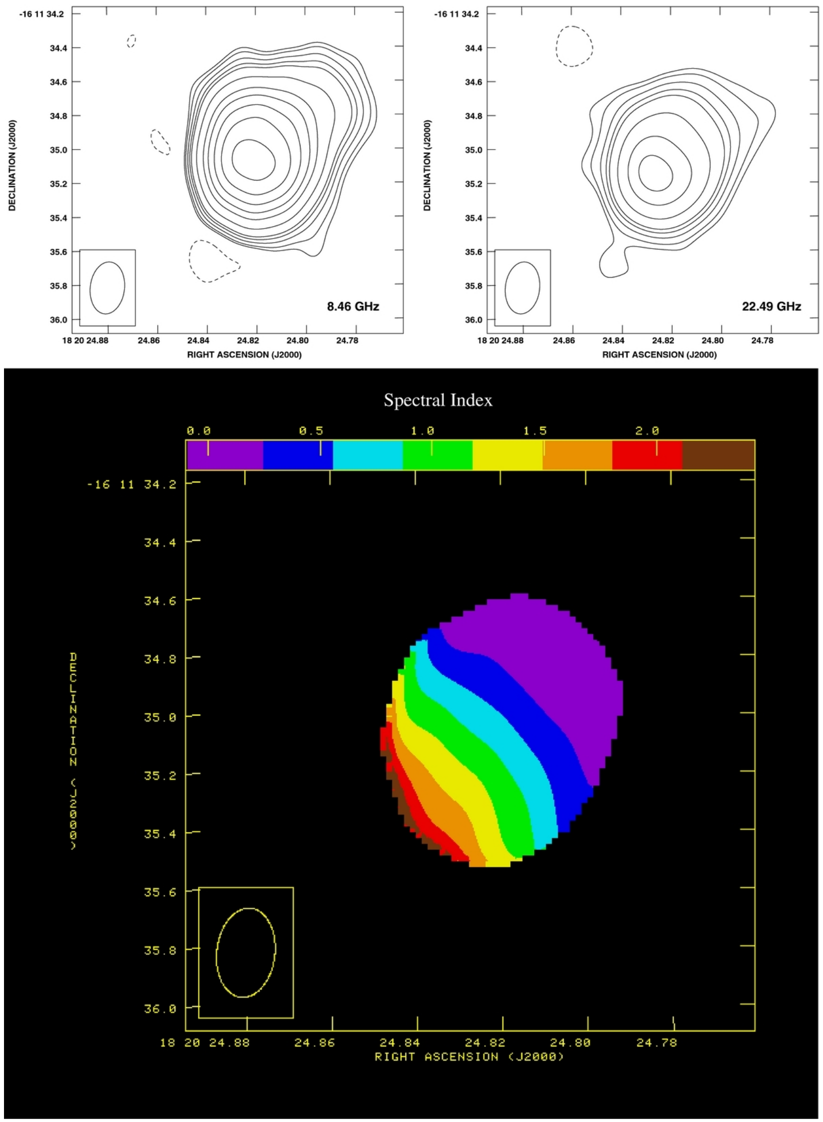


Figure 3 from Compact Radio Sources in M17
Luis F. Rodríguez et al. 2012 ApJ 755 152 doi:10.1088/0004-637X/755/2/152

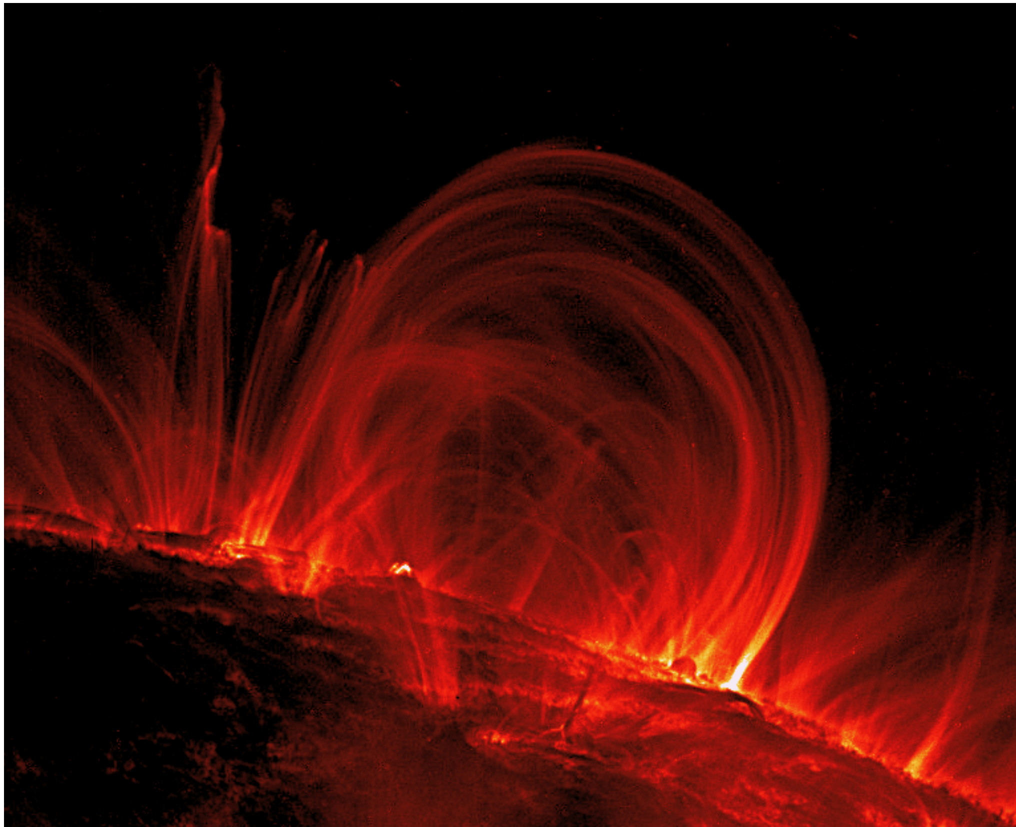


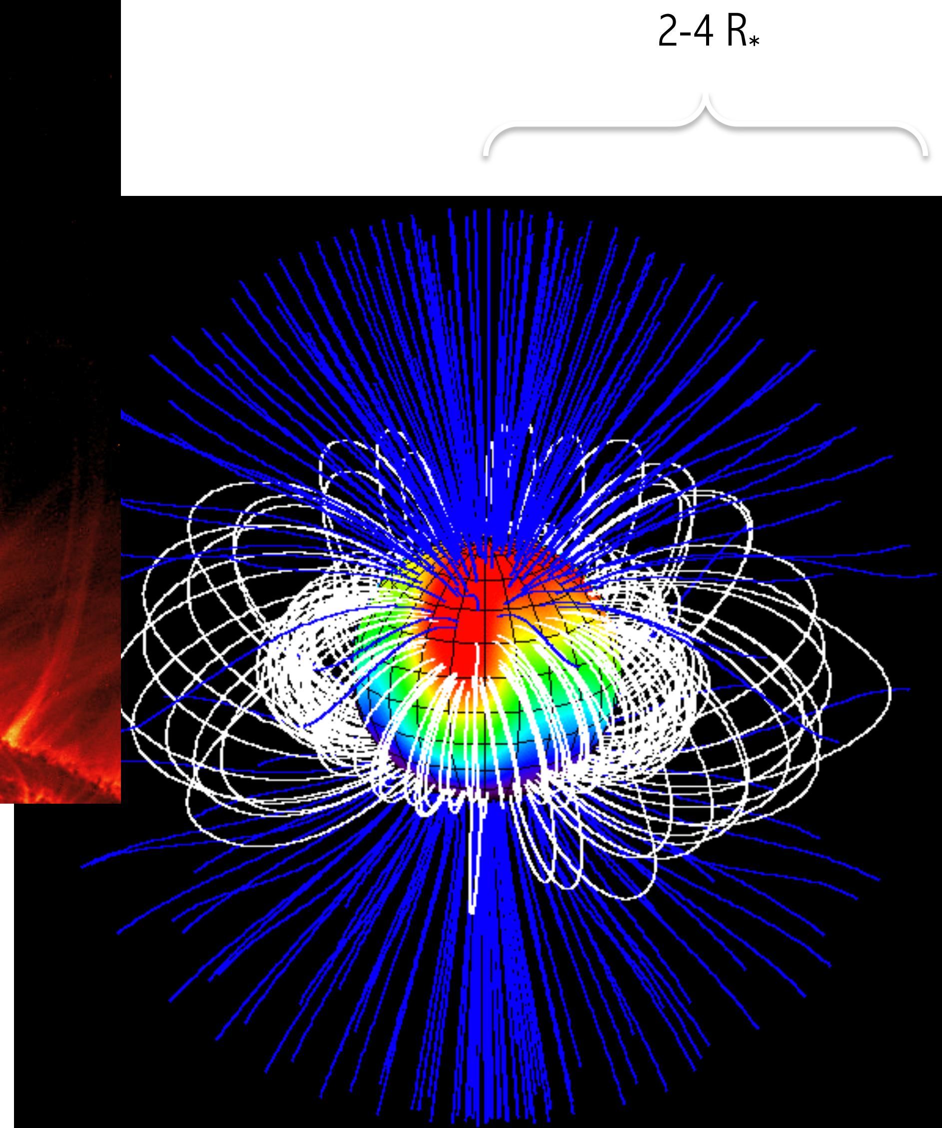
In the case of M17 UC1, the power-law spectrum with slope of ≈1 is explained by the gradient in free-free opacity across the face of the nebula.

