Star formation across the mass spectrum

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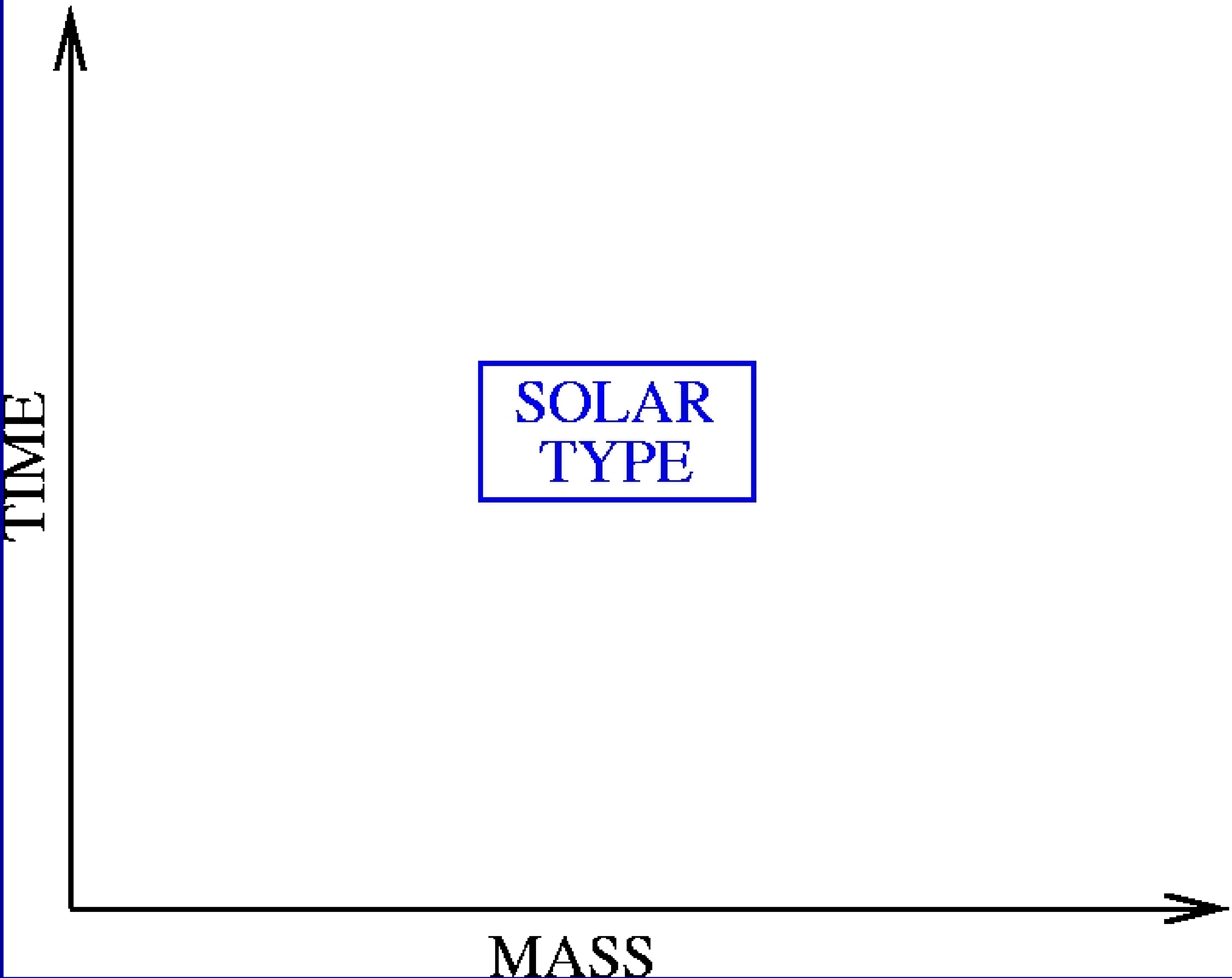
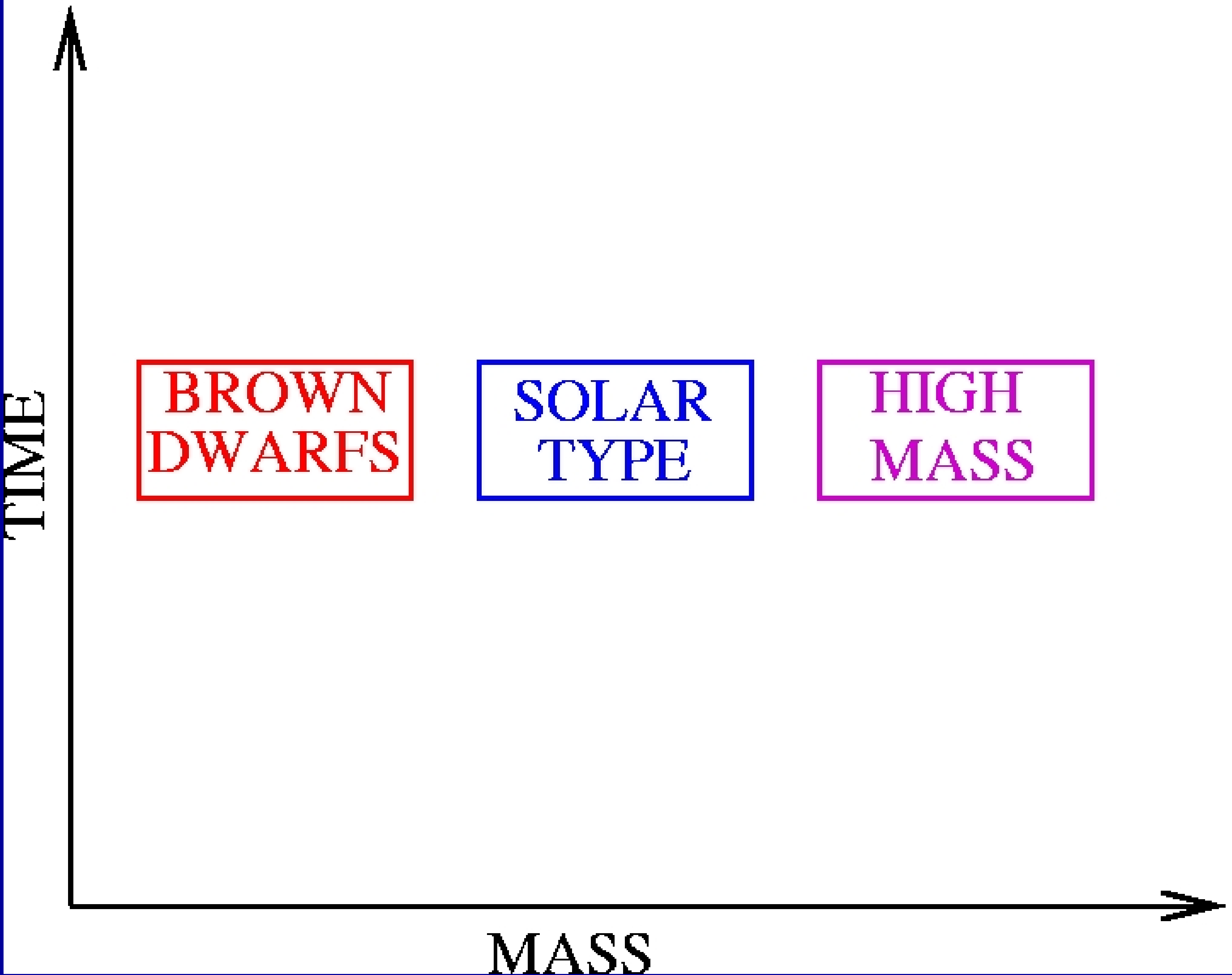
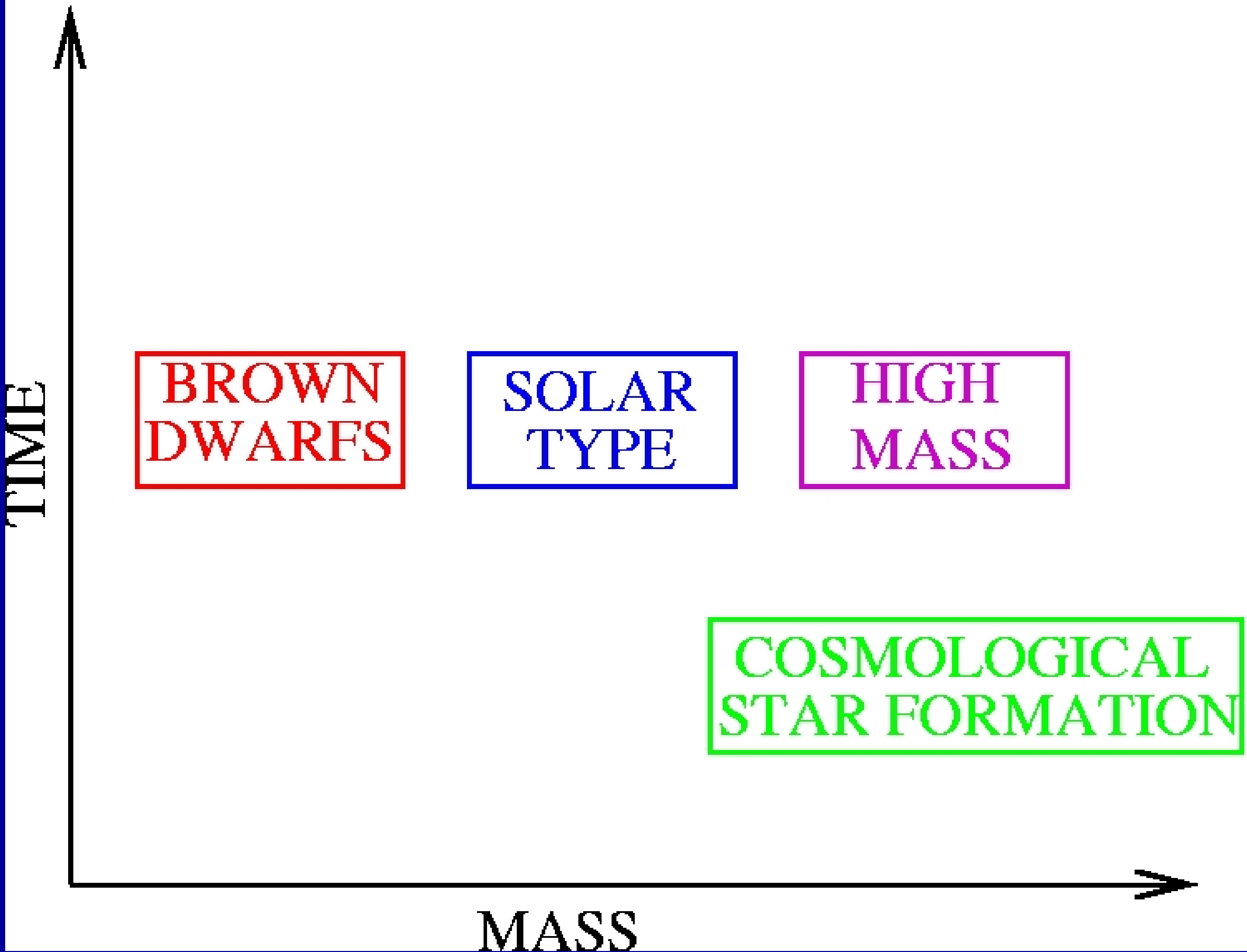
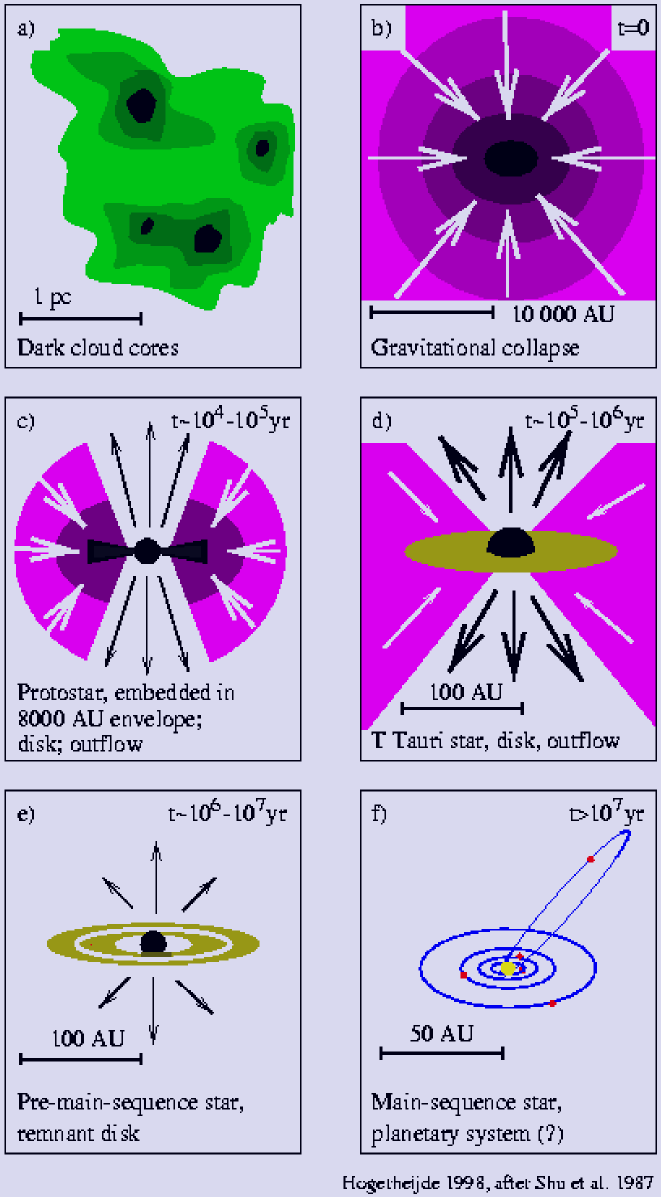
- Our understanding of low-mass (solar type with masses between 0.1 and 10 M_{SUN}) star formation has improved greatly in the last few decades.
- Can we extend the model to high mass stars and to brown dwarfs?
- Presentation that emphasizes radio results.


