High Angular Resolution Observation of Ammonia Lines towards the Hot Molecular Core near G31.41+0.31

Juan Manuel Mayén Gijón

IAA-CSIC

Guillem Anglada (IAA-CSIC)

Mayra Osorio (IAA-CSIC)

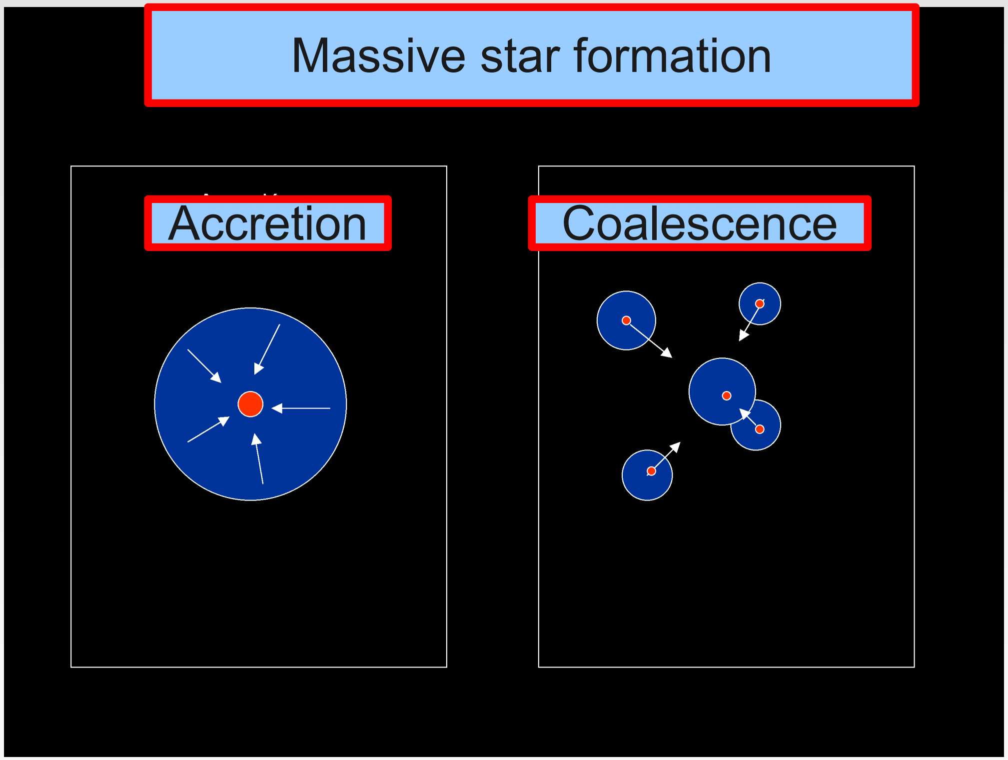
Jose Francisco Gomez (IAA-CSIC)

Luis Felipe Rodriguez (CRyA-UNAM)

Susana Lizano (CRyA-UNAM)

High-mass star formation: Problems

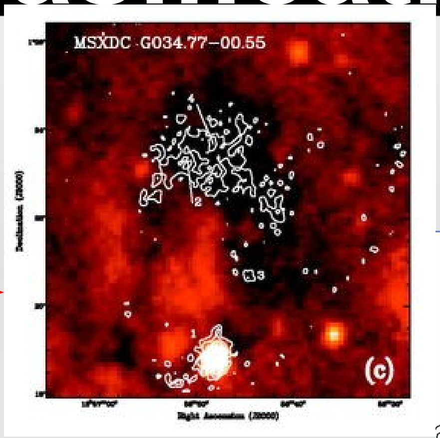
- Unlike low-mass star formation, high mass star formation is very unkown
- Problems:
  - Fewer high-mass stars
  - Farther than low-mass stars
  - High-mass stars form in groups
  - Faster evolution
- Scenarios:
  - Coalescense:crashing and merging low mass stars
  - Accretion
    - Monolithic accretion: similar to low mass stars
    - Competitive accretion



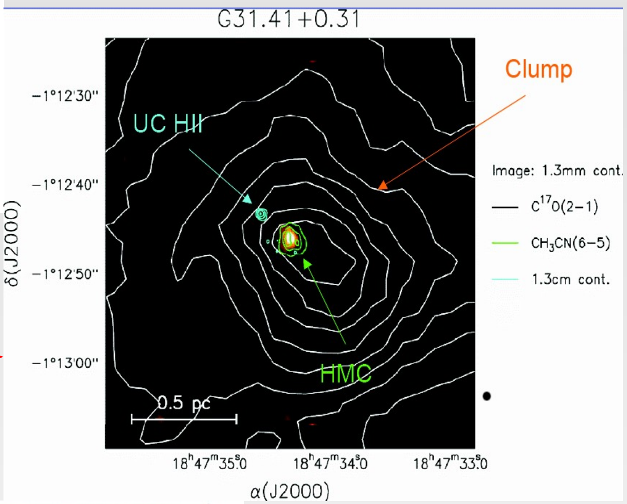
High-mass star formation: Observational clasification

Proposed observational sequence:

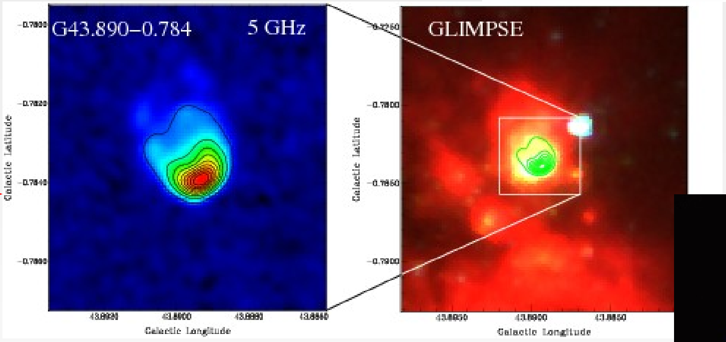
1) Infra-Red Dark Clouds (IRDC)



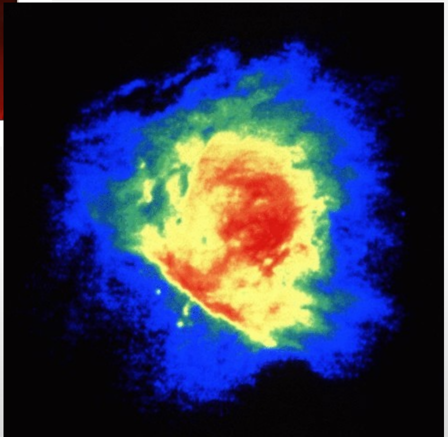
2) Hot Molecular Cores (HMC)



3) Hypercompact and ultracompact HII regions



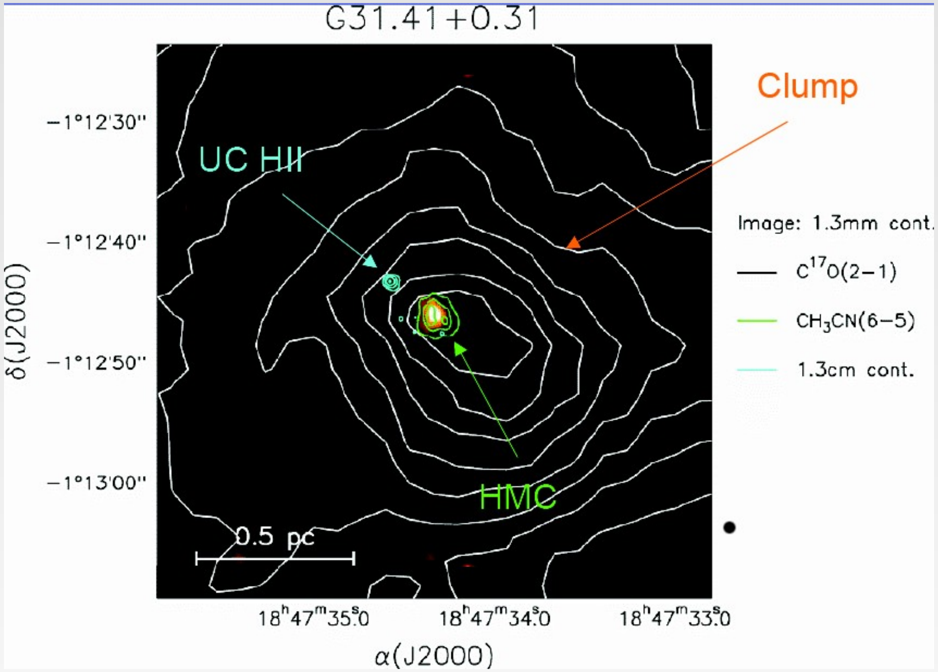
4) Classic HII regions



High-mass star formation: HMC

Hot Molecular Cores (HMC)

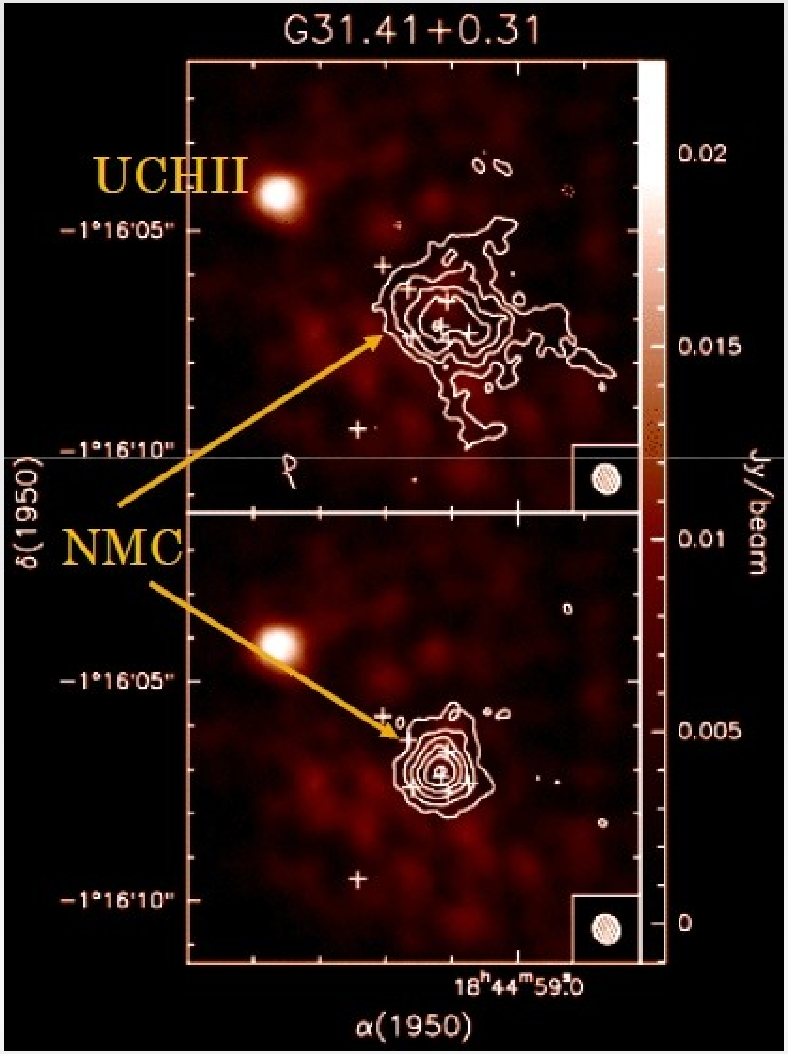
- It is believed to be the first stage with evidence of the existence of an internal star
- condensation of gas and dust:
  - Hot: ~100K
  - Dense: 10^6-10^8 cm^{-3}
  - Luminous:L ~10^3-10^5 $L_\odot$
  - Small: 0.1 pc (~2" at a typical distance of 5kpc)
- Close to UCHII, associated with masers
- Strong millimeter dust emission
- High excitation molecular transitions
- OB STAR INSIDE
- Weak or inexistent photoionization
- High accretion rate?? Osorio et al. 1999 tested this hypothesis
- Precursor of UCHII regions
- Osorio et al. 2009 model G31.