Until now, the sources discussed are free-free (thermal) emitters. We will not discuss here ionized stellar winds and jets.

Let us discuss now some non-thermal sources.

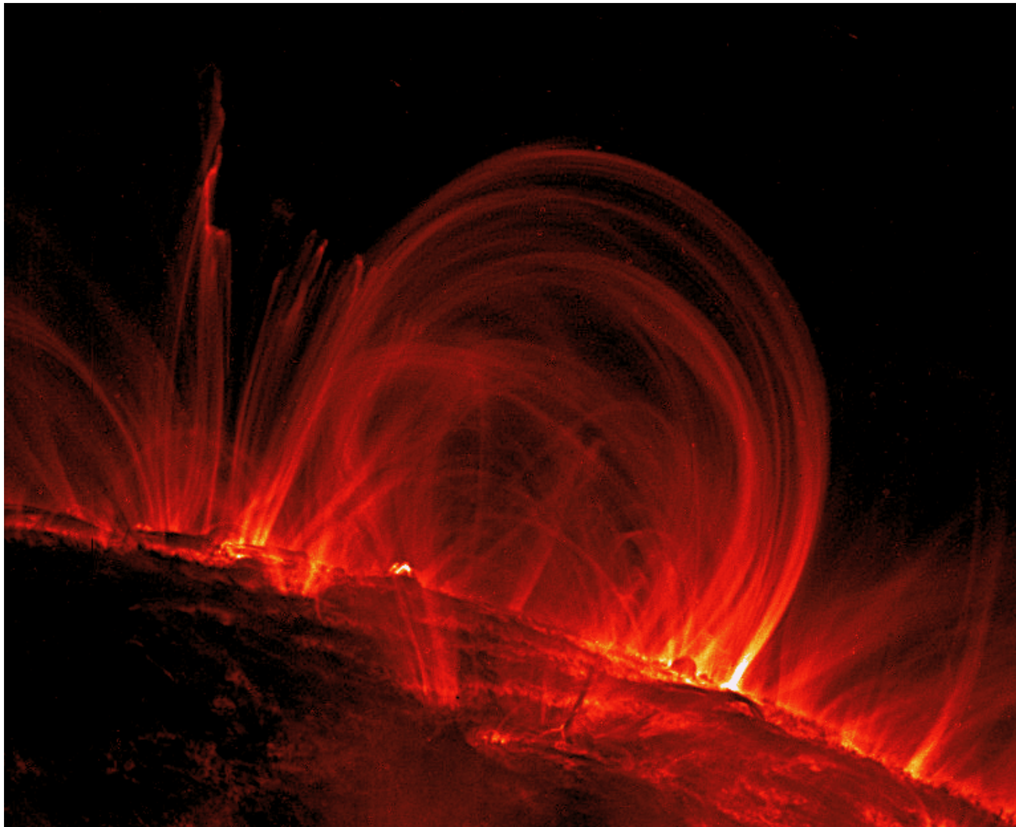
Some low-mass young stars emit via the gyrosynchrotron mechanism

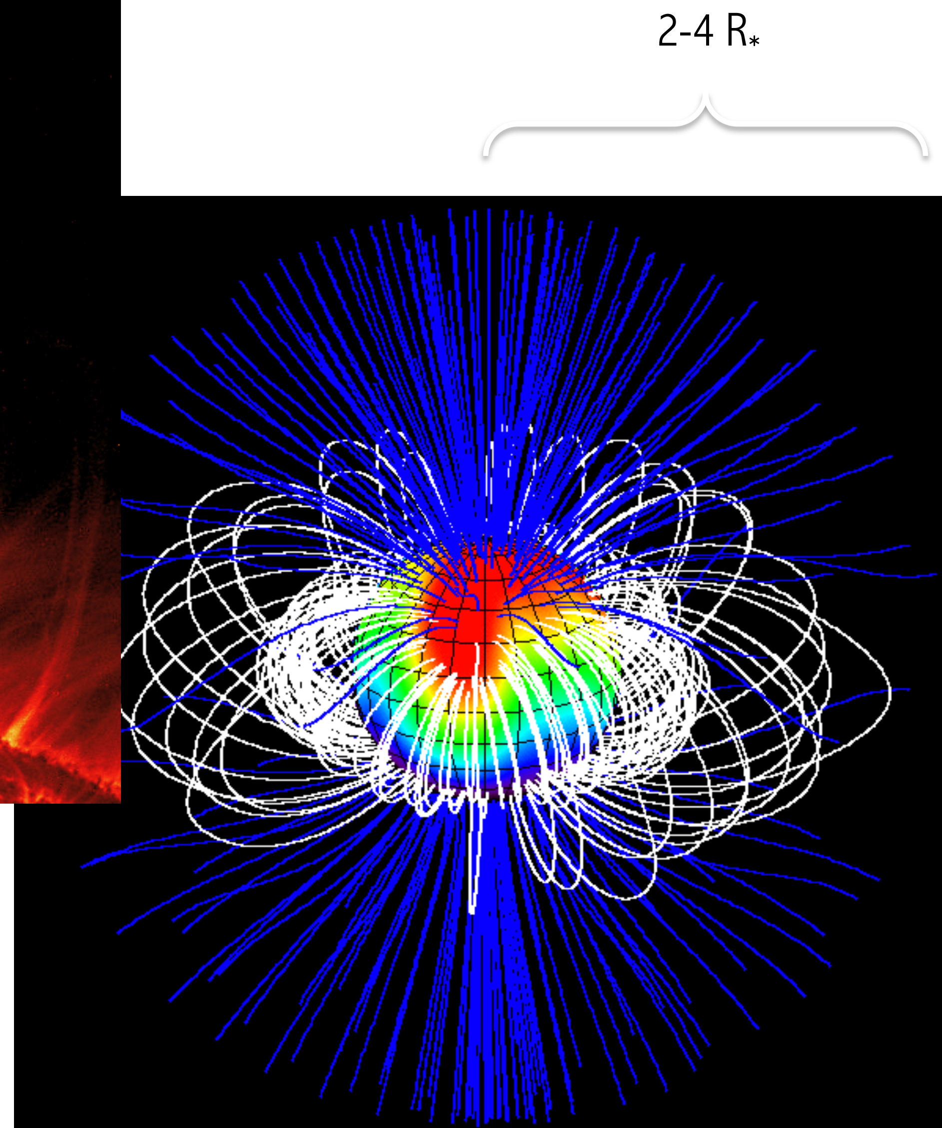




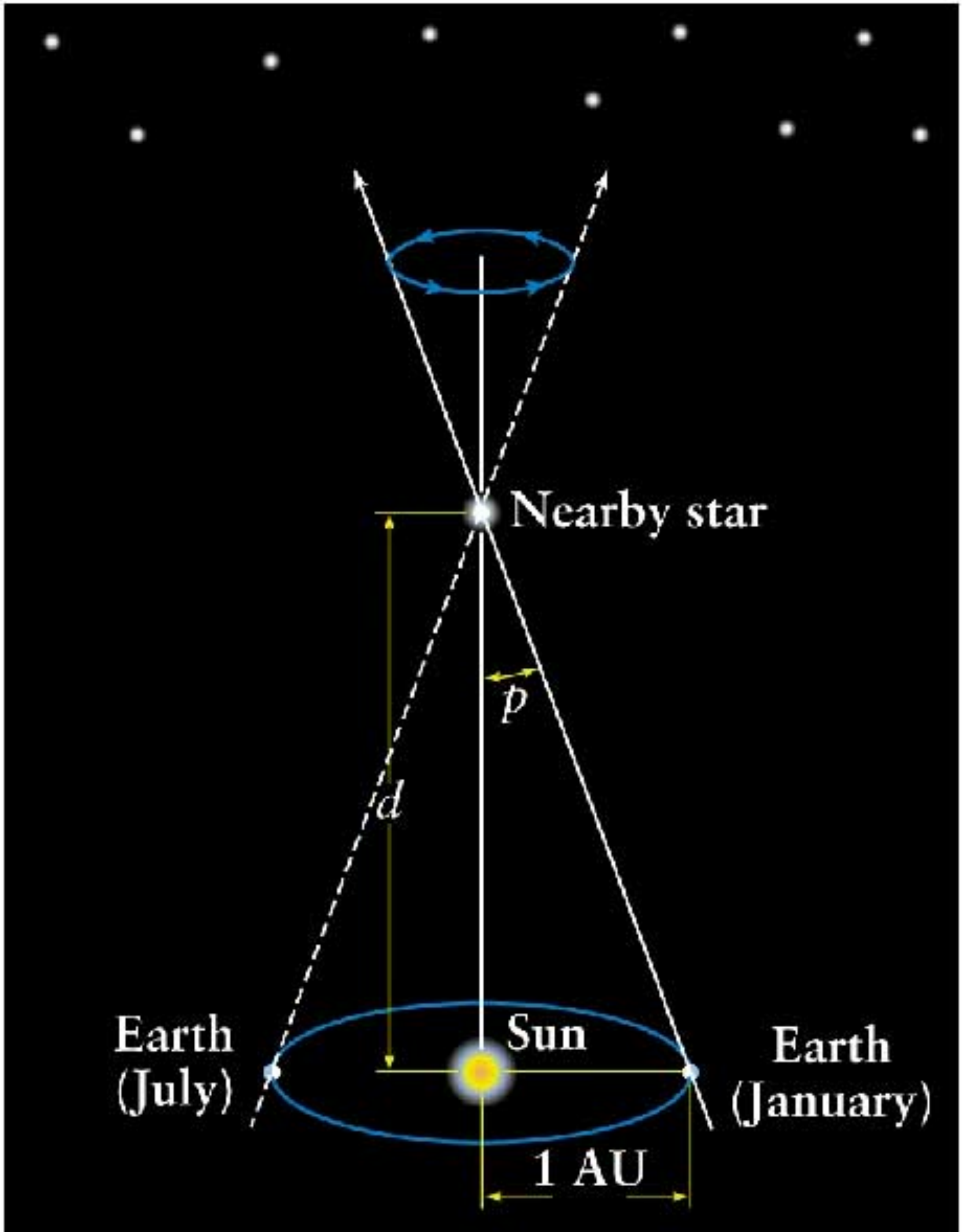
Gyrosynchotron emission is produced by mildly relativistic electrons (possibly produced in magnetic reconnection events) in stellar magnetic field.