TIME
SOLAR TYPE
MASS


TIME
BROWN DWARFS
SOLAR TYPE
HIGH MASS
MASS


TIME
BROWN DWARFS
SOLAR TYPE
HIGH MASS
COSMOLOGICAL STAR FORMATION
MASS

LOW MASS STAR FORMATION



a) Fragmentation of cloud

b) Gravitational contraction

c) Accretion and ejection

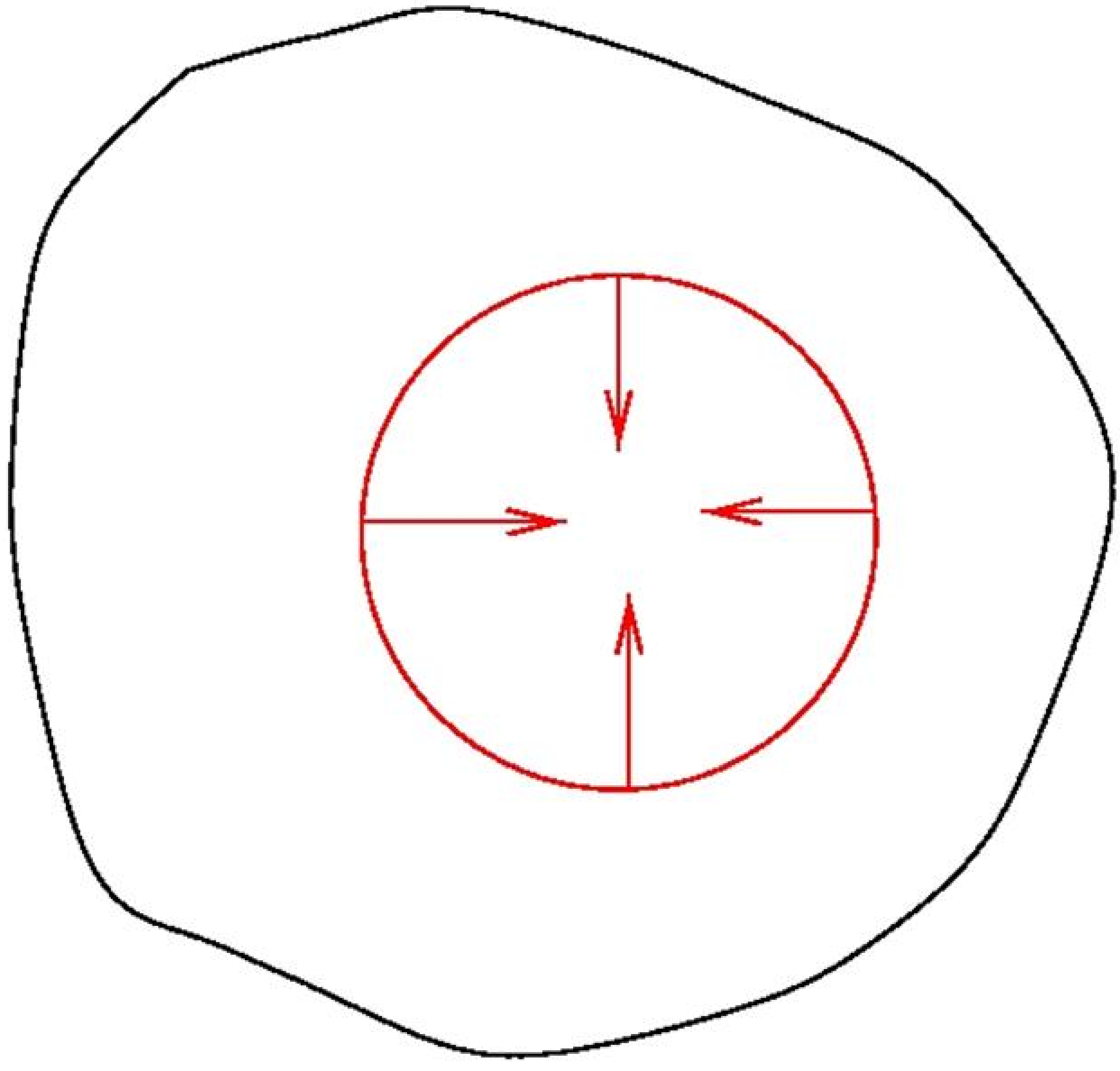
d) Formation of disk

e) Residual disk

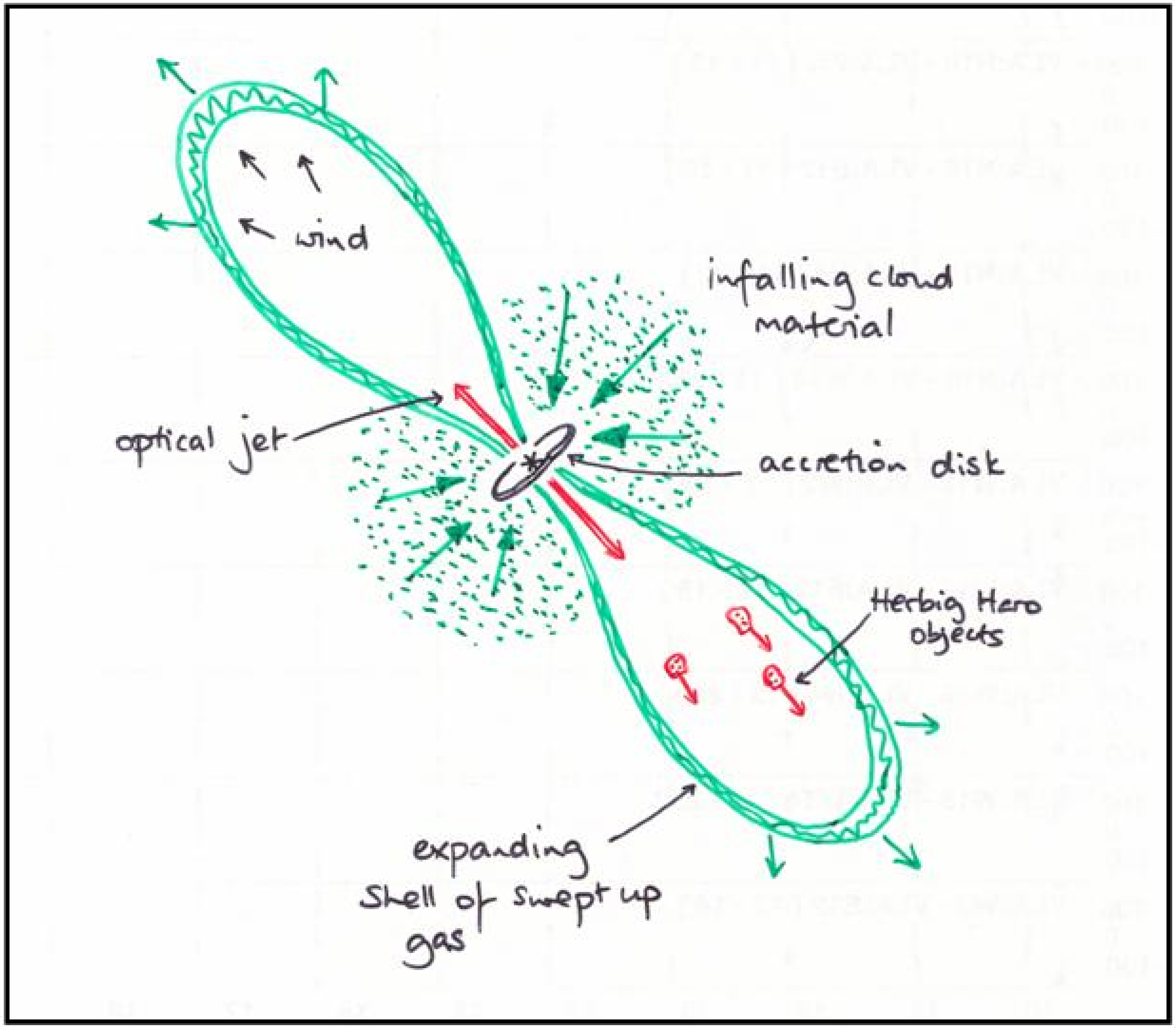
f) Formation of planets

(Shu, Adams & Lizano 1987)

<1980



Current picture of low-mass star formation



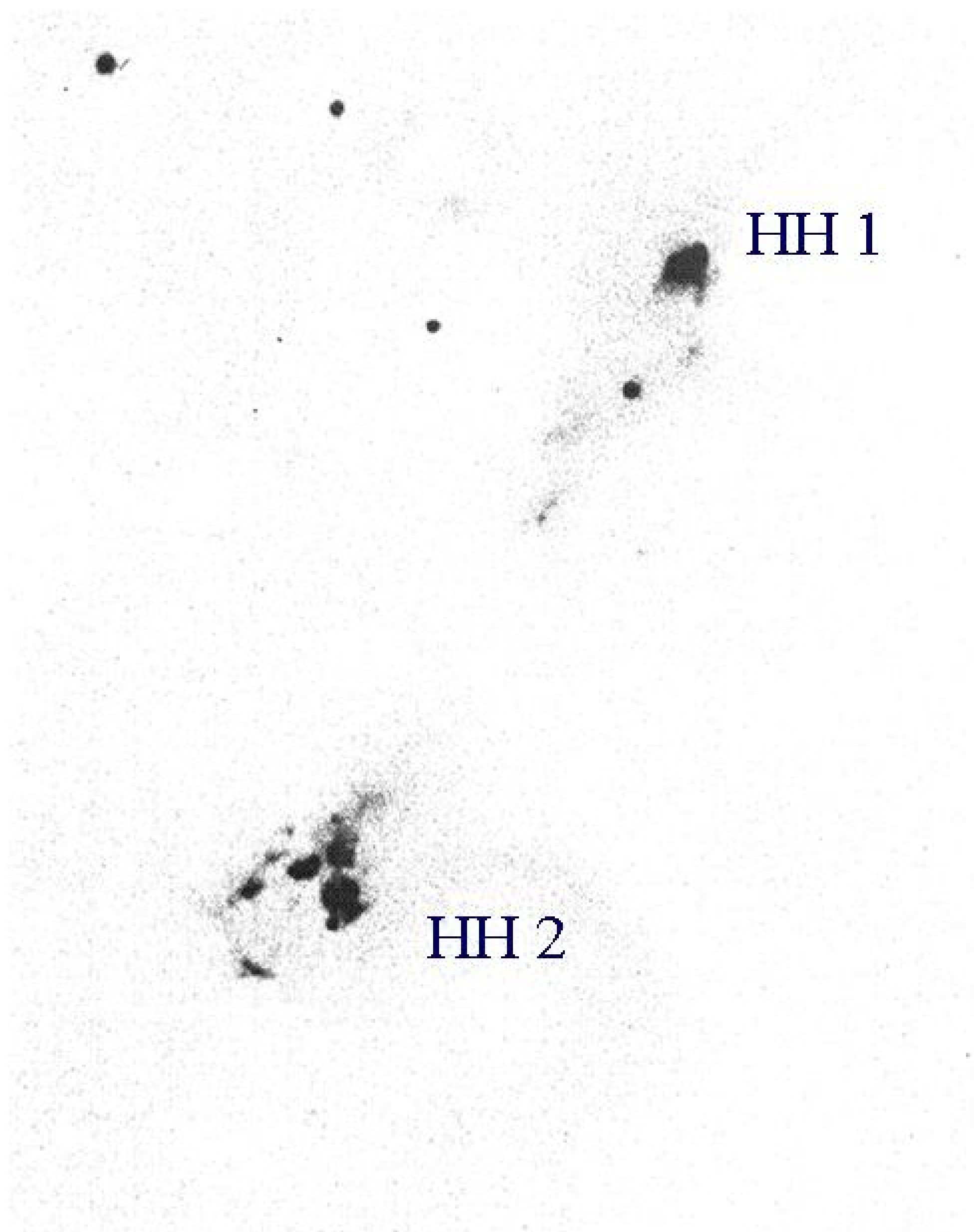


FIG. 3. Contrast-enhanced enlargement of the region of HH 1, HH 2, and the C-S star, from 120-in. plate ED-32; see Fig. 7 for identifications. The faint nebulosity centered on the C-S star is apparent, and its elongation in the directions of HH 1 and HH 2. The small ring of faint nebulosity to the upper left of HH 1, and the much larger ring to the right of HH 2 are real.

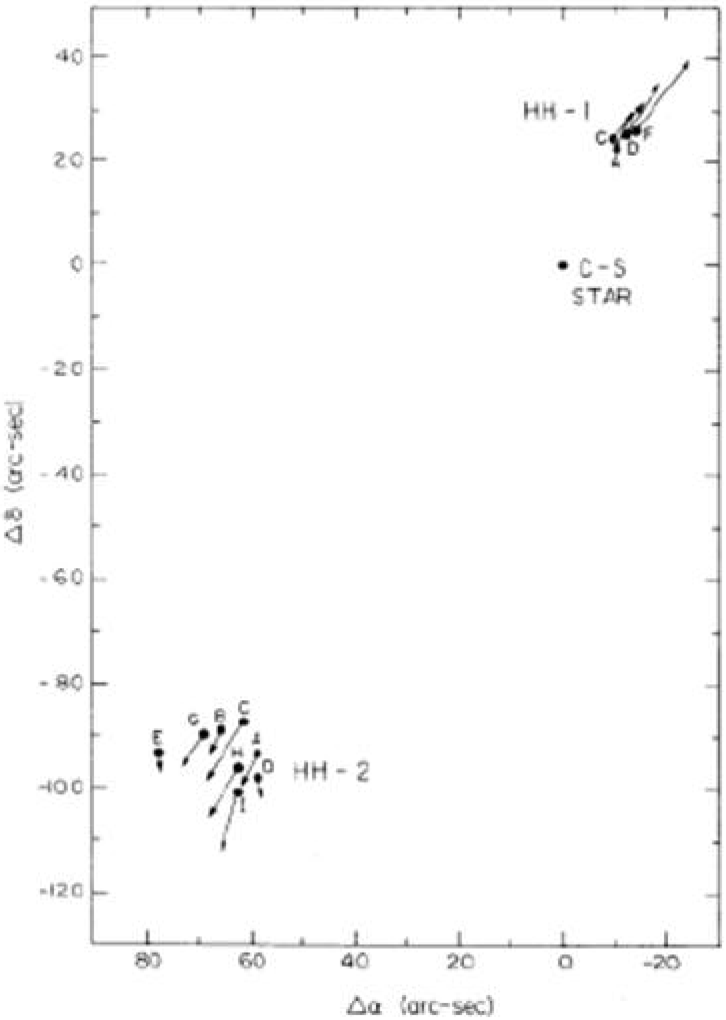
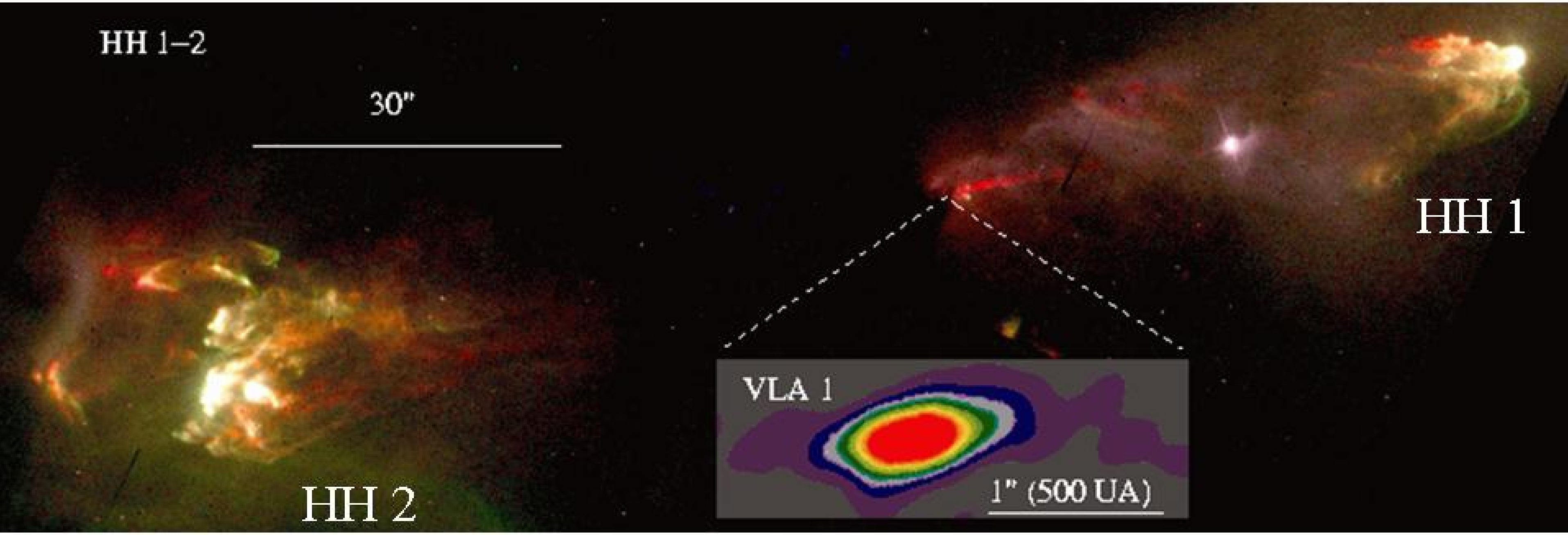
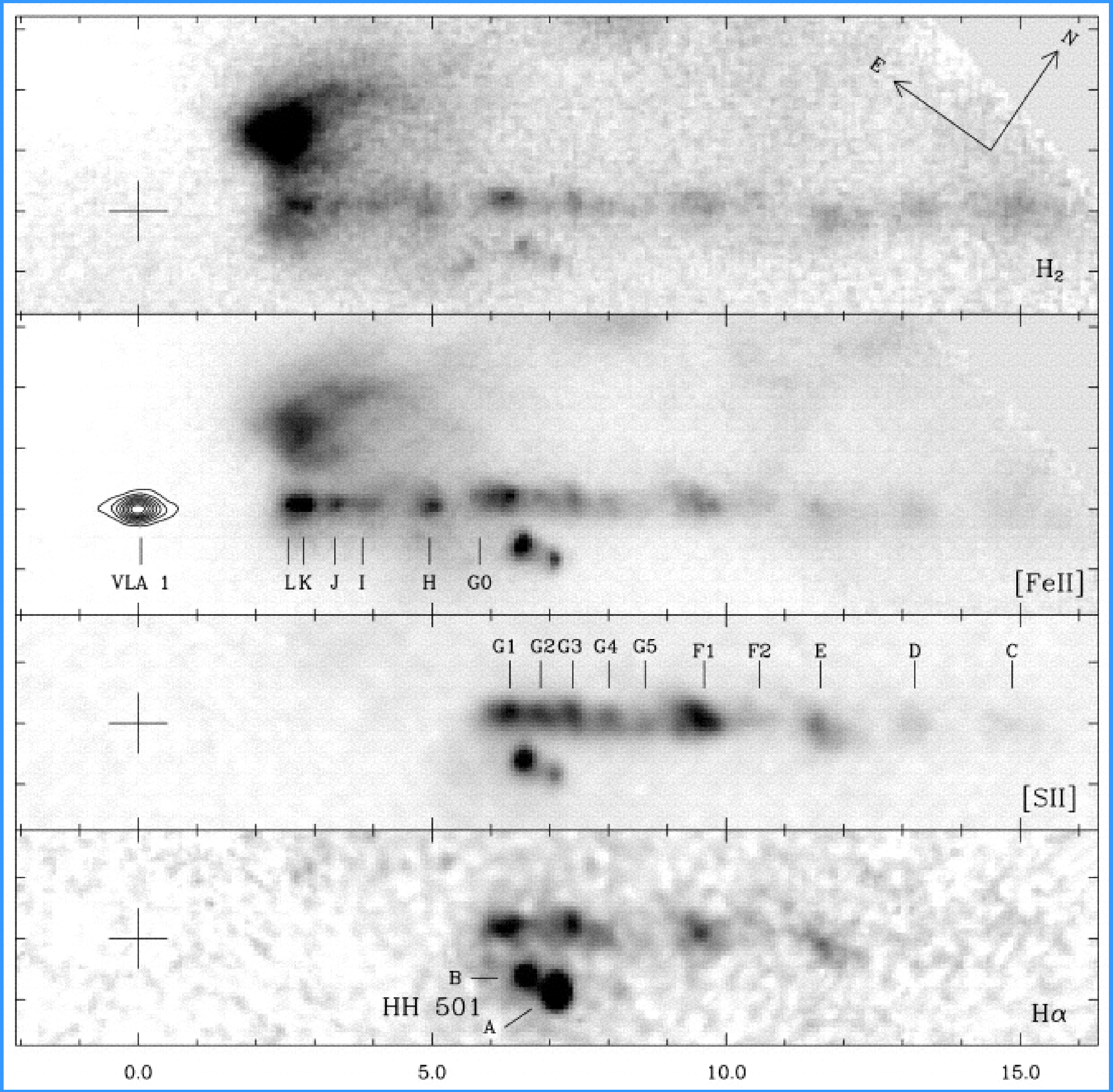


