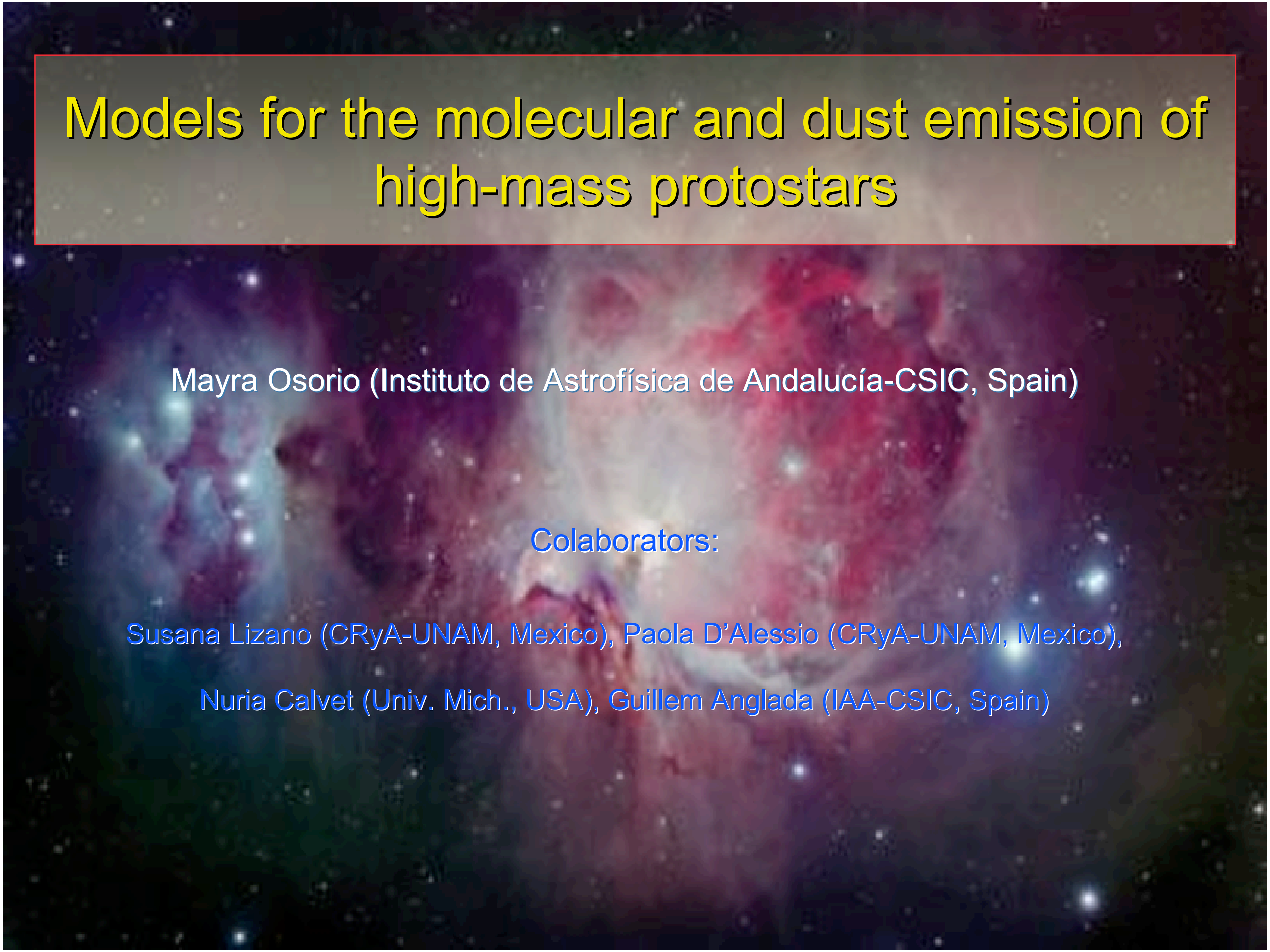

Models for the molecular and dust emission of high-mass protostars

Mayra Osorio (Instituto de Astrofísica de Andalucía-CSIC, Spain)

Colaborators:

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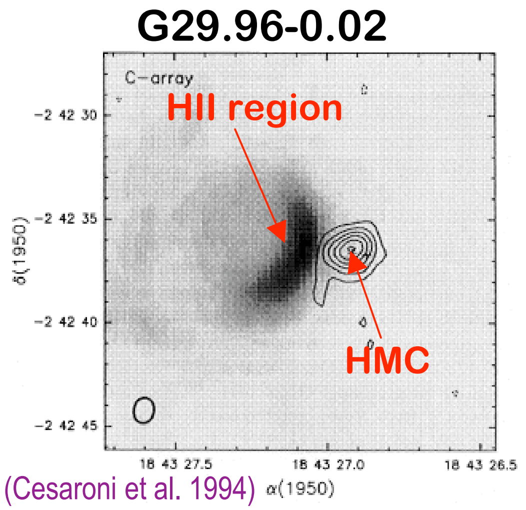
Nuria Calvet (Univ. Mich., USA), Guillem Anglada (IAA-CSIC, Spain)

Overview

I will summarize our attempts to model the spectral energy distribution (SED) of the dust, as well as the molecular line emission of Hot Molecular Cores (HMCs).

HMCs are small (5”), dense (10^6-10^8 cm^{-3}), hot (100-300 K) condensations in the vicinity of the UCHII regions, characterized by mm continuum emission, high excitation molecular lines, or water maser emission.

They are not associated with photoionized gas, since they have weak or undetectable cm emission.


G29.96-0.02

(Cesaroni et al. 1994)

In our modeling we adopted a dynamically self-consistent collapse model, which depends only of a small number of free parameters to determine the physical structure of the core. We always take into account variations of temperature, density, and velocity inside the core.

We compare our model predictions with high angular resolution data, such as data from large interferometers or mid-IR data from 8m Gemini telescopes.

I will show that taking into account variations of the physical properties along the core can be important to interpret future observations with large interferometers such as the EVLA or ALMA.

Overview

The main hypothesis of these models is that high-mass protostars are formed via accretion. We calculate for an infalling envelope onto a high-mass protostar:

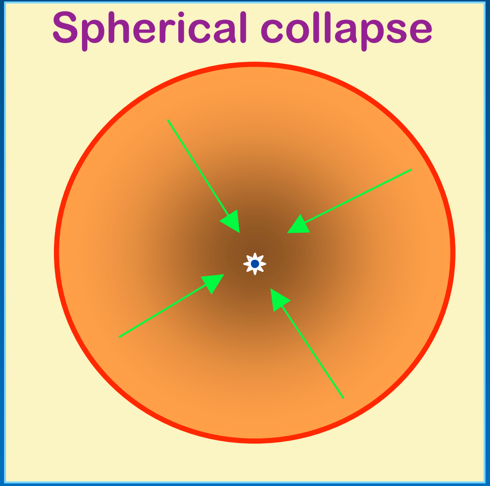
- The Spectral Energy Distribution (SED) of the dust continuum emission.
- The spectra of the molecular line emission.

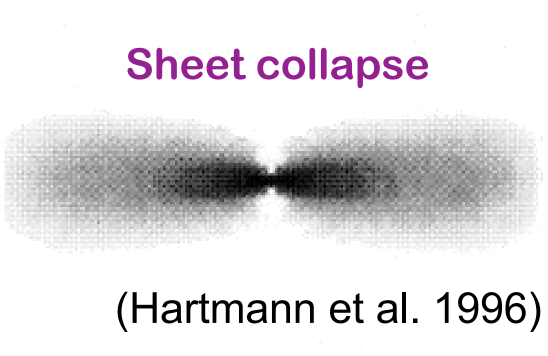
For the SED calculation we adopted two approaches:

- Spherical infalling envelopes with a radial distribution of temperature, density, and velocity resulting from the dynamical collapse of the Singular Logatropic Sphere (SLS). Only two free parameters (M_* and dM/dt) (Osorio, Lizano, D'Alessio 1999) are required.
- Flattened infalling envelopes, with flattening in the inner region due to rotation and at large scales due to the natural elongation of the maternal cloud (De Buizer, Osorio, Calvet 2006).