Some low-mass young star emit via the gyrosynchrotron mechanism



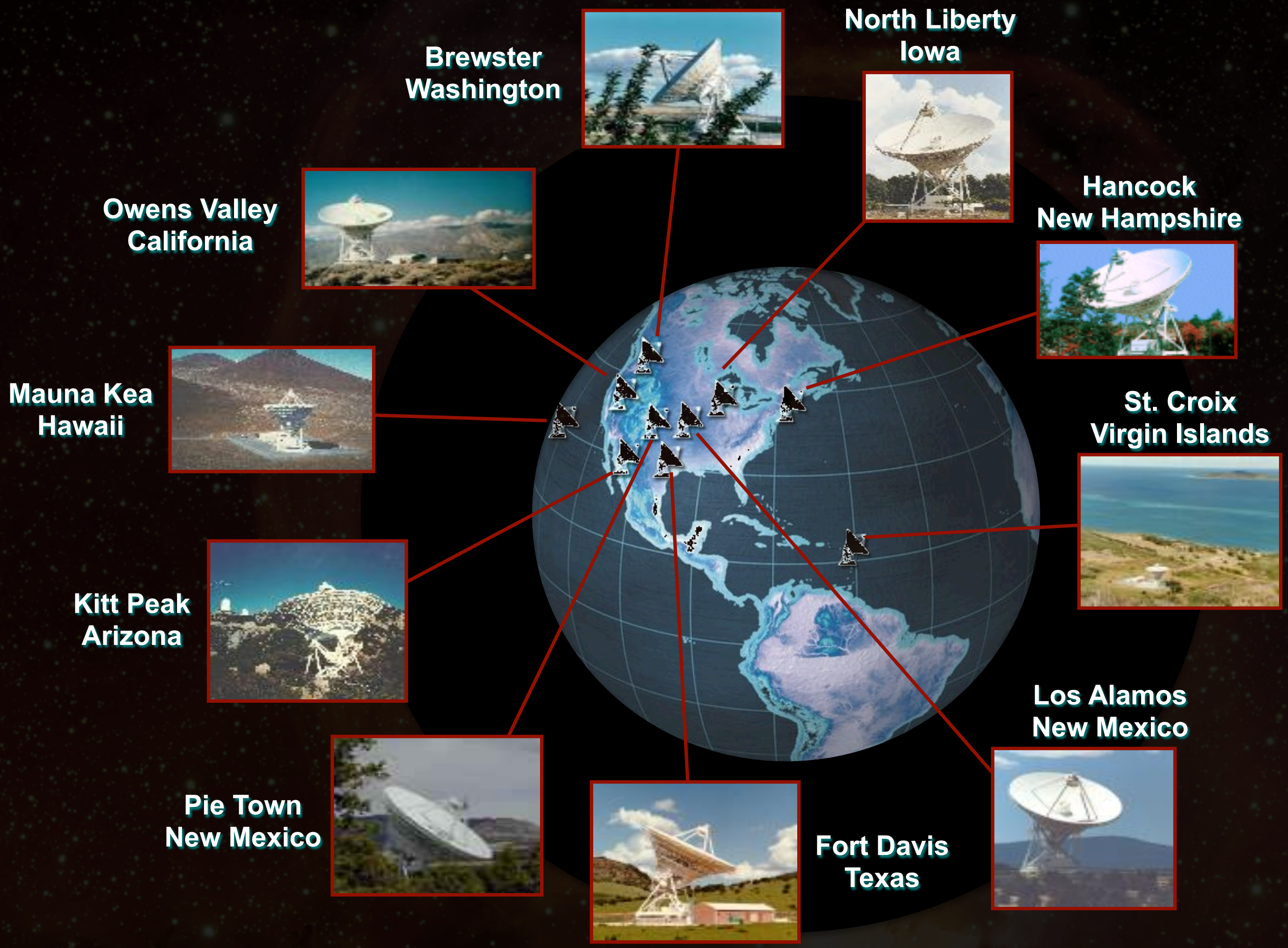


This makes them ideal point sources for parallax (distance) measurements.



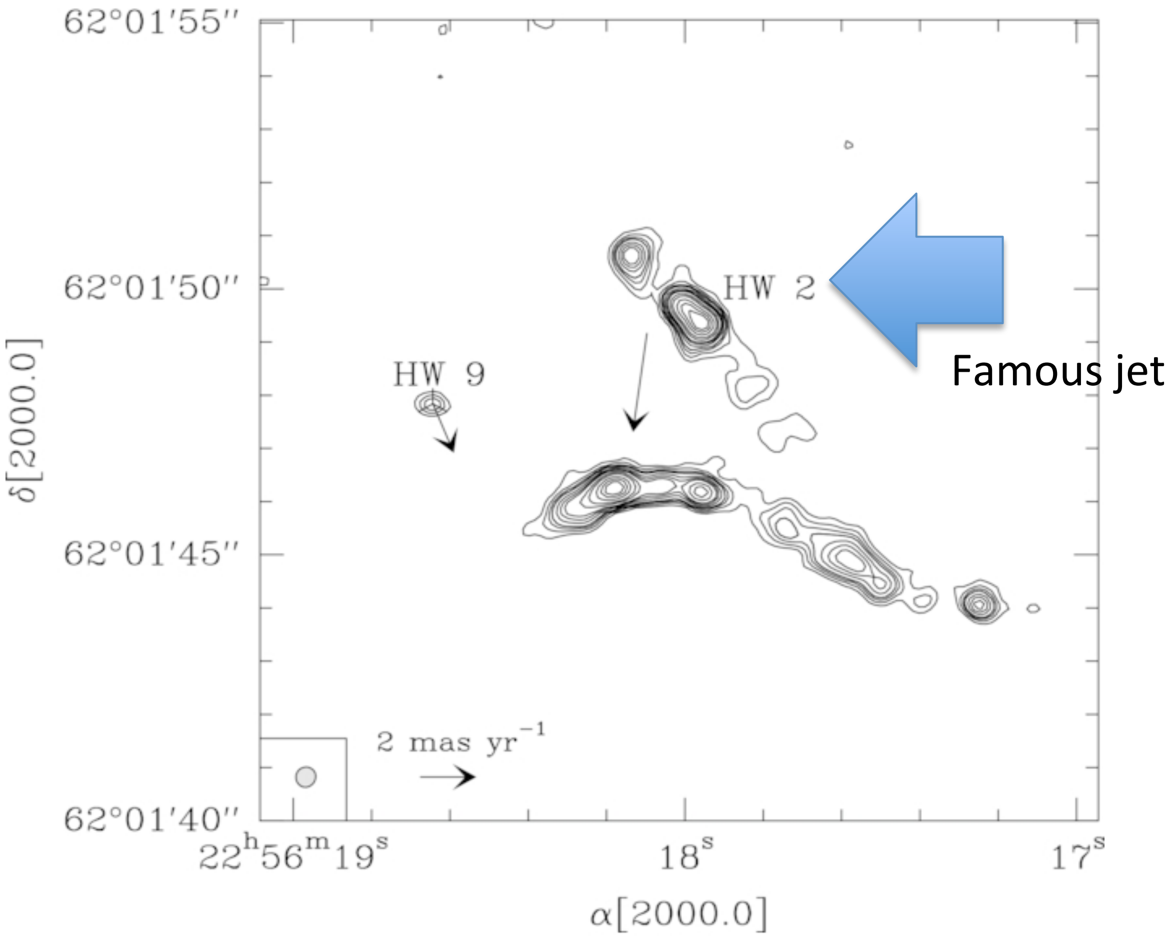
Trigonometric parallax: the most straightforward way if getting distances.