G31 HMC

- Location:
  - 5” to the SW of UCHII G31.41+0.31
  - Distance: 7.9 kpc
  - V_{LSR}= 97.5 km/s
- One of the hottest HMC:
  - Strong dust emission
  - High excitation molecular transitions:
    - HCO^{+}, SiO (Maxia et al. 2001)
    - ^{13}CO (Olmi et al. 1996)
    - CS (Anglada et al.1996)
    - H_2S, $C^{18}O$ (Gibb, Mundy & Wyrowski 2004)
    - CH_3CN (Beltrán et al. 2005)
    - NH_3 (4,4) VLA B-configuration (Churchwell et al. 1990, Cesaroni et al. 1998)
    - NH_3 (4,4) VLA A configuration (Cesaroni et al. 2010)
- 2 radio continuum sources towards the center of G31HMC. AT LEAST 1 OF THEM IS A YOUNG STELLAR OBJECT (Araya et al. 2007)
- Velocity gradient:
  - SW-NE direction
  - Controversial interpretation

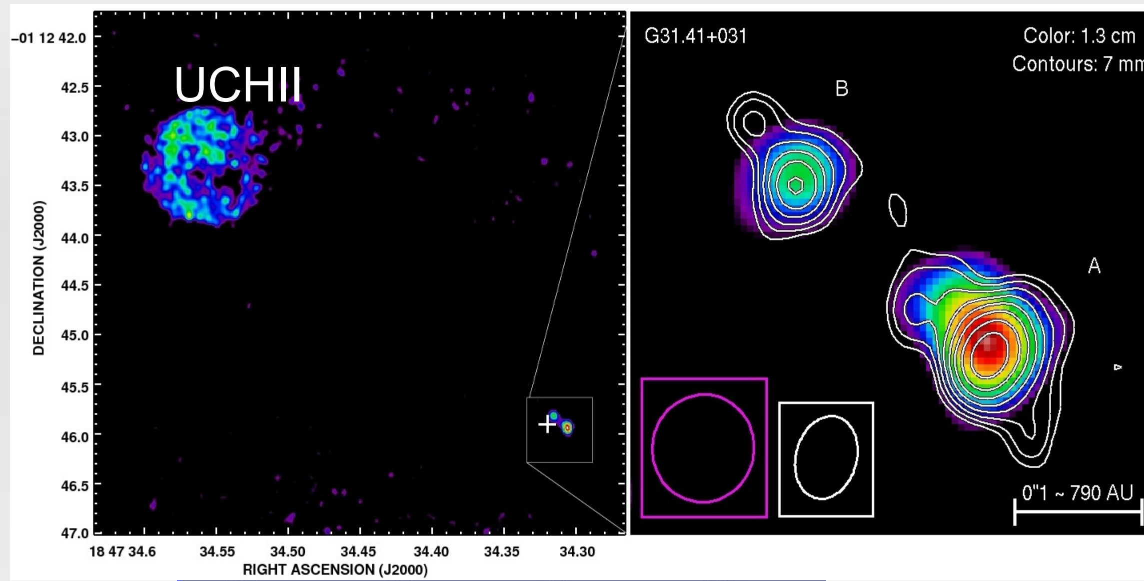
(4,4) NH_3 observation

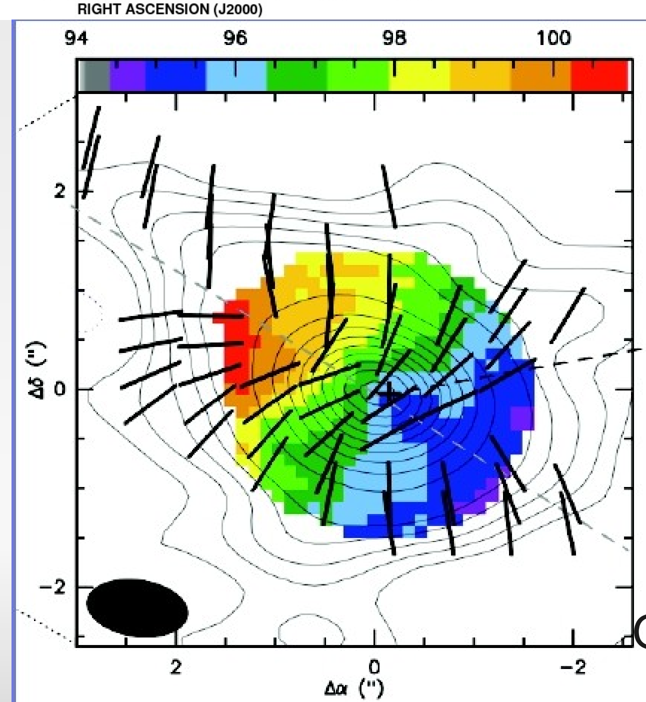


Cesaroni et al. 1998

G31 HMC

- Location:
  - 5” to the SW of UCHII G31.41+0.31
  - Distance: 7.9 kpc
  - V_{LSR}= 97.5 km/s
- One of the hottest HMC:
  - Strong dust emission
  - High excitation molecular transitions:
    - HCO^+, SiO (Maxia et al. 2001)
    - ^{13}CO (Olmi et al. 1996)
    - CS (Anglada et al.1996)
    - H_2S, $C^{18}O$ (Gibb, Mundy & Wyrowski 2004)
    - CH_3CN (Beltrán et al. 2005)
    - NH_3 (4,4) VLA B-configuration (Churchwell et al. 1990, Cesaroni et al. 1998)
    - NH_3 (4,4) VLA A configuration (Cesaroni et al. 2010)
- 2 radio continuum sources towards the center of G31HMC. AT LEAST 1 OF THEM IS A YOUNG STELLAR OBJECT
- Velocity gradient:
  - SW-NE direction
  - Controversial interpretation



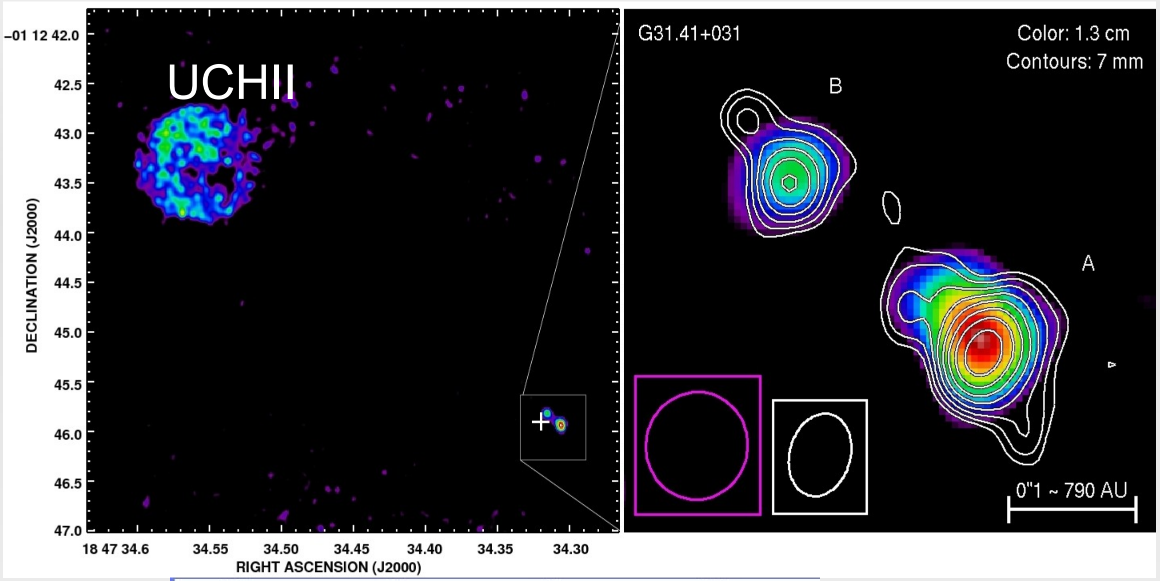


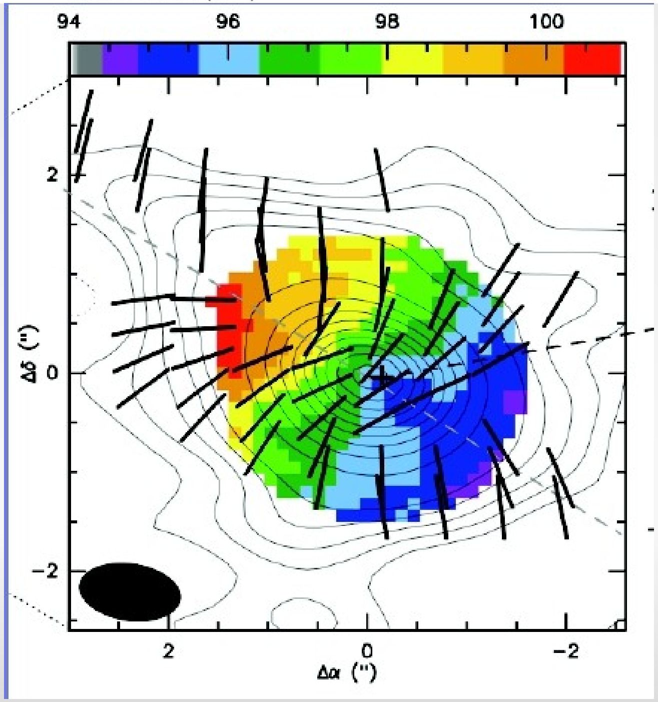
hourglass

Girart et al. 2009

G31 HMC

- Location:
  - 5” to the SW of UCHII G31.41+0.31
  - Distance: 7.9 kpc
  - V_{LSR}= 97.5 km/s
- One of the hottest HMC:
  - Strong dust emission
  - High excitation molecular transitions:
    - HCO^+, SiO (Maxia et al. 2001)
    - ^{13}CO (Olmi et al. 1996)
    - CS (Anglada et al.1996)
    - H_2S, $C^{18}O$ (Gibb, Mundy & Wyrowski 2004)
    - CH_3CN (Beltrán et al. 2005)
    - NH_3 (4,4) VLA B-configuration (Churchwell et al. 1990, Cesaroni et al. 1998)
    - NH_3 (4,4) VLA A configuration (Cesaroni et al. 2010)
  - **NH_3(2,2), NH_3(3,3), NH_3(5,5), NH_3(6,6) VLA B-configuration (Mayén et al. In preparation)**
- 2 radio continuum sources towards the center of G31HMC. AT LEAST 1 OF THEM IS A YOUNG STELLAR OBJECT
- Velocity gradient:
  - SW-NE direction
  - Controversial interpretation