For the molecular line emission calculation we adopt:

- A SLS envelope with the physical properties derived from a fit to the observed SED. The molecular abundance is the only free parameter in thr line calculation (Osorio, Anglada, Lizano,D'Alessio 2007)





(Hartmann et al. 1996)

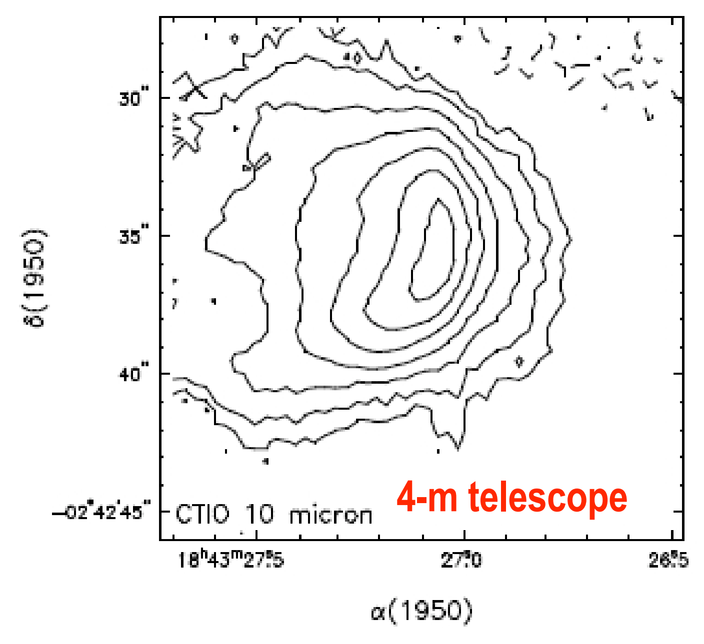
Overview

To properly model these sources high angular resolution data are required because:

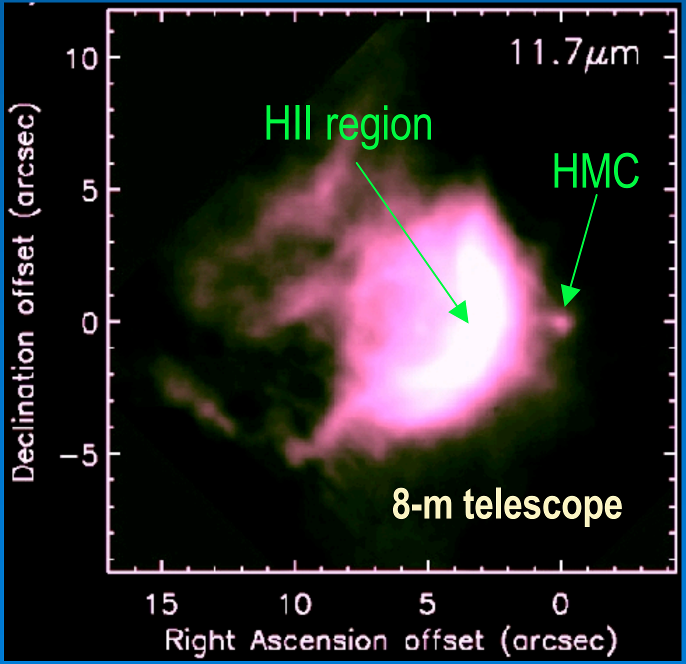
- **HMCs are distant (D>2 kpc)**
- **They are found near (2”-4”) UCHII regions.**

An example:

G29.96-0.02 HMC



(Watson et al. 2003)



(De Buizer et al. 2005)

Spectral Energy Distribution of an sphericaly symmetric infalling envelope

(Osorio, Lizano, D'Alessio 1999)

We modeled the SED of four prototypical HMCs:

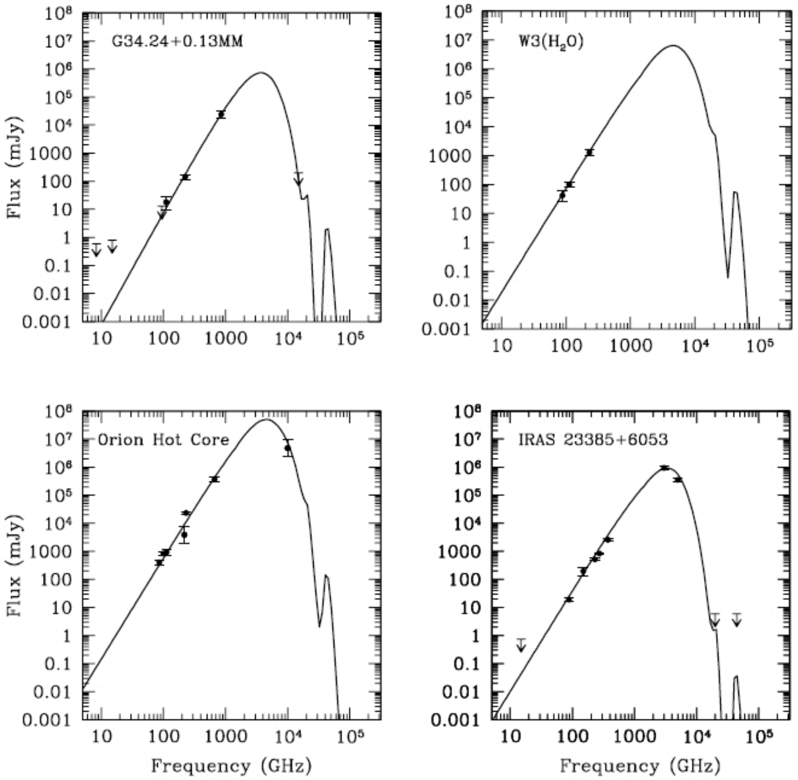
G34.24+0.13MM, W3(H2O), Orion HMC, and IRAS 23385+6053,

adopting the density structure of a SLS (McLaughlin & Pudritz 1997). The physical parameters of the star and of the envelope were obtained in this way.

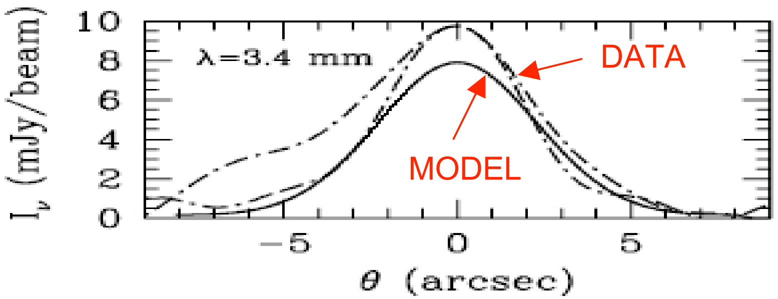
RESULTS:

- We found that the emission of a HMC was consistent with that of a massive envelope collapsing onto a young (age < 10^5 yr), early type star (B star), with a high mass accretion rate (dM/dt=10^{-4}-10^{-3} Mo/yr).
- We show that stars of up to 20 Mo can be formed via accretion (radiation pressure does not stop the collapse).

High angular resolution mm data (Molinari et al. 1998) allow to fit the intensity profile and to further constrain the models.



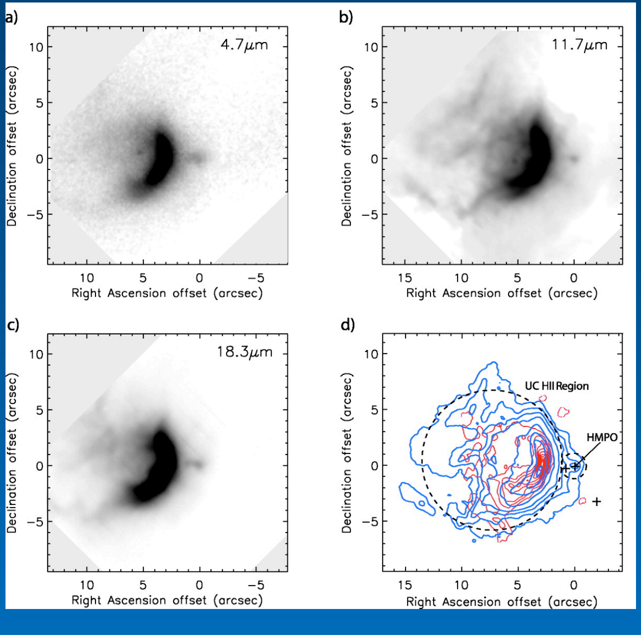
Intensity profile of IRAS23385+6053

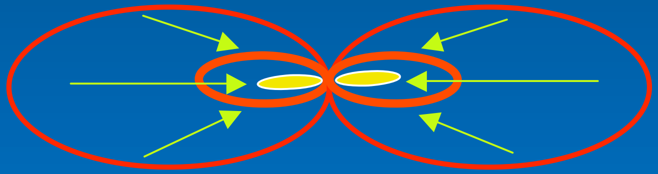


Spectral Energy Distribution of a flattened infalling envelope

(De Buizer, Osorio, Calvet 2005)

For several sources, subarcsec angular resolution near- and mid-IR data (e.g., 8m Gemini telescope) are available. Since this wavelength range is very sensitive to the geometry of the core, we included in our models rotation and flattening (Hartmann et al. 1996). The inner part of these envelopes is similar to the solution of Terebey et al (1984), it but has been modified to have a more realistic representation of the shape of star-forming cores.



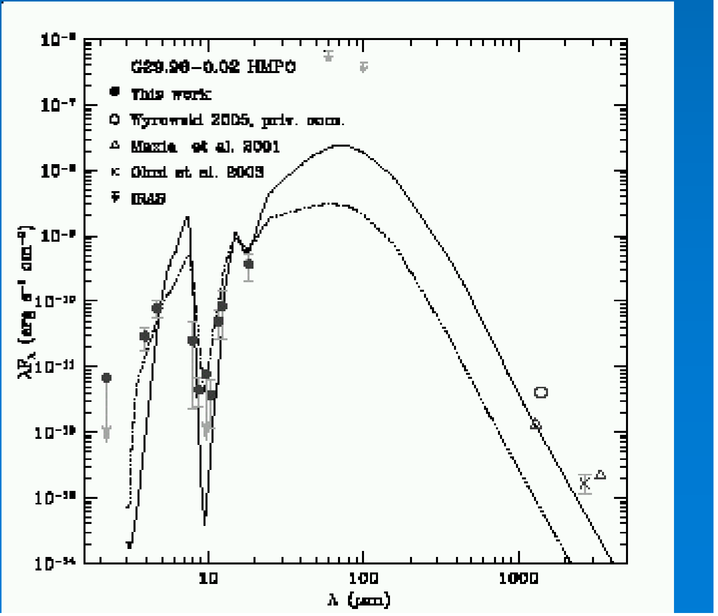


Problem: data are scarce and more than one fit is possible.