...you need Very Long Baseline Interferometry (VLBA, EVN, VERA, LLAMA...)

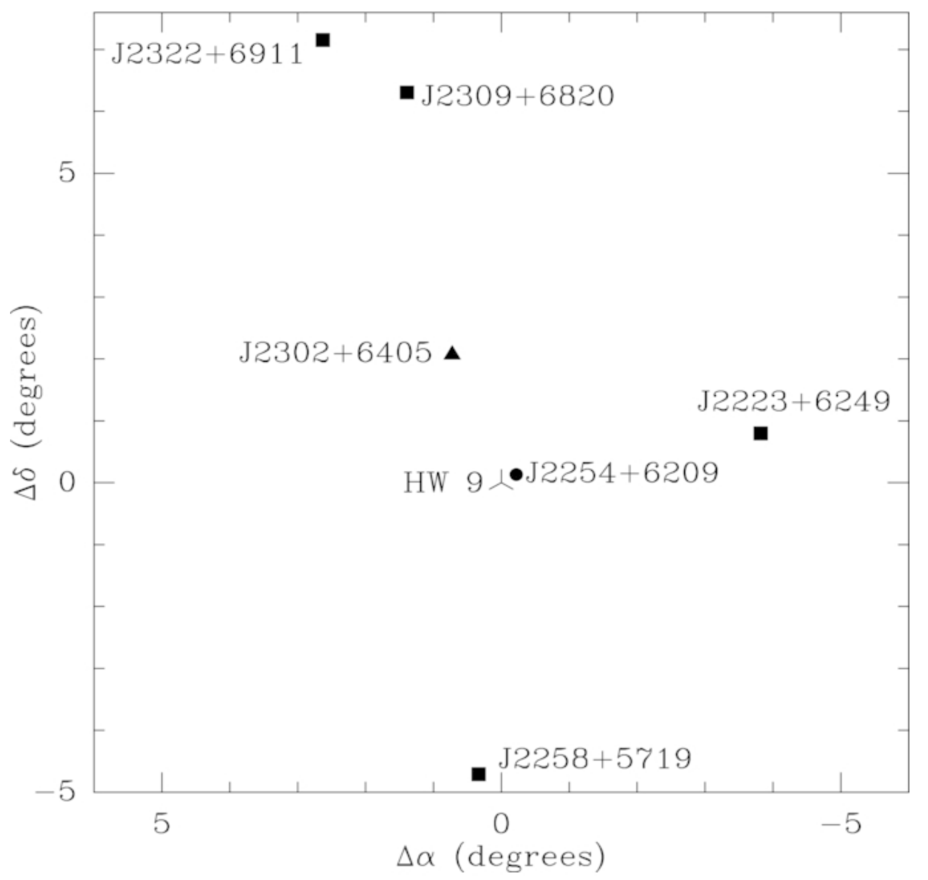


Milliarcsecond angular resolution and positional accuracy

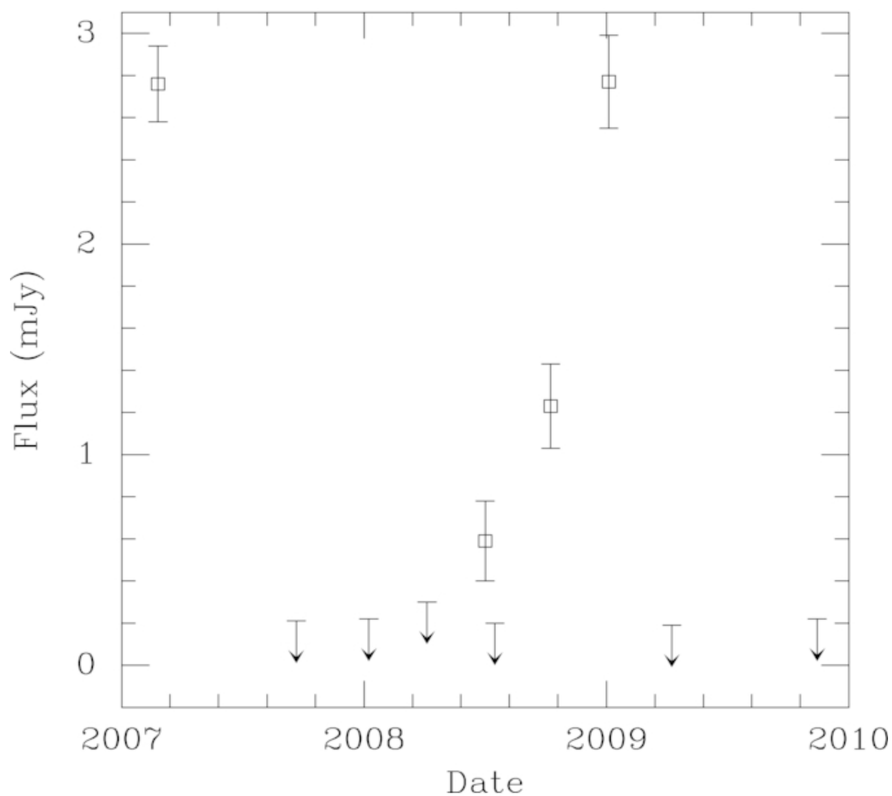
Find gyrosynchrotron source in region with the VLA… (HW 9)



Find gain calibrators around source of interest. Observe with the VLBA…

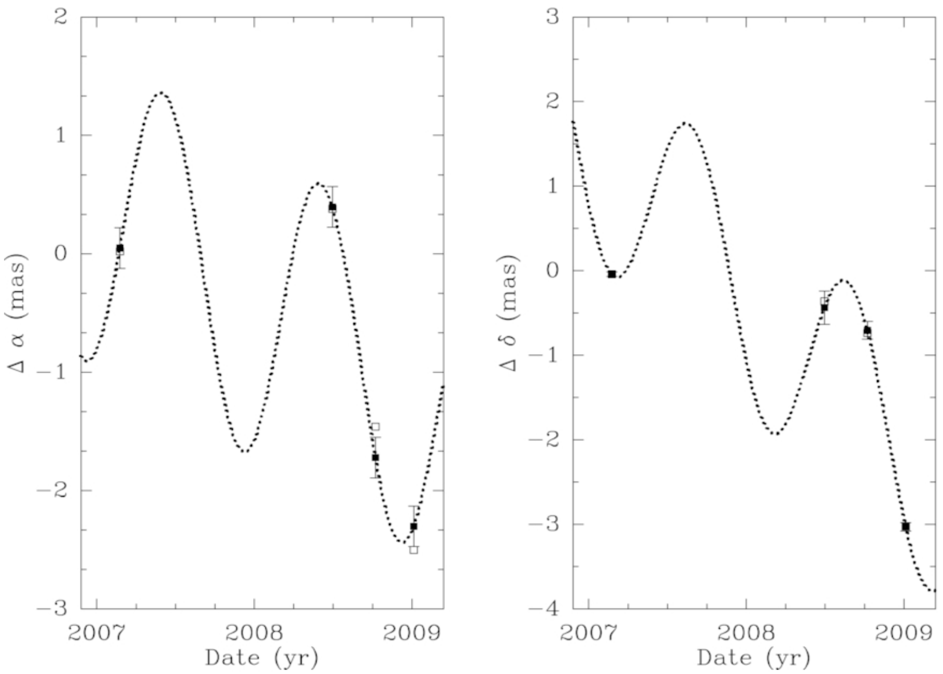


This source in particular is not a very good case because it is off most of the time…

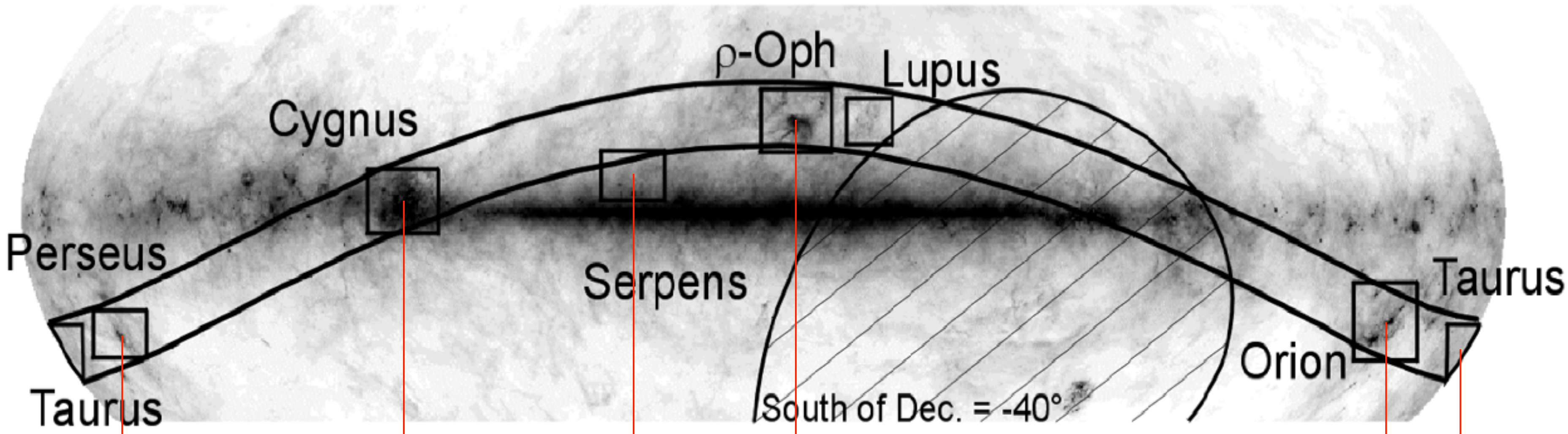


Fit positions to model of parallax + proper motion and get distance.