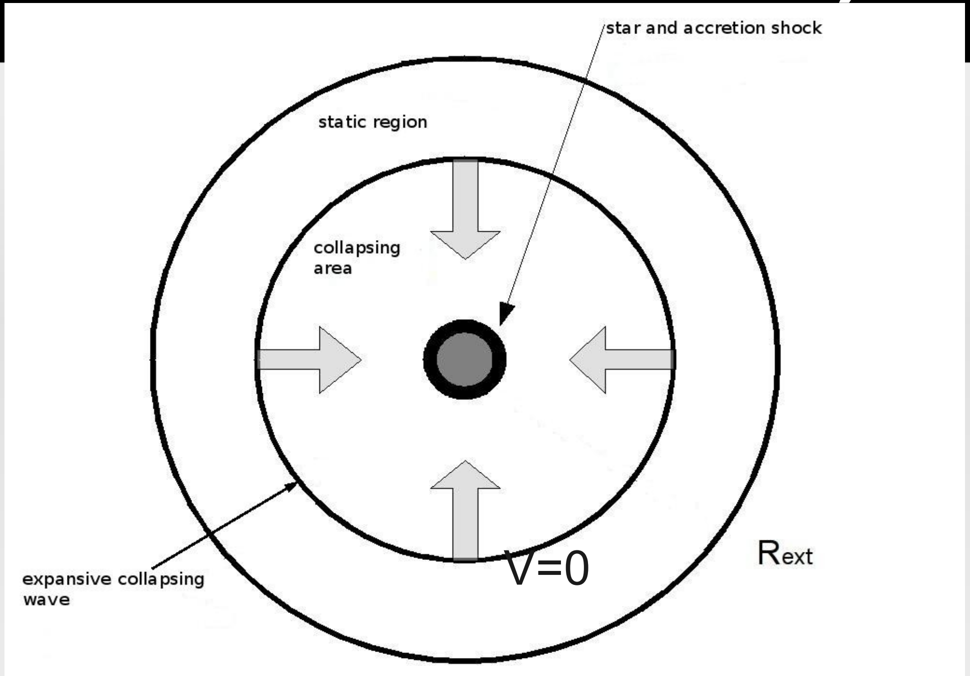




hourglass

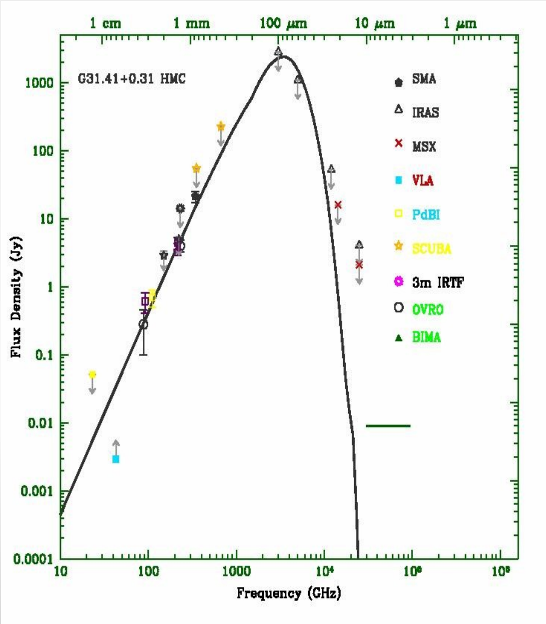
Girart et al. 2009

Collapsing model (Osorio et al. 2009)

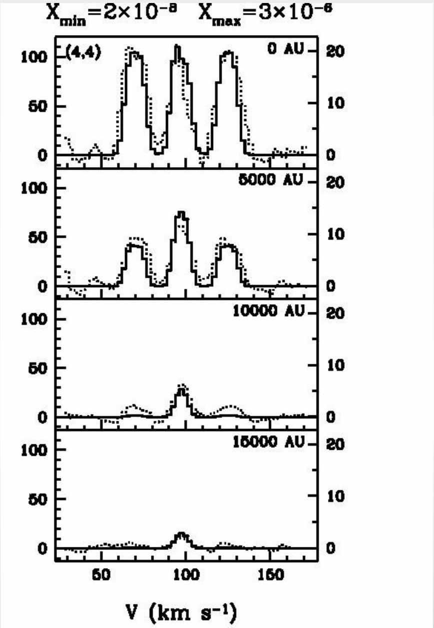


- Structure:
  - Spherical envelope of gas and dust
  - Collapse is dominant (no rotation)
  - O star inside
  - Collapsing wave moves outwards setting the matter into motion towards the central star
  - Heating: star radiation + accretion shocks
- Model:
  - Reproduces SED and NH3(4,4) observation (Cesaroni et al. 1998)
  - $M_*=20\text{-}25M_\odot$
  - $L_{tot}=8\times10^4 L_\odot$
  - $dM/dt=3\times10^{-3} M_\odot/yr$

SED fit

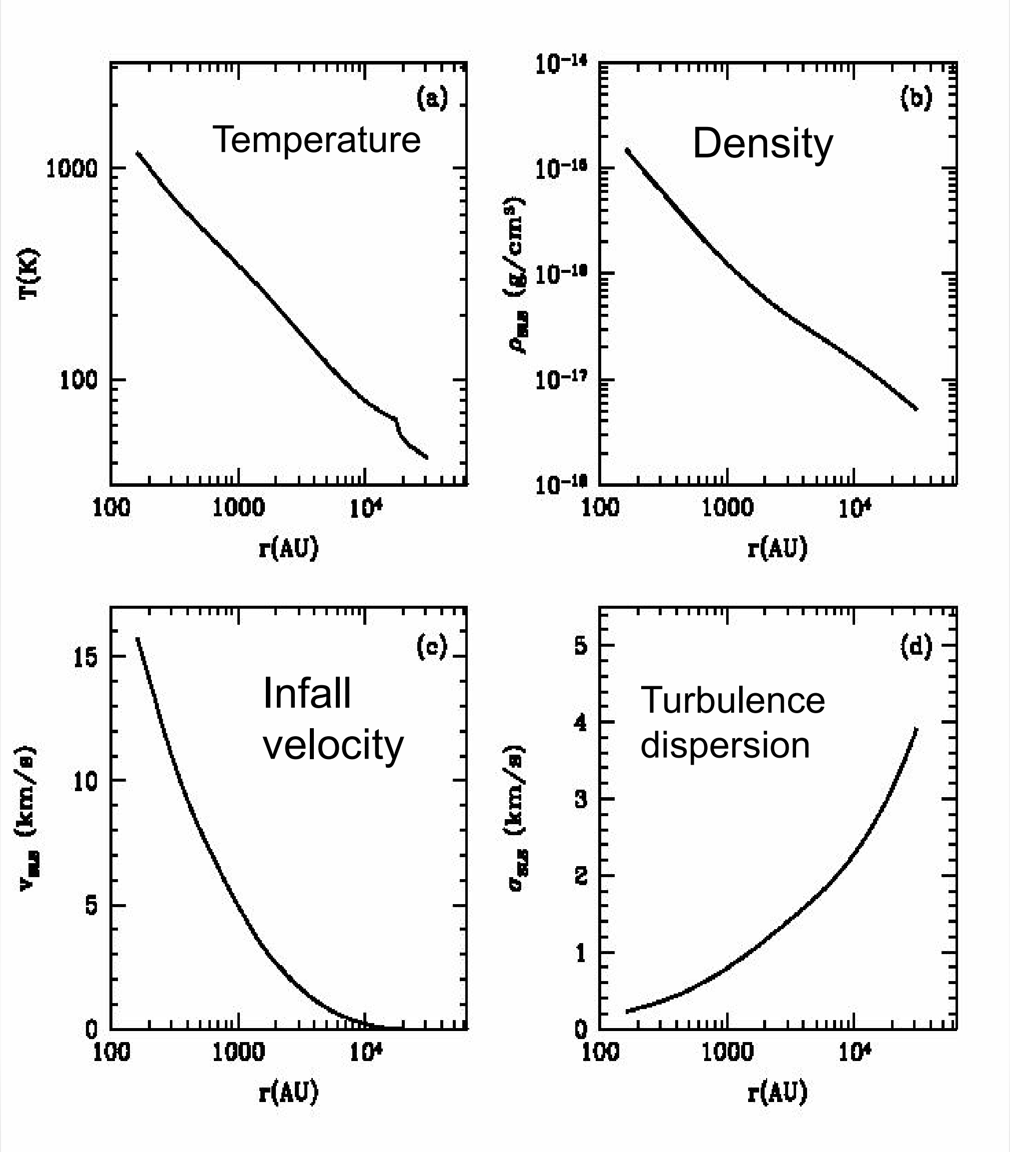


NH3(4,4) fit



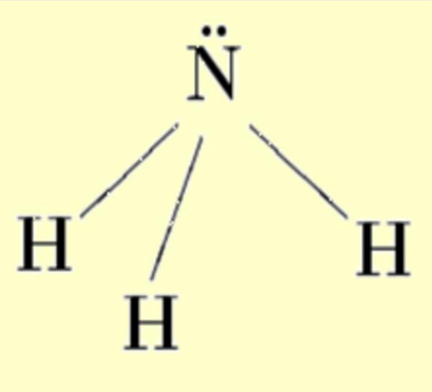
Collapsing model (Osorio et al. 2009)

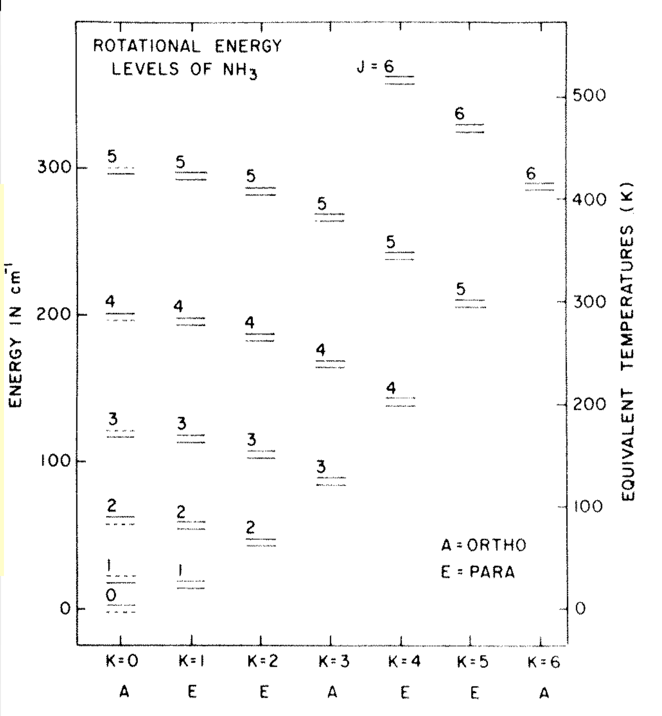
- Structure:
  - Spherical envelope of gas and dust
  - Collapse is dominant (no rotation)
  - O star inside
  - Collapsing wave moves outwards setting the matter into motion
  - Heating: star radiation + accretion shocks
- Model:
  - Reproduces SED and NH3(4,4) observation (Cesaroni et al. 1998)
  - M_{*}=20-25$M_{\odot}$
  - L_{tot} =8x$10^{4}L_{\odot}$
  - dM/dt=3x$10^{-3}M_{\odot}$/yr
- To test the model we carried out additional B-configuration VLA ammonia inversion line observations

