Molecular Line Emission from Star-Forming Regions and Carbon Stars

Fumitaka Nakamura (National Astronomical Observatory of Japan)

Outline

- **Lecture 1**

  ISM (Interstellar Medium)

  Line Emission

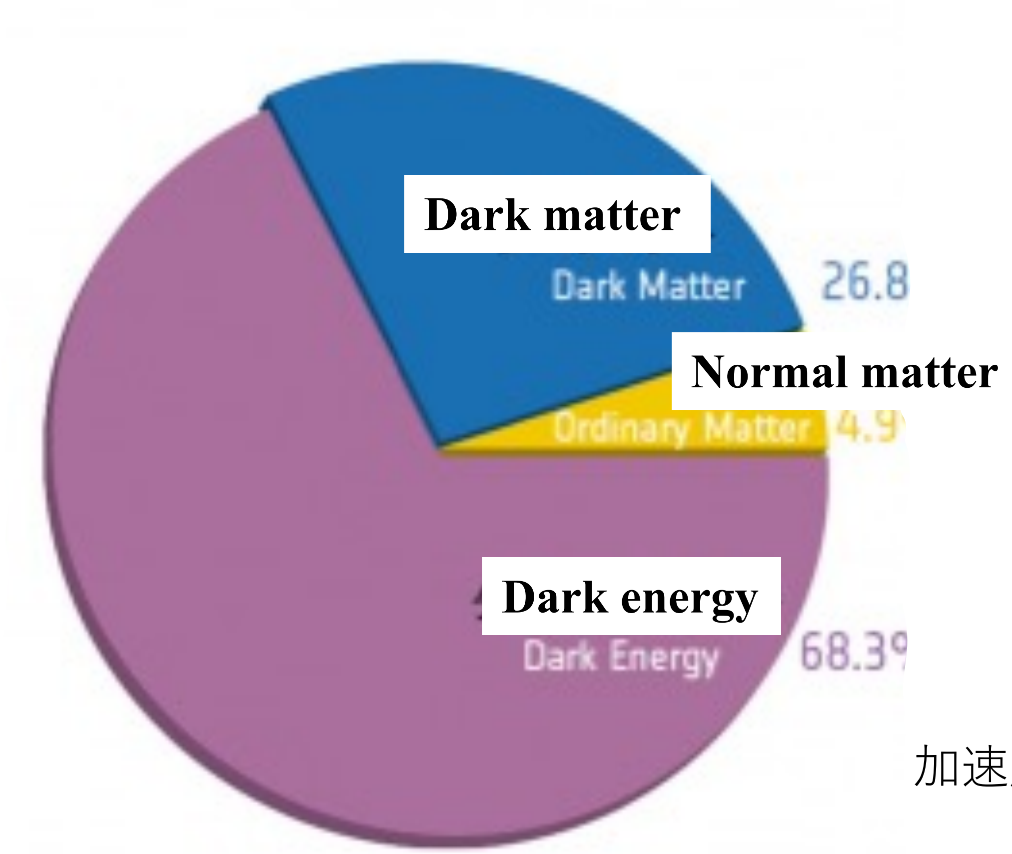
  mechanism

- **Lecture 2**

  Molecular line observations of carbon stars

  Molecular line observations of star-forming regions (protostellar outflows)

Cosmic Pie (Energy Distribution in our Universe)



- Dark energy=70%, dark matter=25%,

normal matter (stars, ISM) =5%

Dark mater is unknown elementary particles?

- Dark energy is the cosmological constant (Λ term) which was introduced by Albert Einstein to make our universe stationary.

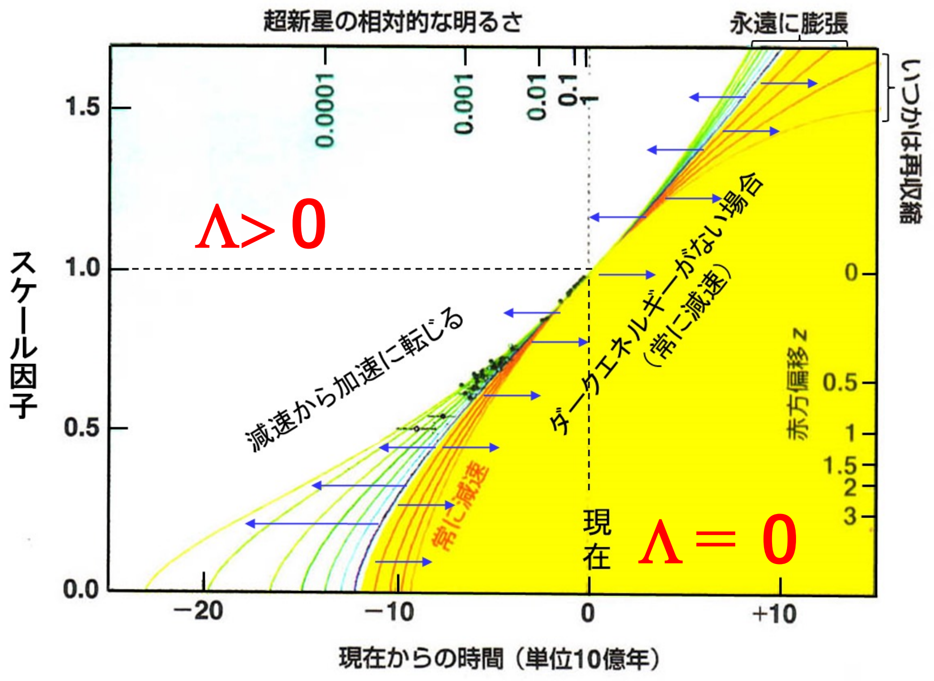
アインシュタイン方程式
一般相対性理論：物体は周囲の時空を歪める

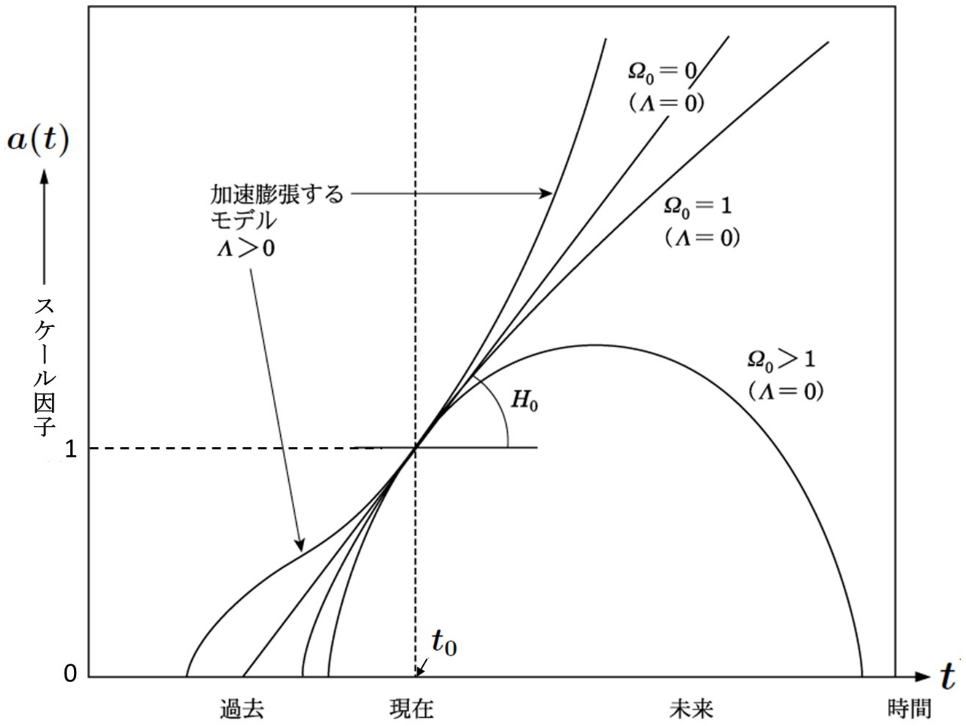
加速度 $$\boxed{\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\rho + \frac{\Lambda}{3}}$$ $\Rightarrow$ 速度 $$\left(\frac{\dot{a}}{a}\right)^2 + \frac{k}{a^2} = \frac{8\pi G}{3}\rho + \frac{\Lambda}{3}$$

アインシュタインは、静止宇宙にするため、宇宙項を導入
aは宇宙のスケール因子と呼ばれる

Accelerating Expansion ：2011 Nobel Prize in Physics

for the discovery of the accelerating expansion of the Universe
through observations of distant supernovae"





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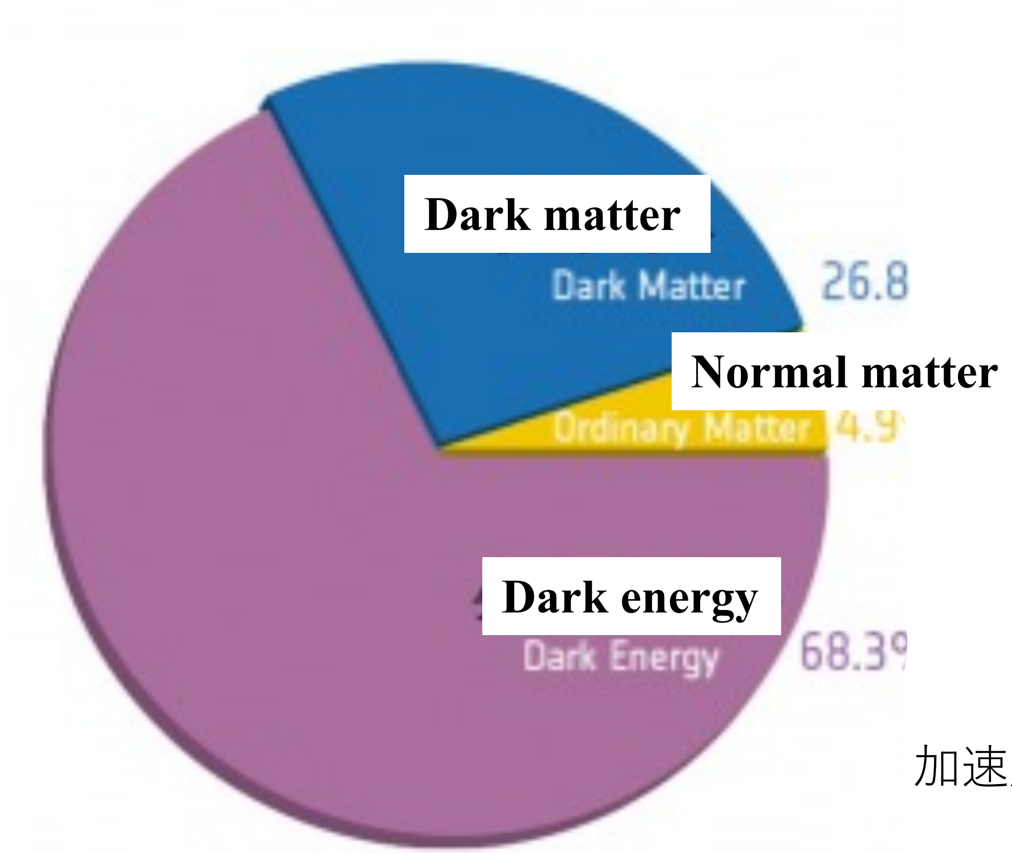