D = 700±30 pc



Local star-formation: the Gould's Belt distance survey



235 ± 15 pc
Hirota et al. (2008, 2011)

1400 ± 80 pc
Rygl et al. (2012)

415 ± 5 pc
Dzib et al. (2010)

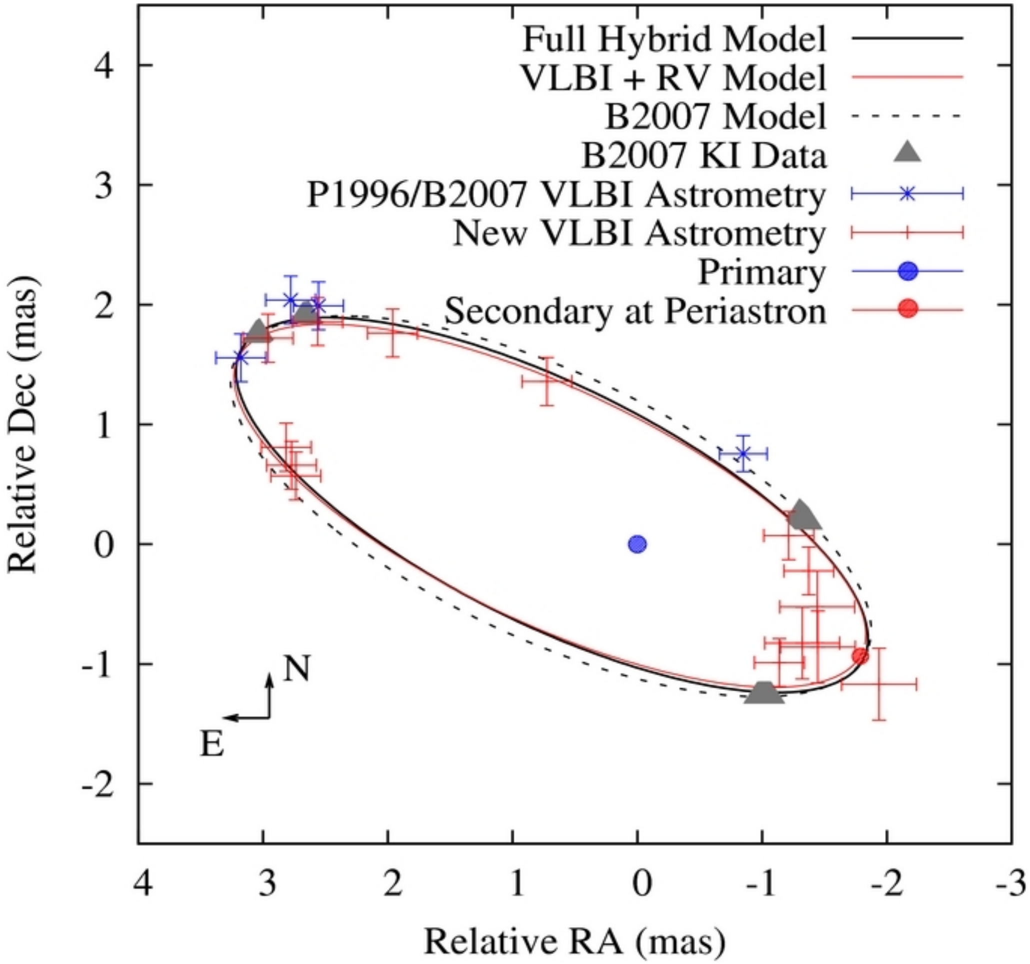
120 ± 4 pc
Loinard et al. (2008)

414 ± 7 pc
Menten et al. (2007)

140 ± 15 pc
Loinard et al. (2005, 2007)
Torres et al. (2007, 2009, 2012)

Loinard et al. (2004-

More than distances



Many of these gyrosynchotron sources have turned out to be close binaries. Correlation between separation and intensity of radio emission.

Particle acceleration to relativistic speeds can take place in the shock produced in the wind interaction region of massive binary systems (via the Fermi mechanism). Electrons will radiate synchrotron emission.

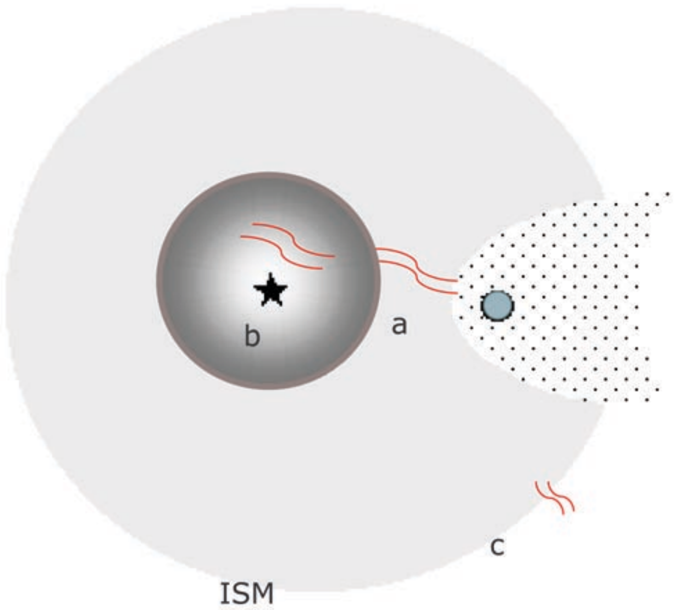
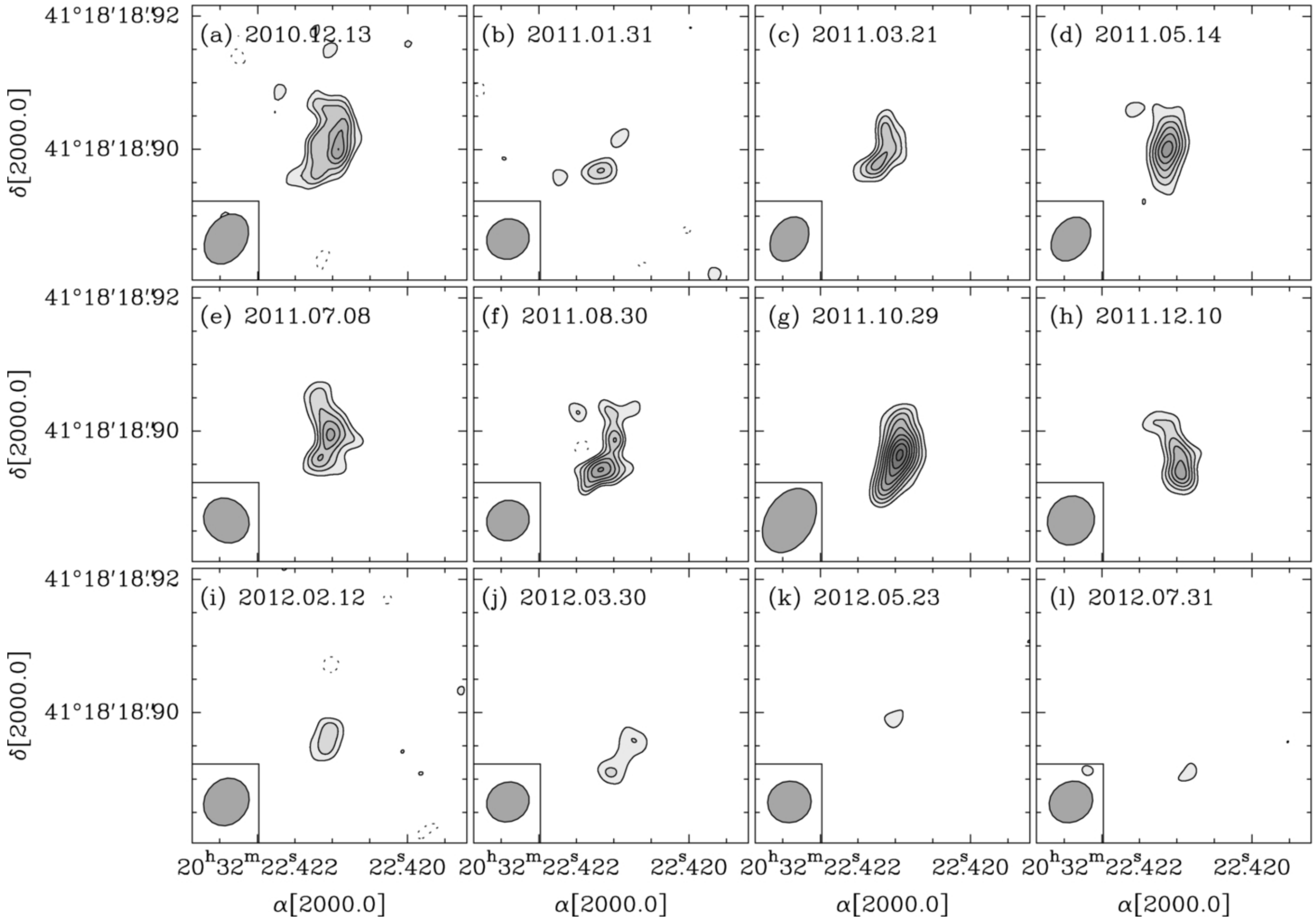


Figure 1. Possible regions for shock-mediated particle acceleration in massive star winds: region a) where, in a massive binary system, two stellar winds collide; region b) in the unstable single stellar wind of an early-type star; region c) at the terminal shock produced when and where the stellar wind encounters the ISM.