FIG. 7. The positions of HH 1, HH 2, and the Cohen-Schwartz star on the plane of the sky (for epoch 1968.0). The arrows indicate the shift in 100 yr due to proper motion. At a distance of 460 pc, 10 arcsec is equivalent to 2.23×10^{-2} pc. For HH 2A, the position is for A′ although the motion vector is for A. The motion of the C-S star is too small to show on this scale. The internal motions in HH 1 and HH 2 are displayed at larger scale in Figs. 8 and 9.

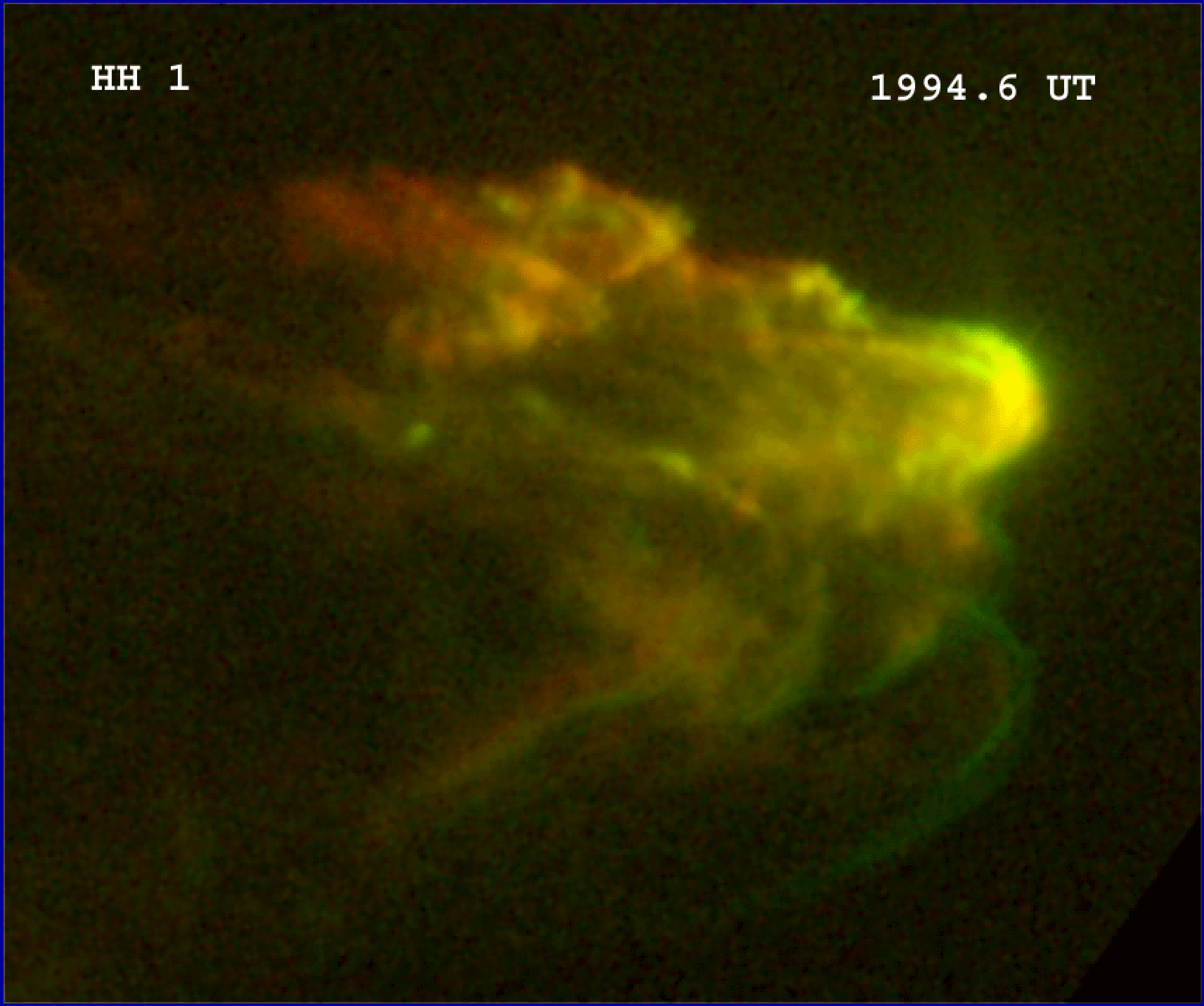

Very Large Array


HH 1–2
30"
HH 1
HH 2
VLA 1
1" (500 UA)



Complementarity of observations at different bands.

Reipurth et al. (2000) HST + VLA

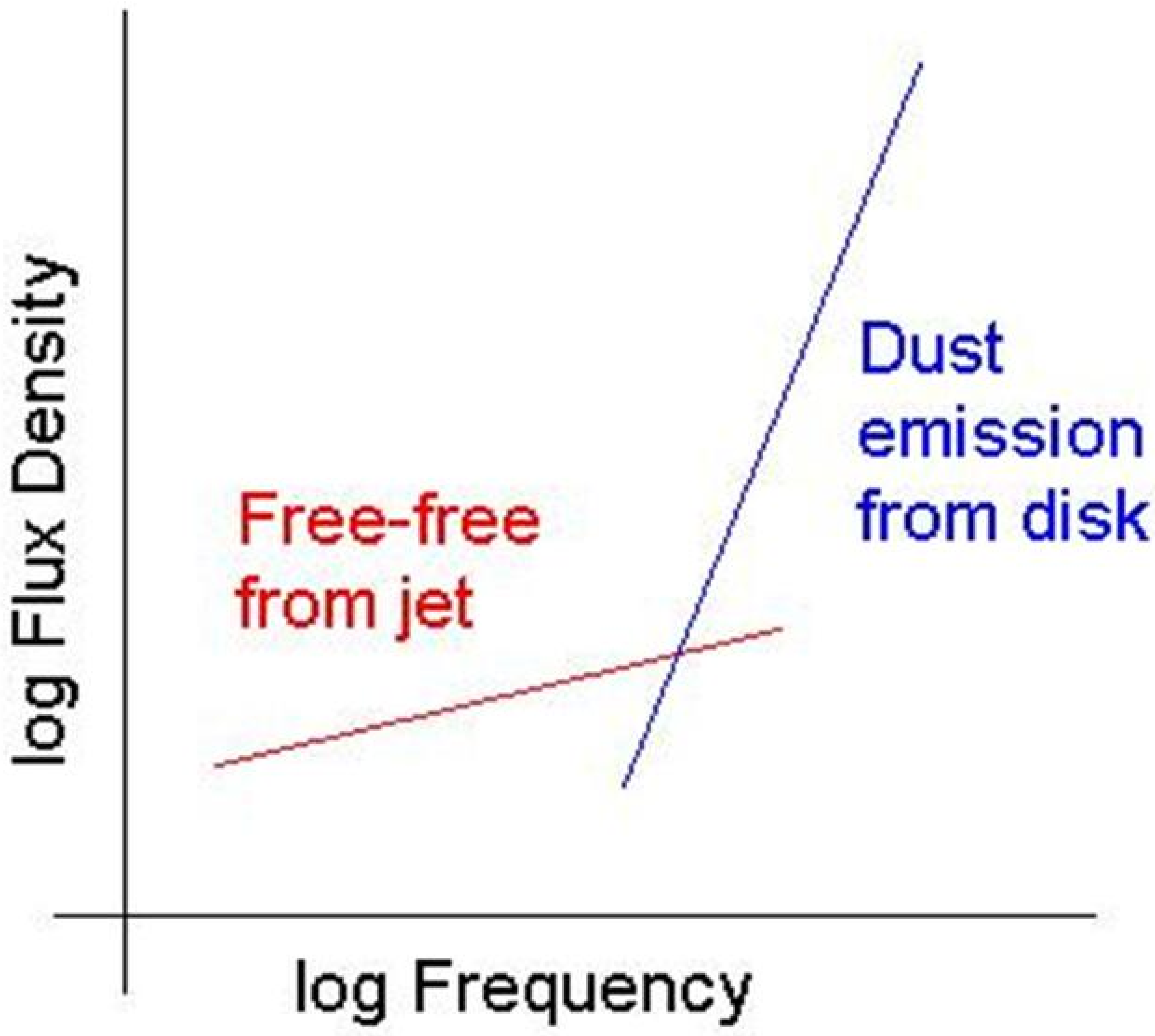

HH 1
1994.6 UT

Disk-Jet Symbiosis

- Disk: Forming star grows by accreting from disk (that accretes from envelope). Eventually, disk will condense into planets, asteroids, comets, etc.
- Jet: Carries away angular momentum and energy from disk, allowing accretion to proceed. They produce HH objects and molecular outflows, affecting energy balance and chemistry of cloud.

Let´s take a look at the jets

- Free-free emission in the radio
- Base of jet usually heavily obscured
- Compact (<1”)



Free-free emission from ionized gas in jet dominates cm region, while thermal emission from dust in the disk dominates mm region.

HII Regions

$$\Delta I_\nu = I_\nu(\tau_\nu) - I_\nu(0) = (F_\nu - I_\nu(0))(1 - e^{-\tau_\nu})$$

$I_\nu(0)$ is blackbody function at T_{bg} = 2.7 K (the cosmic microwave background).

F_ν is blackbody function at $T_{ex} \approx$ 10,000 K (the electron temperature of the ionized gas).

Neglect *$I_\nu(0)$* to get

$$\Delta I_\nu = F_\nu (1 - e^{-\tau_\nu})$$

Since $S_\nu = \Delta I_\nu \Omega_\nu$, and using R-J approximation:

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

HII Regions

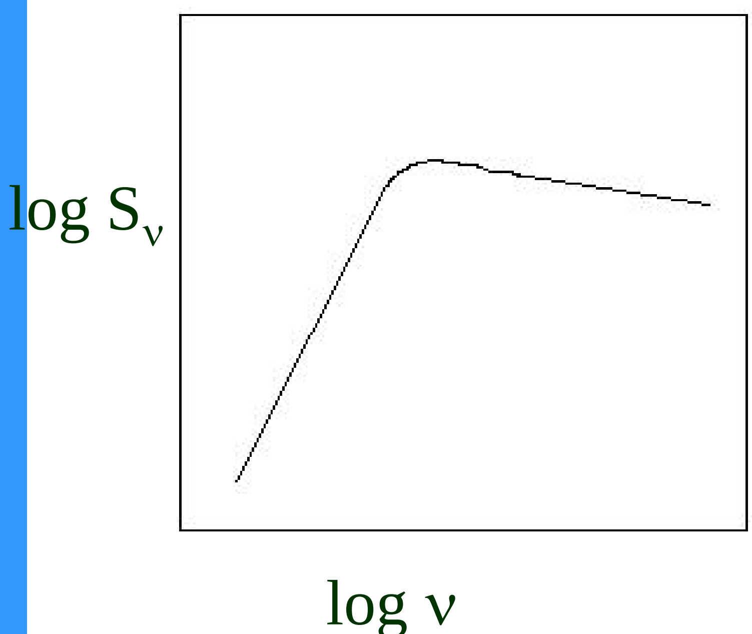
$$S_\nu = \frac{2kT_e\nu^2}{c^2}(1-e^{-\tau_\nu})\Omega_\nu$$

$$\tau_\nu \propto n_e^2\, l\, \nu^{-2.1}$$

For (more or less) homogeneous HII region, Ω_ν is approximately constant with ν. We then have the two limit cases for $\tau_\nu > 1$ (low frequencies) and for $\tau_\nu < 1$ (high frequencies):

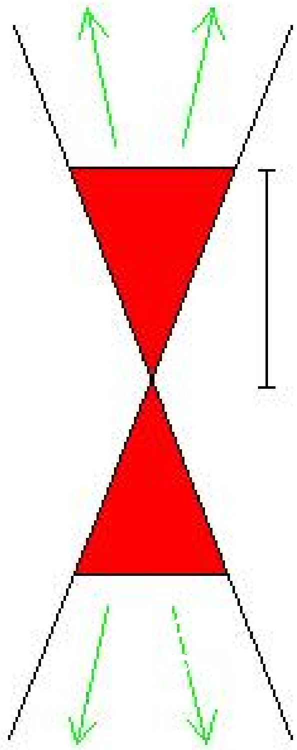
$S_\nu \propto \nu^2$ (optically thick)

$S_\nu \propto \nu^{-0.1}$ (optically thin)