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Planetary Nebula

Protostellar Outflow

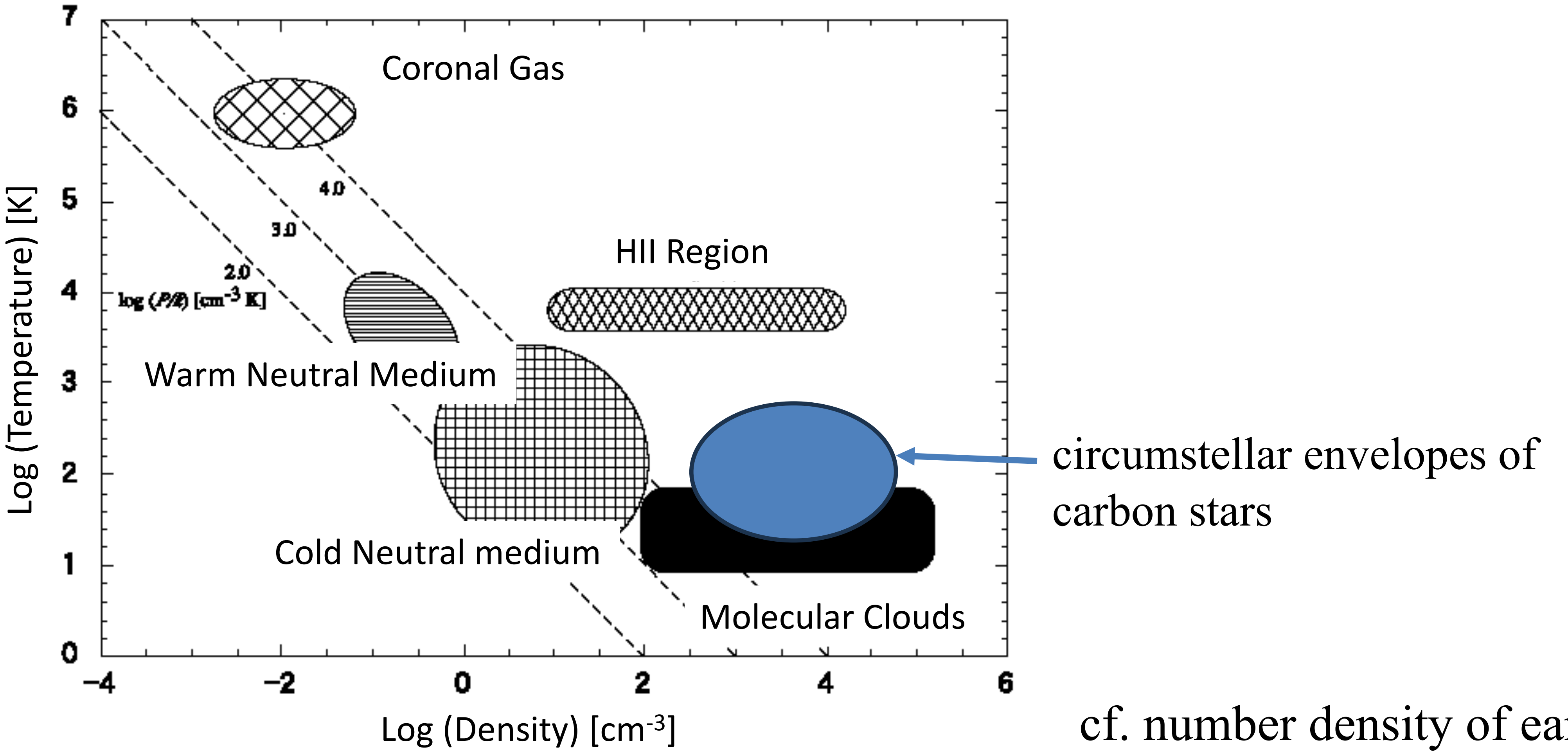
- Orion Nebular Cluster Region
- CO (J=1-0) image
- False color image

  green=cloud

  red=redshifted

  blue=blueshifted

Interstellar Medium (ISM) phase



From Chronological Scientific Tables

cf. number density of earth atmosphere at gound level is $\sim 3 \times 10^{19}$ cm^{-3}

Pressure Equilibrium?

Thermodynamics

Equation of State of the ideal gas

$P = n\, k_B\, T$

P = pressure

n = number density

k_B = Boltzmann constant

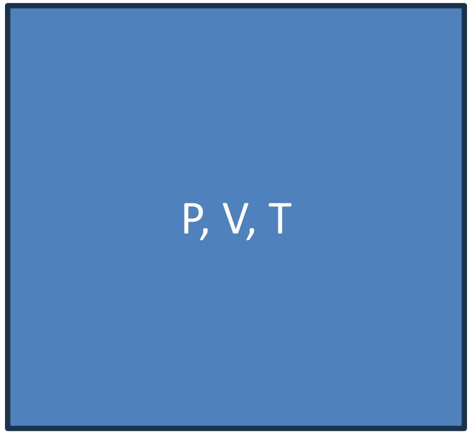
T =Temperature

$PV = n_{mol}\, R\, T$

n_{mol}=mol number

R=gas constant

V=volume



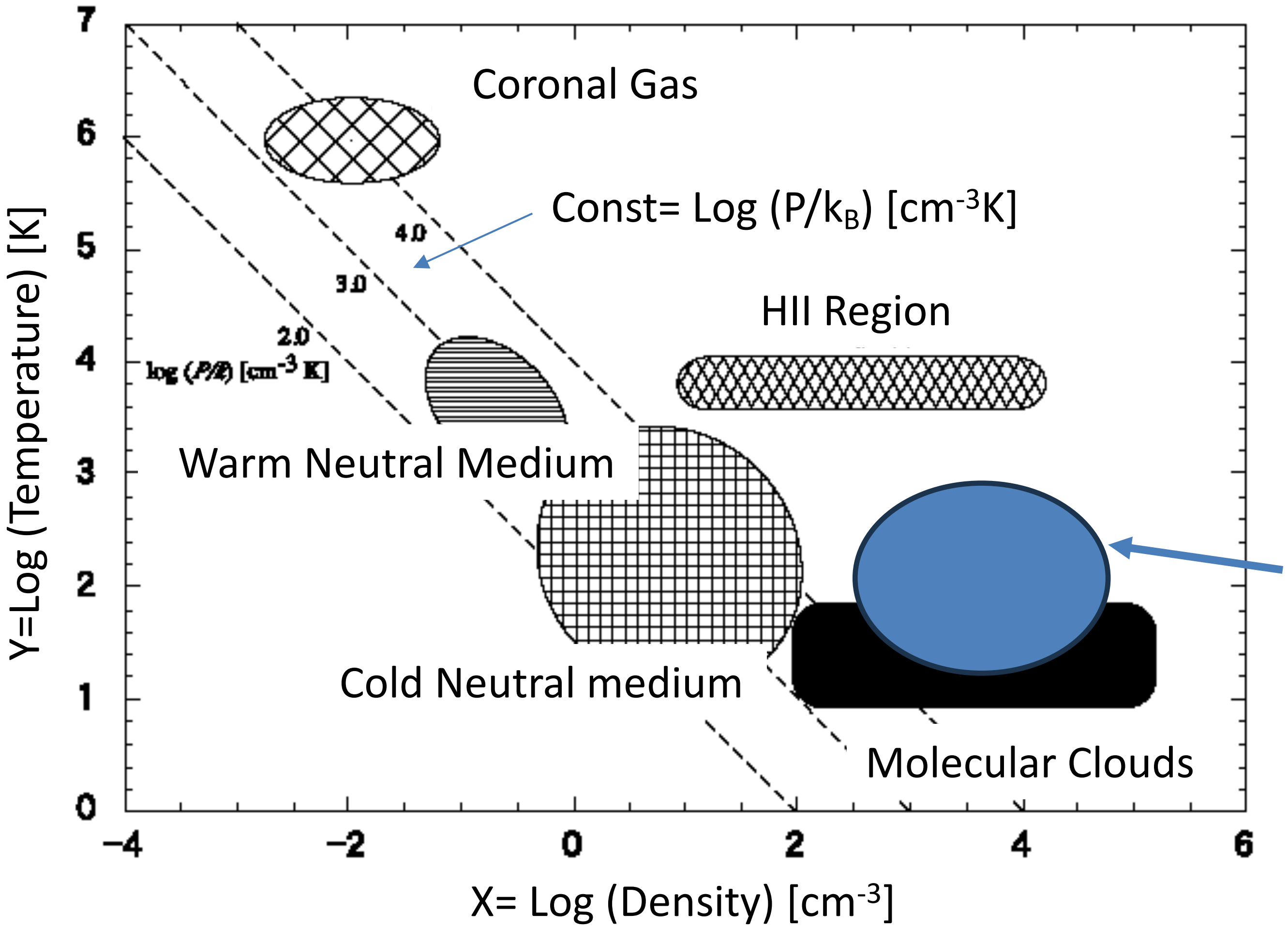
$$\log(P/k_B) = \log(n\, T)$$

$$\log(P/k_B) = \log(n) + \log(T)$$

$$\log(T) = -\log(n) + \log(P/k_B)$$

$$Y = -X + const$$

Interstellar Medium (ISM) phase



From Chronological Scientific Tables

Coronal, Warm Neutral Medium (WNM), and Cold Neutral Medium (CNM) are close to **pressure equilibrium**