RESULTS FOR G29.96-0.02 HMC:

- B1 star (10 $M_{\odot}$), dM/dt ~10^{-2} $M_{\odot}$/yr, Rc ~600 AU, i=10 °

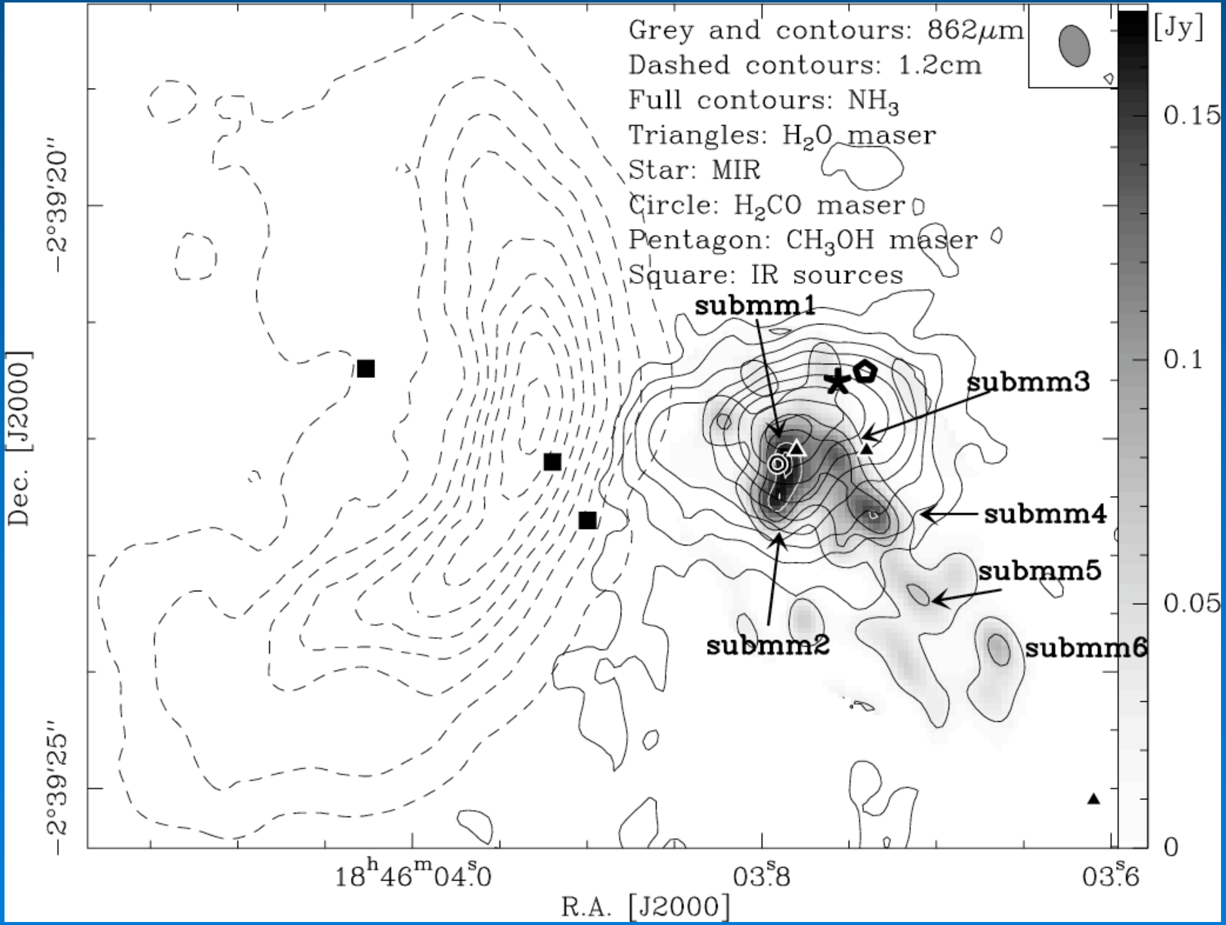
Note that the centrifugal radius is several hundreds of AU. This is the scale where the formation of disks is expected to occur. It is in good agreement with the observed size of one of the best studied examples of a disk in a B protostar (Ceph A HW2, Patel et al. 2005, Torrelles et al. 2007).



Spectral Energy DIstribution of a flattened infalling envelope

(De Buizer, Osorio, Calvet 2005)

However, higher angular resolution data (~0.3”) from the SMA (Beuther et al. 2007) reveal that the source is more complex, and several YSOs could be present. A more complete multiwavelength dataset at subarcsecond angular resolution would be required to determine the SEDs of the individual objects in order to accurately model this source.



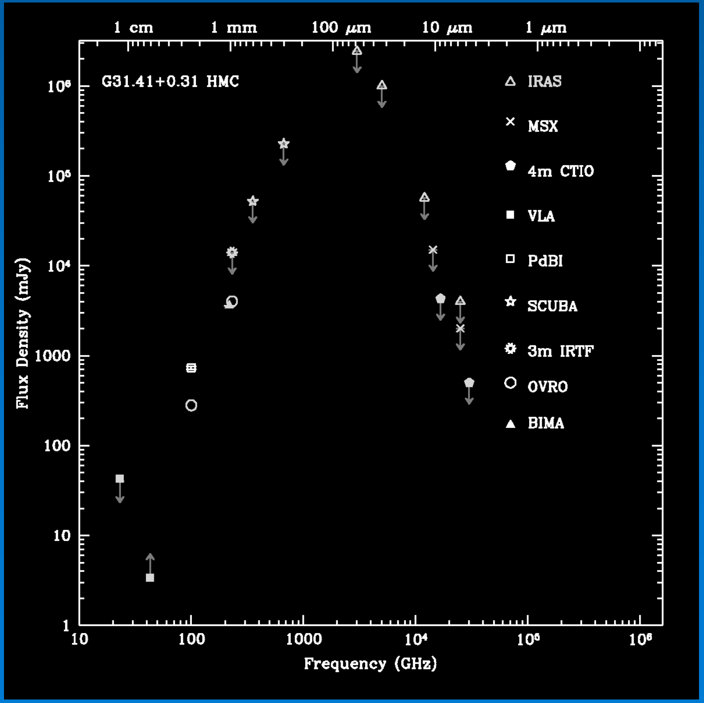
(Beuther et al. 2007)

Modelling of the molecular line emission

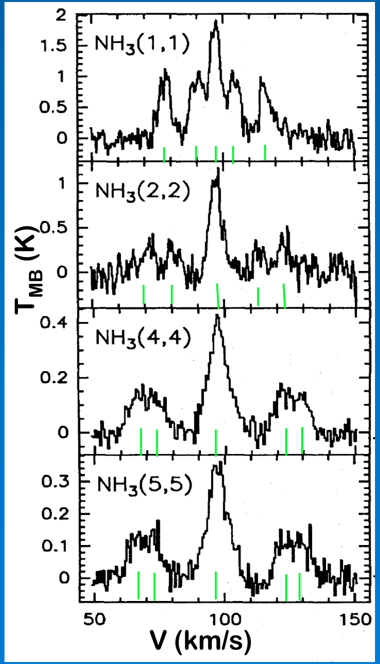
(Osorio et al. 2007)

- An additional diagnostic to obtain more information is the molecular emission, which is sensitive to the velocity structure inside the source (Osorio et al. 2007).
- I will present a model for G31.41+0.31 HMC to reproduce simultaneously the dust and ammonia emission observed at high angular resolution. The observed SED is fitted with a SLS envelope, whose physical properties are used to calculate the ammonia line emission with the ammonia abundance as the only free parameter.