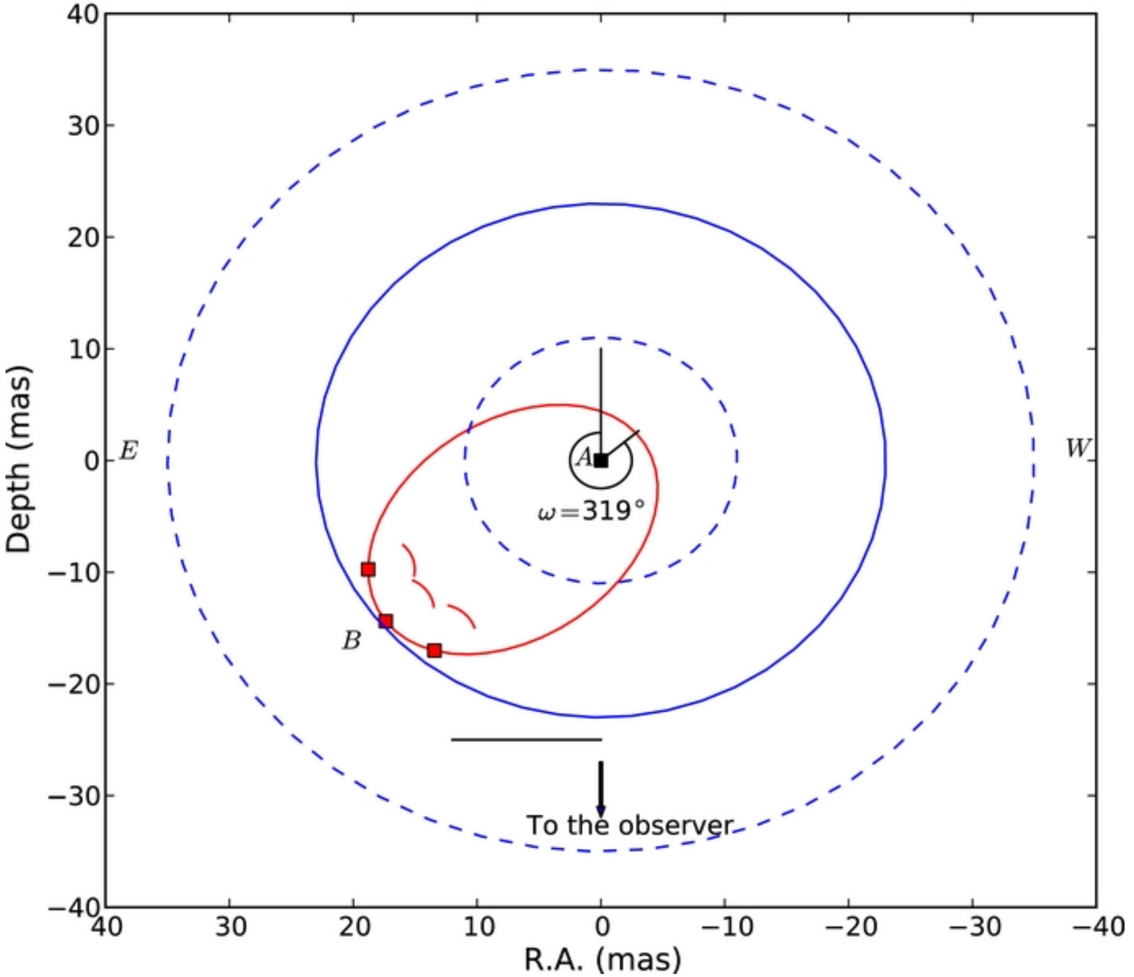
Benaglia (2009)

With VLBI observations you can follow the motion and morphology changes of wind-interaction region.

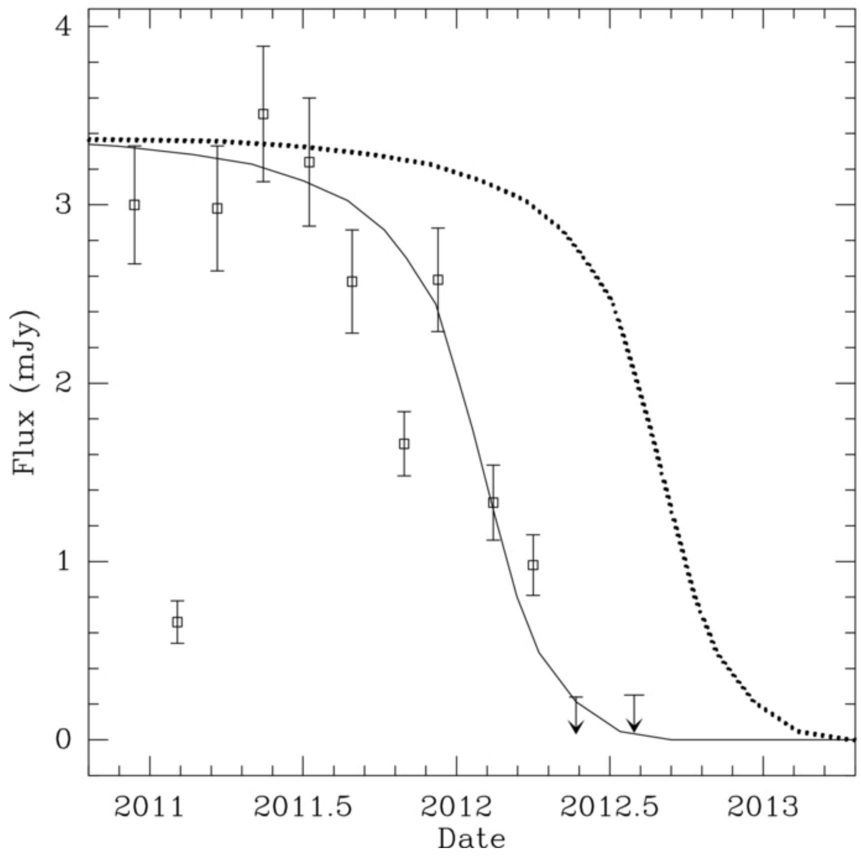


Cyg OB2#5; Dzib et al. (2013)

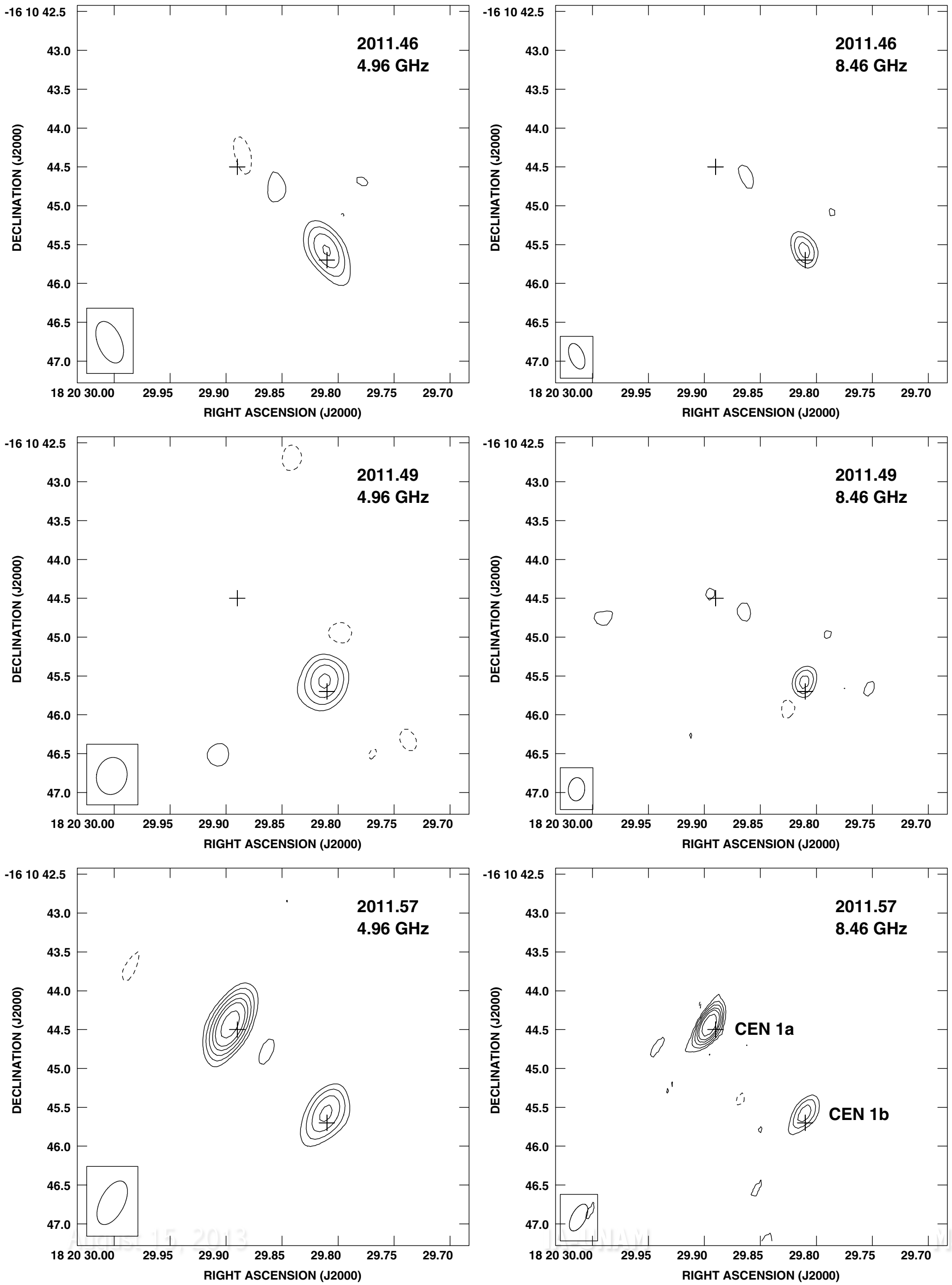
Eccentric orbit. Wind-interaction region plunges in and out of radio photosphere of star(s), becoming undetectable for periods of time.