Thermal Jets

$n_e \propto \xi^{-2}$



$$\tau_\nu(\xi) \propto n_e^2\, l\, \nu^{-2.1}$$

$$\tau_\nu(\xi) \propto \xi^{-3} \nu^{-2.1}$$

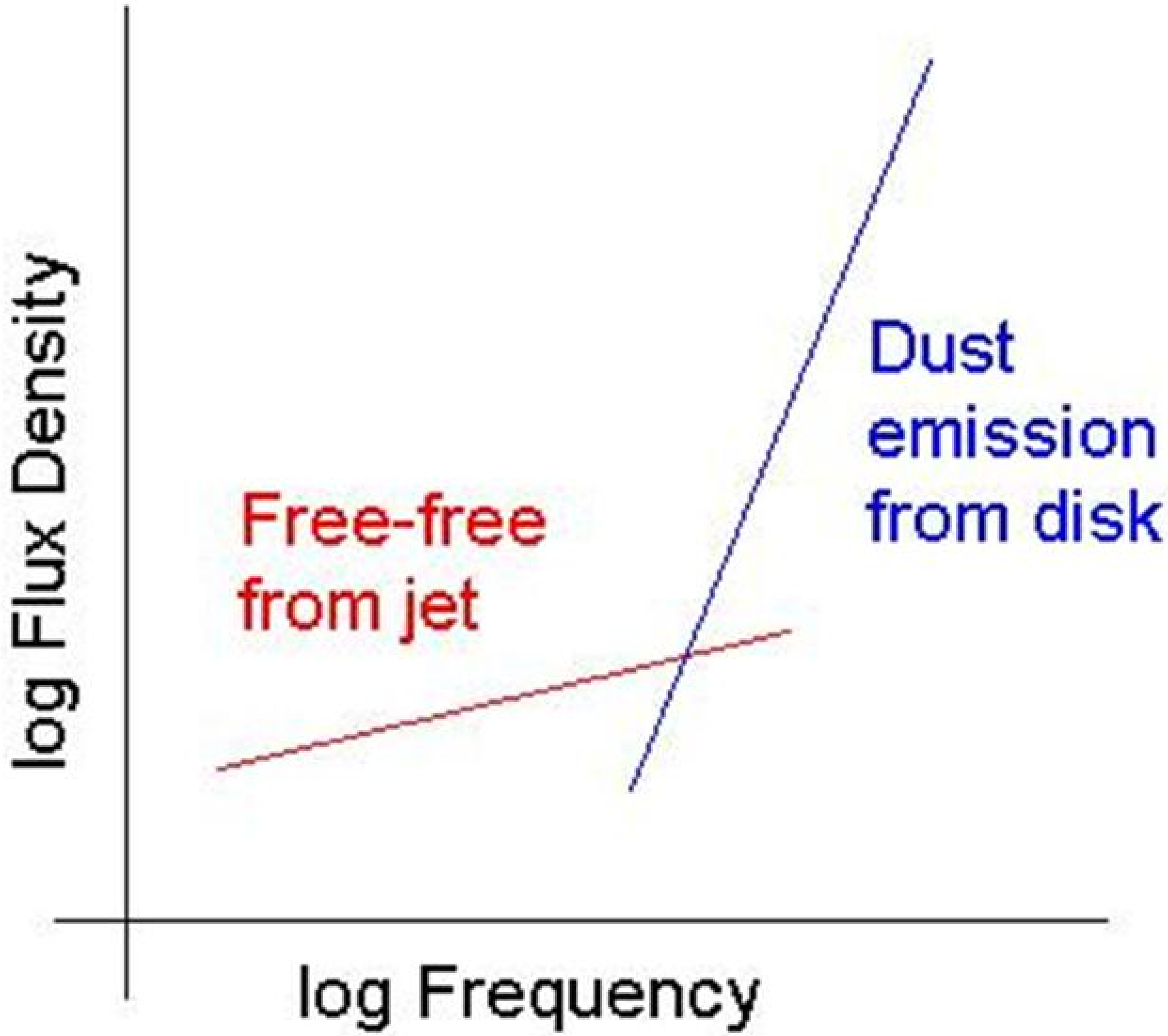
We define ξ_c when $\tau_\nu(\xi_c) = 1$

Then $\xi_c \propto \nu^{-0.7}$ => size of source decreases with ν!

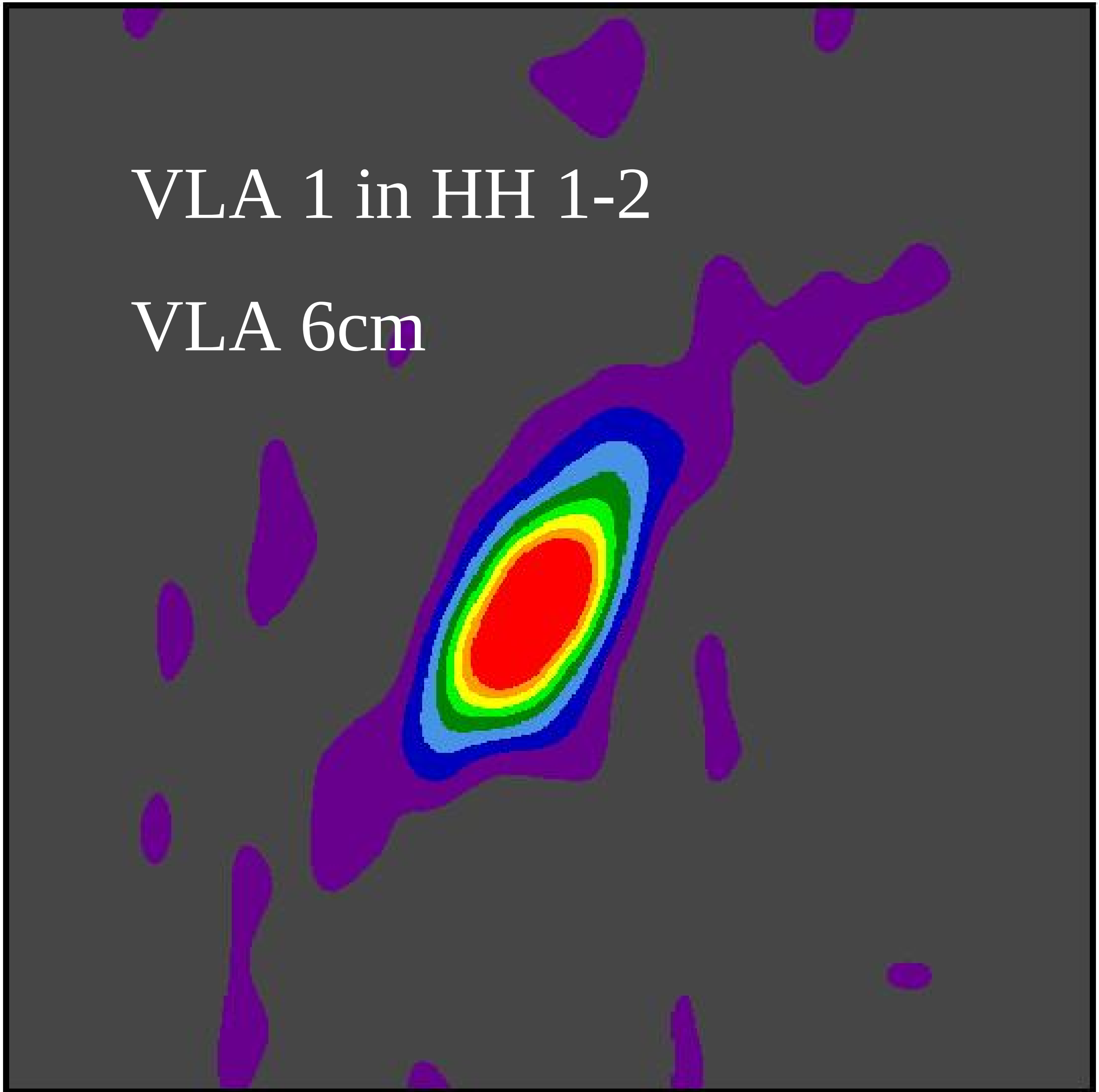
Since $S_\nu \propto \nu^2\ \xi^2_c \propto \nu^2\ \nu^{-1.4} \propto \nu^{0.6}$

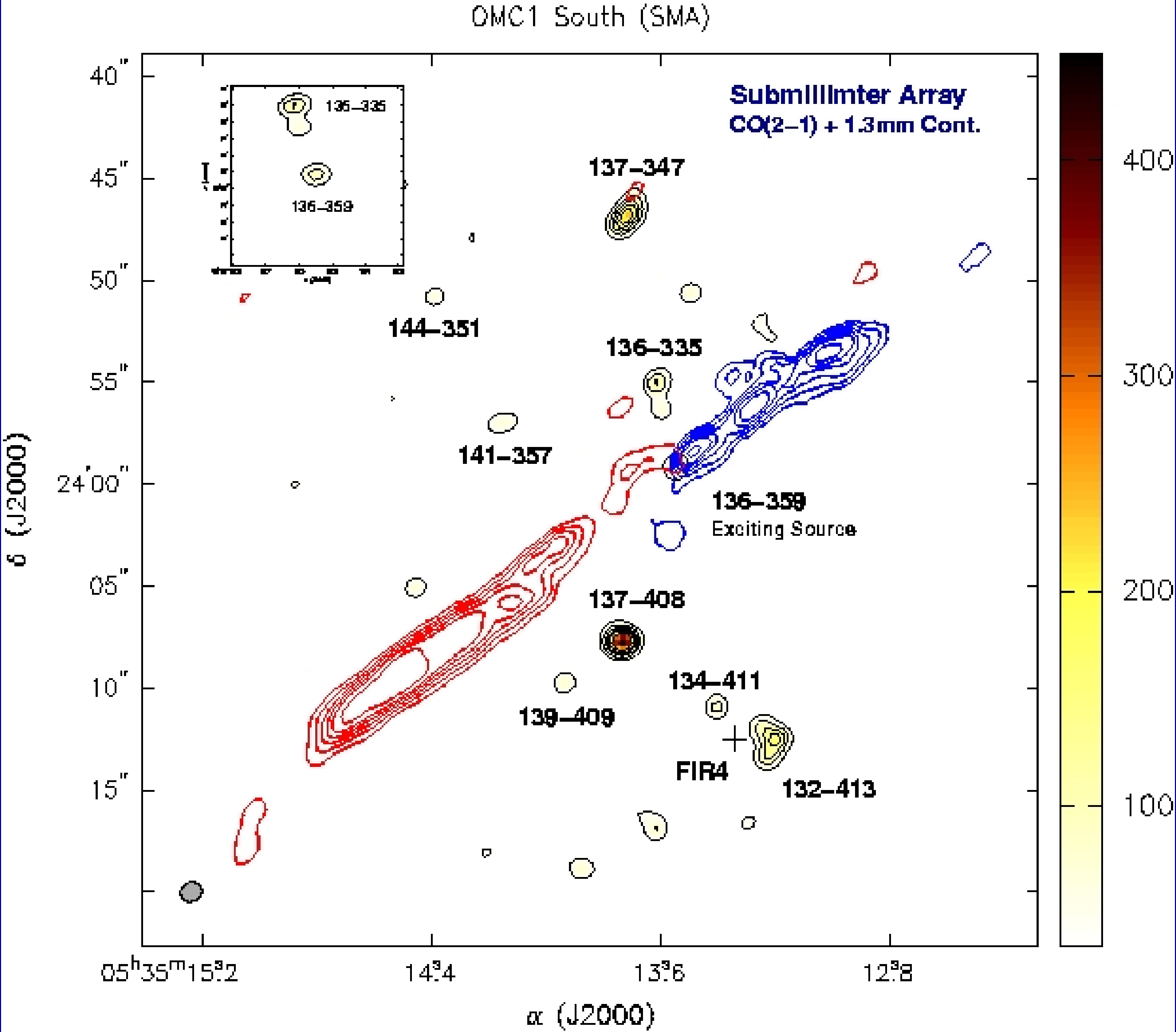
$\theta_\nu \propto \nu^{-0.7}$

$S_\nu \propto \nu^{0.6}$



Free-free emission from ionized gas in jet dominates cm region, while thermal emission from dust in the disk dominates mm region.


VLA 1 in HH 1-2
VLA 6cm


OMC1 South (SMA)
Submillimter Array
CO(2–1) + 1.3mm Cont.
137–347
144–351
136–335
141–357
136–359
Exciting Source
137–408
134–411
139–409
FIR4
132–413
40"
45"
50"
55"
24'00"
05"
10"
15"
δ (J2000)
05h35m15.2
14.4
13.6
12.8
α (J2000)
400
300
200
100

Dust Emission

$$\Delta I_\nu = I_\nu(\tau_\nu) - I_\nu(0) = (F_\nu - I_\nu(0))(1 - e^{-\tau_\nu})$$

$I_\nu(0)$ is blackbody function at T_{bg} = 2.7 K (the cosmic microwave background).

F_ν is blackbody function at $T_d \approx$ 10-300 K (the temperature of the dust).

Neglect $I_\nu(0)$ to get

$$\Delta I_\nu = F_\nu (1 - e^{-\tau_\nu})$$

Since $S_\nu = \Delta I_\nu \Omega_\nu$, and using R-J approximation:

$$S_\nu = \frac{2kT_d \nu^2}{c^2}(1 - e^{-\tau_\nu})\Omega_\nu$$

Dust Emission

$$S_\nu = \frac{2kT_d\nu^2}{c^2}(1-e^{-\tau_\nu})\Omega_\nu$$

$$\tau_\nu \propto n_d\, l\, \nu^{0-2}$$

For (more or less) homogeneous dust region, Ω_ν is approximately constant with ν. We then have the two limit cases for $\tau_\nu > 1$ (low frequencies) and for $\tau_\nu < 1$ (high frequencies):

$S_\nu \propto \nu^2$ (optically thick at high ν, IR wavelengths)

$S_\nu \propto \nu^{2\text{-}4}$ (optically thin at low ν, millimeter wavelenghts)

Power law index of opacity depends, to first approximation, on relative sizes between grain of dust and wavelength of radiation: $a << \lambda \rightarrow 2$; $a >> \lambda \rightarrow 0$

Dust Emission

If dust is optically thin:

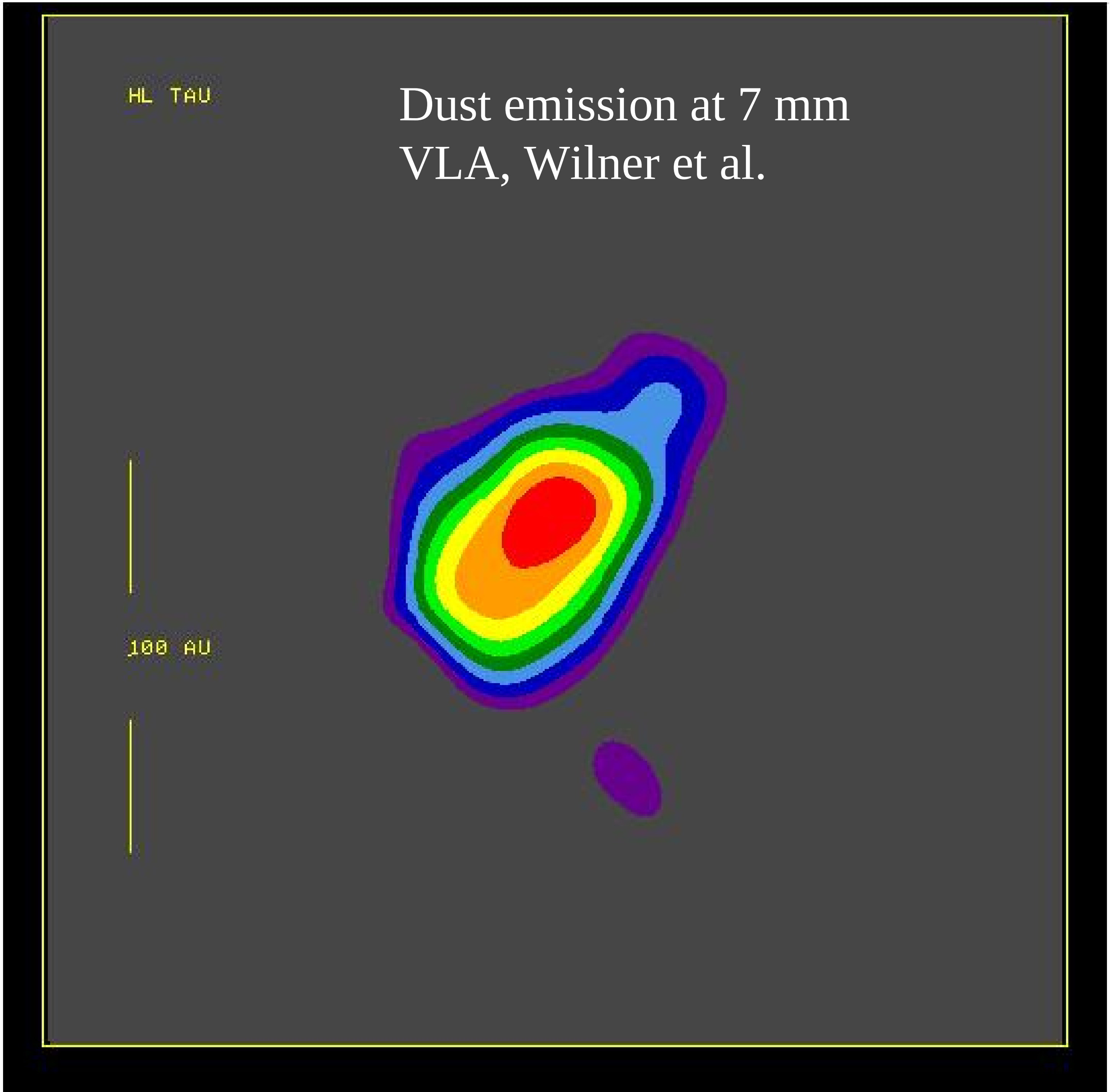
$$S_\nu \propto T_d \; n_d \; l \, \Omega \; \nu^{2-4}$$; and since

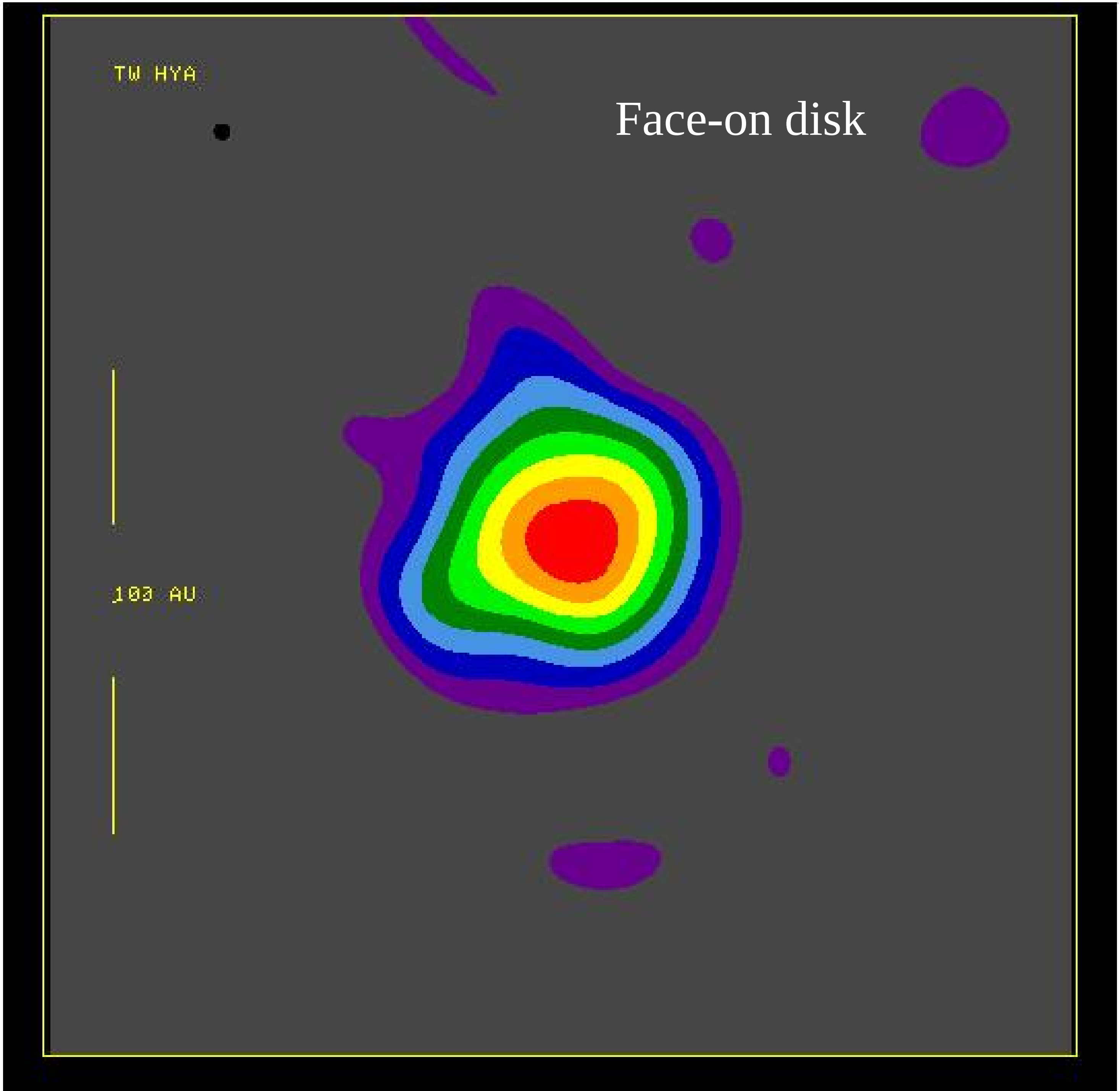
$$n_d \, l \, \Omega = n_d \frac{V}{d^2} = \frac{M_d}{d^2}$$

$$S_\nu \propto T_d \frac{M_d}{d^2} \nu^{2-4}$$

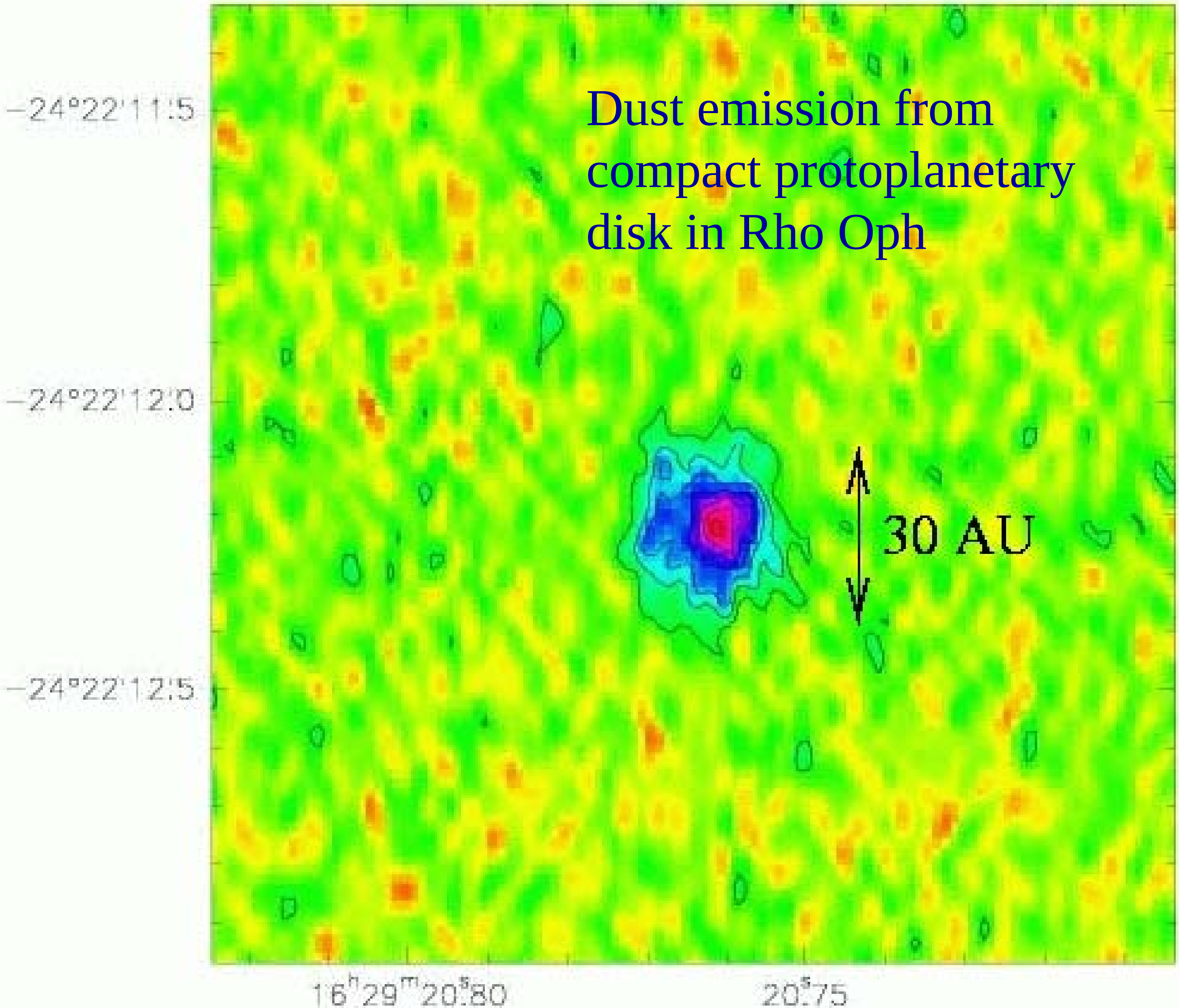
If you know flux density, dust temperature, distance to source, and opacity characteristics of dust, you can get M_d.

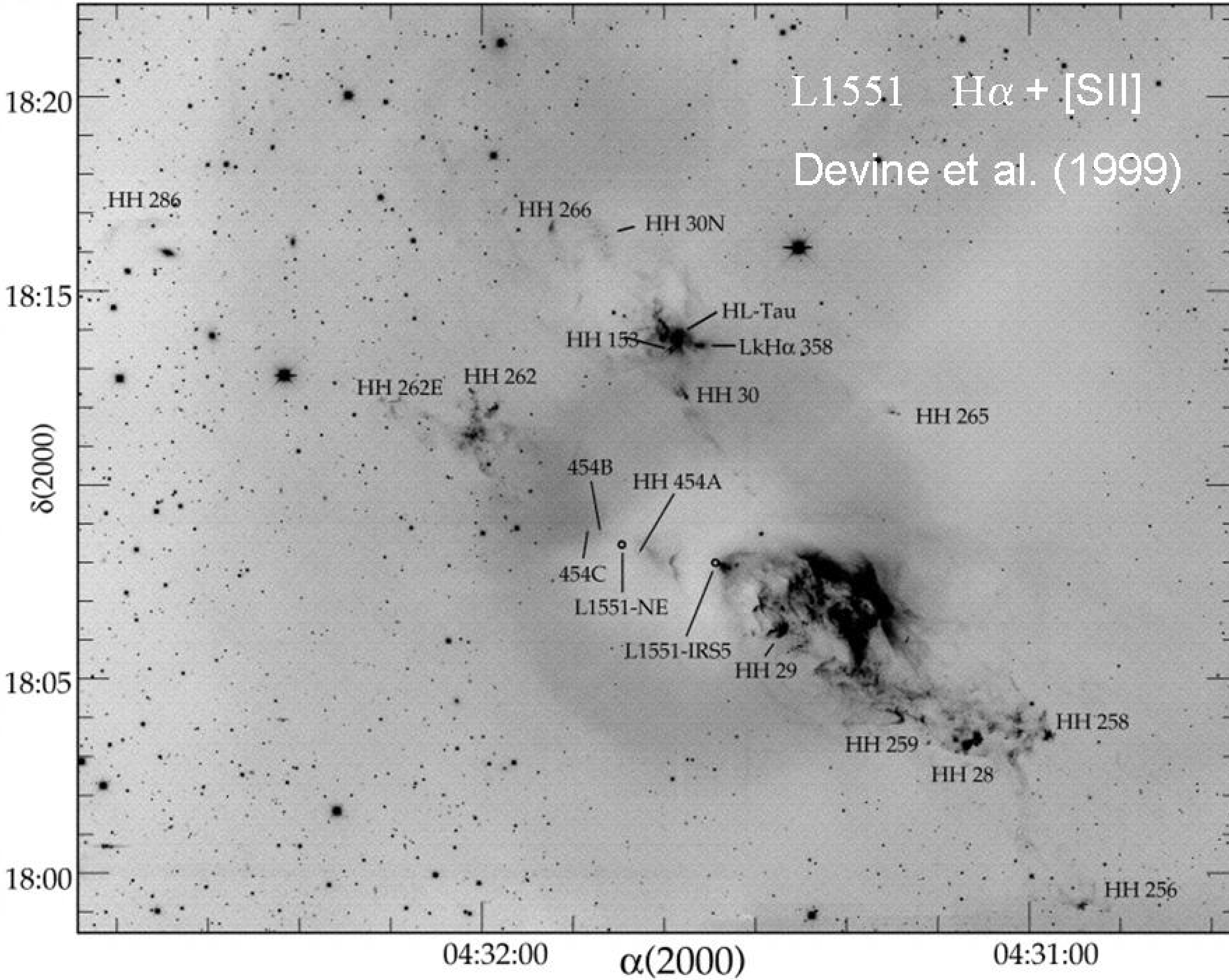
Assume dust to gas ratio and you get total mass of object.