Observed SED

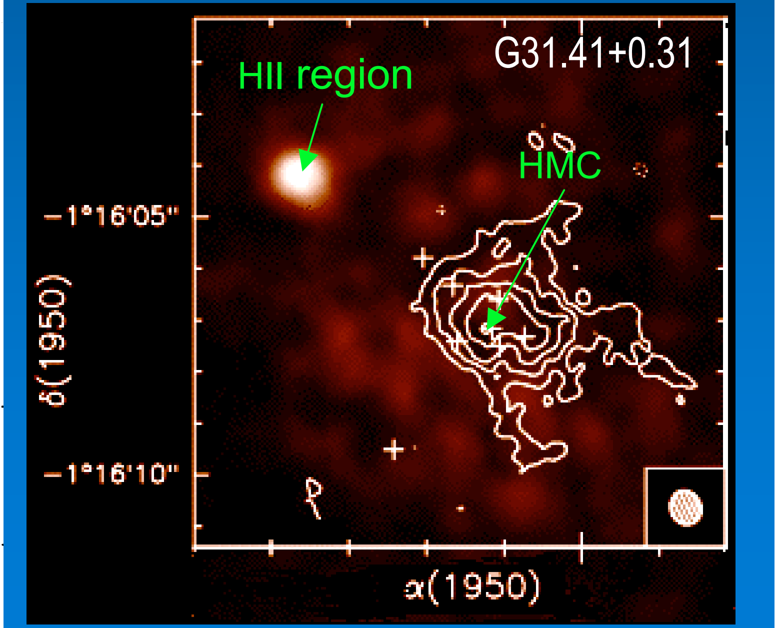


100-m spectra (beam=40")



(Cesaroni et al. 1992)

VLA $NH_3(4,4)$ image (beam=0.6")

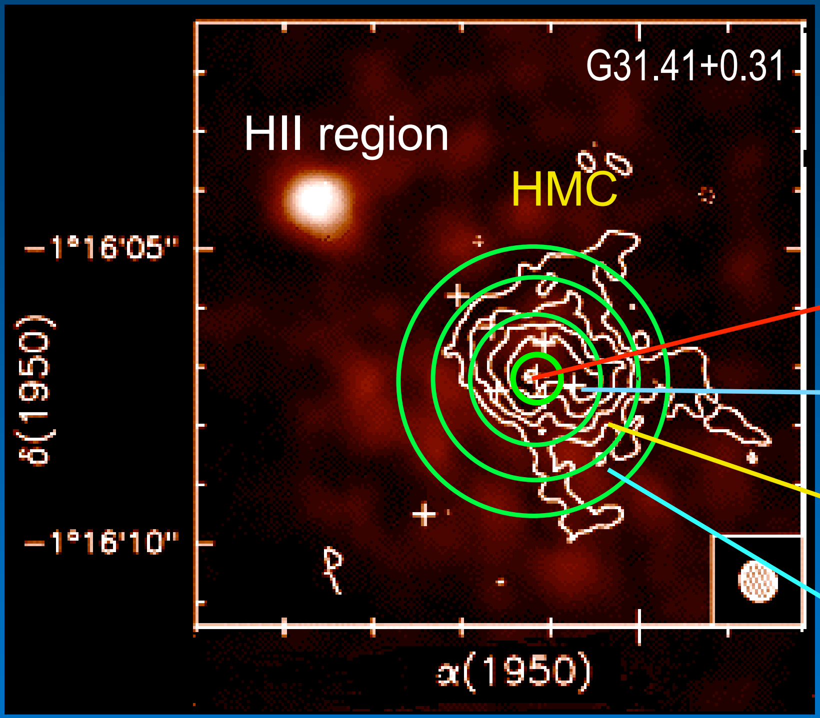


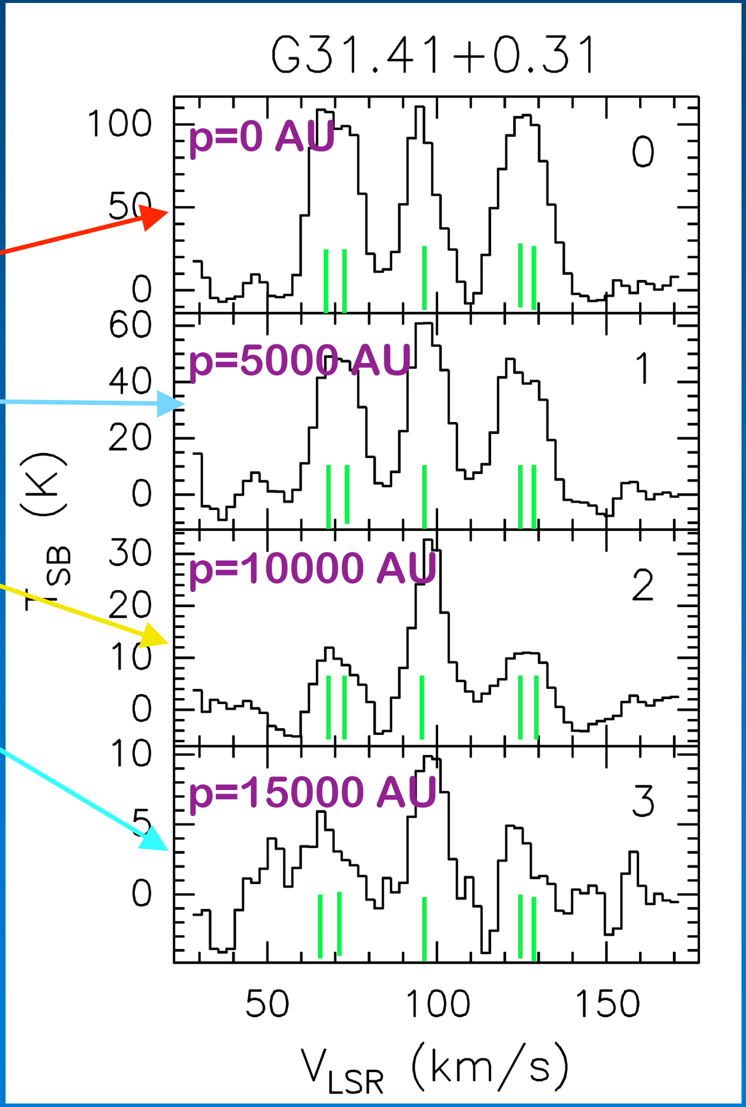
(Cesaroni et al. 1998)

VLA NH_3 (4,4) observations of G31.41+0.31 (Cesaroni et al. 1998)

VLA angular resolution is 0.”6
=> The core is spatially resolved

Spectra obtained by averaging the ammonia emission over circular annuli around the center





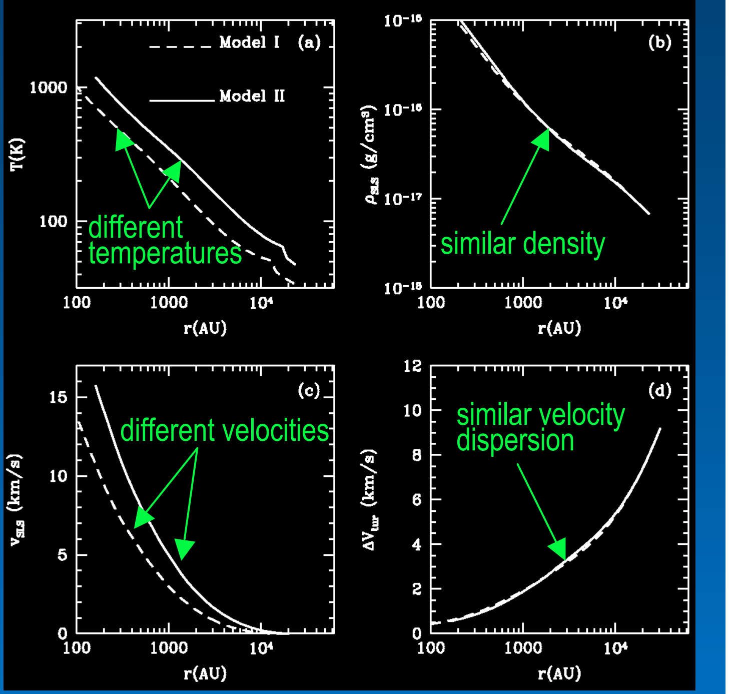
- High brightness temperatures suggest high kinetic temperatures
- The high ratio between satellites and main line suggests a high opacity (since $\tau_{sat}/\tau_{main}=1/60$)
- Lines are broad: Hyperfine lines are blended, suggesting large turbulent motions

p is the projected distance to the center

Modelling of the molecular emission of G31.41+0.31 HMC. Fitting the SED

Following Osorio et al. (1999), the physical structure of the HMC is obtained from the **fitting** to the **SED**. Thus, for a given **M_*** and **dM/dt**, and using the **SLS** one can determine the **density, velocity, temperature, and velocity dispersion** inside the envelope.

Given the uncertainties, for **G31.41+0.31 HMC** we found **two models** that can explain the SED.