HII regions and molecular clouds are out of this equilibrium

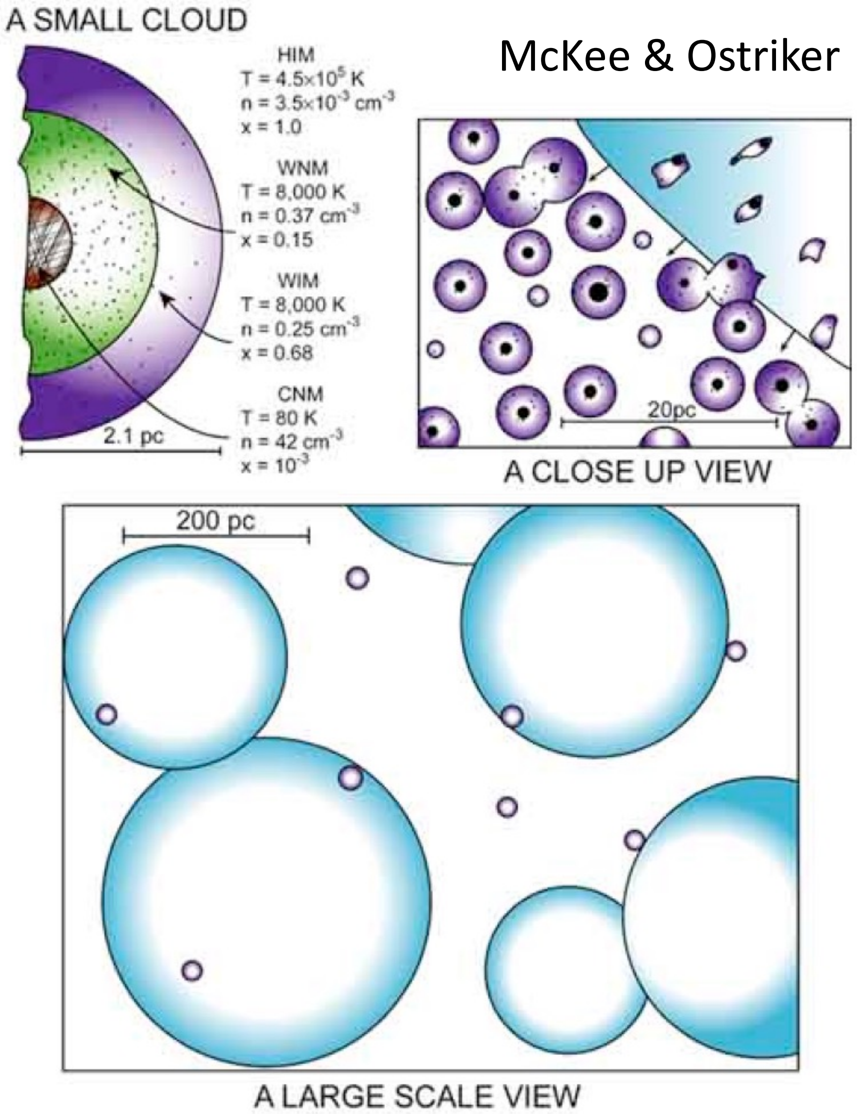
circumstellar envelopes of carbon stars

$$\log(T) = -\log(n) + \log(P/k_B)$$

cf. number density of earth atmosphere at gound level is $\sim 3 \times 10^{19}$ cm^{-3}

ISM three phase model

McKee & Ostriker



A small cloud contains a CNM core surrounded by WNM.
The small clouds are interacting with hot bubbles created by SNe.

Most volume is occupied by hot bubbles.

Molecular clouds contain most of the ISM mass but the volume fraction is tiny.

Radiation from ISMs

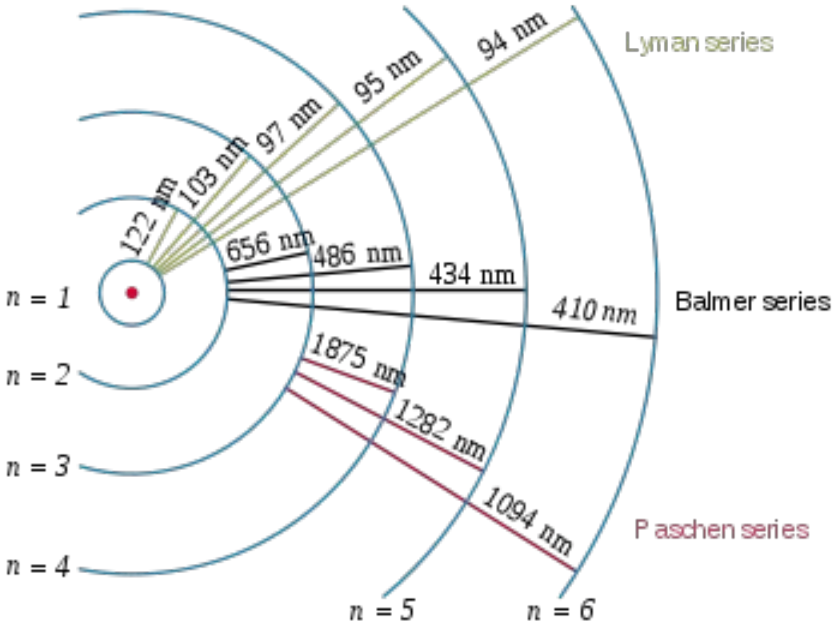
- ISMs emit or absorb line radiation whose strength is determined by ISM conditions such as ionization degree, density, and temperature.
- Astronomers use the information of radiation to study the ISM conditions.

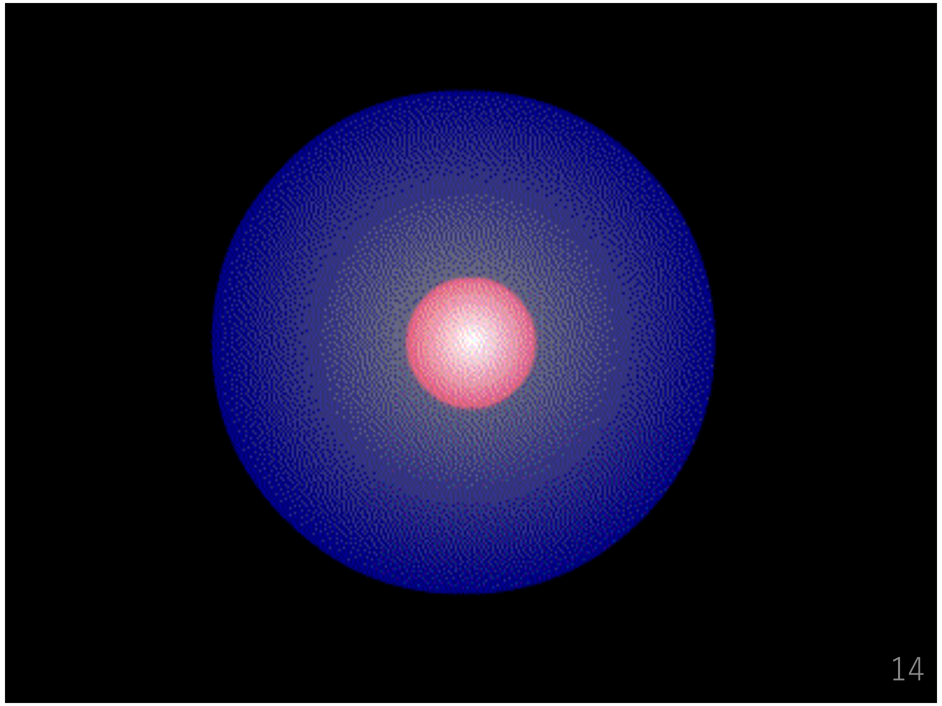
Emission and Absorption of Interstellar Gas

According to quantum mechanics, energy levels of atom and molecules are not continuous but **discrete**.

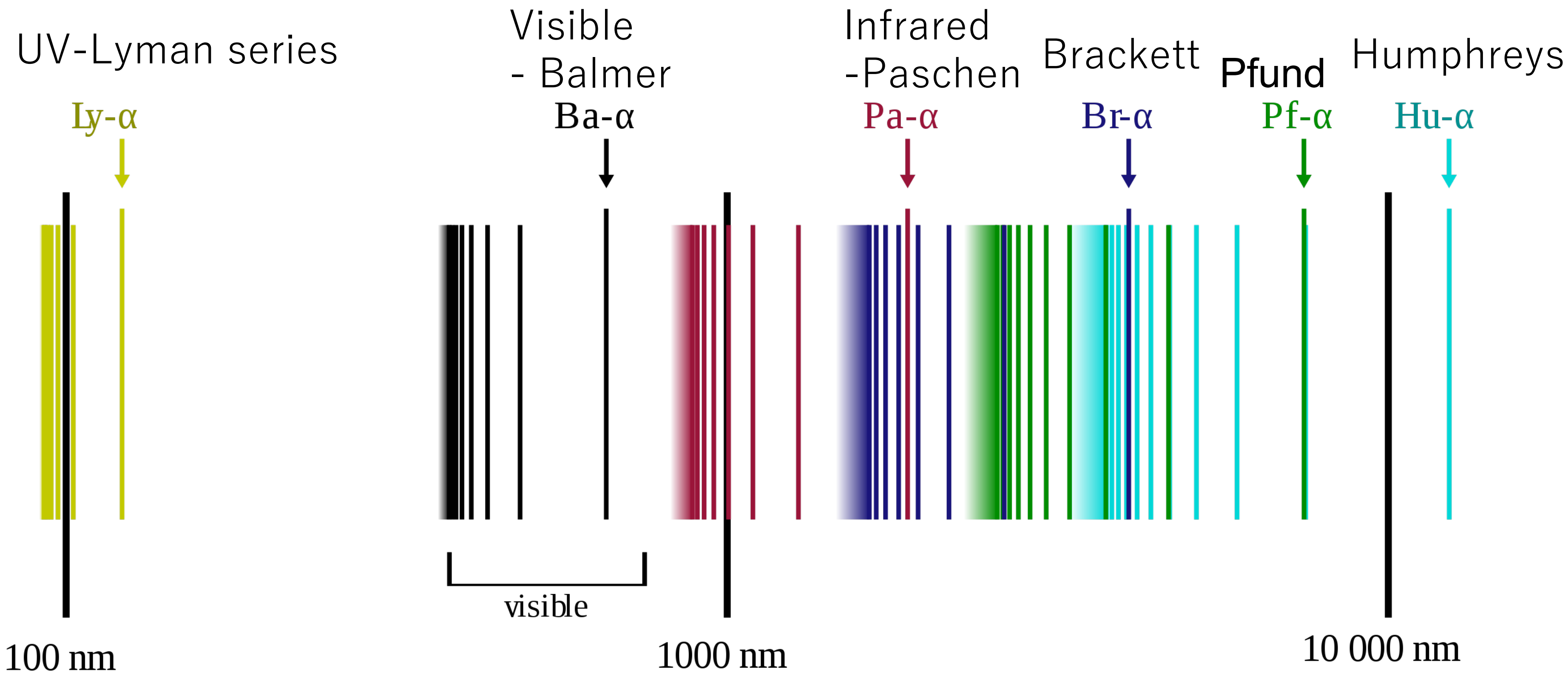
→

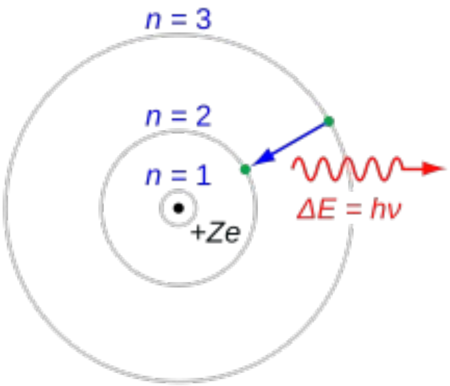
When atom transits from a high energy level to a low energy level, it radiates **line emission** with some specified wavelength, corresponding to the energy difference between both levels.