HL TAU
Dust emission at 7 mm
VLA, Wilner et al.
100 AU


TW HYA
Face-on disk
103 AU

IRAS 16293-2422




L1551 Hα + [SII]
Devine et al. (1999)
HH 286
HH 266
HH 30N
HL-Tau
HH 153
LkHα 358
HH 262E
HH 262
HH 30
HH 265
454B
HH 454A
454C
L1551-NE
L1551-IRS5
HH 29
HH 258
HH 259
HH 28
HH 256
18:20
18:15
18:05
18:00
δ(2000)
04:32:00
04:31:00
α(2000)

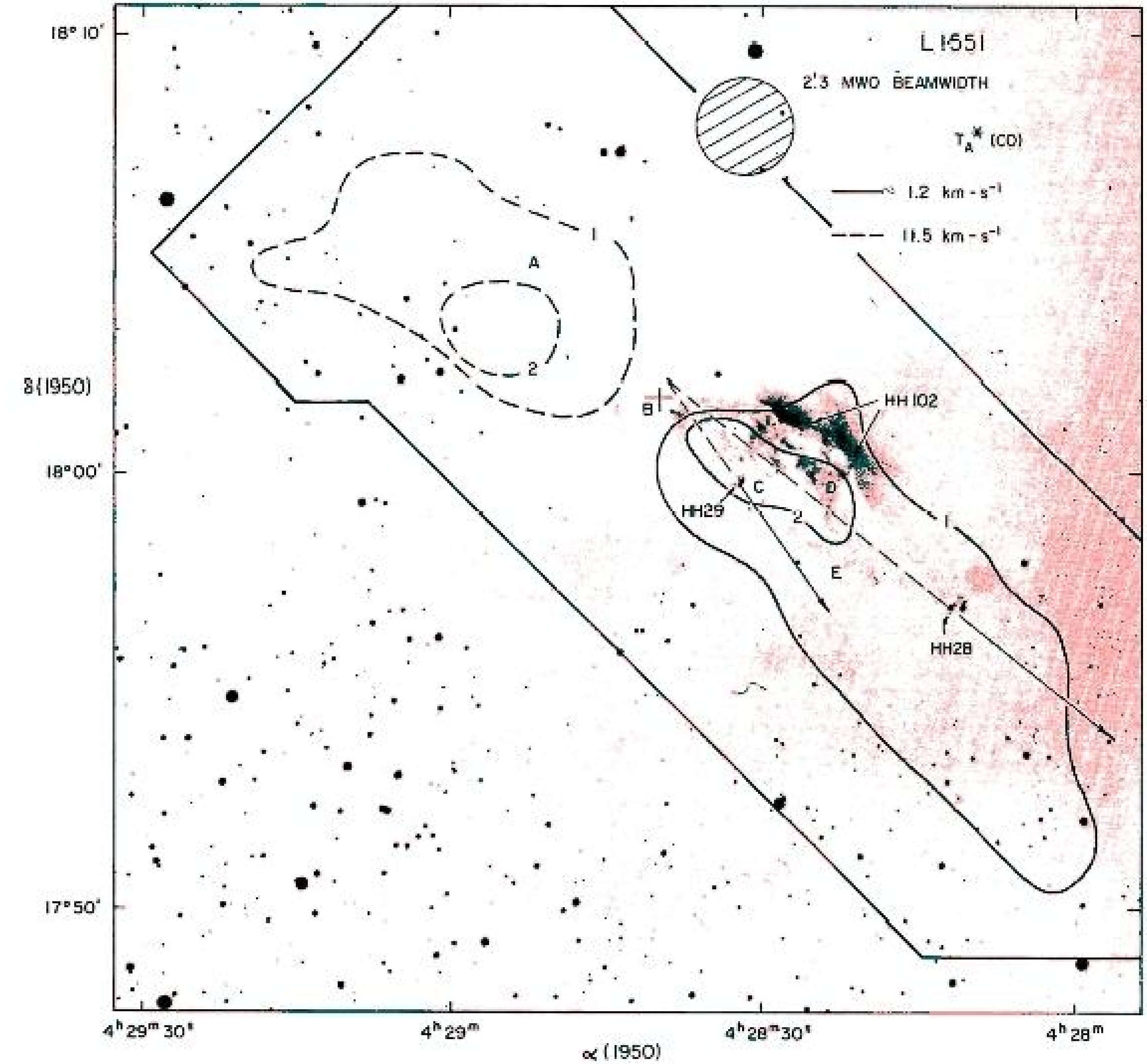
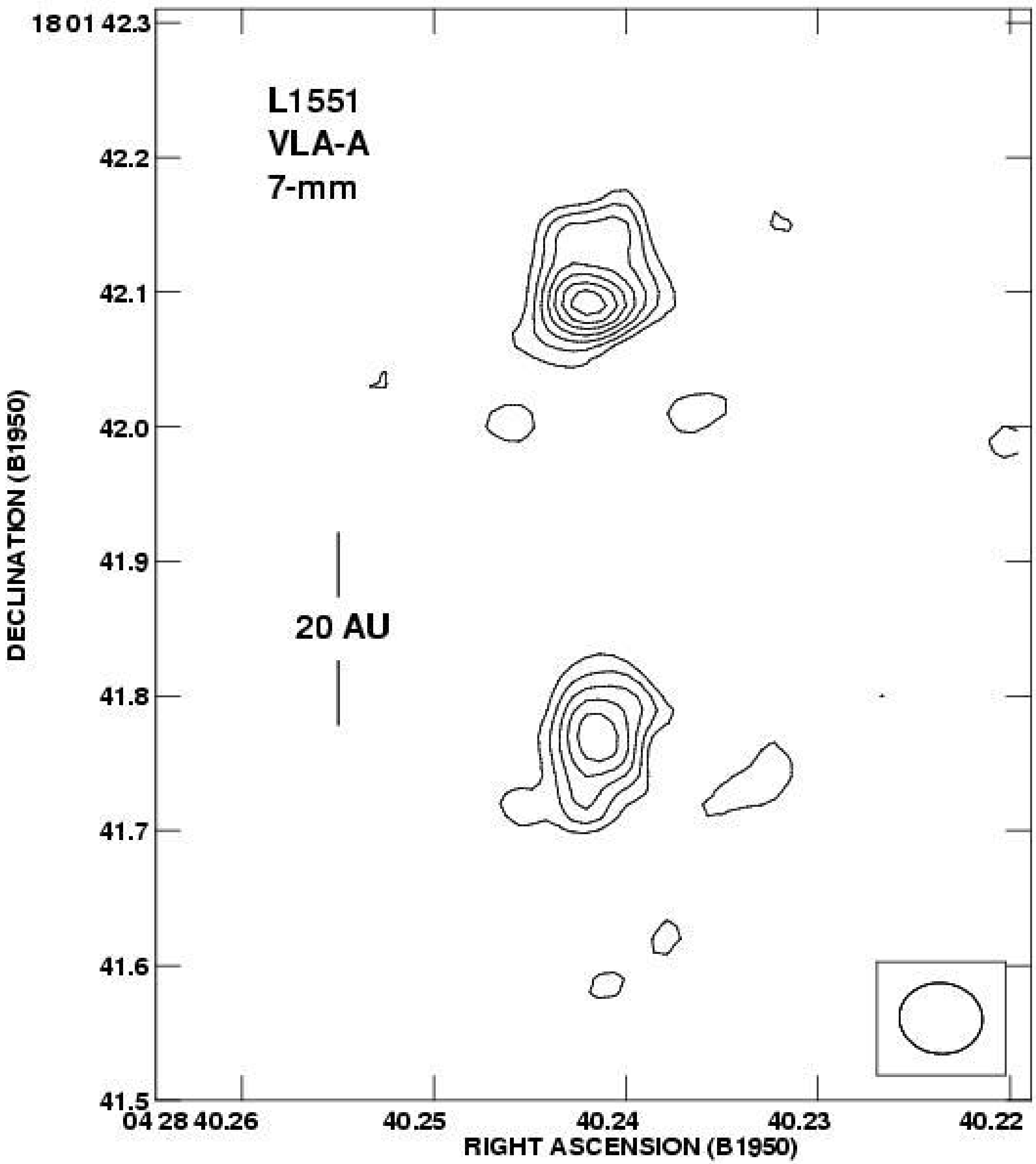


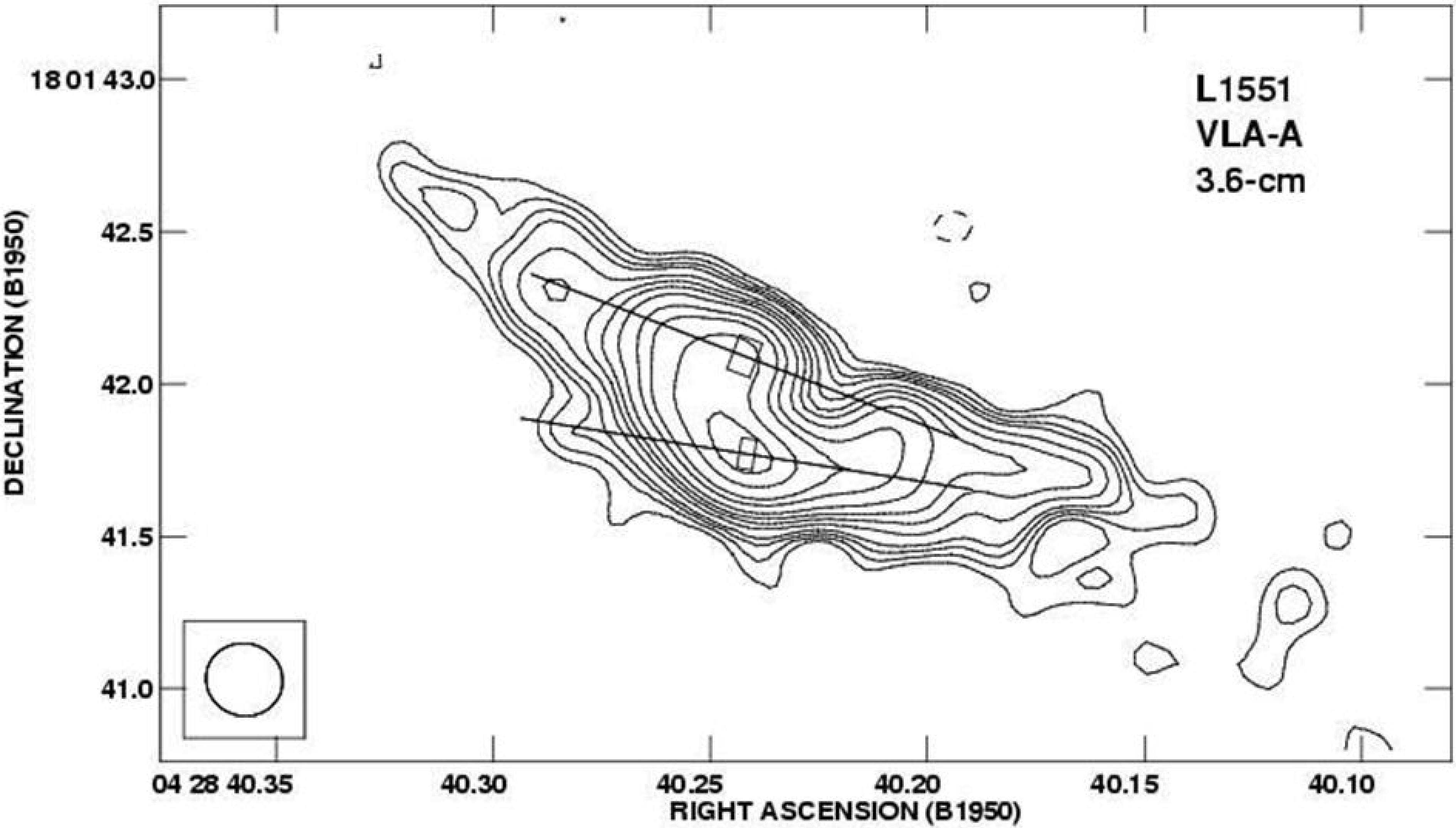
FIG. 2.—Contour map of the $J = 1\text{–}0$ ^{12}CO antenna temperatures in the broad velocity components, superposed on an optical photo of the region taken by Strom with the 4 m telescope at KPNO. The map is based on CO spectra taken at 115 positions within the enclosed border with 1′–2′ spacings. A cross indicates the position of IRS-5; letters A–E indicate the positions of the five spectra in Fig. 1 from top to bottom. Also shown are the directions of the proper motions of the two compact Herbig-Haro objects, HH28 and HH29; tracing their motion backward suggests a common origin at the infrared source.

L1551 IRS5

- Near-IR source (Strom et al. 1976) that excites bipolar outflow (Snell et al. 1980)
- Located in Taurus at 140 pc
- Bolometric luminosity of 30 L_{SUN}
- Embedded in dense core (1000 AU)
- Believed to be prototype of single star in formation

Rodríguez et al. 1998





L1551
VLA-A
3.6-cm
DECLINATION (B1950)
18 01 43.0
42.5
42.0
41.5
41.0
04 28 40.35
40.30
40.25
40.20
40.15
40.10
RIGHT ASCENSION (B1950)