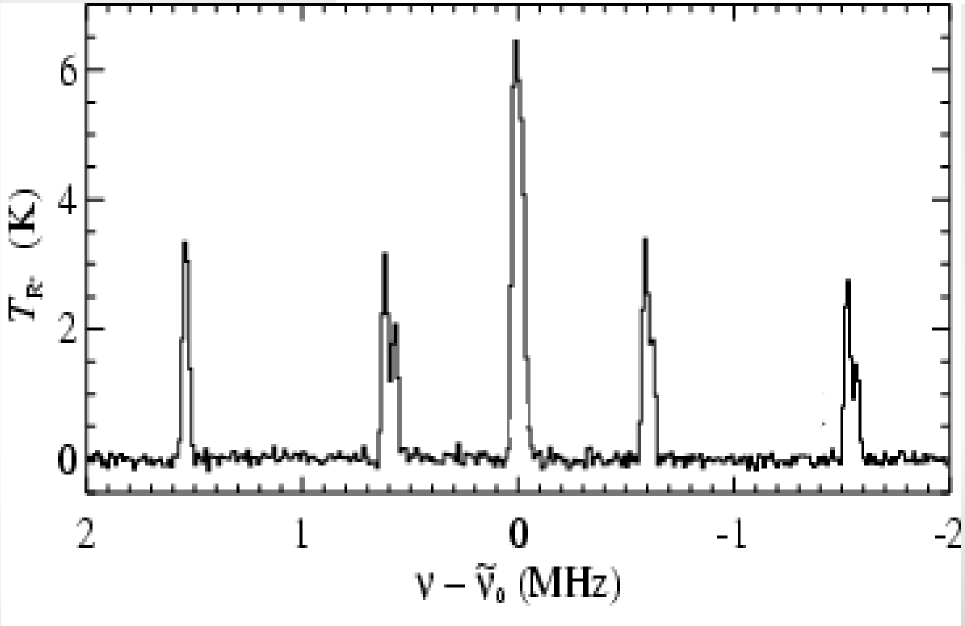


Ammonia inversion transitions

- Why ammonia inversion transitions?
  - High dense tracer. $n_{crit}=10^3$ cm^{-3}. Isolate HMC
  - Temperature in HMCs can activate inversion transitions.
  - Inversion transitions are close in frequency.
  - Hyperfine structure makes ammonia sensitive to many physical parameters. No isotopes need
- Hyperfine structure (inversion transition: 5 observable lines)
  - main line: more intense and thicker
  - + 2pairs of satellite lines:
    - Located symmetrically respect to the main line
    - Less intense, depends on (J,J)
    - Separation depends on (J,J)
    - thinner
  - Satellites penetrate deeper
  - Sensitive to physical parameter: opacity, excitation Temperature, rotational temperature...
  - Magnetic hyperfine structure negligible







Ammonia inversion transitions

Transition (J,J)	Main line relative Intensity	Inner satellite relative intensity	Separation Velocity (km/s)	Outer satellite relative intensity	Separation Velocity (km/s)	Ground energy level (K)
(2,2)	0.79629	0.05185	16.55	0.0500	25.78	64
(3,3)	0.89352	0.02678	21.47	0.02645	28.88	123
(4,4) Archive data	0.93500	0.01629	24.21	0.01620	30.43	201
(5,5)	0.95629	0.01094	25.91	0.01090	31.40	296
(6,6)	0.96863	0.00785	26.92	0.00783	31.46	410

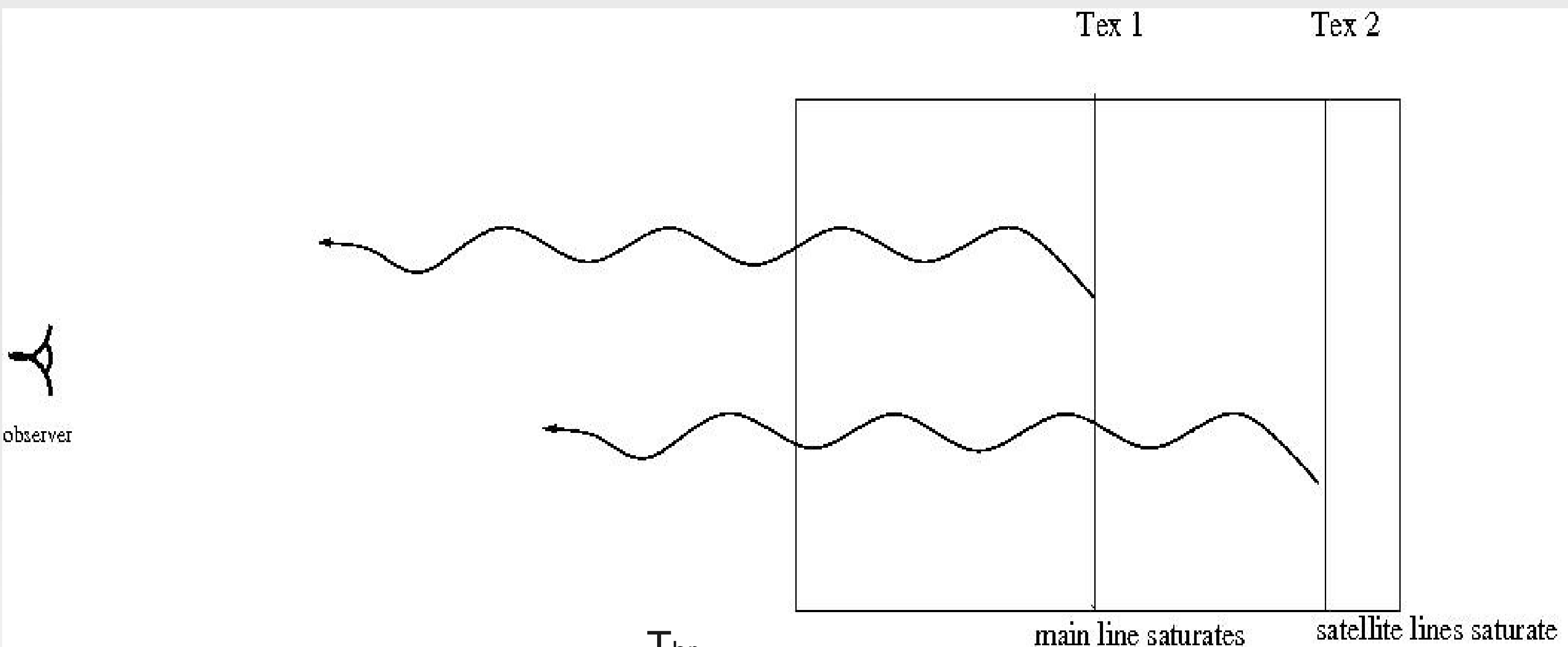
Ammonia inversion transitions

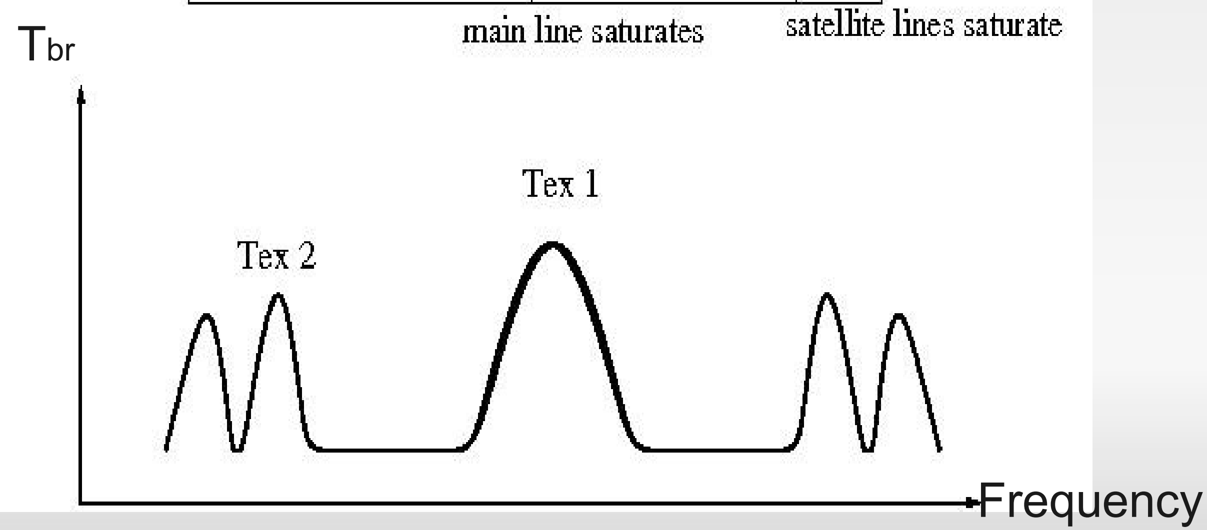
Transition (J,J)	Main line relative Intensity	Inner satellite relative intensity	Separation Velocity (km/s)	Outer satellite relative intensity	Separation Velocity (km/s)	Ground energy level (K)
(2,2)	0.79629	0.05185	16.55	0.0500	25.78	64
(3,3)	0.89352	0.02678	21.47	0.02645	28.88	123
(4,4) Archive data	0.93500	0.01629	24.21	0.01620	30.43	201
(5,5)	0.95629	0.01094	25.91	0.01090	31.40	296
(6,6)	0.96863	0.00785	26.92	0.00783	31.46	410

16

120

Ammonia inversion transition



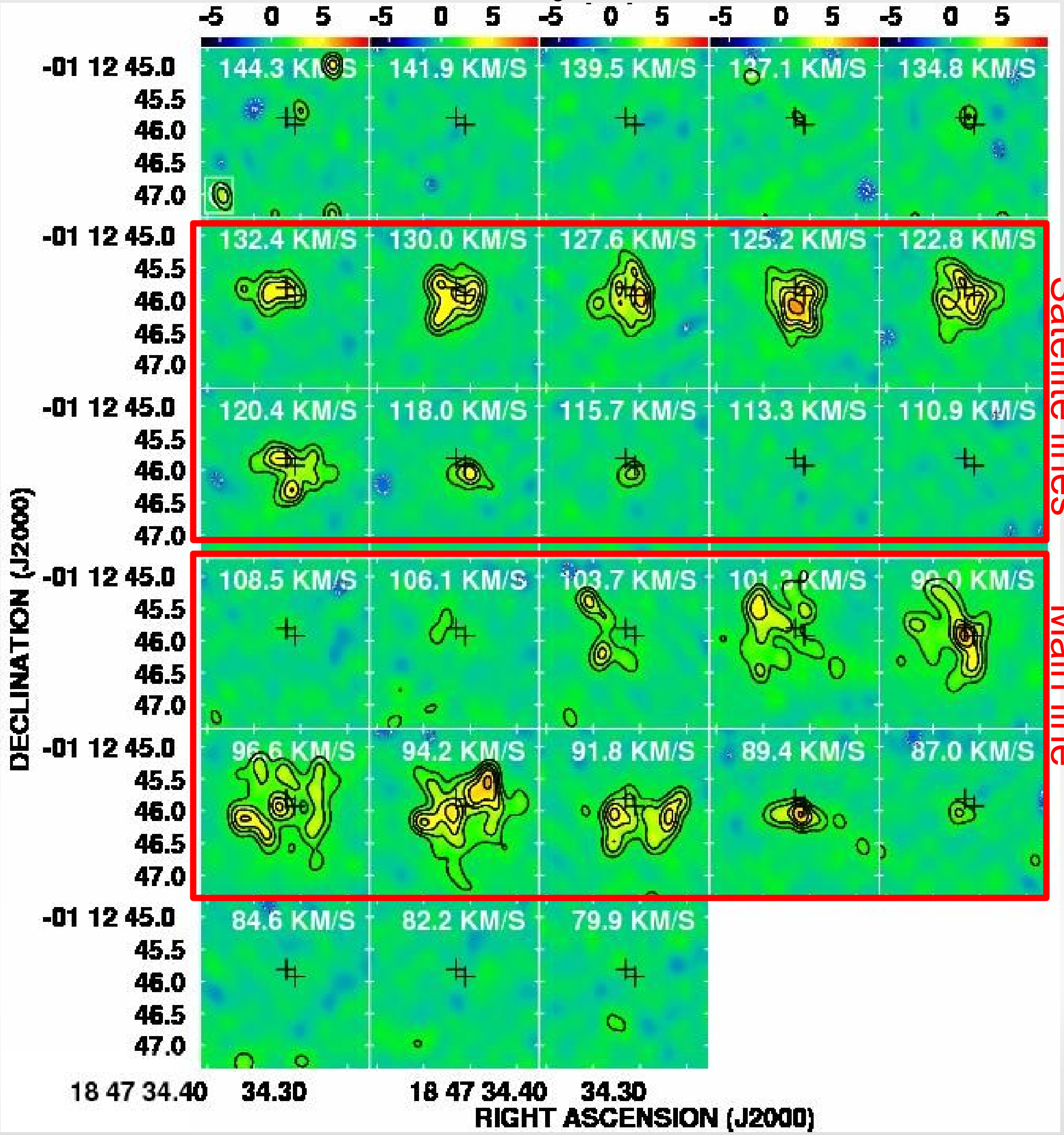


By studying different lines we could see different parts of the core:
-(5,5) and (6,6) trace the hottest part
-satellite lines trace deeper part