Physical structure of G31.41+0.31

MODEL I

M_*=12 $M_\odot$

dM/dt=1.6x10^{-3} $M_\odot$/yr

L_{tot}=50,000 $L_\odot$

M_{env}=1,000 $M_\odot$

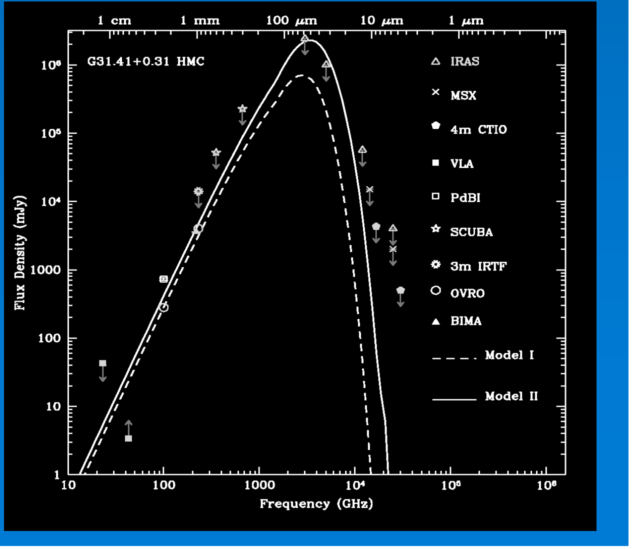
MODEL II

M_*=25 $M_\odot$

dM/dt=2.7x10^{-3} $M_\odot$ /yr

L_{tot}=280,000 $L_\odot$

M_{env}=1,500 $M_\odot$



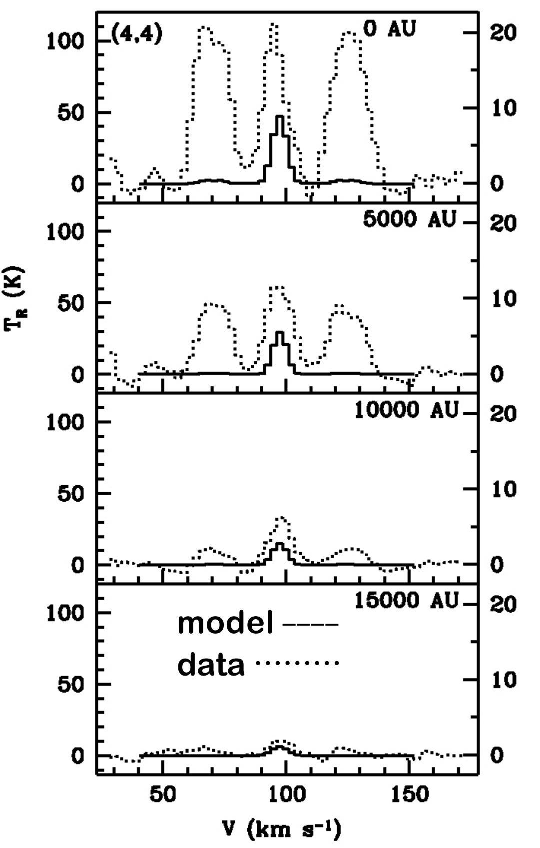
Although the models have different T and V distributions both can explain the SED.

BUT, CAN THEY EXPLAIN THE MOLECULAR EMISSION?

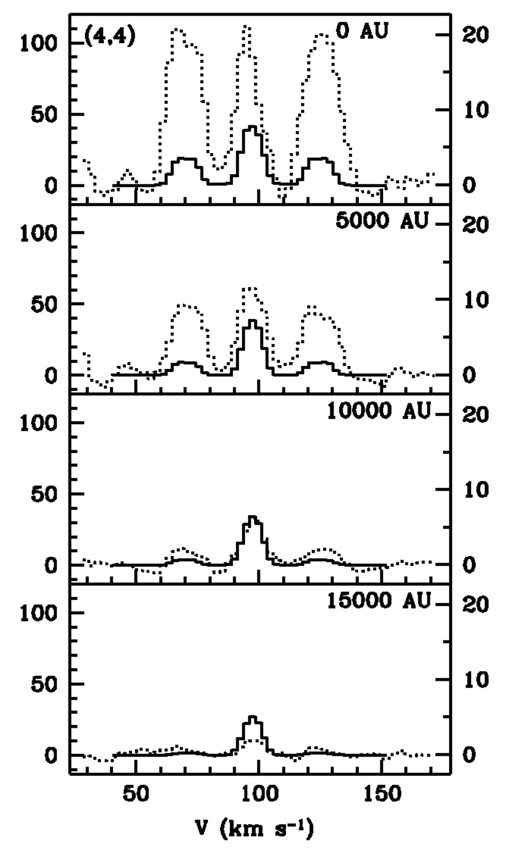
MODEL I
$M_*=12\ M_\odot$
$dM/dt=1.6\times10^{-3}\ M_\odot/yr$
$L_{tot}=50{,}000\ L_\odot$
$M_{env}=1{,}000\ M_\odot$

+ Constant gas-phase NH_3 abundance along the envelope

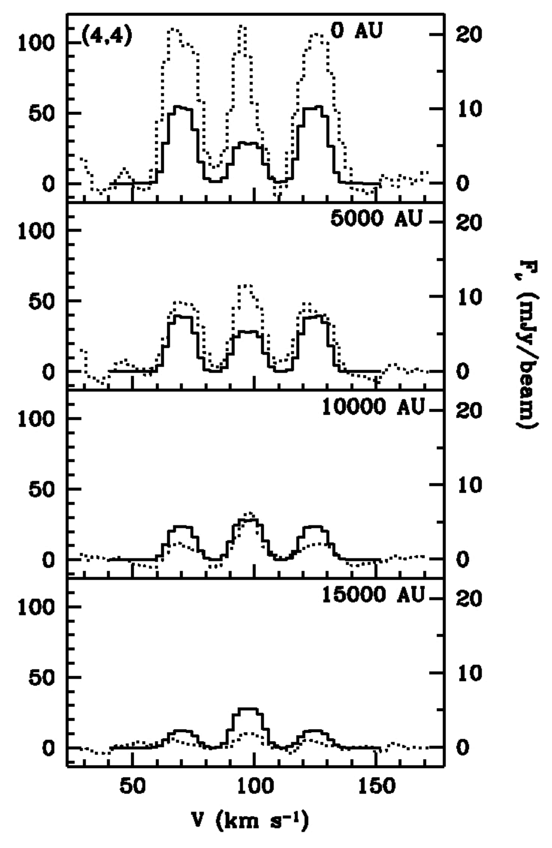
Model I is far from reproducing the observations with a constant ammonia abundance



$[NH_3/H_2]=5\times10^{-8}$



$[NH_3/H_2]=5\times10^{-7}$

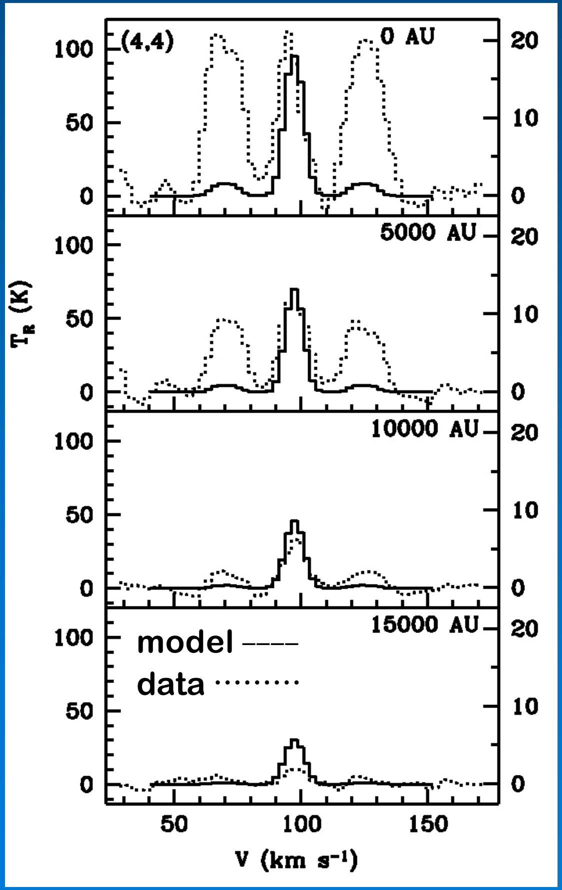


$[NH_3/H_2]=5\times10^{-6}$

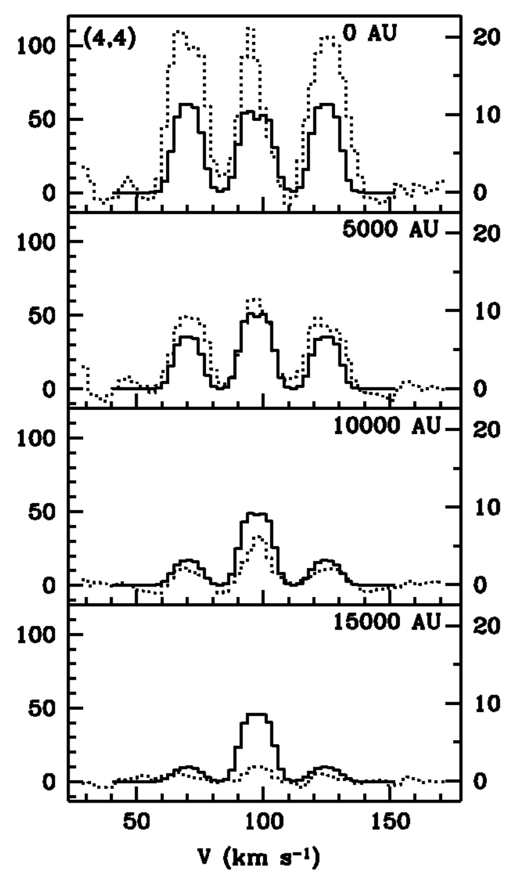
MODEL II
$M_* = 25\ M_\odot$
$dM/dt = 2.7\times10^{-3}\ M_\odot/yr$
$L_{tot} = 280{,}000\ L_\odot$
$M_{env} = 1{,}500\ M_\odot$

\+ Constant gas-phase abundance along the core

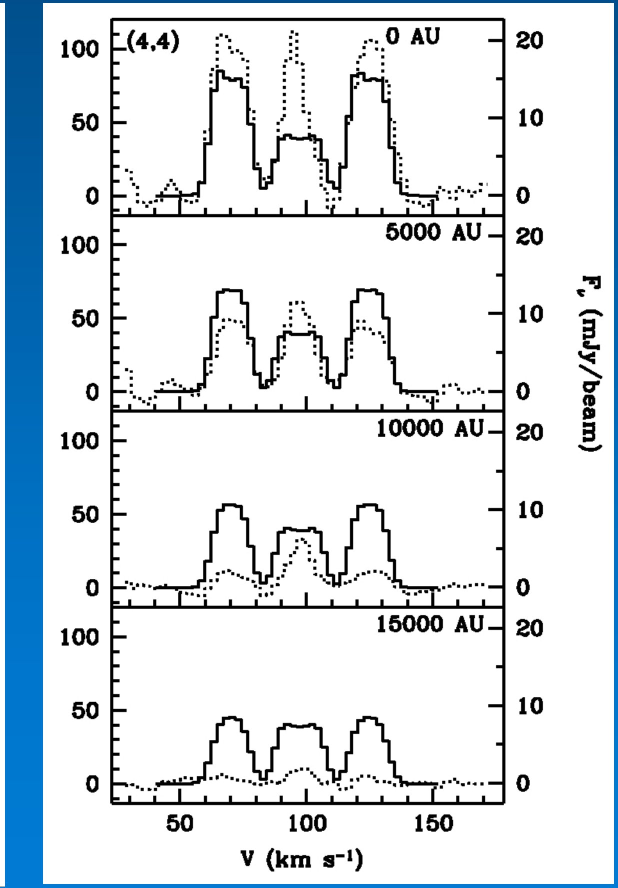
Model II is more promising than model I since the main line is well reproduced with a low abundance and the satellite lines are reproduced with a high abundance.