As the angular resolution of an interferometer is

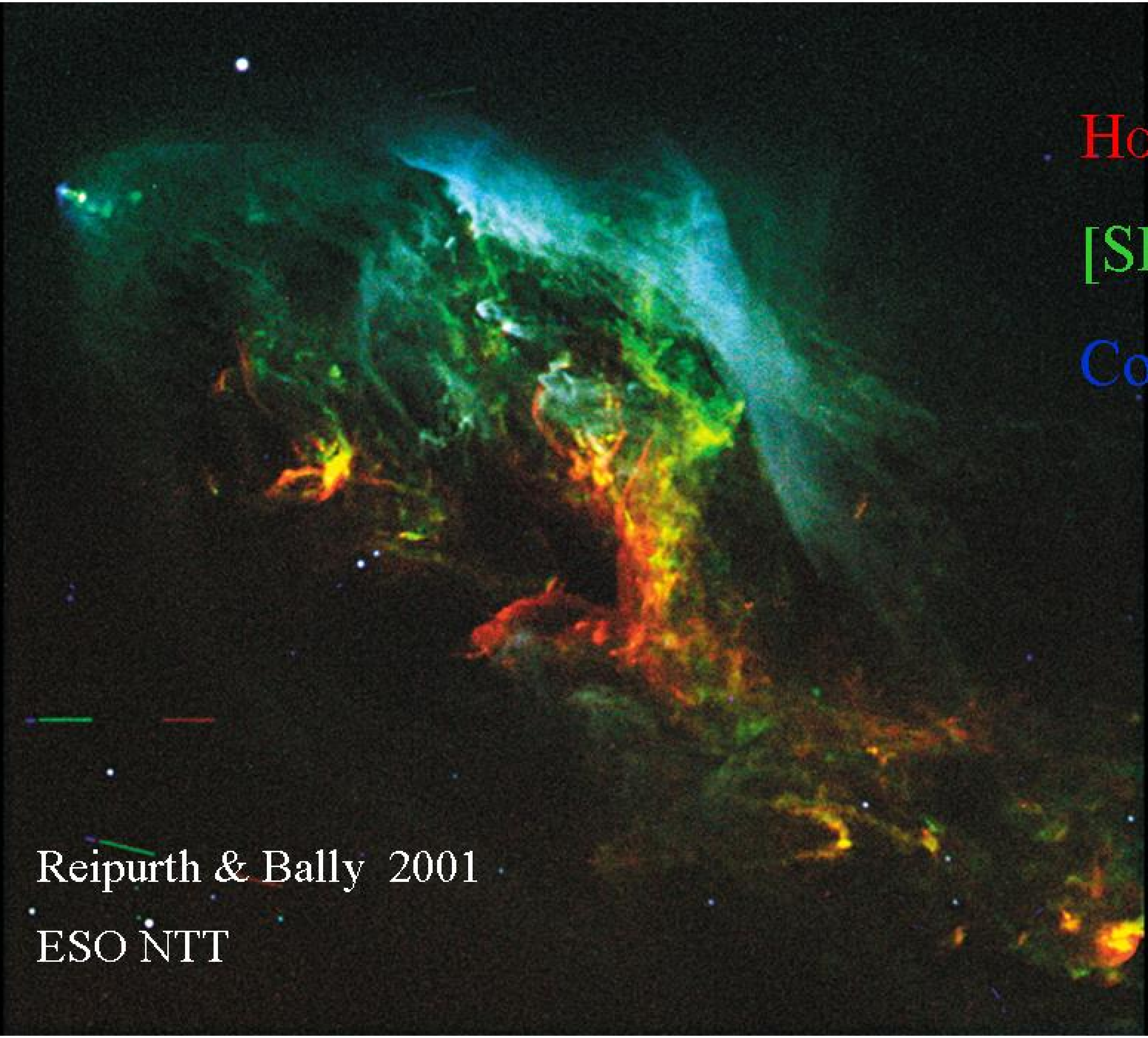
$\theta = \lambda / B$

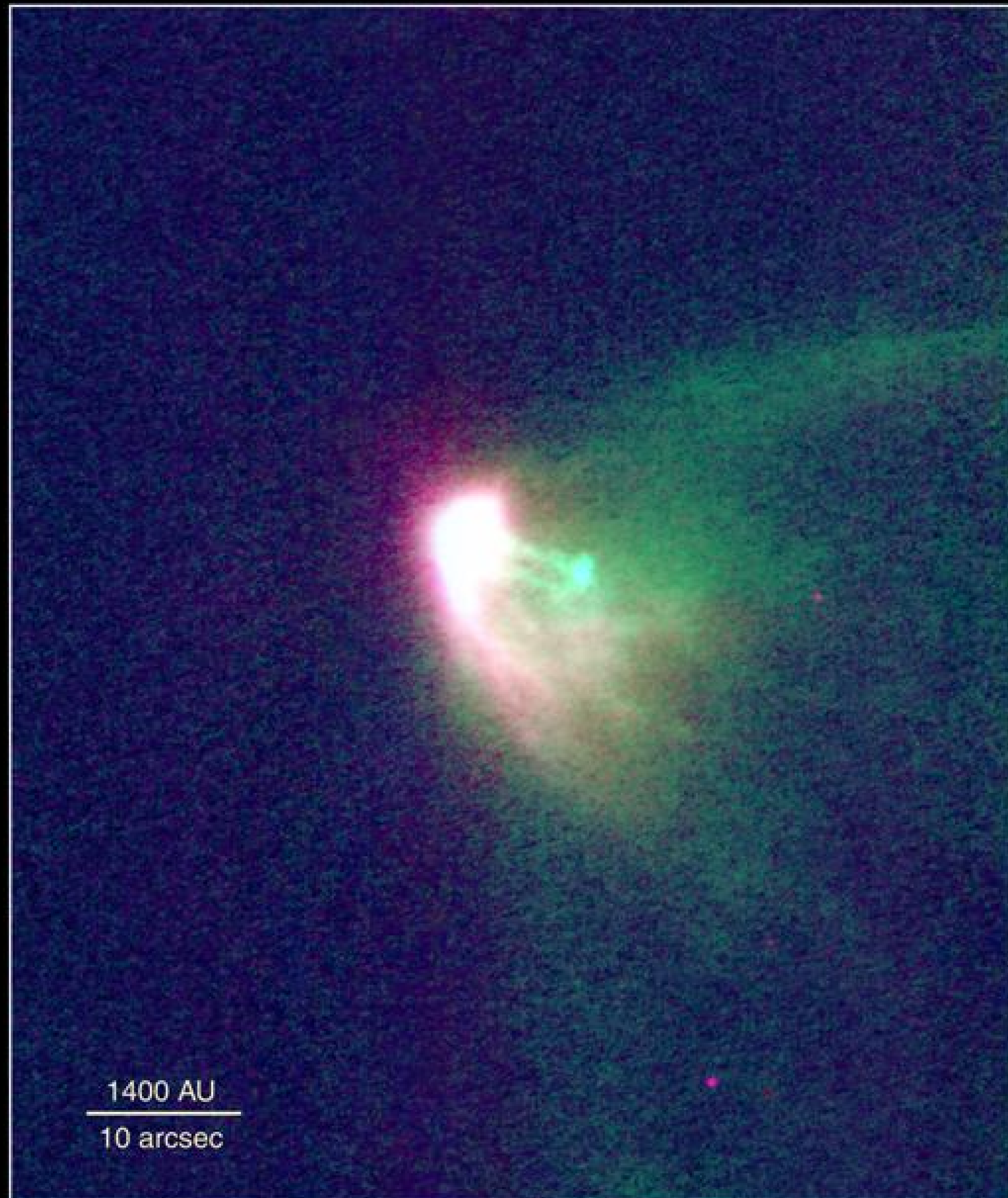
You cannot compare observations at 3.6 cm and 7 mm made with the same baseline B.

Two stars...

Two disks...

Two jets?


Hα
[SII]
Cont.
Reipurth & Bally 2001
ESO NTT



Two Jets from L1551-IRS5

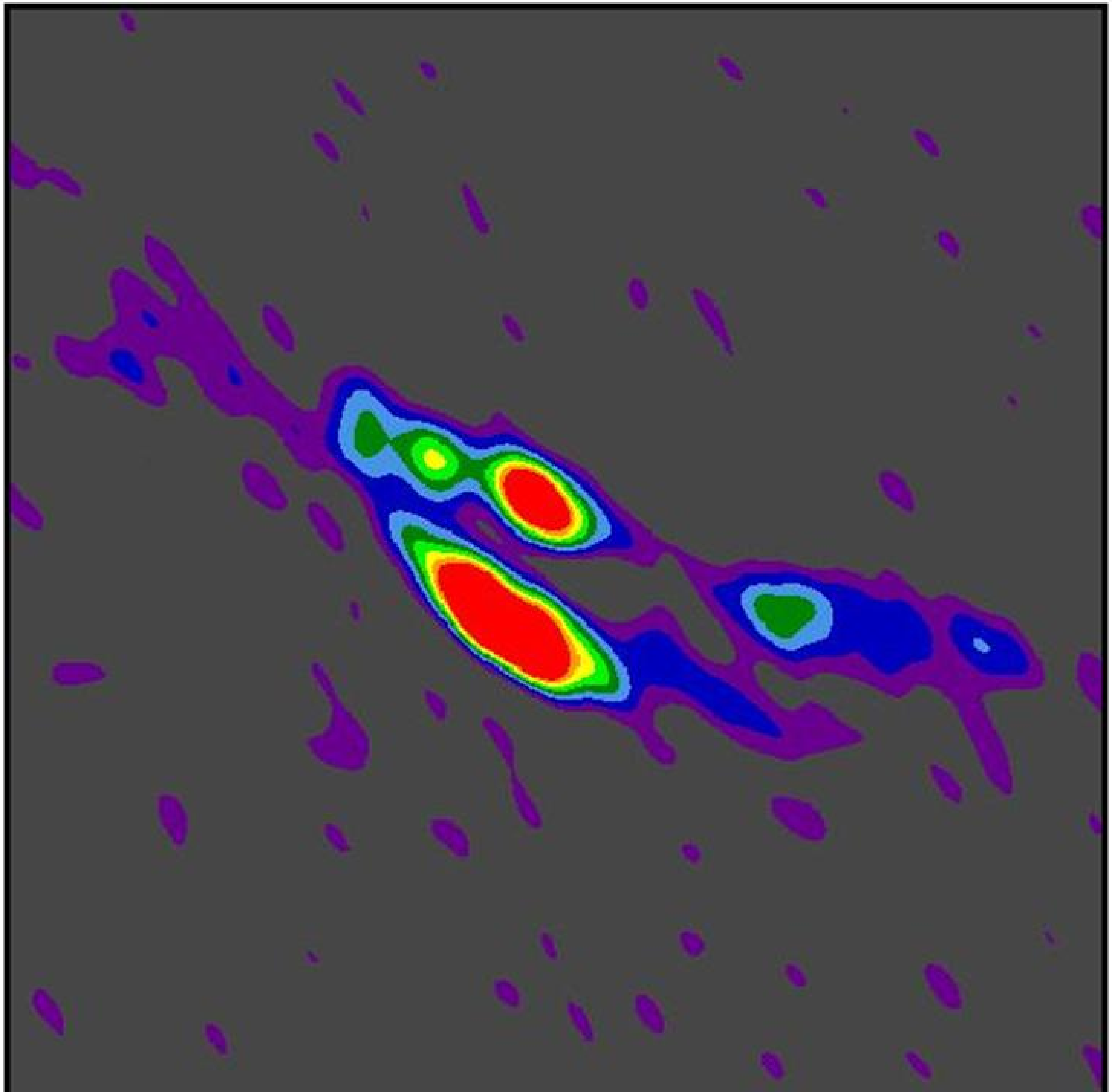
Subaru Telescope, National Astronomical Observatory of Japan

CISCO (J, K′)