Dr. Phan Hien's lecture





H-alpha

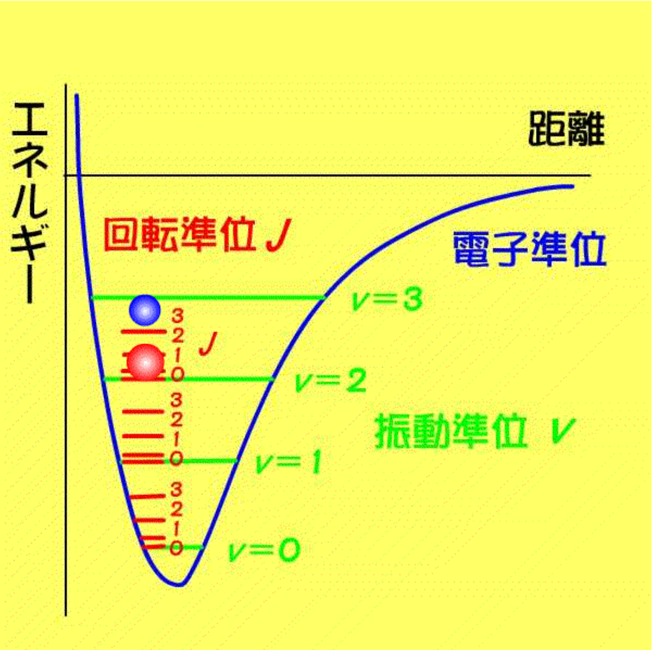
One of the most important lines in astronomy

656.46 nm

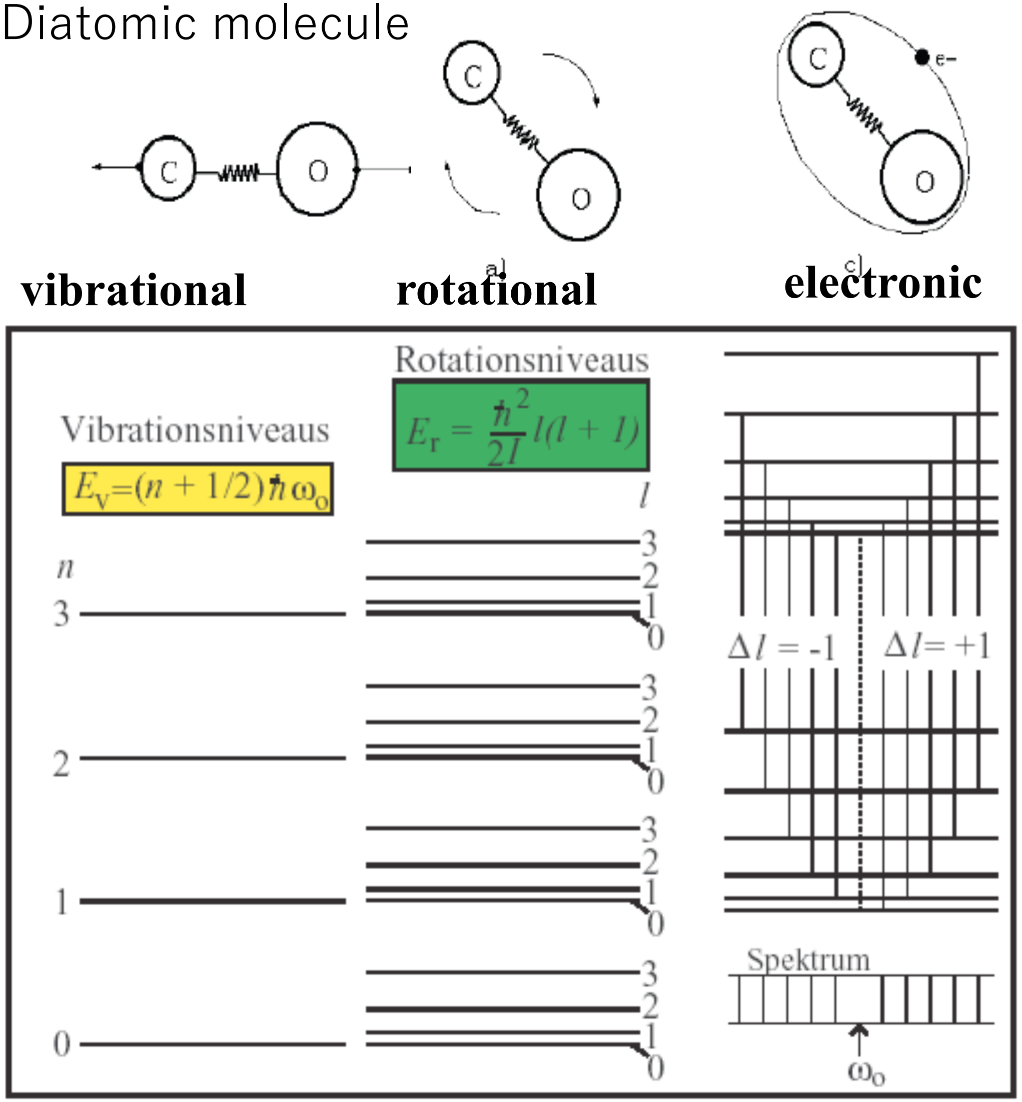
Energy Level for Molecules

$E_{rot} < E_{vib} < E_{elec}$

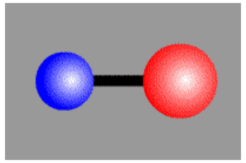
Radio infrared visible-UV

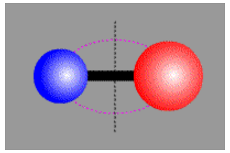


Diatomic molecule



Klessen (2010)





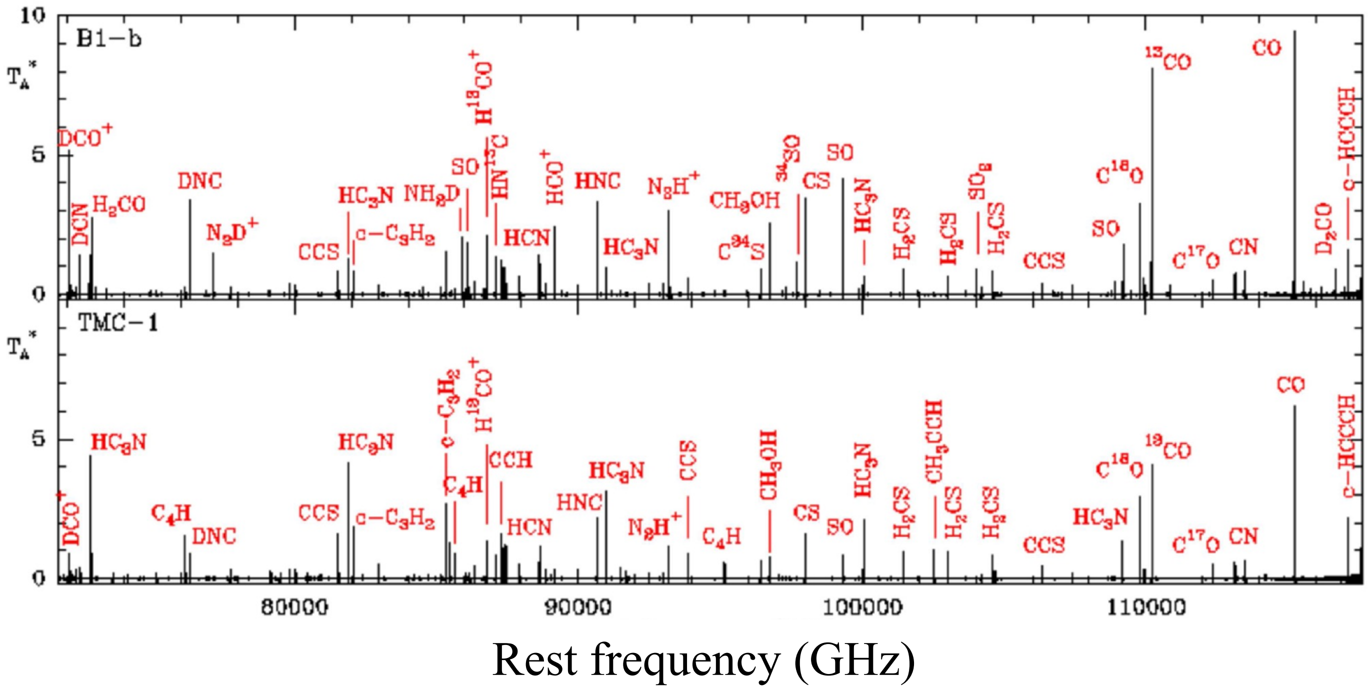
Molecules can **vibrate** or **rotate** around an axis.