Observations: channel cube

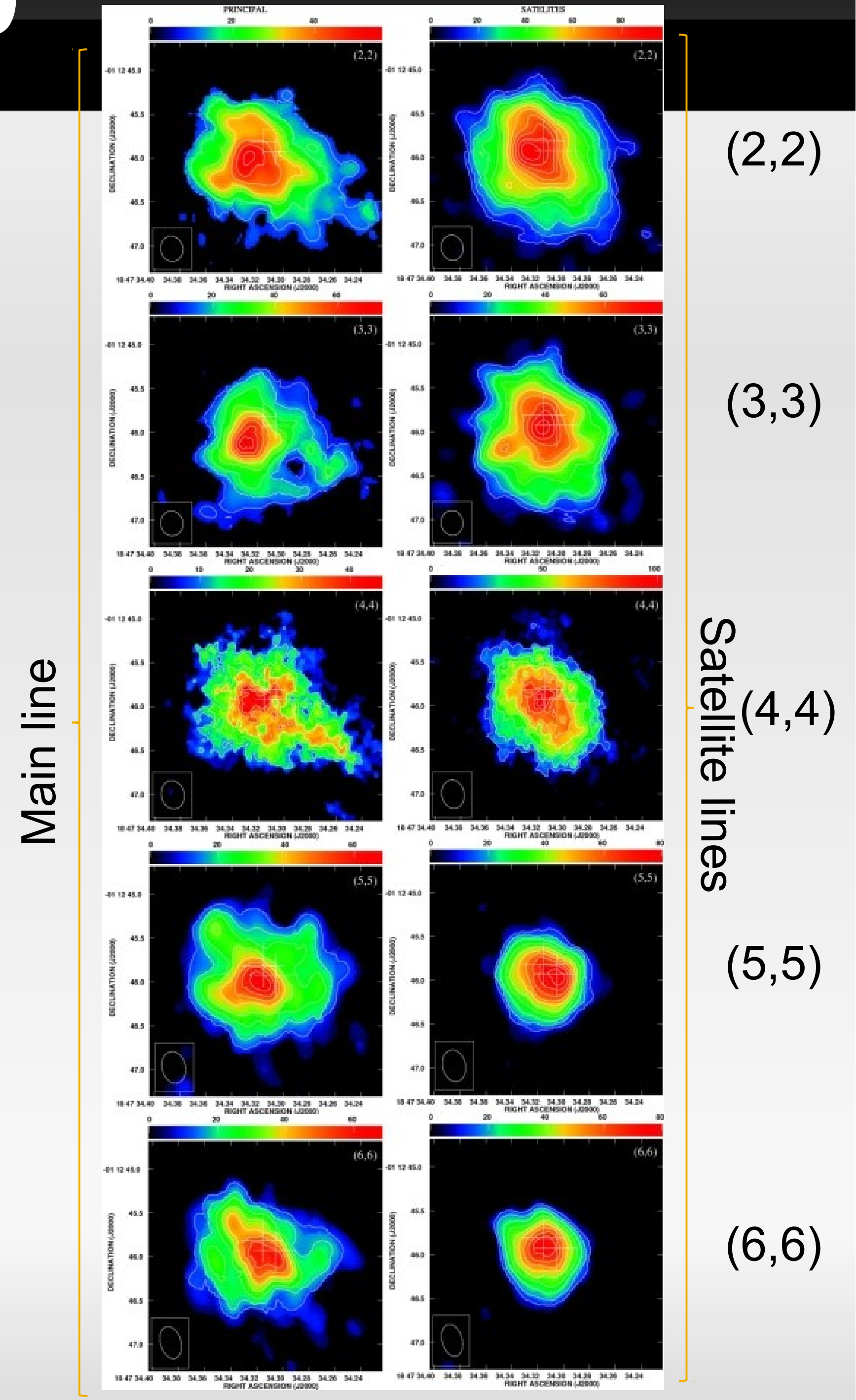
- B-configuration VLA:
  - (2,2), (3,3), (5,5), (6,6) inversion transitions
  - Beam~0.3"
  - Bandwidth~80 km/s
  - Spectral resolution=~2.4 km/s
  - 31 channels
- Additional A-configuration VLA (4,4) data archive have been analyzed
  - 64 channels
  - Bandwidth ~160km/s
  - Δv ~2.4 km/s
  - Beam forced to 0.3" to compare with B-configuration observations.
- Single condensation towards the continuum sources
- Velocity structure

$NH_3(5,5)$



Observations: MOM0

- Main line emission maps:
  - Similar size for all transitions
    => HOT GAS in the outer part
  - Irregular. SENSITIVE TO DENSITY INHOMOGEITIES IN THE OUTER PART
- Satellite lines:
  - Low excitation: (2,2), (3,3), (4,4)
    - same extension as main line HIGH OPACITY
  - High excitation: (5,5), (6,6)
    - inner region
    - Compact and regular



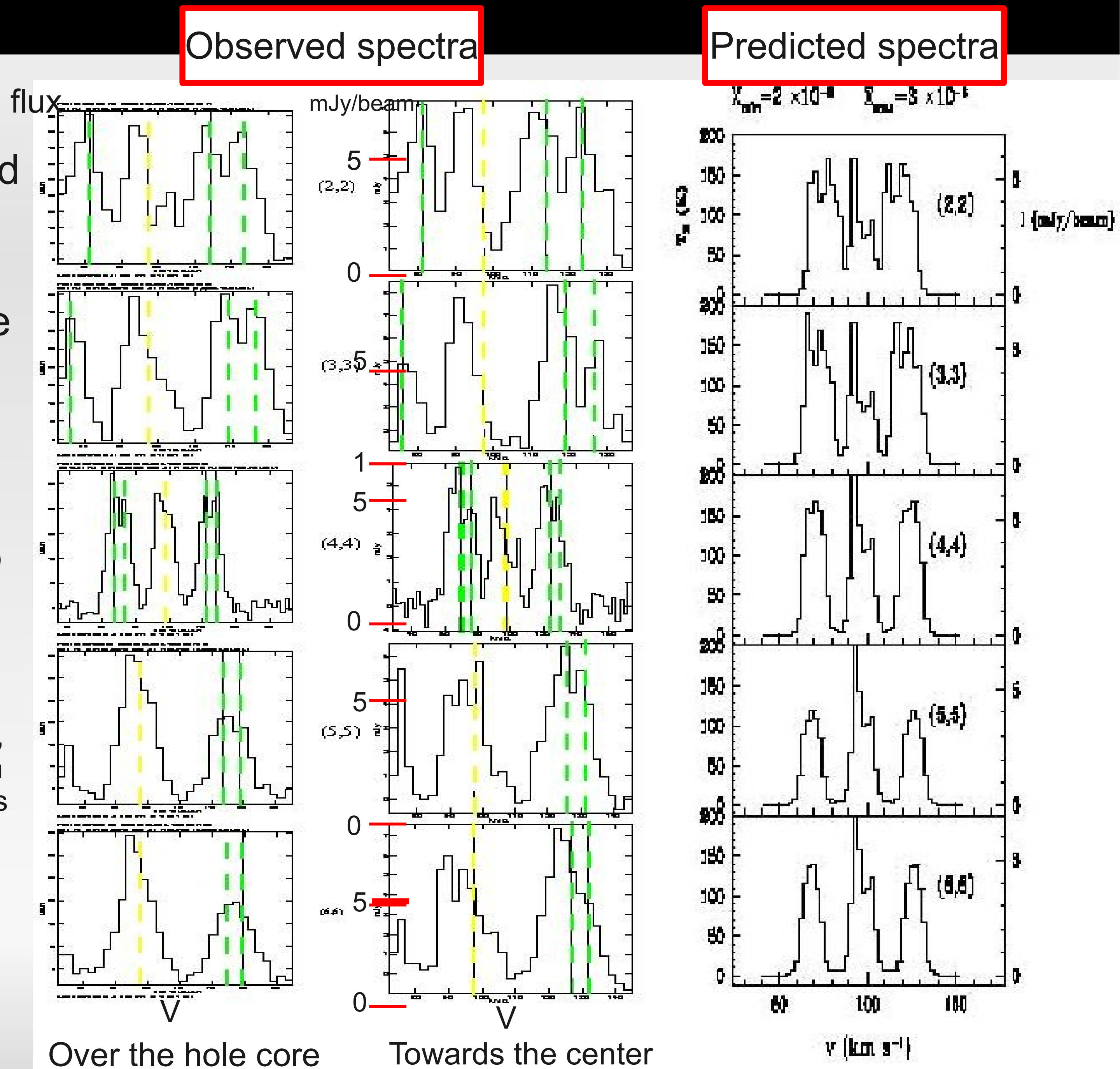
Observations: Spectra

- Unusual large widths. Satellite lines are merged

- Intensities agree with the model. MODEL'S TEMPERATURE DISTRIBUTION CLOSE TO REALITY

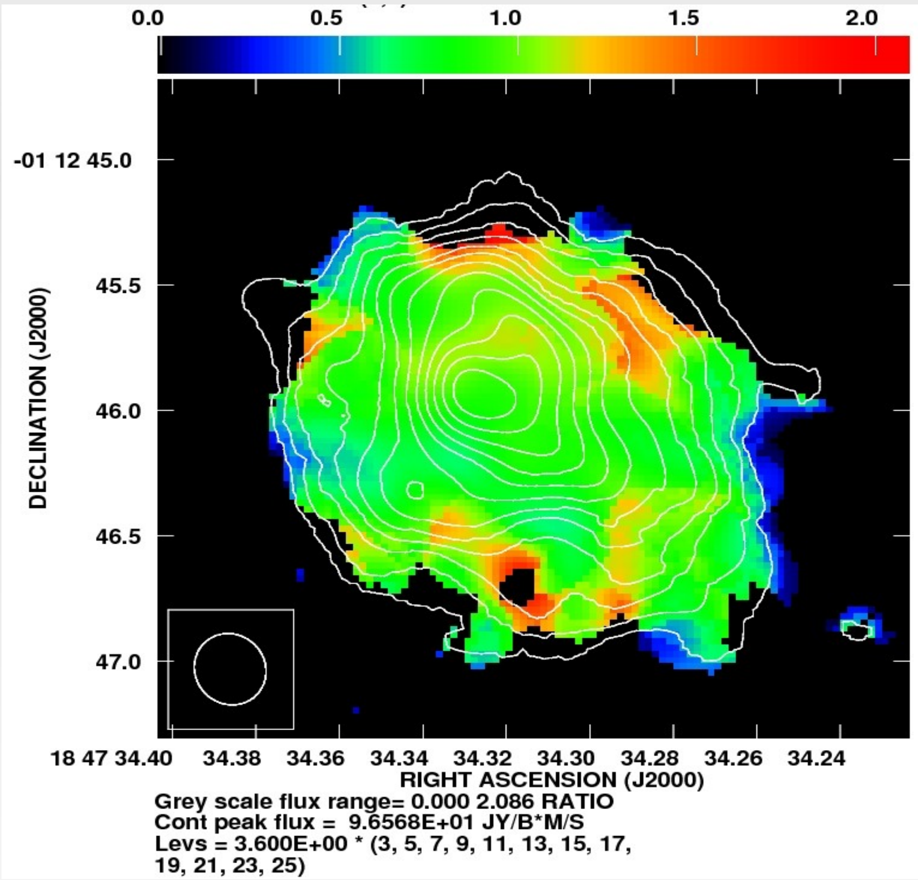
    - The model fitted the $NH_3(4,4)$ VLA B-configuration observation