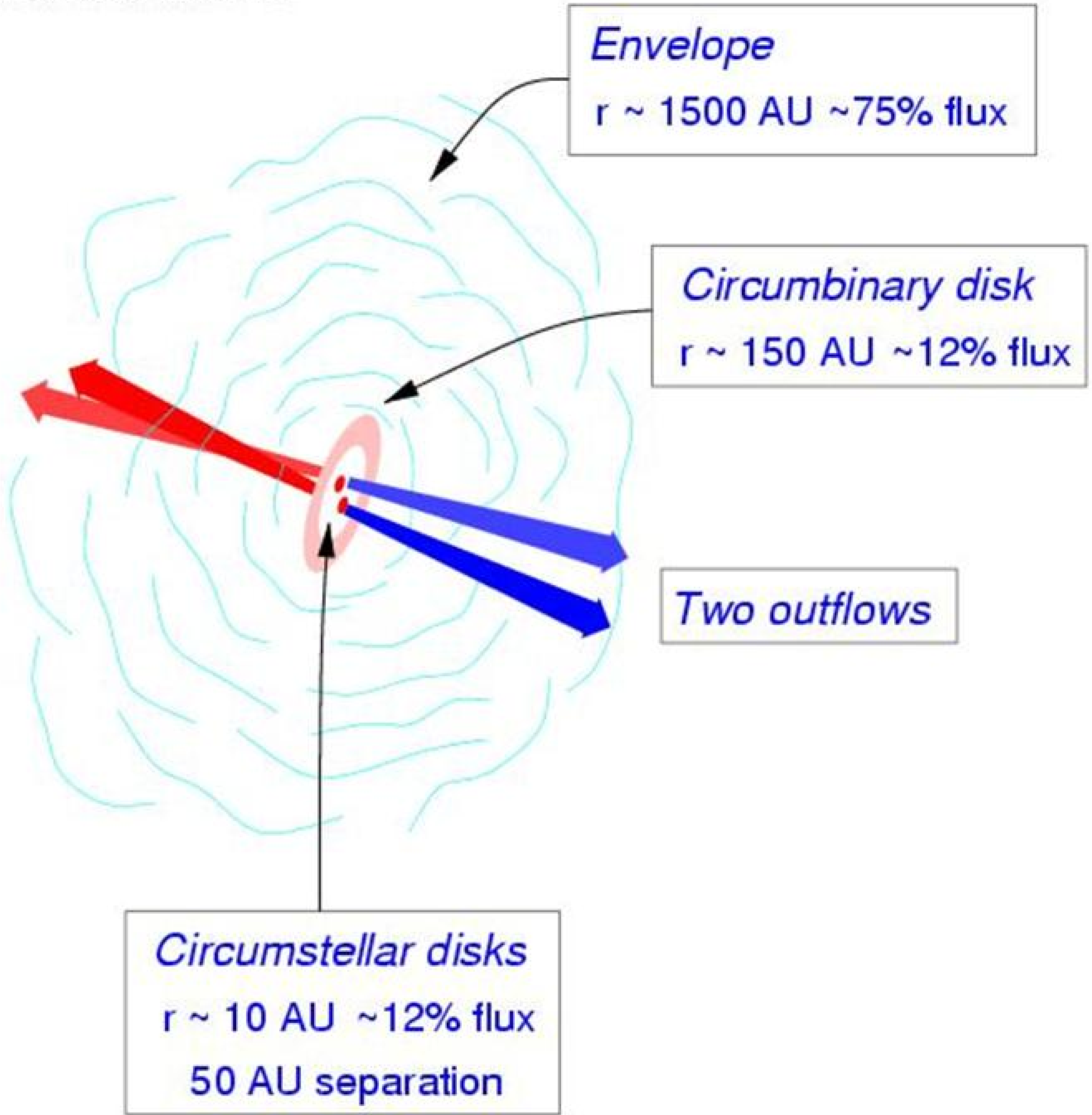
June 10, 1999


Very Large Array

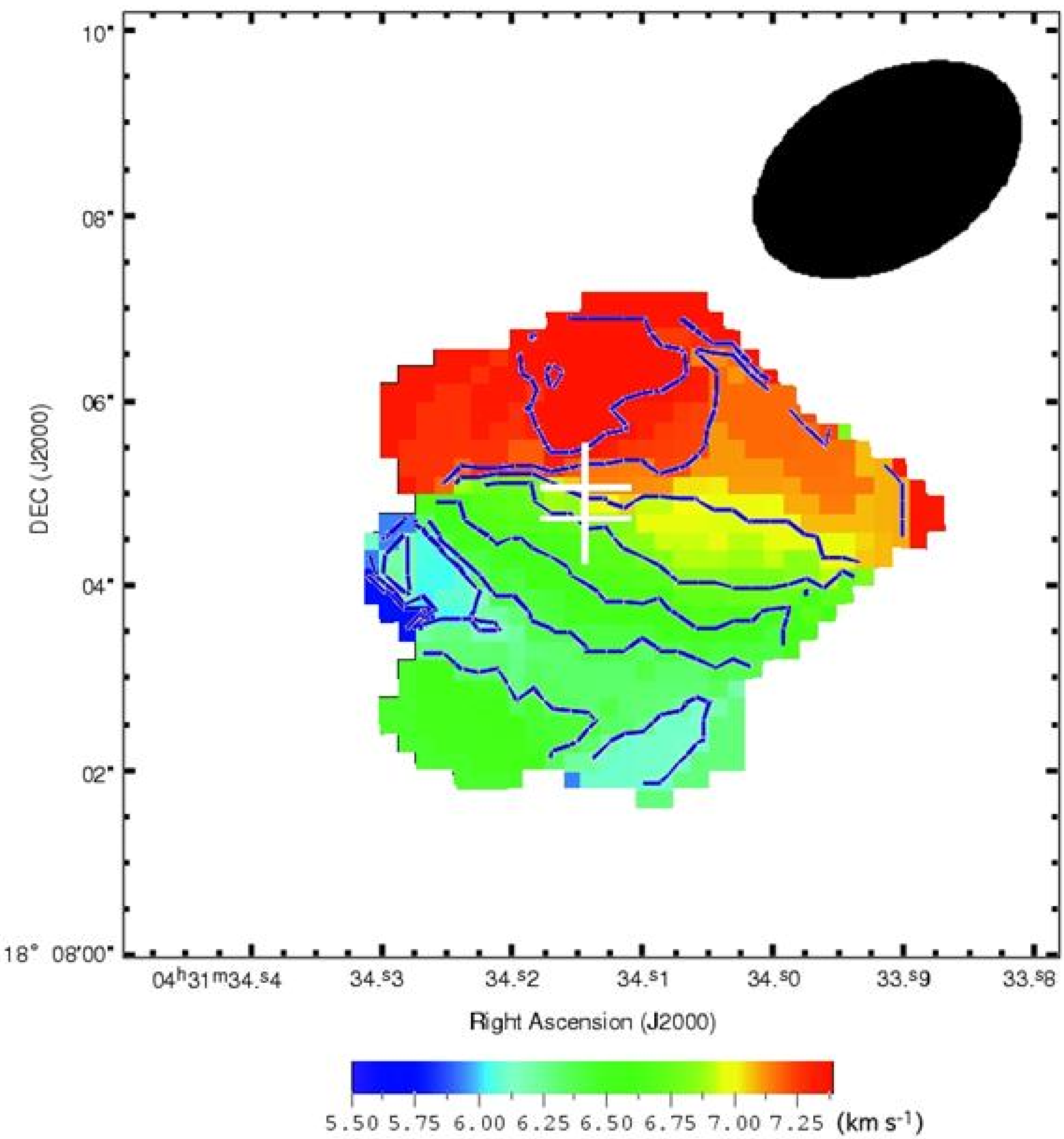

Pie Town antenna



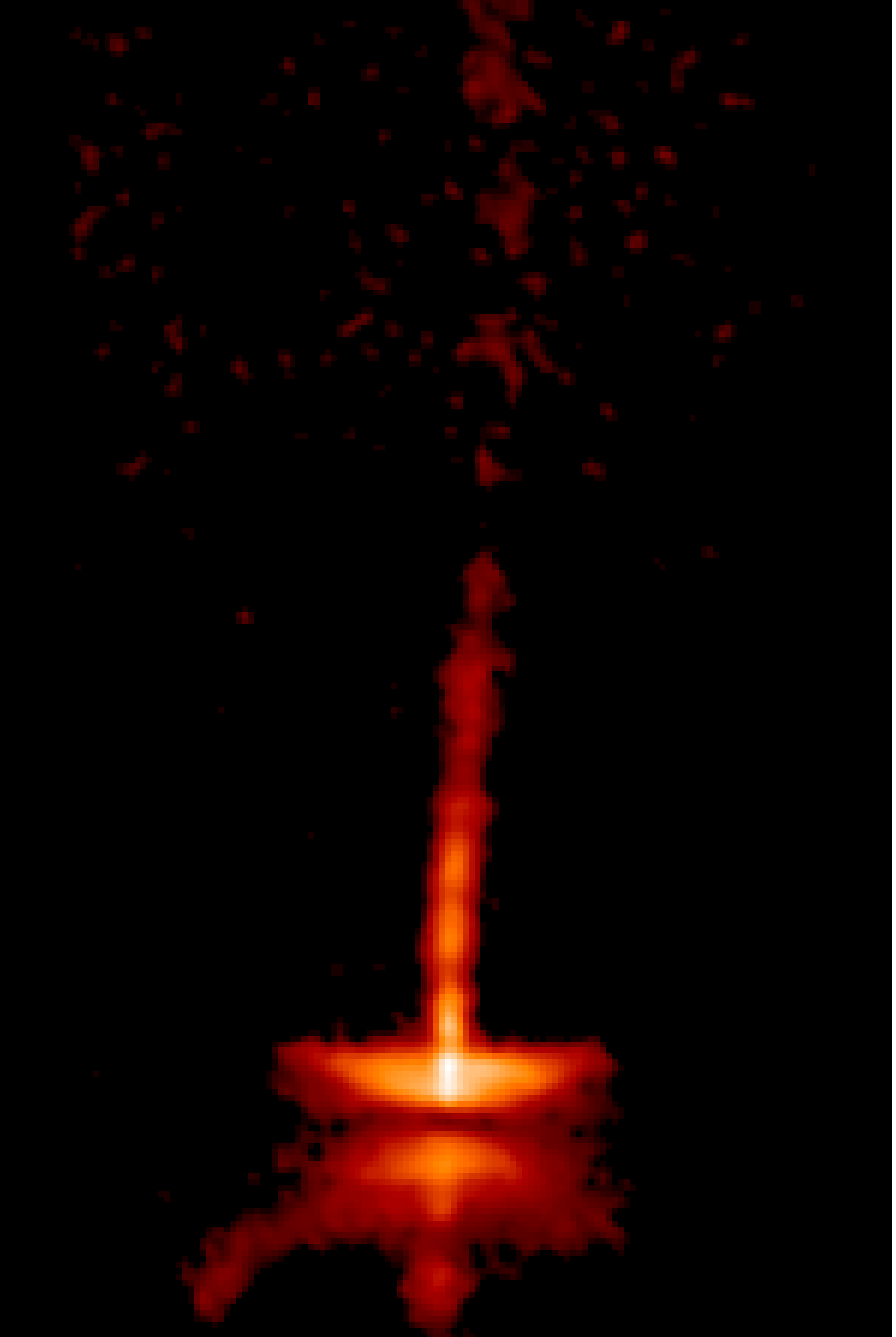
L1551 IRS 5


Envelope
r ~ 1500 AU ~75% flux
Circumbinary disk
r ~ 150 AU ~12% flux
Two outflows
Circumstellar disks
r ~ 10 AU ~12% flux
50 AU separation

SubMillimeter Array (SMA) in Mauna Kea, Hawaii



SMA observations of CS (J=7-6) line show rotating circumstellar envelope that probably feeds the disks at the center (Takakuwa et al. 2004).

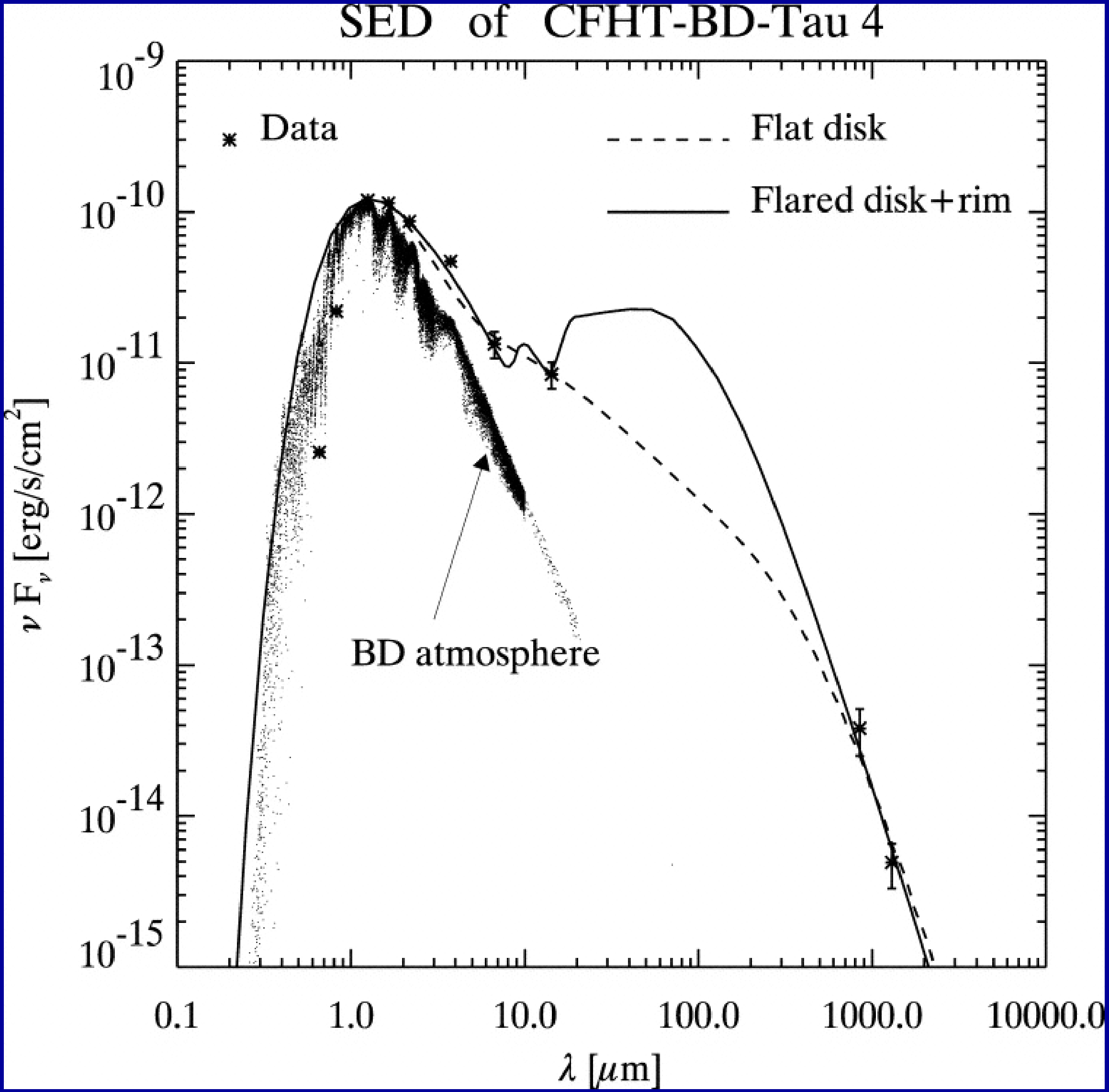


R-band HST images by Watson et al. of HH 30

Now, there is no doubt that solar mass stars form surrounded by protoplanetary disks and driving collimated outflows.

What about brown dwarfs?

- The field of brown dwarf formation is very young, but there is evidence of the existence of disks and outflows associated with them and even of the formation of planets in their disks…



Pascucci et al. (2005) argue that SED in this brown dwarf is well explained by dust emission in a disk.

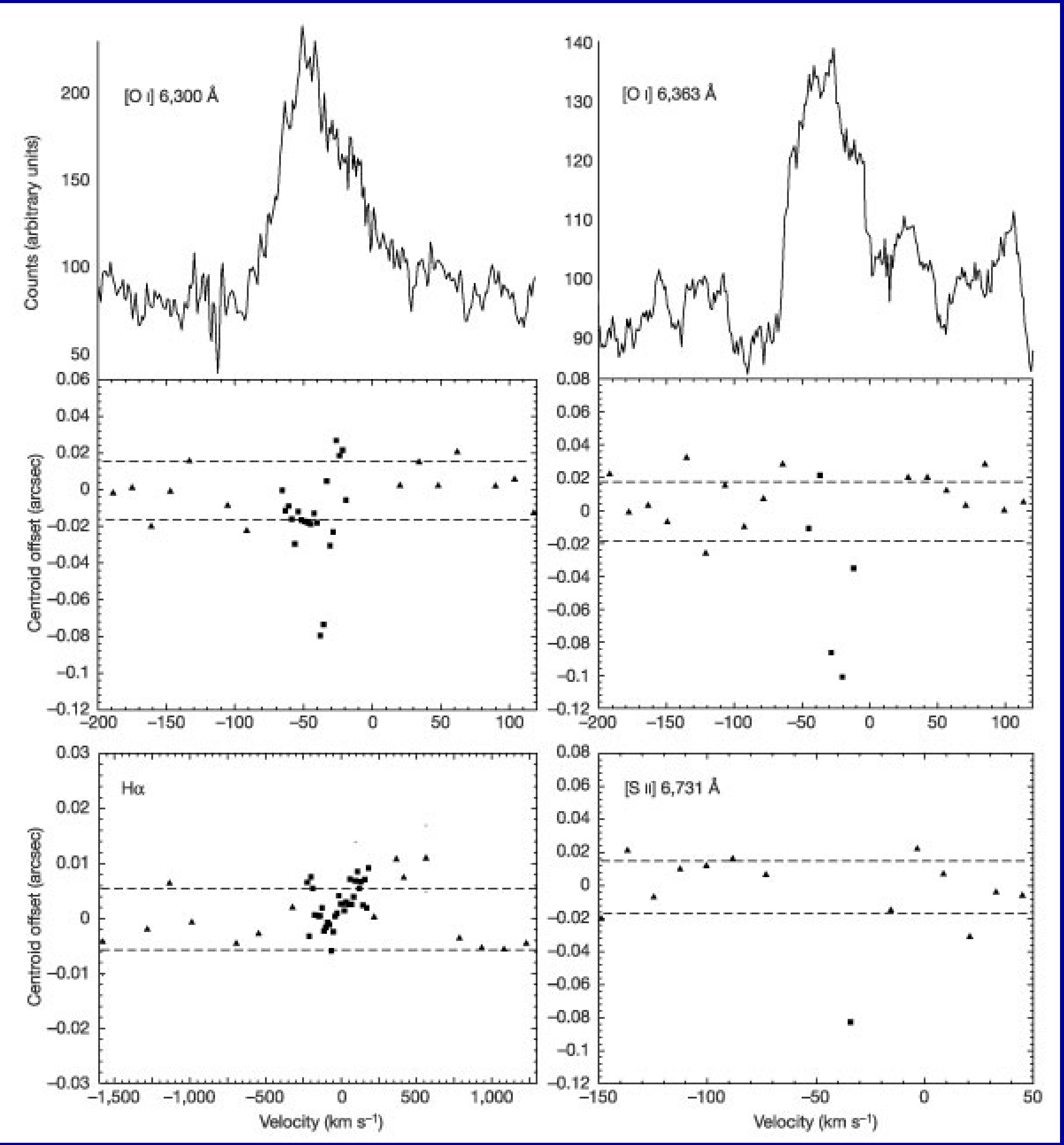
M(BD) = 70 MJ

L(BD) = 0.1 L(sun)

M(disk) about 1 MJ

Dimensions of disk are not given since no images are available.

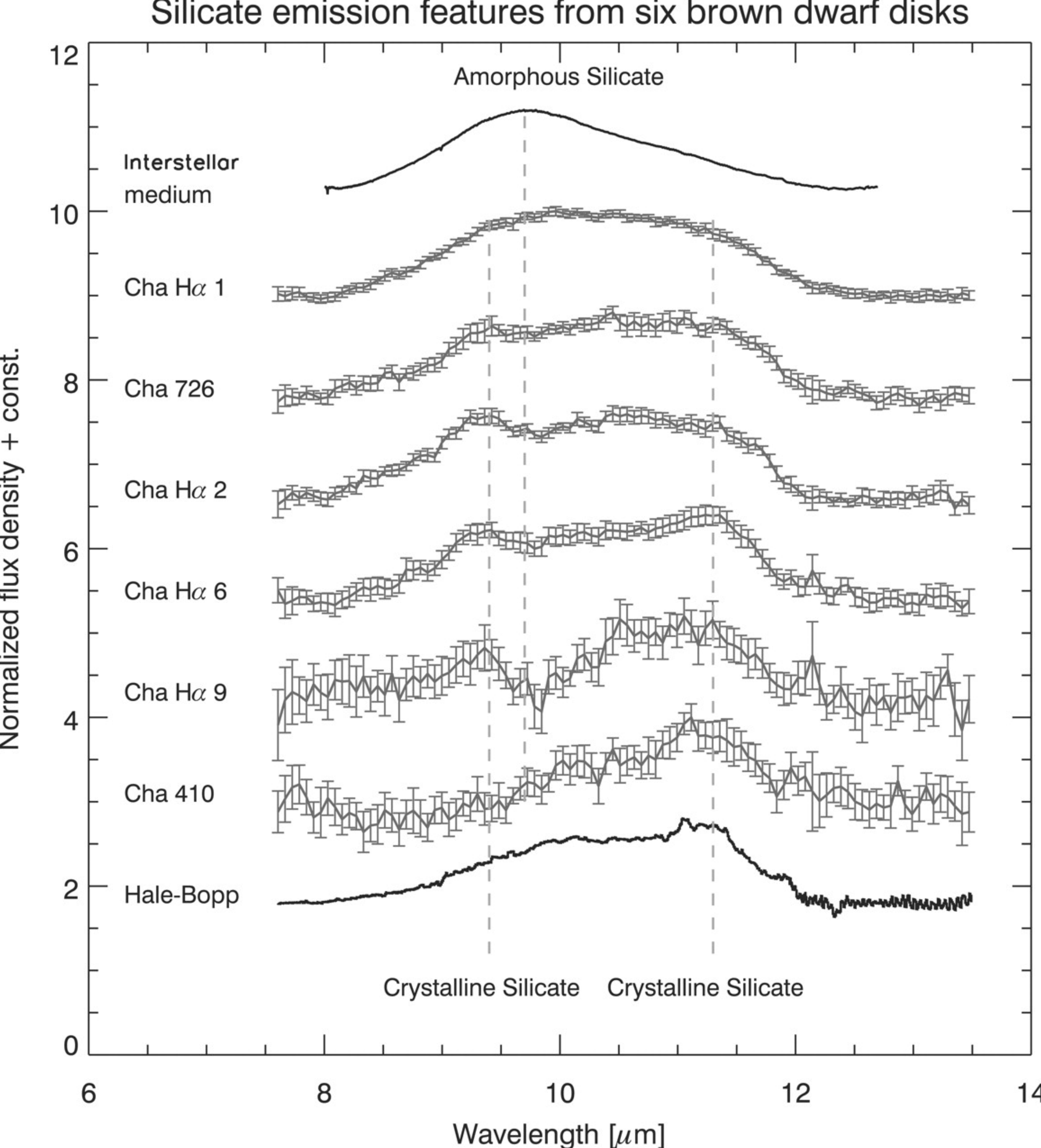
Data from ISOCAM, JCMT, and IRAM 30m



Spectro-astrometric observations of Whelan et al. (2005) show blueshifted features attributed to outflow (microjets). Lack of redshifted features attributed to obscuring disk.

Brown dwarf is Rho Oph 102 with mass of 60 MJ.

Data from Kueyen 8m VLT telescope.



Presence of crystalline silicate in these six brown dwarfs (Apai et al. 2005) is taken to imply growth and crystallization of sub-micron size grains and thus the onset of planet formation.

Data from Spitzer Space Telescope.

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

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

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

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

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 $M_* > 10 M_\odot$ 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). Jets and disks expected in standard model
- Ultracompact HII region: Accretion has ceased and detectable HII region exists (many are known)