Rotational motions have lowest energies
→ important for cold molecular clouds

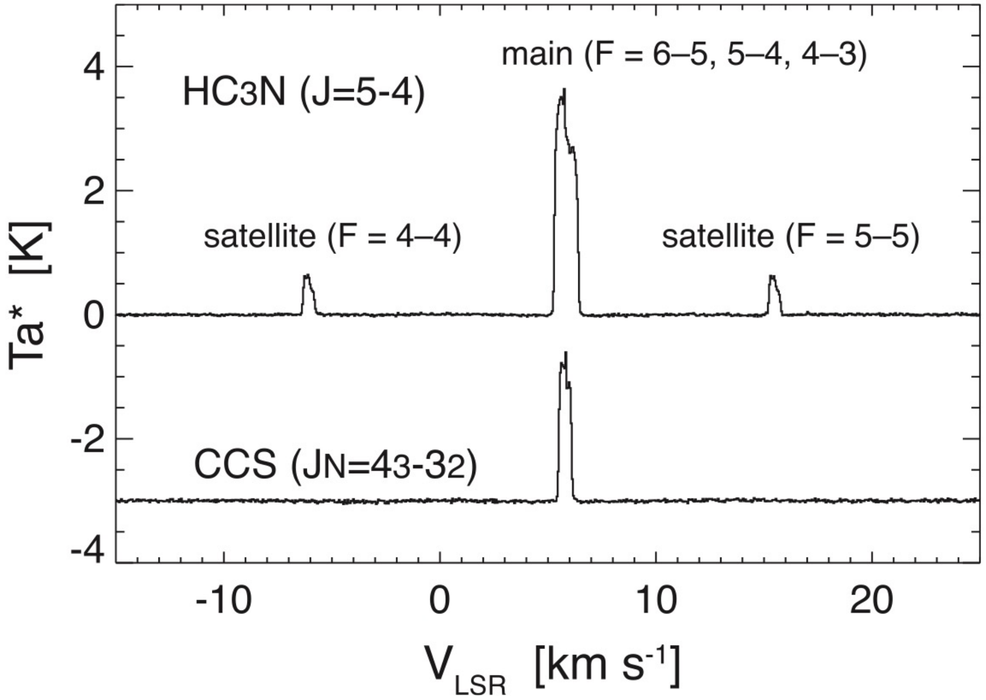
Example of molecular lines

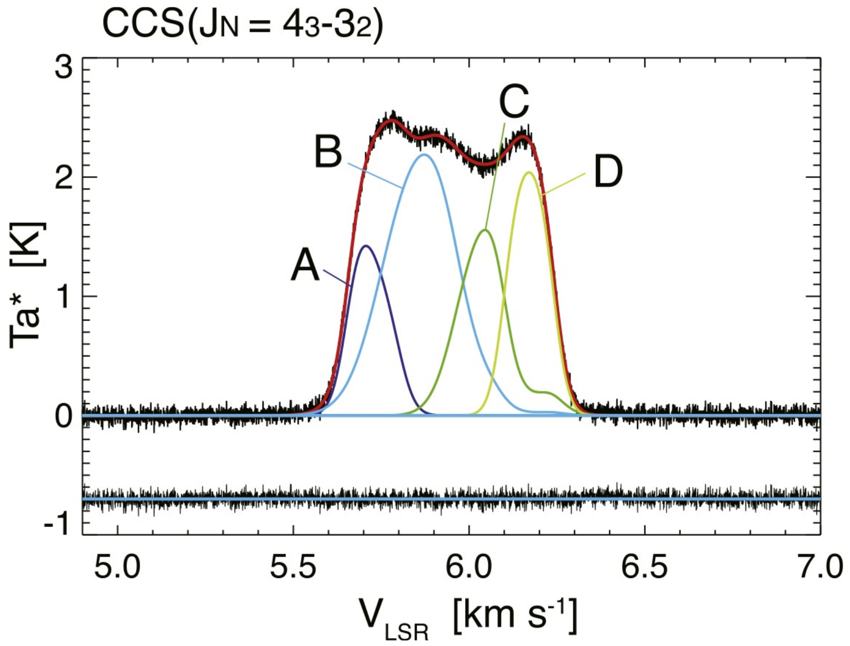
- The combination of atoms into molecules leads to the creation of unique types of energy states and therefore unique spectra of the transitions between these states.

- We can recognize the molecules from their lines!   Each line has an unique frequency which is called "rest frequency".



Detailed structure of molecular lines 1





Each line has **a finite width.**
The horizontal line is often shown with velocity.
The actual observed frequencies are shifted by the bulk motion of objects (Doppler effect).

Doppler effect

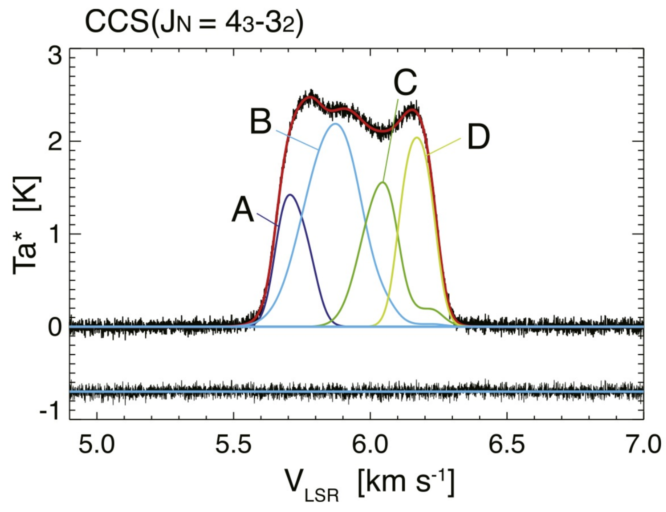
The Doppler effect is the relationship between an observed frequency and the radial velocity of the emitting source.
Velocities are usually calculated respect to the Local Standard of Rest (LSR), an ideal point in rotation around the Galactic center as far as the Sun.

The relationship between velocity and frequency is:

$$\frac{\Delta\nu}{\nu_0} = \frac{\nu_0 - \nu}{\nu_0} = \frac{V_0}{c}$$

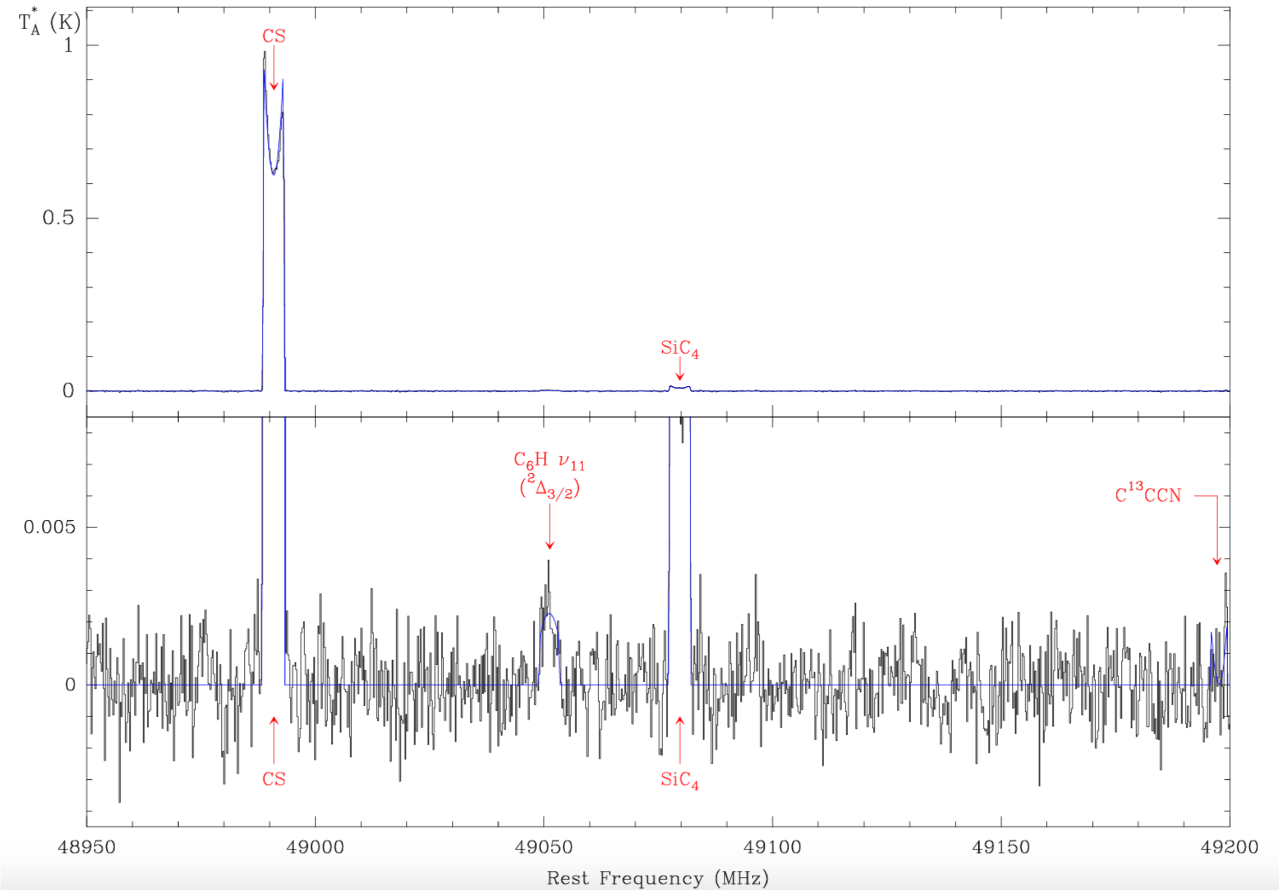
$$\underbrace{\nu}_{\text{Observed freq.}} = \underbrace{\nu_0}_{\text{rest freq.}} - \frac{V_0}{c}\nu_0$$

Therefore, observed frequencies of molecular lines shift respect to observer.



We can obtain the velocity information of objects.

Detailed structure of molecular lines 2



Carbon star IRC+10216

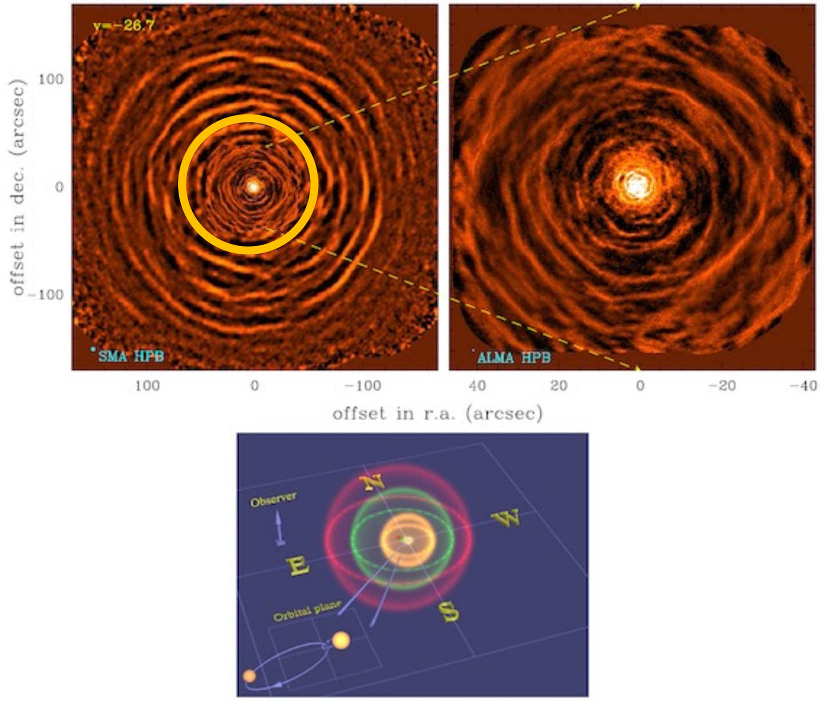


Figure 1: The CO(2-1) emission at the star velocity (v=-26 km s^{-1}) at different scales: *left frame* 380″ × 380″ SMA map (HPBW 3″) with, at its center, the 90″ × 80″ 27 field mosaic ALMA map; *center frame* ALMA map (HPBW 0.34″×0.31″) at an enlarged scale. *right frame* Schematic view of the 3 brightest shells of the IRC+10216 envelope and (at an enlarged scale) of the binary star system with a mass ratio 4:1 and eccentricity 0.92, orbiting in the plane of the sky. The blue dots show the SMA and ALMA half-power beam widths.