    - $NH_3(2,2)$, $NH_3(3,3)$, $NH_3(5,5)$, $NH_3(6,6)$ VLA B-configuration observations were predictions

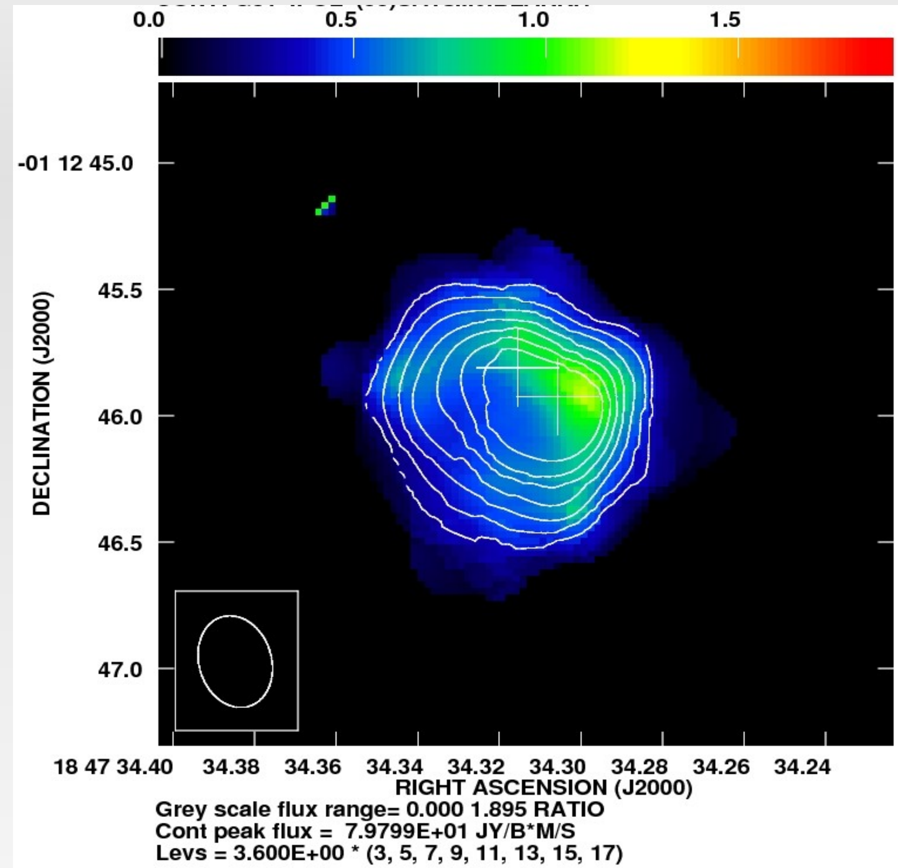


Observations: opacity

SAT(2,2)/MAIN(2,2)



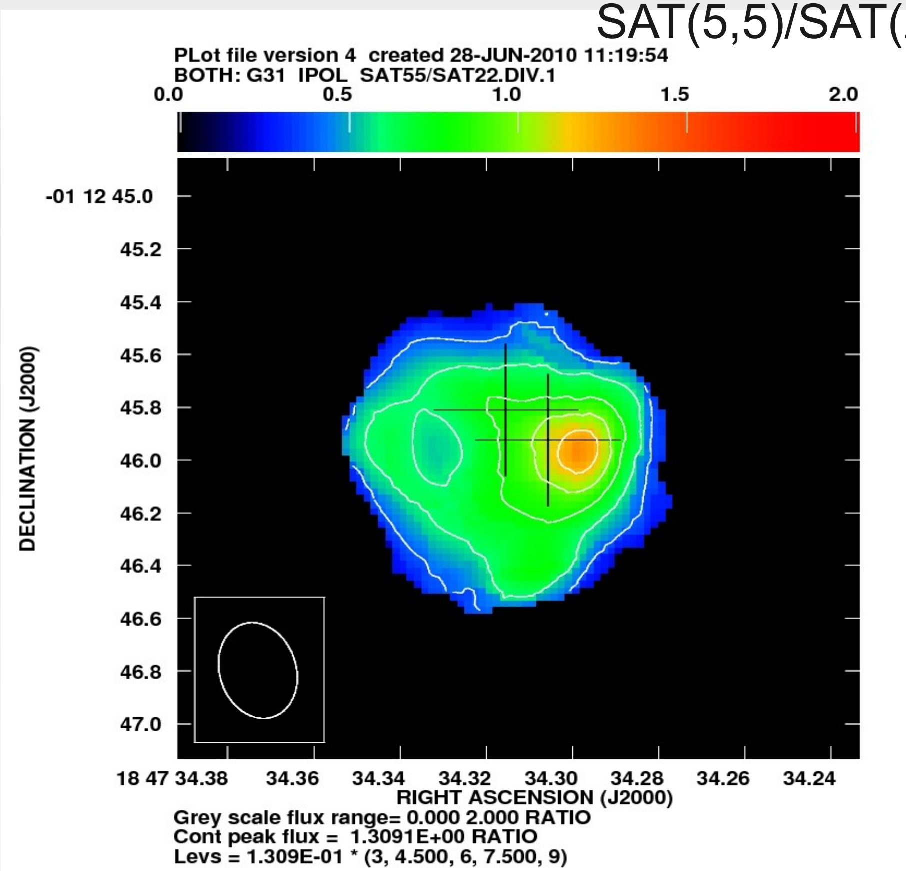
SAT(5,5)/MAIN(5,5)

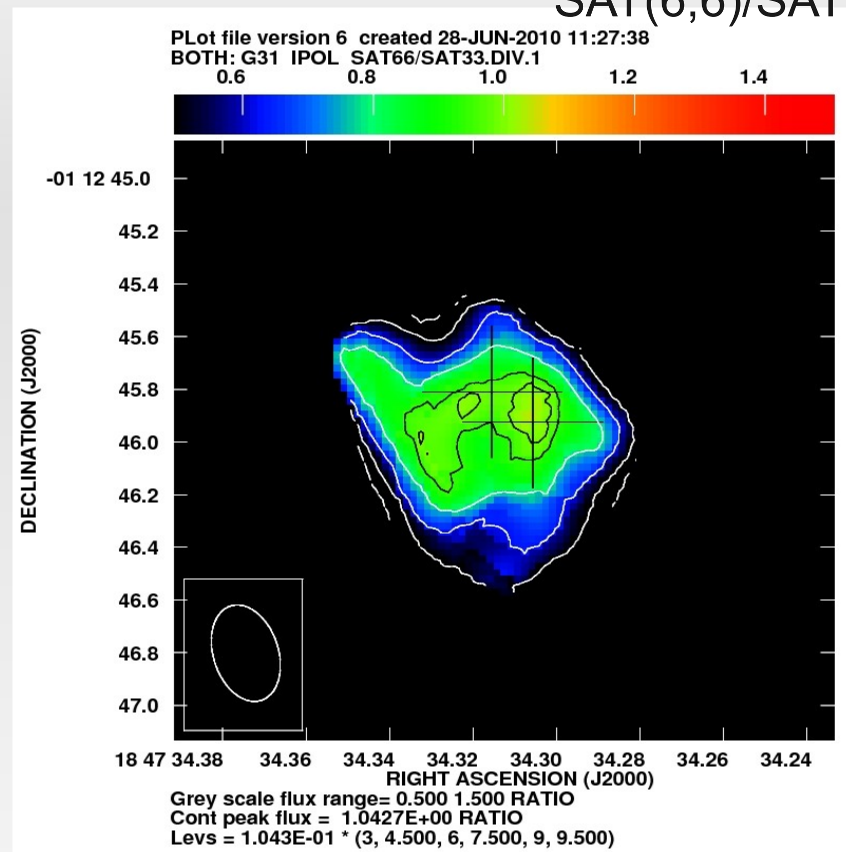


- Ratio SAT(2,2)/MAIN(2,2) is close to 1 over the hole emission=> high opacity in the outer part
- To be more sensitive to the opacity we need thinner lines

- T55main line=60=> ratio=0.5
- T55main line=200=> ratio=0.9
- To be more sensitive to physical parameters we need thinner lines

Observations: Temperature Gradients

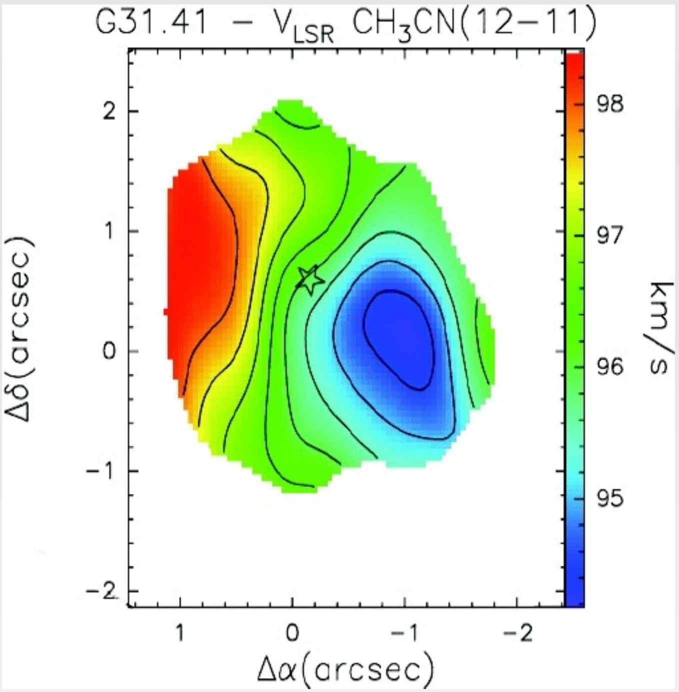




- Ratio close to 1 => high opacity
- Not conclusive because of the very high thickness
- Maximum at the position of one continuum sources?
- We need thinner lines to be more sensitive.