$[NH_3/H_2] = 5\times10^{-8}$



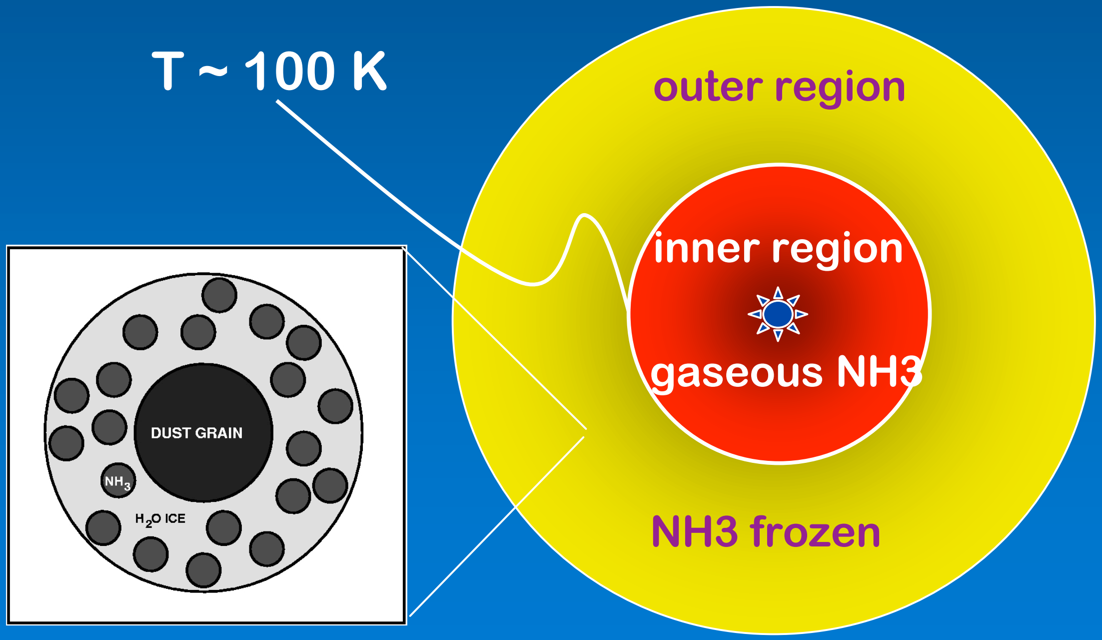
$[NH_3/H_2] = 5\times10^{-7}$

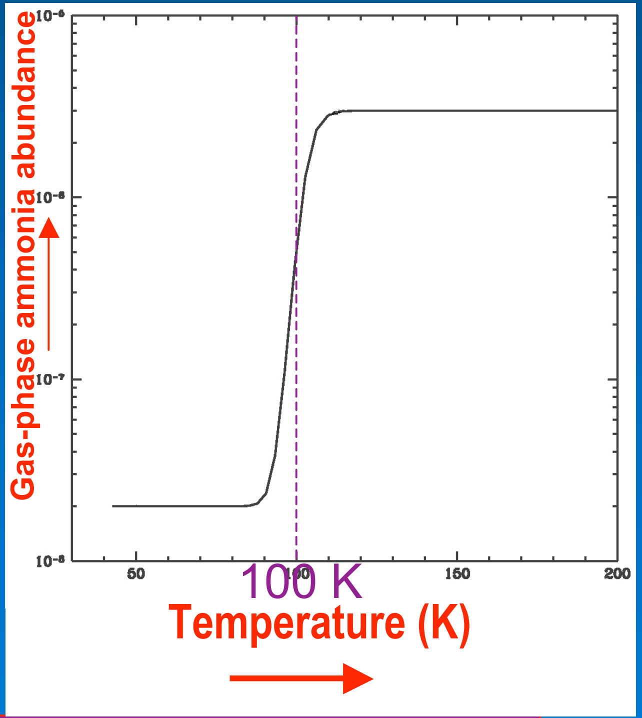


$[NH_3/H_2] = 5\times10^{-6}$

Variable gas-phase abundance:
Sublimation of ammonia molecules trapped on water ice mantles

A more realistic scenario is to assume that most of the ammonia molecules are frozen in water ice mantles of dust grains in the outer and colder regions of the core. Ammonia molecules are released to the gas phase at the water sublimation temperature (~100 K). This transition temperature is calculated assuming thermal balance between sublimation and condensation (Sandford & Allamandola 1992) for the physical conditions of the core.



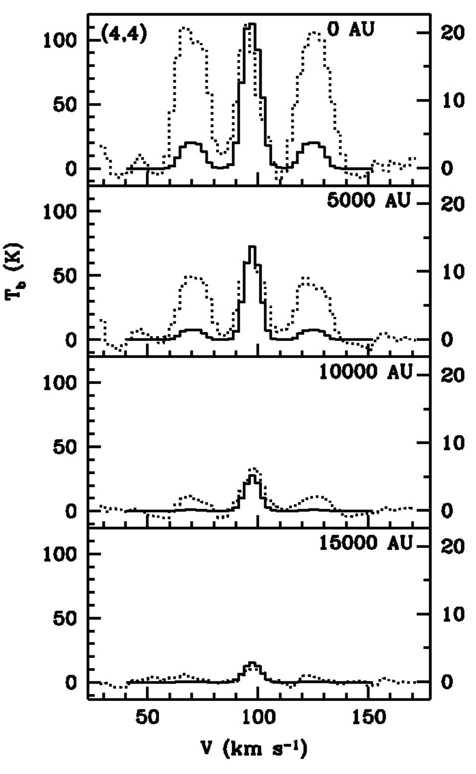


Outer regions (T<Tsub) ⟶ ammonia frozen ⟶ low abundance

Inner regions (T>Tsub) ⟶ ammonia sublimated ⟶ high abundance

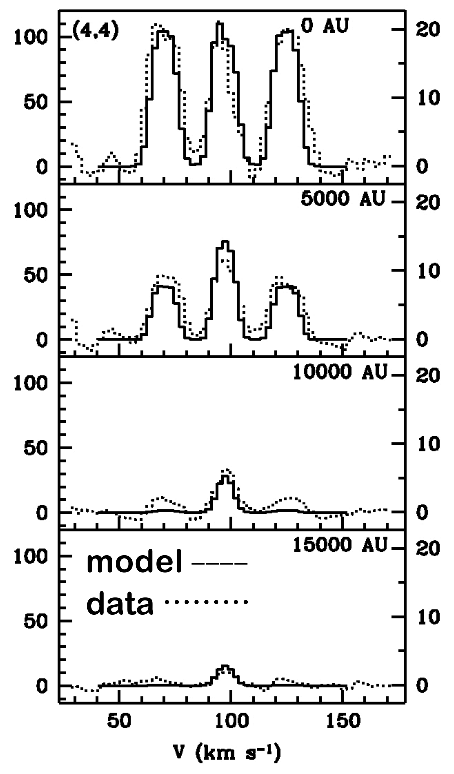
Model II using variable gas-phase abundace inside the envelope

Simplest hypothesis: A constant total (solid+gas) ammonia abundance is assumed, but the gas-phase ammonia abundance increases in the inner regions of the envelope as a result of sublimation.