(1) The horizontal line is given in velocity.
(2)The line has a finite line width

The actual observed frequencies shift due to the bulk motion of objects.（Doppler effect)

Line Broadening

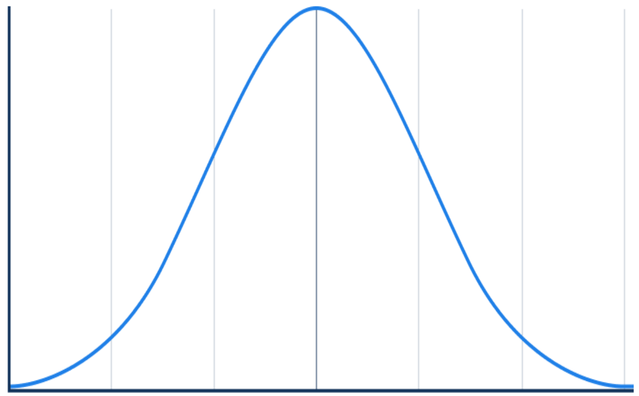
-intrinsic broadening (natural broadening)

each line has a narrow width that is related to the Heisenberg uncertainty principle

$$\Delta t \Delta E \sim \hbar$$

-thermal motion

Maxwell distribution



-Internal motion (supersonic turbulence)

for molecular clouds

- bulk motion such as expansion and contraction

circumstellar envelopes of carbon stars

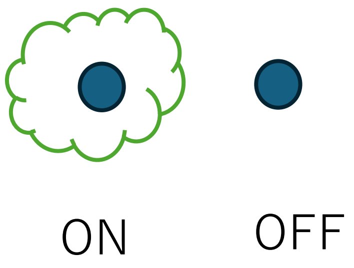
ON-OFF Observation

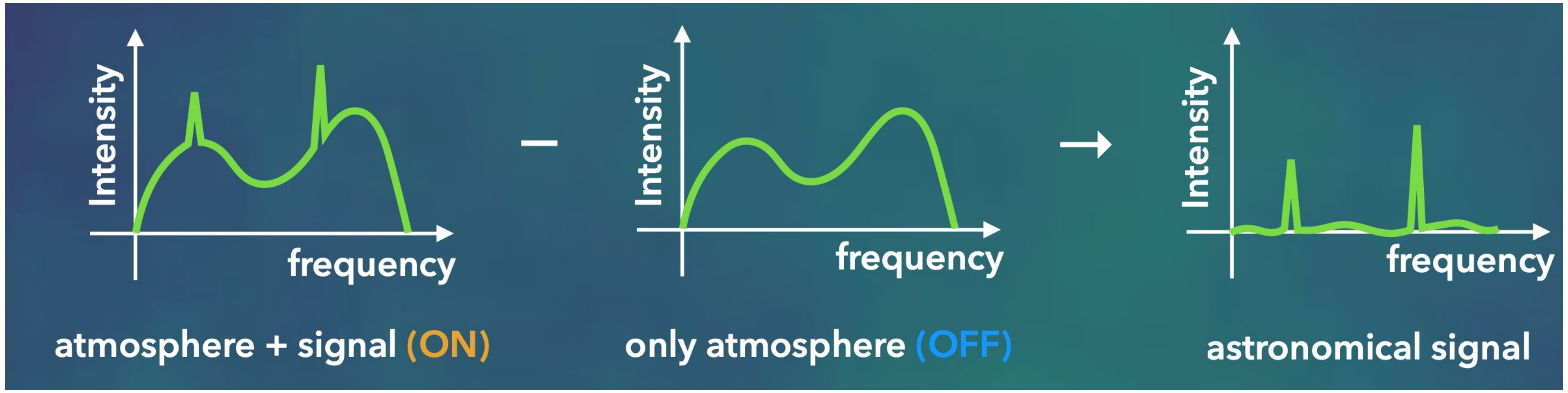
- Position-SWitching (PSW) observations

  ON : target observation

  OFF : Blank Sky Observation (Choose nearby position)

  reduced spectrum => ON-OFF





Extraction of physical quantities from spectral line data

- LTE analysis (analysis of optically thin molecular line)

  -Boltzmann distribution at each energy level

  -Rotational Diagram: Temperature, Column density

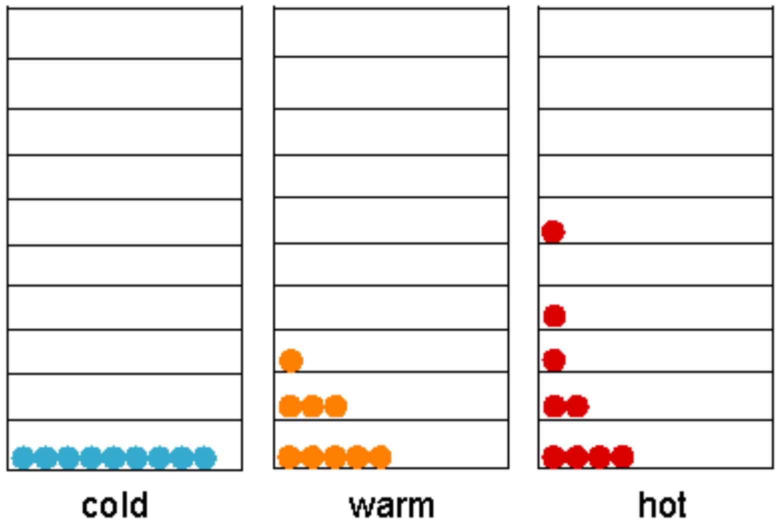
- Non-LTE analysis (analysis of optically thick lines)

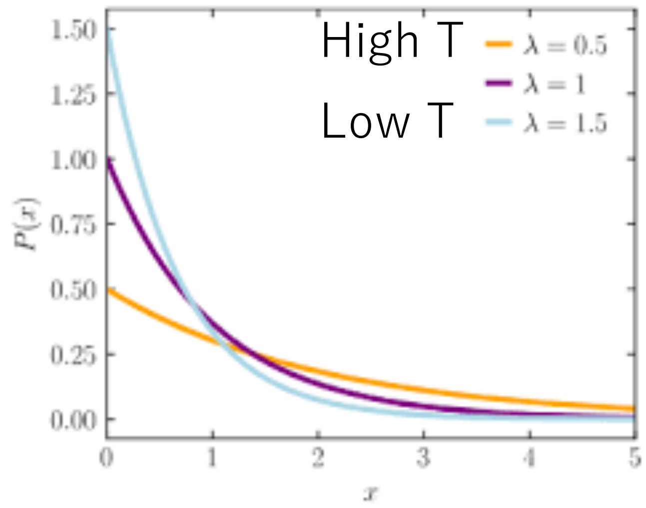
  It is necessary to simultaneously solve the statistical equilibrium equation for the molecular energy levels and the radiative transfer equation.

  -RADEX (van der Tak et al. 2007, A&A, 468, 627)

  https://var.sron.nl/radex/radex.php

Local Thermodynamic Equilibrium





Exp (-λx), λ = 1/kT

The population at each energy level follows the Boltzmann distribution which is approximated by a single temperature

$$P_i = \frac{g_i e^{-\frac{\varepsilon_i}{kT}}}{\sum_i g_i e^{-\frac{\varepsilon_i}{kT}}}$$

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  -Rotational Diagram: Temperature, Column density

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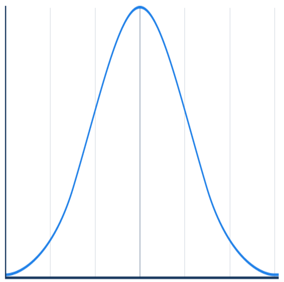
Column Density Estimation

$$N_{\rm tot}^{\rm mol} = \frac{3k}{8\pi^3 \nu \mu_s^2 S} \frac{Q_{\rm rot}(T_{\rm ex})}{g_u} \exp\left(\frac{E_u}{kT_{\rm ex}}\right) \int T_{\rm S} dV$$

$g_u = 2J_u + 1$

Integrated intensity (from obs)

μ_s is the dipole moment, S is the line strength,
$\mu^2 S$ is the line strength in Debye unit
E_u/k is the upper energy in unit of K,
$Q_{rot} = kT/hB$ is the rotational partition function, and B is the rotational constant.



Assuming the T_{ex}, we can derive column density from the observed integrated intensity.