Disappearance of wind-interaction region.



JVLA results; Rodriguez et al. 2012



CEN 1A and CEN 1B, the two O4 stars that ionize M17, are also radio sources and most probably close massive binaries each of them.

Finally, let us talk of two “new” types of sources:

-Radio sources at the center of ultra or hypercompact HII regions. What are they?

-A source with a very peculiar radio spectrum.

NGC 6334(A); Carral et al. (2002)

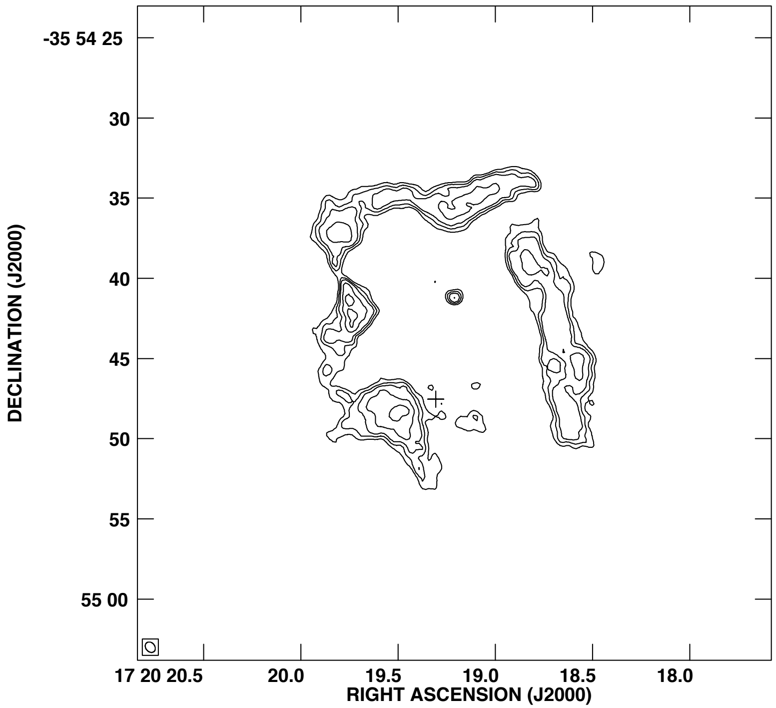


FIG. 4.—The 3.5 cm image of the H II region NGC 6334A. Contours are −4, 4, 5, 6, 8, 10 and 12 × 1.3 mJy beam^{-1}, the rms noise of the image. The compact source near the center of the nebula is proposed to trace the exciting star. There are no known counterparts to this radio source. The small cross marks the position of IRS 19, taken from 2MASS. The half-power contour of the beam (0″.72 × 0″.56; P.A. = 41°) is shown in the bottom left corner of the image.

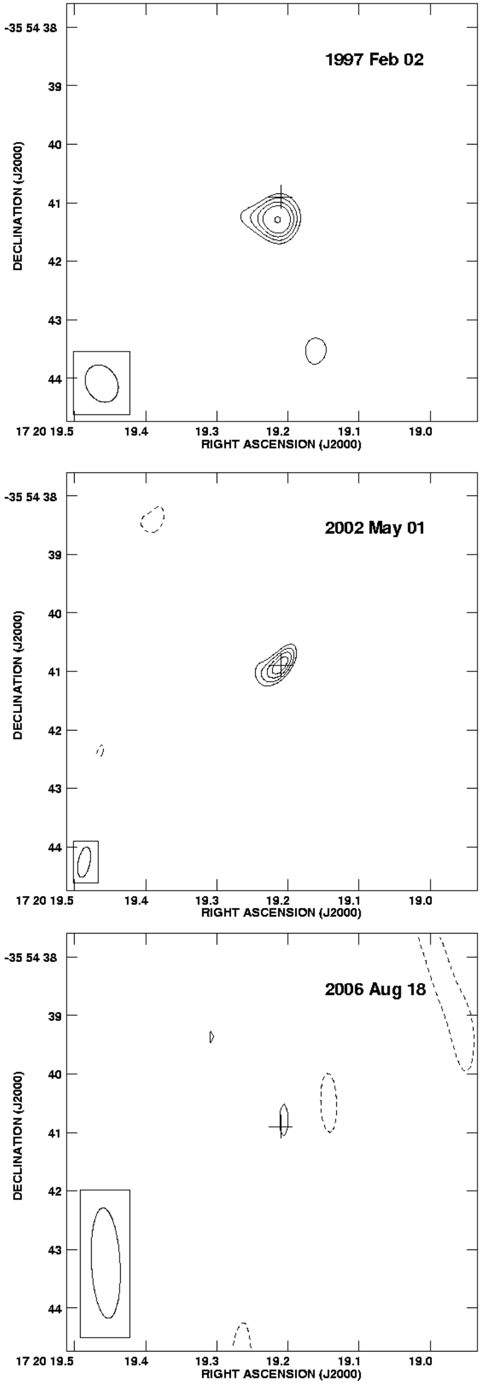
Point source at center of shell-like UCHII region

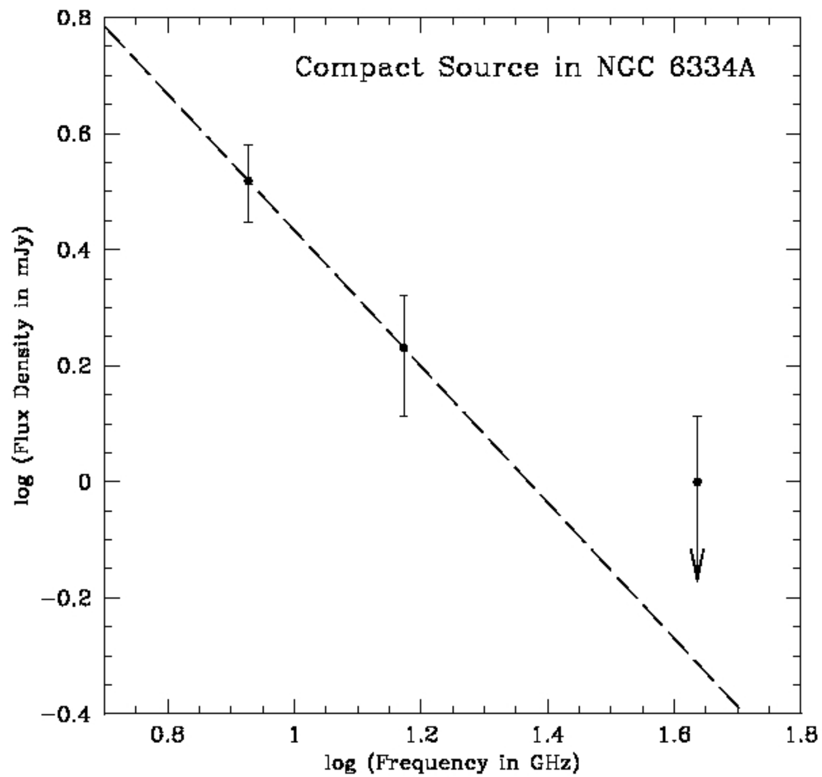
Source at center of shell-like NGC 6334(A) HII region.

Compact, time-variable, synchrotron spectrum.