Observations: Kinematics (MOM1)

Beltran et al. 2004
PdB, beam=0.8”



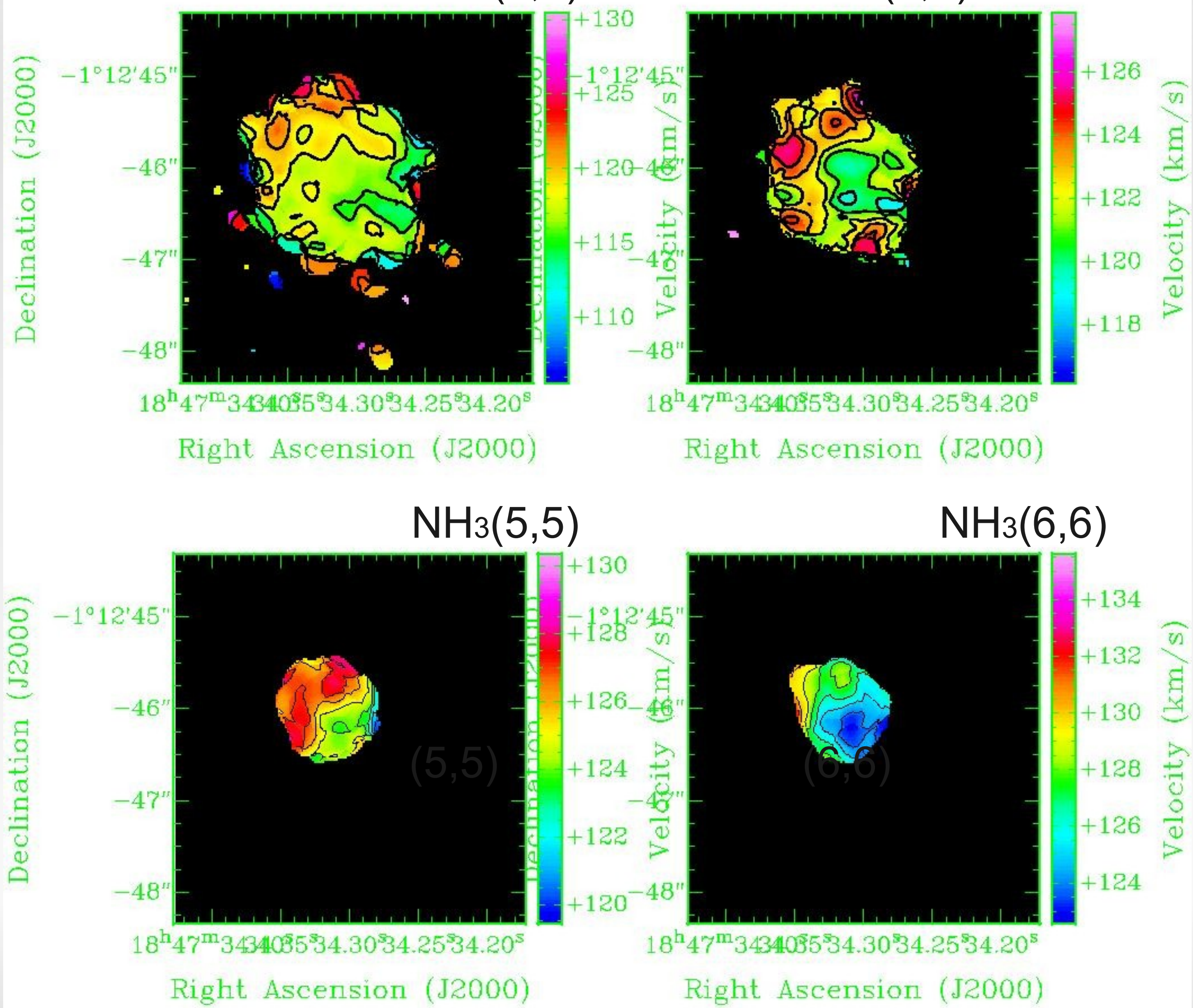
Interpreted as rotating toroid

- NH_3 Gradient:
  - Same orientation
  - Same value
  - than CH_3CN(12-11) gradient
- Reminiscent JIN-JAN, what does it mean?

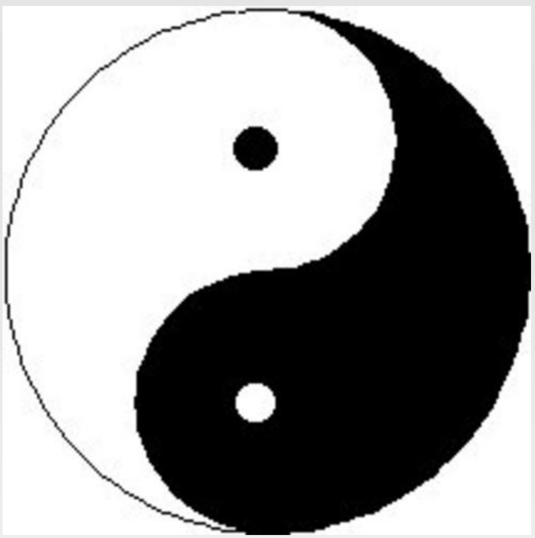
VLA, beam=0.3”

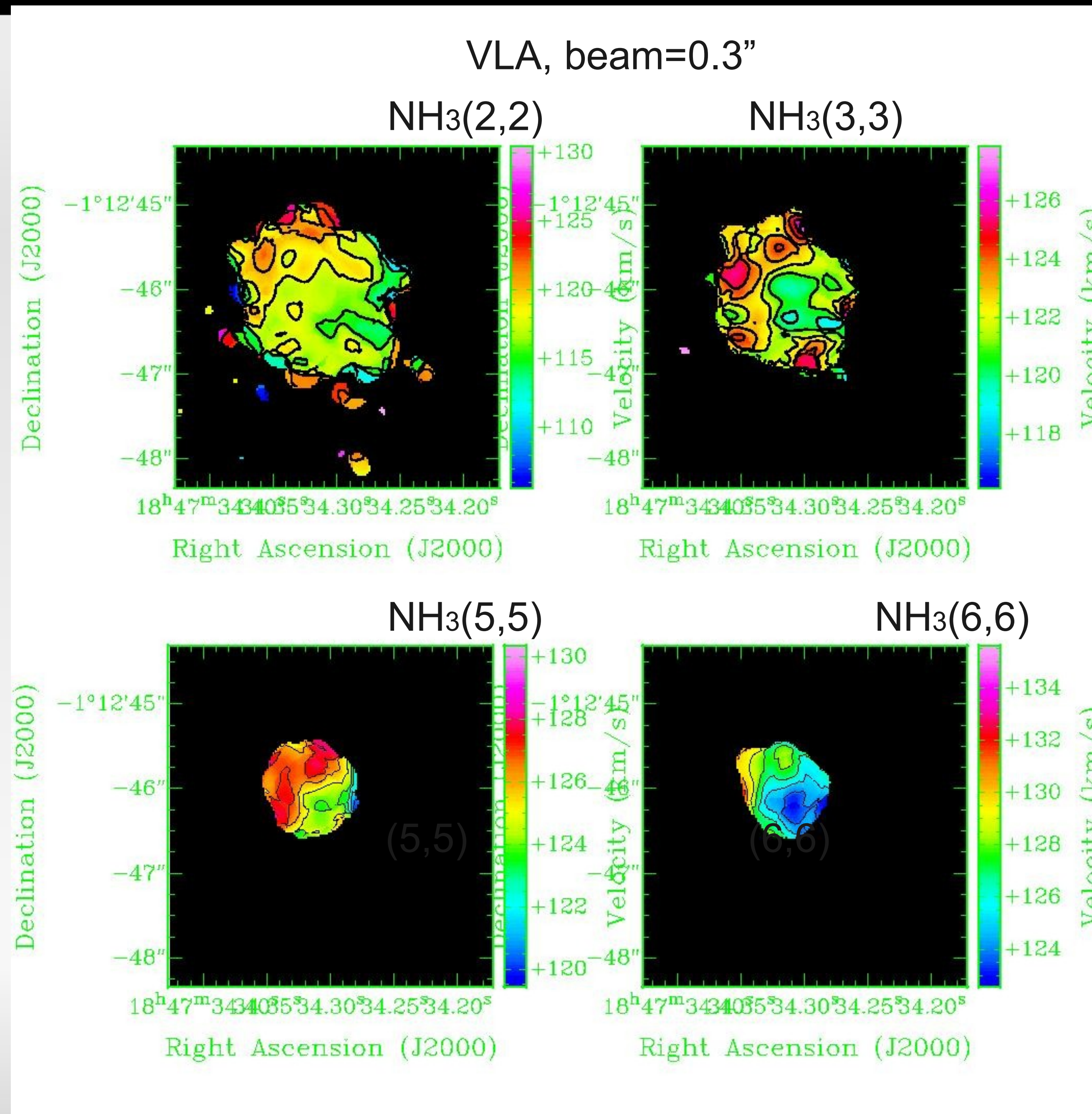
NH_3(2,2) NH_3(3,3)

NH_3(5,5) NH_3(6,6)



Observations: Kinematics (MOM1)



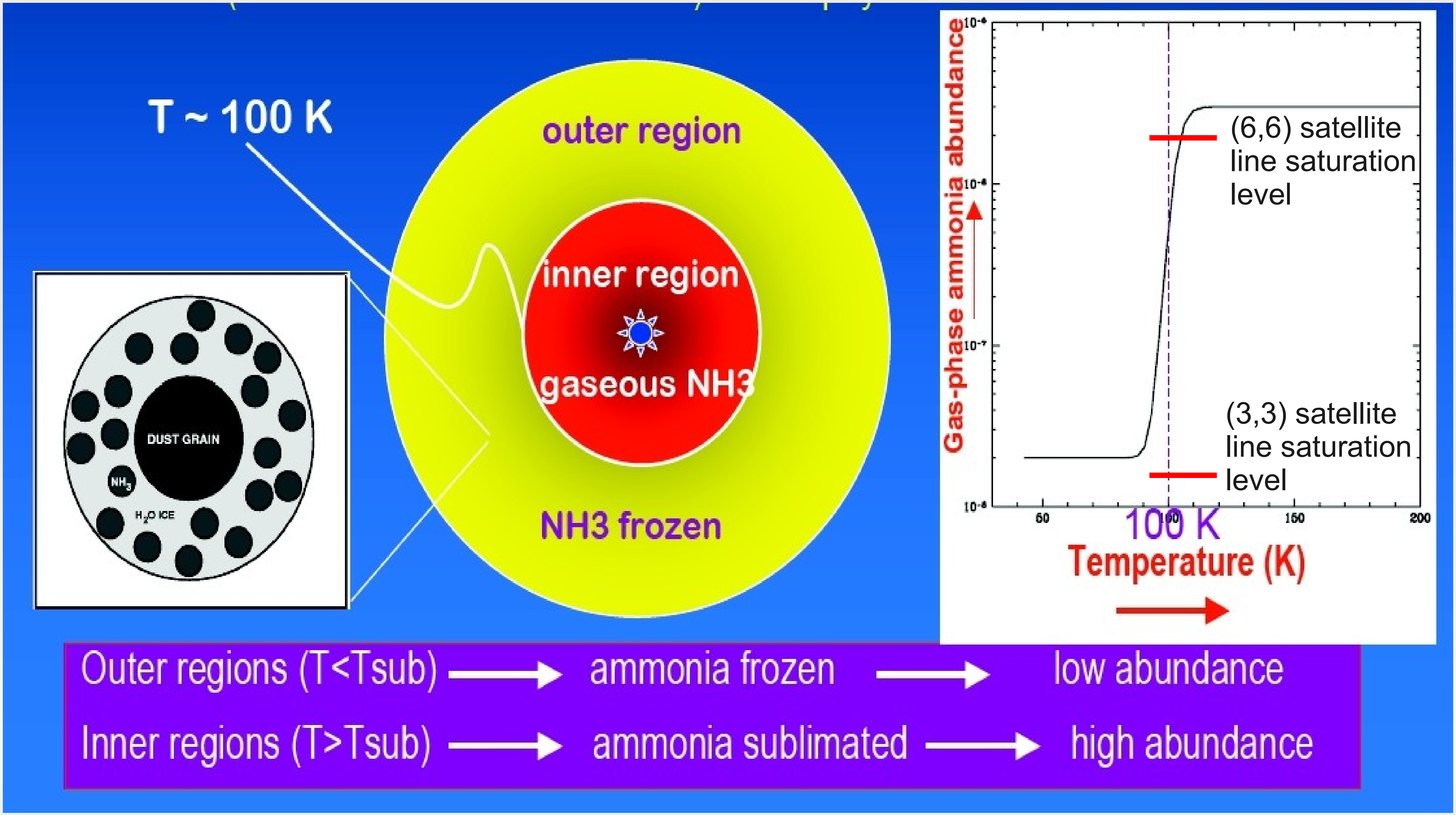


- NH_3 Gradient:
  - Same orientation
  - Same value
  - than CH_3CN(12-11) gradient
- Reminiscent JIN-JAN, what does it mean?