Dr. Tomomi Shimoikura's lecture

Rotational Diagram

Assuming the Boltzmann distribution and optically thin

$$N_u = N_{\mathrm{tot}} \frac{g_u}{Q(T)} \exp\left(-\frac{E_u}{kT}\right)$$

Partition function $Q(T) = \Sigma_i g_i \exp\left(-\frac{E_i}{kT}\right)$

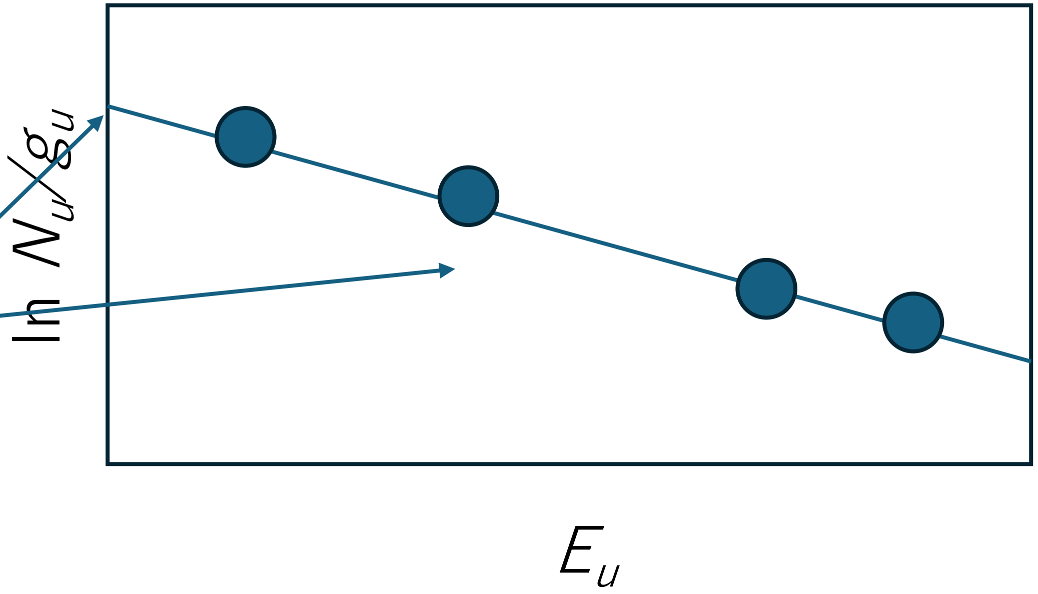
Subscript u indicates the energy state at u

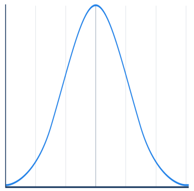
$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{tot}}{Q(T)}\right) - \frac{E_u}{k_B T}$$

$$\ln\frac{N_\mathrm{u}}{g_\mathrm{u}} = \ln\frac{3k\int T_\mathrm{S} dv}{8\pi^3 \nu \mu^2 S}$$

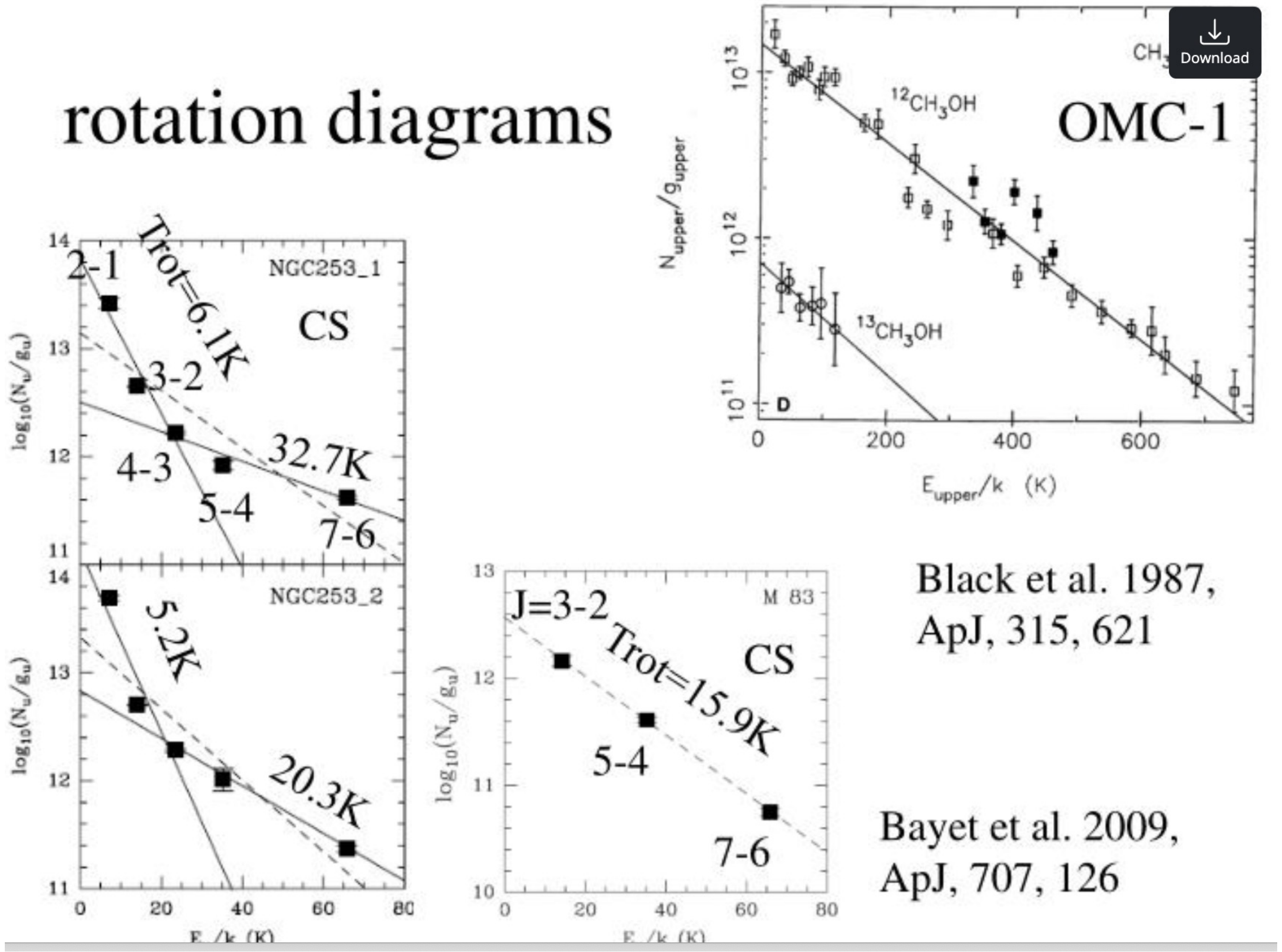
Slope => $-1/k_B T$

Intersept => N_{tot}





Example of Rotational Diagram



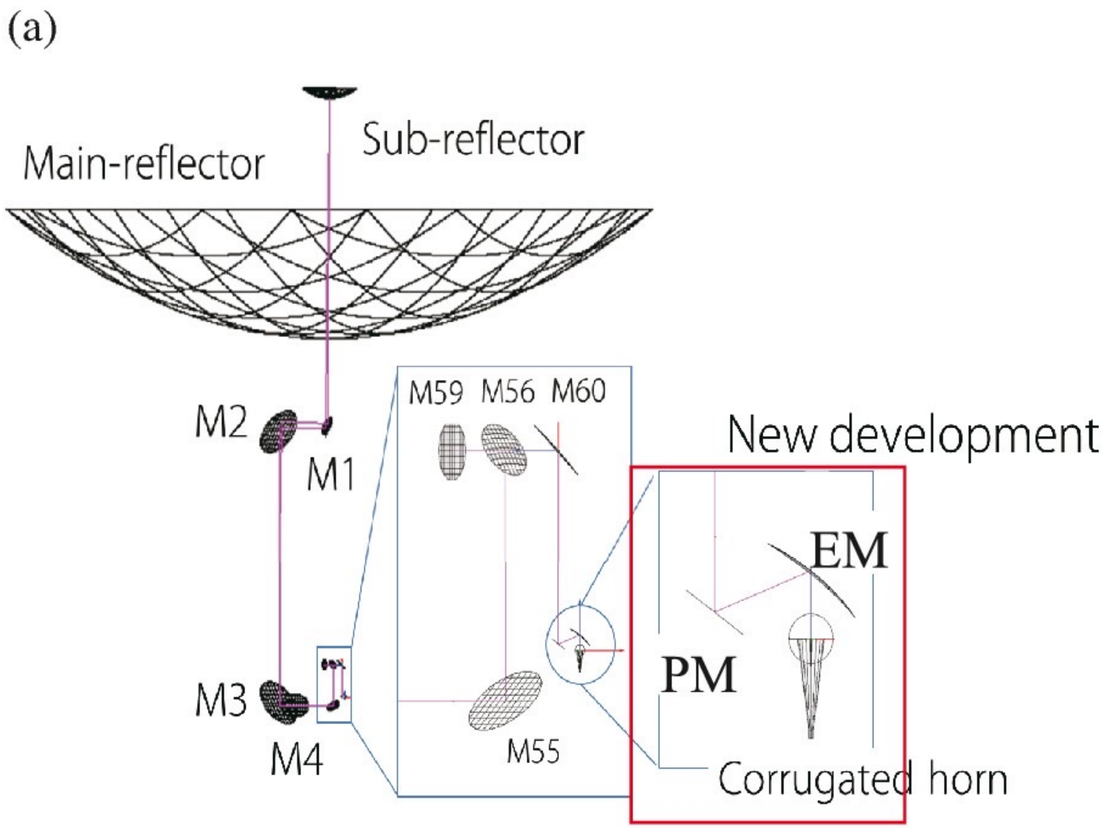
Observations of Carbon Stars and Star-Forming Regions using Molecular Line Emission

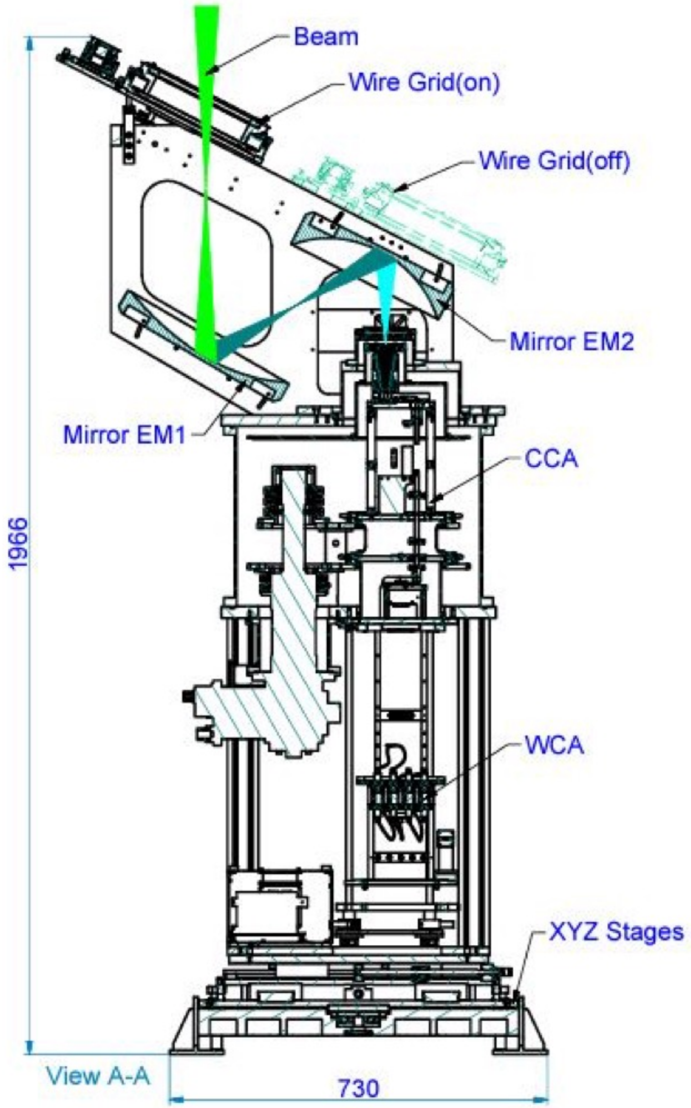
NAOJ and Nobeyama 45m telescope

- One of the largest single dish telescopes
- 30-40 GHz (eQ)
- ~100 GHz (e.g., CO (J=1-0))

2021 11/25
eQ installation
@45m cabin

Fig. 2. (a) Optics and the beam propagation design of the NRO 45-m telescope. PM and EM denote the plane and ...