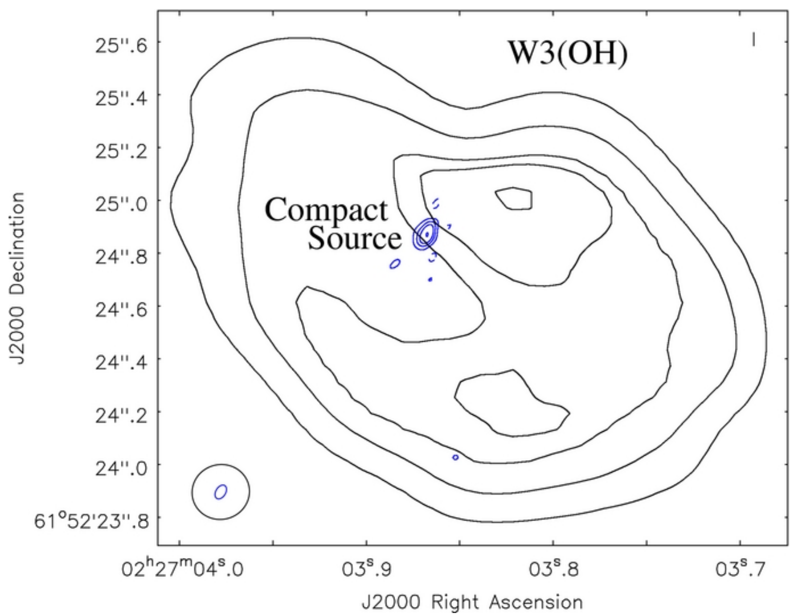
⇒ Most likely wind-interaction region in massive binary.

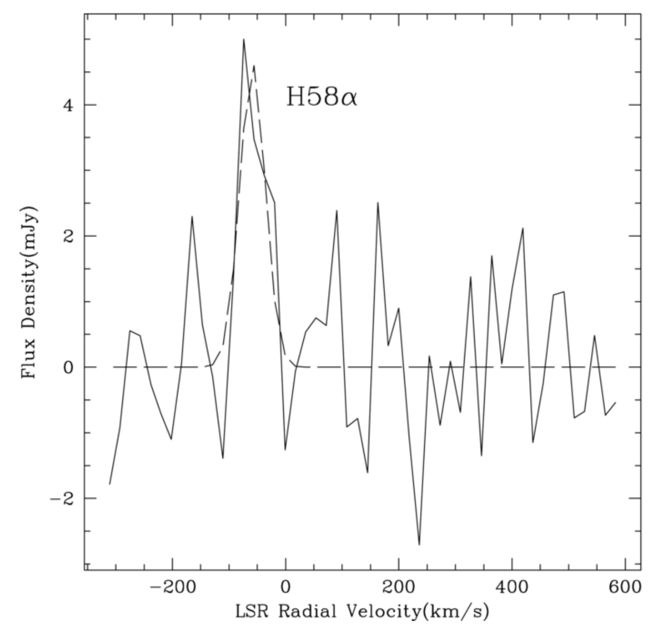
Distance determination, period of system.





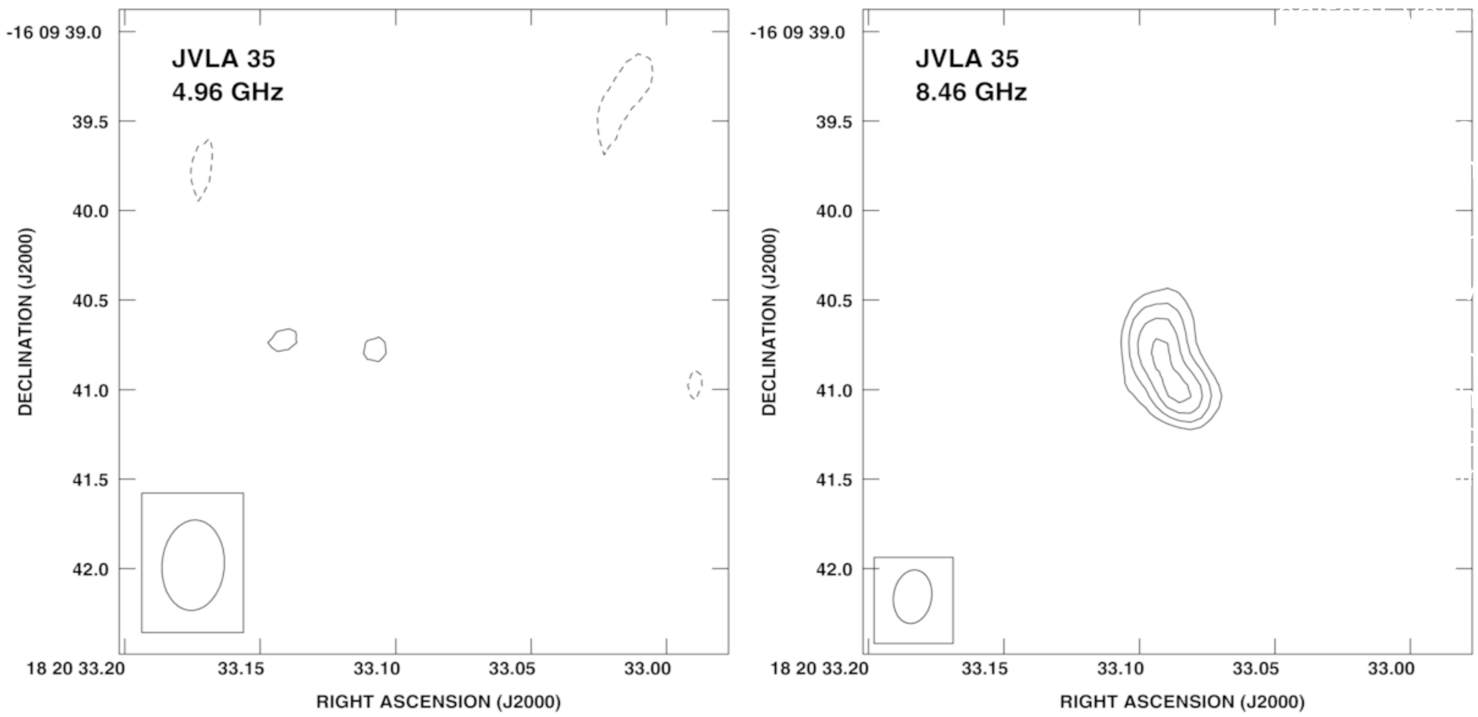
Compact source at center of W3 (OH).
Free-free spectrum, radio recombination line.
We may be seeing photoevaporating disk associated with ionizing star of the region.
Slope = 1.3±0.3. Massive transition object?



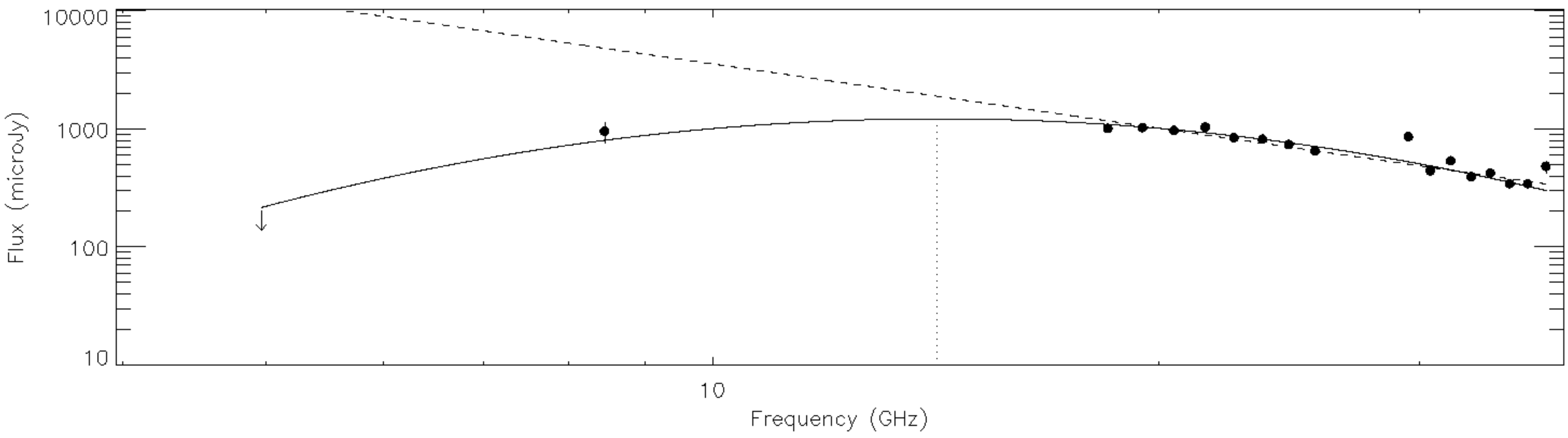


Dzib et al. (2013)

Our biggest problem now is understanding M17 JVLA 35. Spectrum and characteristics cannot be explained with any of the mechanisms discussed.



M17 JVLA 35



Spectrum similar to self-absorbed synchrotron, but angular size and turnover at high frequency imply too large a magnetic field.

Conclusions

Study of compact radio sources in regions of massive star formation is only starting. Many astronomical uses.

Although mostly understood, there are many unknowns in the field.