Conclusions

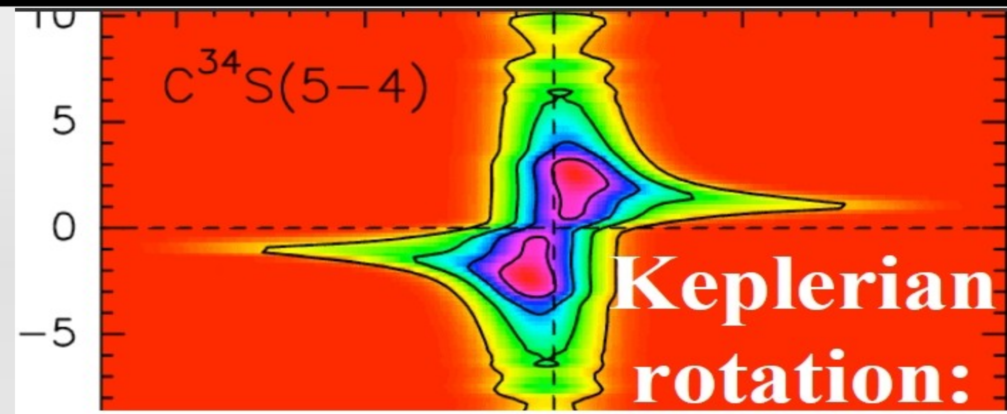
- We have analyzed NH_3 inversion transitions (2,2) to (6,6) VLA B-configuration observations with resolution of 0.3” towards G31HMC. We compare our observation with a collapsing model previously fitted to the SED and NH3(4,4) VLA B-configuration observations
- We find extreme high opacity conditions
- The intensity predicted by the model agree with the intensity observed, which suggests that physical condition predicted by the model could be a good approximation to the reality.
- However optically thinner transitions will be very valuable to further testing the physical conditions of this model

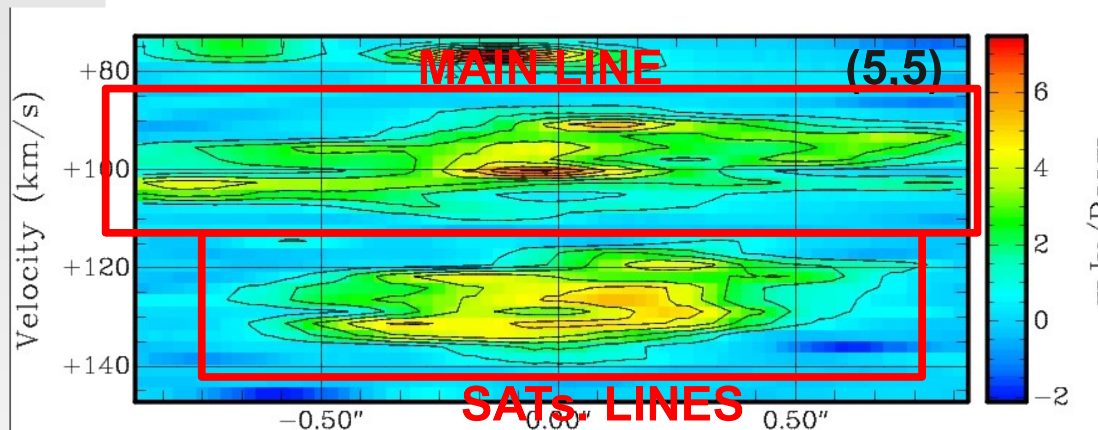
Observation: Spectra

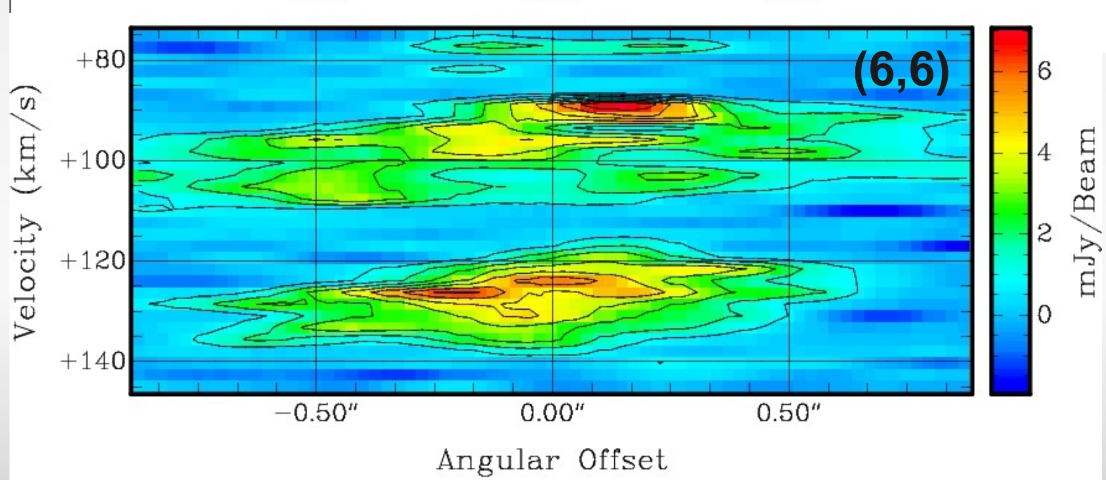


Observation: kinematic (POS-VEL)

- Disks around B-type stars
  - Disk have been detected in B stars (Bik & Thi 2004)
  - Disk have masses similar to the central star
  - Are stable and in keplarian rotation
- Disk around O-type stars
  - Not detected yet
  - Rotating toroids
  - Masses higher than the central star
  - No keplarian rotation

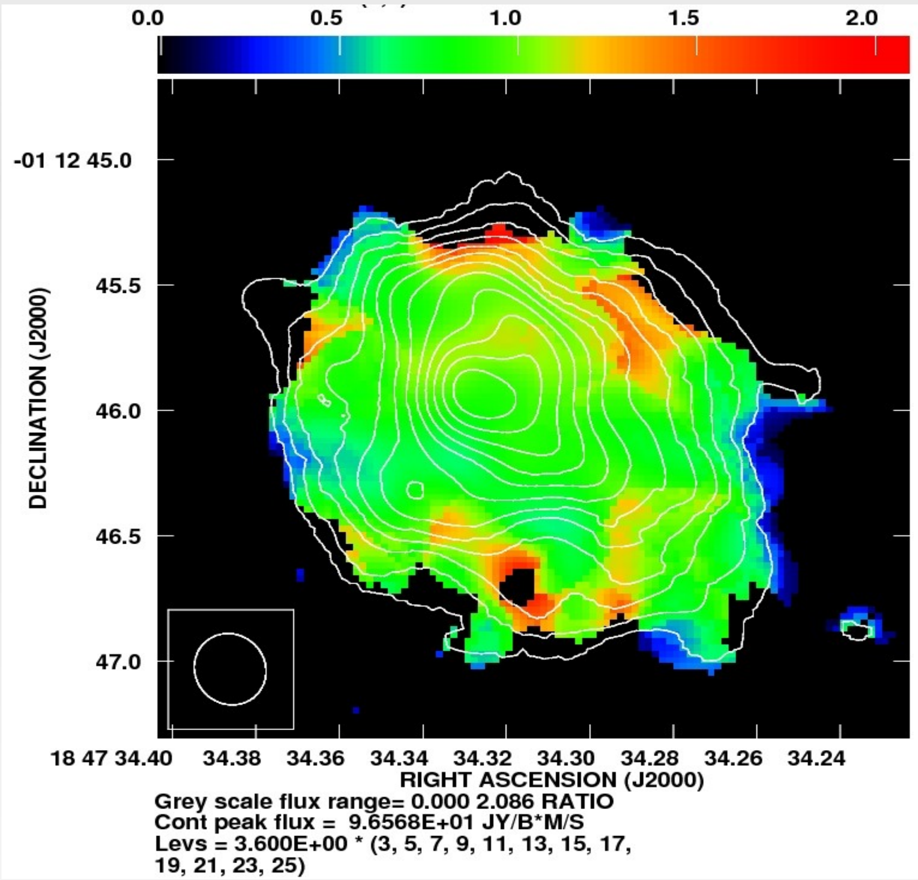




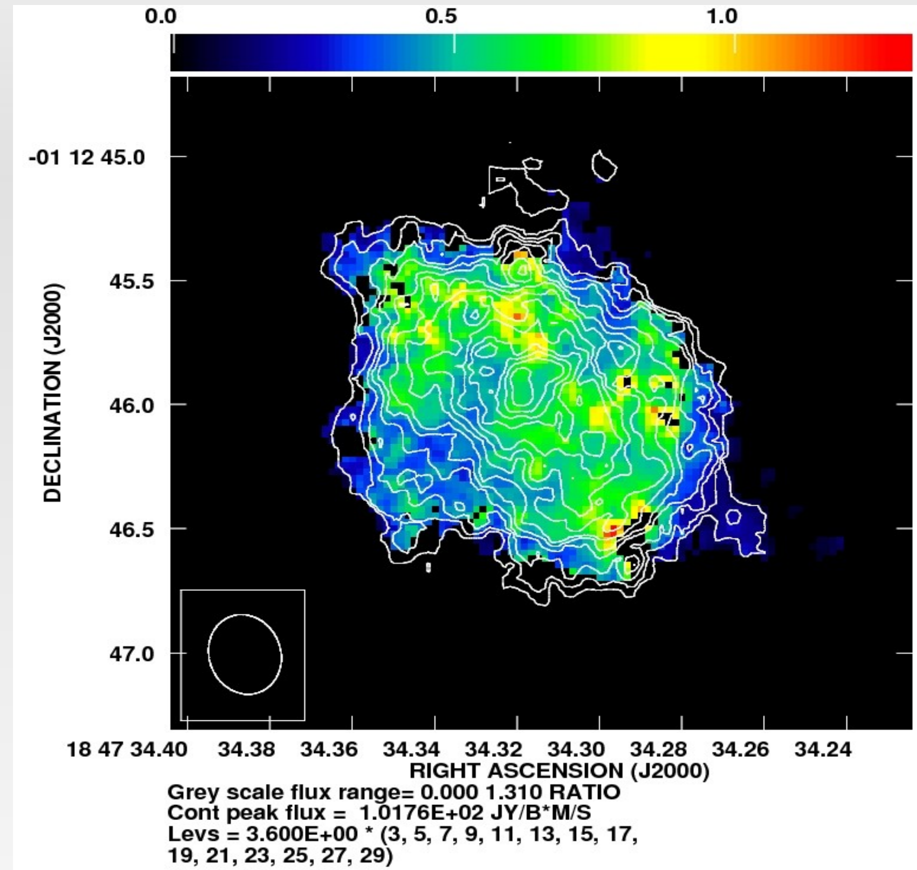


Observations: opacity

SAT(2,2)/MAIN(2,2)



SAT(4,4)/MAIN(4,4)



- Ratio SAT(2,2)/MAIN(2,2) is close to 1 => high opacity in the outer part
- Ratio SAT(5,5)/MAIN(5,5) is around 0
- High optical depth
- To be more sensitive to physical parameters we need thinner lines