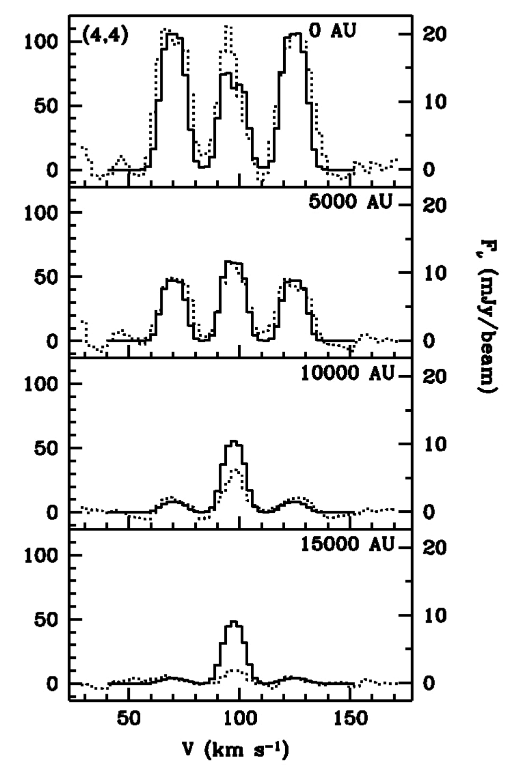
$[NH_3/H_2]_{min}=2x10^{-8}$

$[NH_3/H_2]_{max}=3x10^{-7}$



$[NH_3/H_2]_{min}=2x10^{-8}$

$[NH_3/H_2]_{max}=3x10^{-6}$

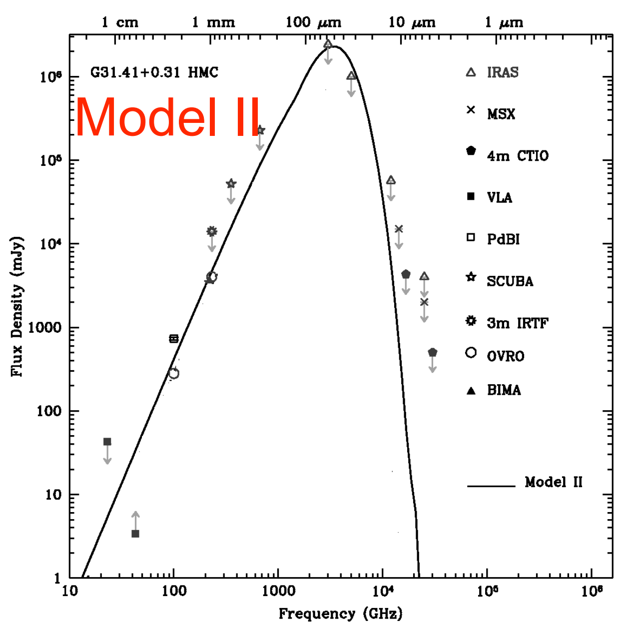


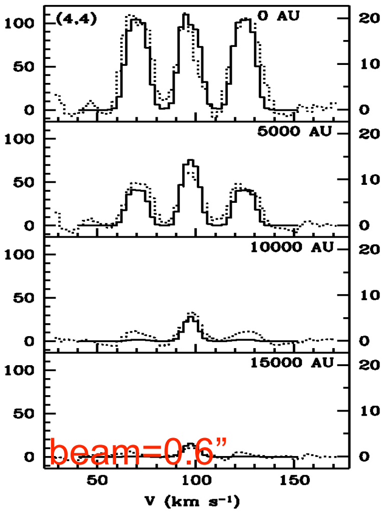
$[NH_3/H_2]_{min}=2x10^{-7}$

$[NH_3/H_2]_{max}=3x10^{-6}$

Other ammonia transitions

The same set of parameters used to fit the SED and the VLA NH_3(4,4) data also reproduces other ammonia transitions:

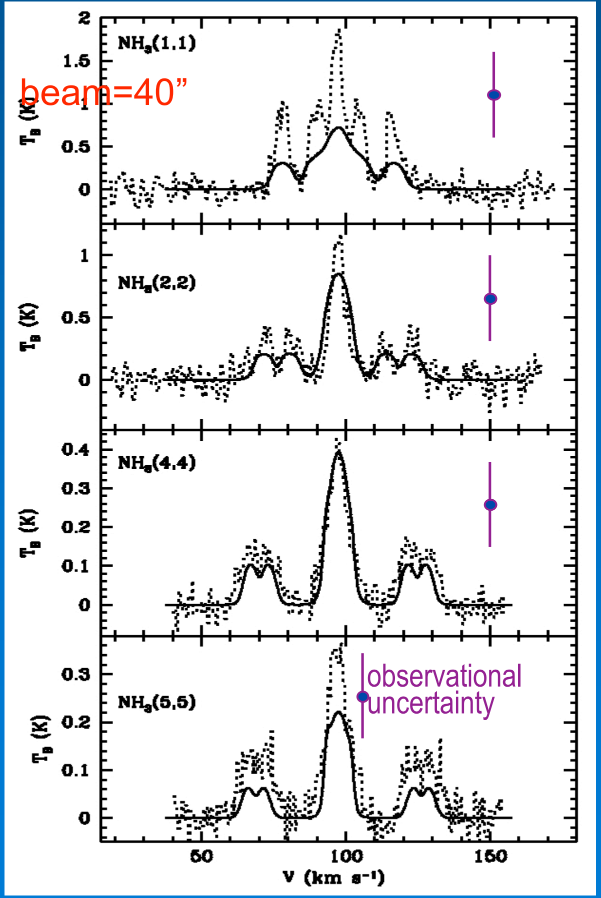




$[NH_3/H_2]_{min}$=2x10^{-8}

$[NH_3/H_2]_{max}$=3x10^{-6}

100-m telescope spectra (Cesaroni et al.1992)



Except for the NH3(1,1) spectrum (that is likely contaminated by emission from the cold ambient cloud), the remaining spectra are well reproduced within the observational uncertainties. Unfortunately, no high angular resolution data are available for these transitions.

CONCLUSIONS

- A spherically symmetric model of the collapse of a SLS can explain the observed SED and the intensity spatial profiles of the continuum dust emission of HMCs, implying that these objects are dominated by accretion.
- In order to fit the data a young, early type central star with a high mass accretion rate is required, suggesting that HMCs are one of the earliest observable phases of massive star formation.
- Inclusion of rotation and the natural elongation of the cloud allows to fit the high angular resolution mid-IR data, providing a determination of additional physical parameters such as the inclination angle or the centrifugal radius. Values of a few hundred AUs are found for this radius, similar to those obtained in high angular resolution observations of disks around massive protostars.
- The ammonia emission and its variations across the core can be reproduced in great detail provided the variation of the gas-phase ammonia abundance due to sublimation of ammonia molecules from ice grain mantles because of the temperature gradient inside the core is taken into account.
- This kind of modeling would be required to explain the details of the observational data that are expected to come from the new generation of high angular resolution facilities (EVLA, ALMA,...).

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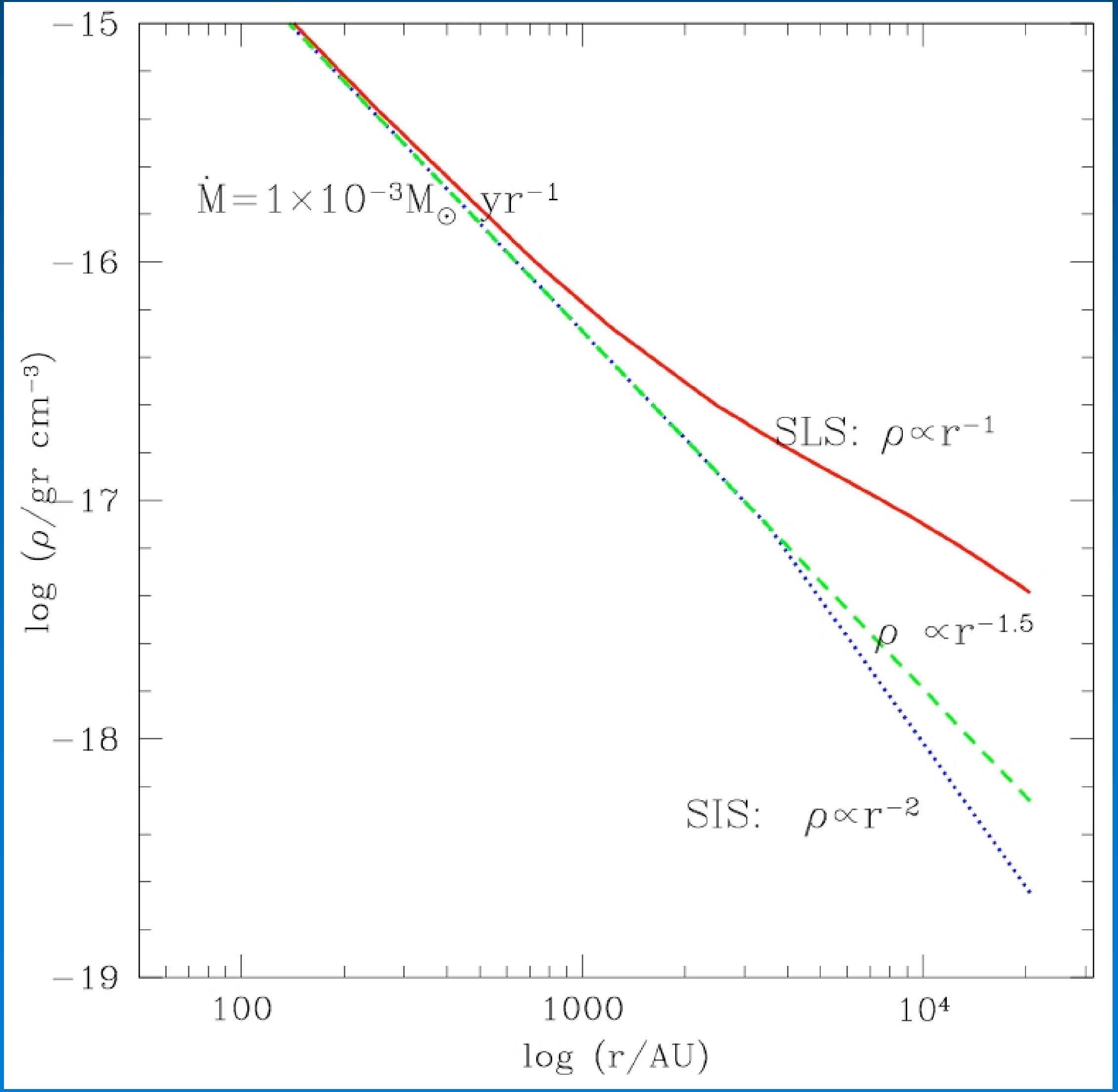
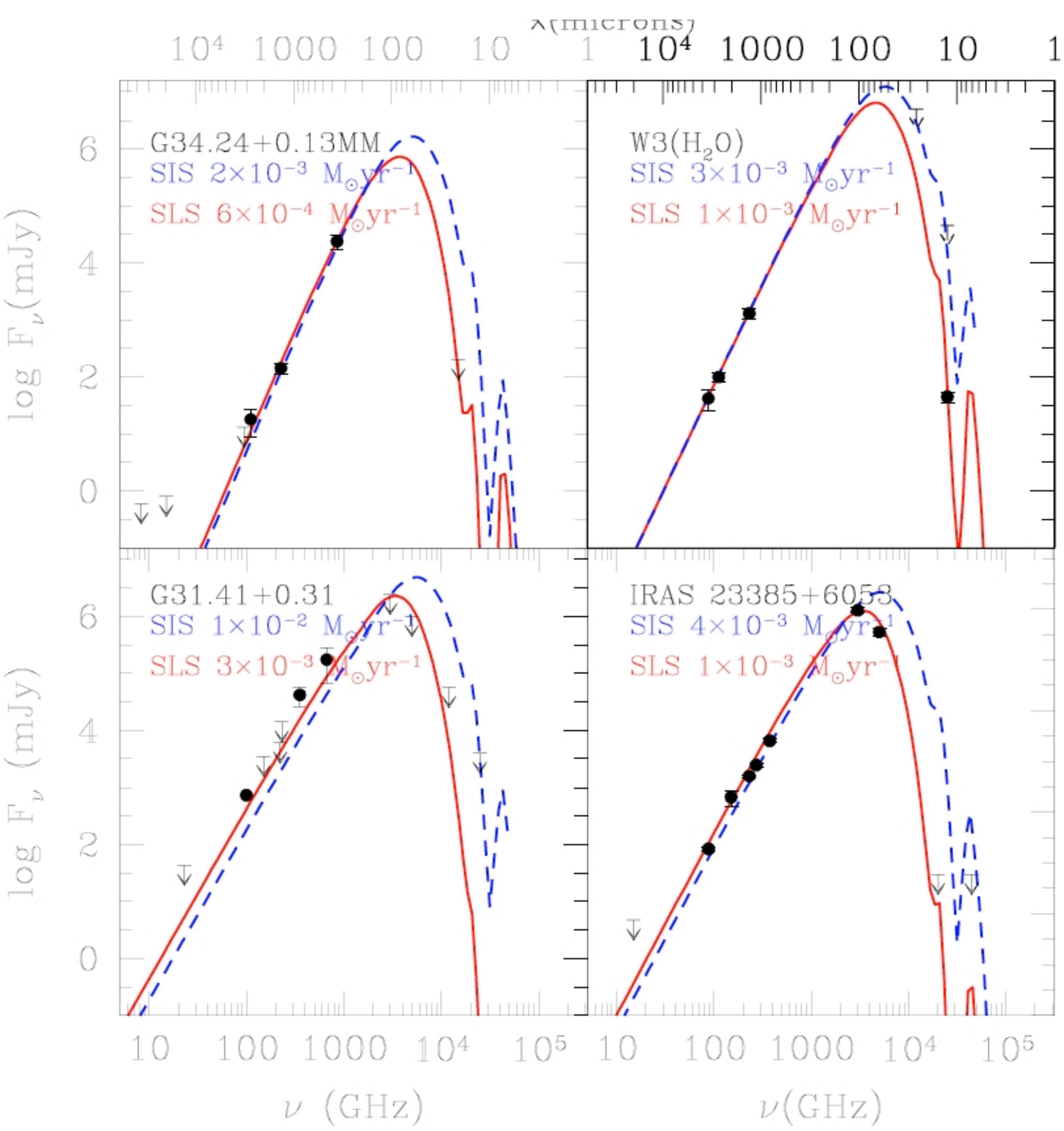
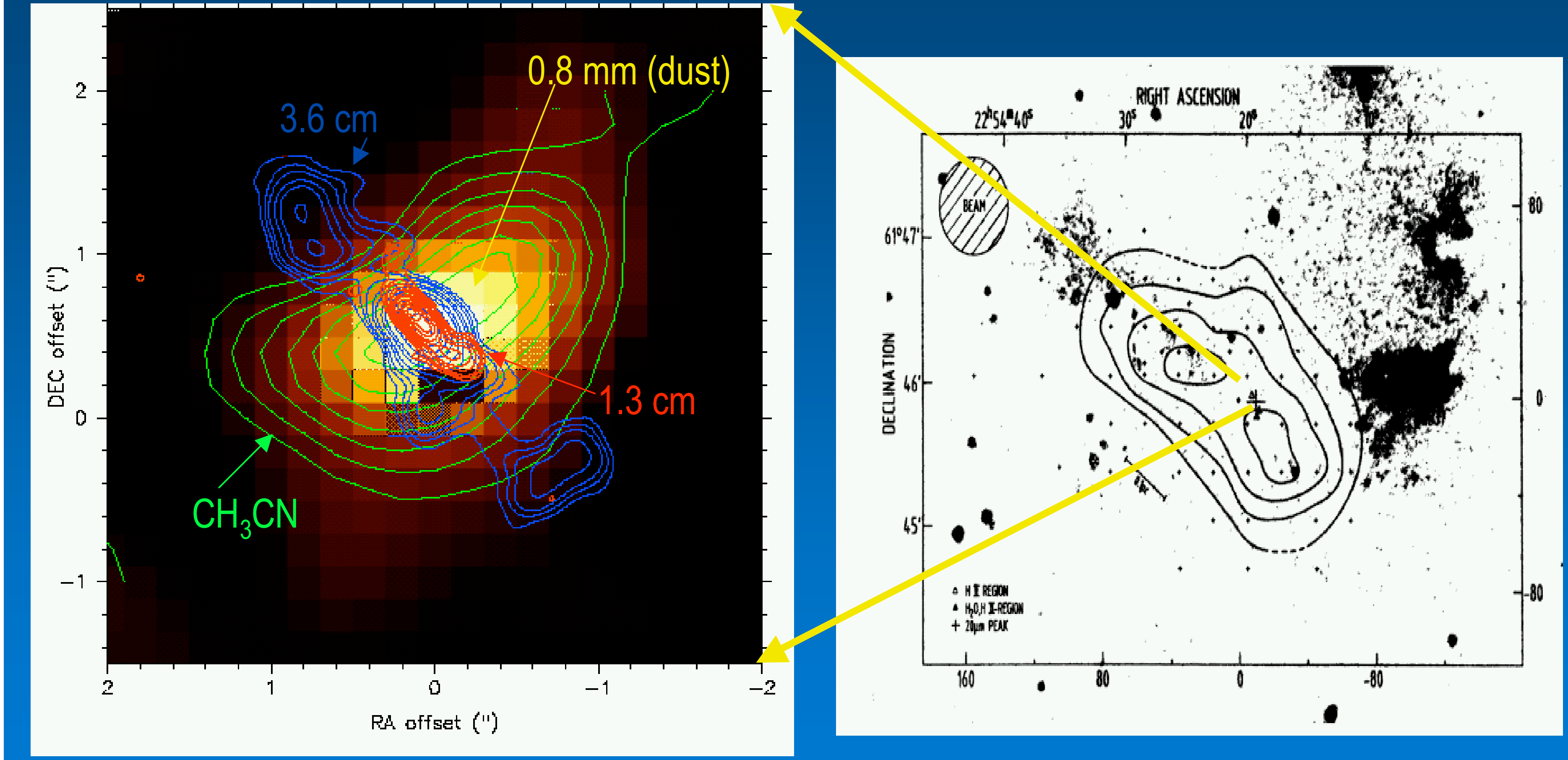
Comparison of SIS, SLS, and free-fall density distributions



Comparison of SIS and SLS SEDs



Cepheus A HW2 (D=730 pc)



SMA (< 1”) , radius=300 AU

Patel et al. 2005

Effelsberg 100m (40”) , radius=72000 AU

Gusten, Chini & Neckel 1984

Model II seems to suggest than a variable abundance can explain the intensity of the main line and satellites simultaneously.

$\tau_{main} \sim 1$

$\tau_{sat} \ll 1$ $T_B \sim T_k \, \tau$

$\tau_{main} \gg 1$

$\tau_{sat} \gg 1$ $T_B \sim T_k$

$\tau_{main} \sim 60 \, \tau_{sat}$