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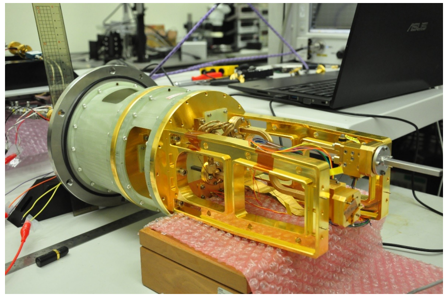
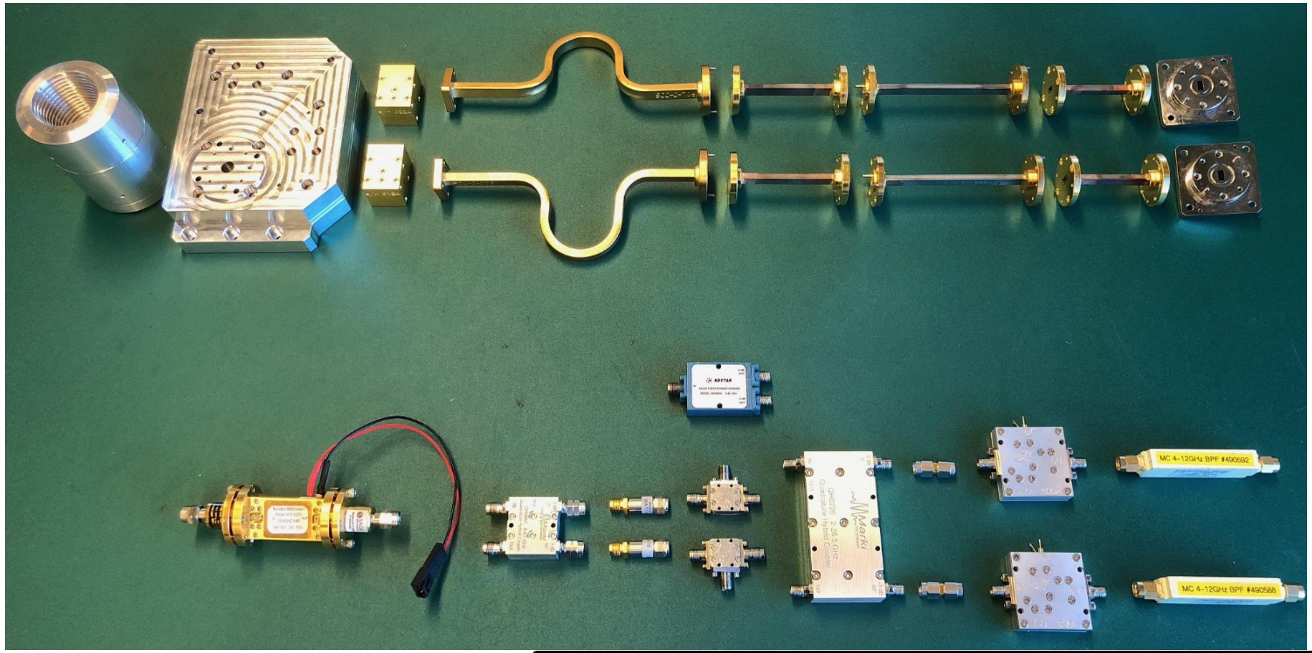
System Diagram





- Follow Band 1 architecture
- New:
  - 2SB feature
  - RF: 30-50 GHz
  - Wider Feedhorn
  - Wider OMT
- All components are verified

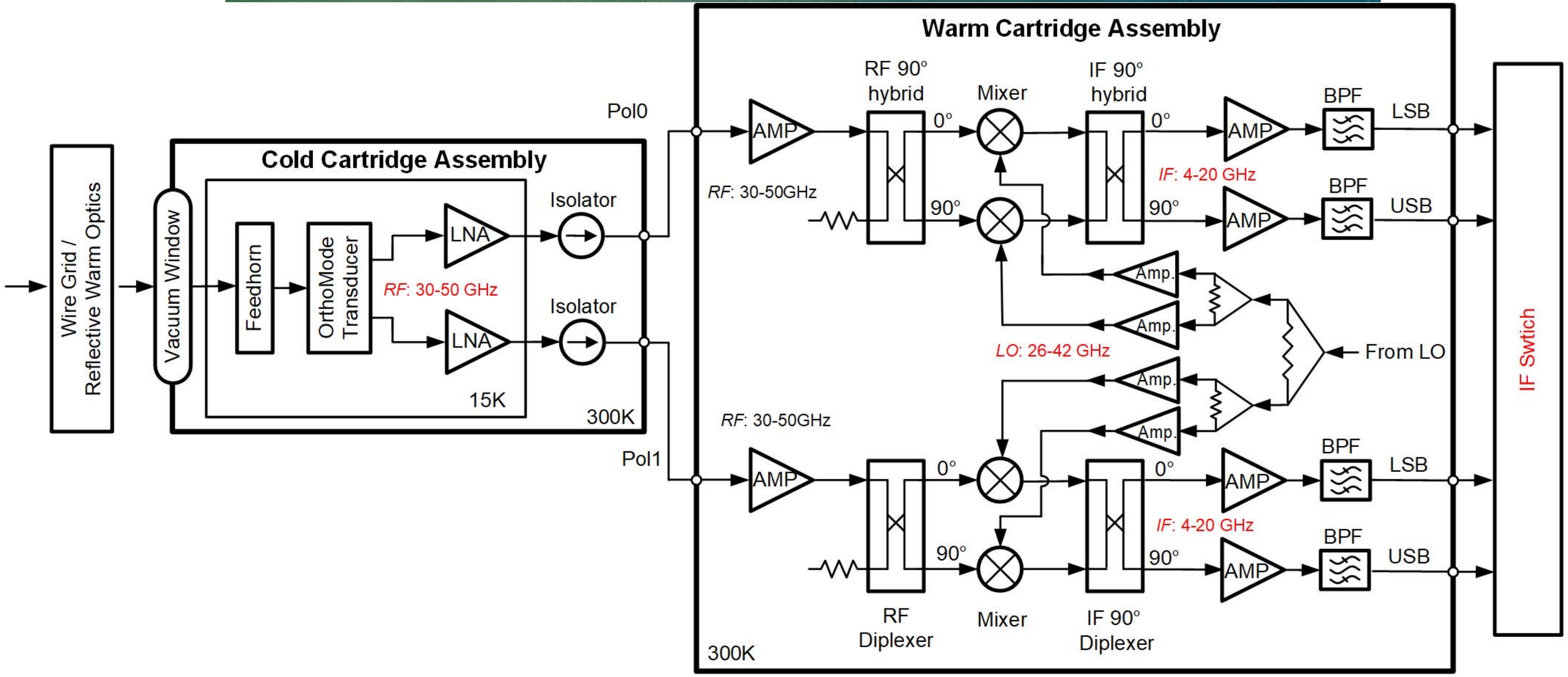


Table 2. Comparison of 30–50 GHz receivers for large single-dish telescopes.

	Green Bank[1]		Effelsberg[2]	Yebes[3]	Tianma[4]	NRO[5]
Dish diameter	100m		100m	40m	65m	45m
σ_{RMS}	240μm		550μm	175μm	2470μm	100μm
η_A	0.58–0.64	0.63–0.67	0.18–0.27	0.59–0.67	0.45–0.55 (43 GHz)	0.50–0.62
Receiver name	Q-band	Ka-band	S7mm	Q-band	Q-band	eQ
Frequency (GHz)	38–50	26–40	33.5–50	31–50	35–50	30–50
Beam	Two-beam	Two-beam	Two-beam	Single pixel	Two-beam	Single pixel
Feed	Dual circular	Single linear	Dual linear	Dual circular	Dual linear	Dual linear
T_{RX}	20–45 K	10–40 K	–	15–40 K	30–40 K	13–25 K
T_{sys} (Zen.)	67–160 K	50–120 K	110–187 K	50 K (32.5 GHz) 110 K (48.5 GHz)	80 K (43 GHz)	30 K (33 GHz) 75 K (43 GHz)
CCS (45 GHz)*	○	×	○	○	○	○
CCS (33 GHz)*	×	○	○	○	○	○
SO (30 GHz)*	×	○	×	×	×	○

Trx = receiver noise temperature
Tsys = system noise temperature

Nakamura et al. 2024

eQ is the receiver having highest sensitivity (lowest Trx and Tsys) and widest bandwidth (30-50 GHz)

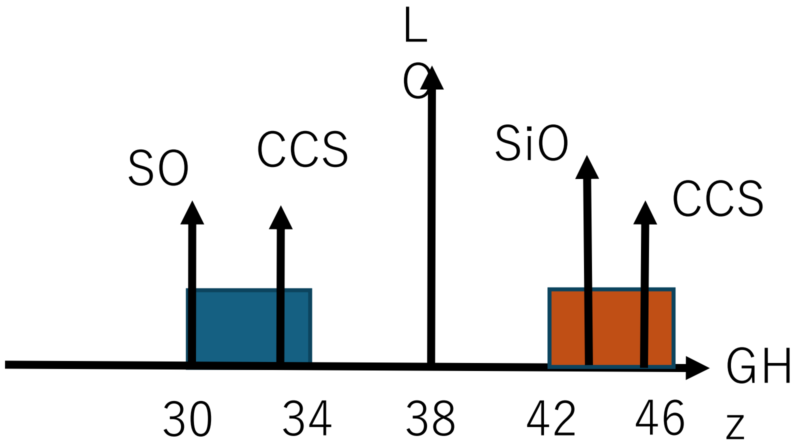
Science Highlight

- Zeeman measurement：($SO(1_0\text{-}0_1)$, $CCS(3_2\text{-}2_1)$, $CCS(4_3\text{-}3_2)$)
- High-z CO detection with CO(1-0) (z=1.30-2.83) and CO(2-1) (z=3.60-6.67)
- Astrochemistry

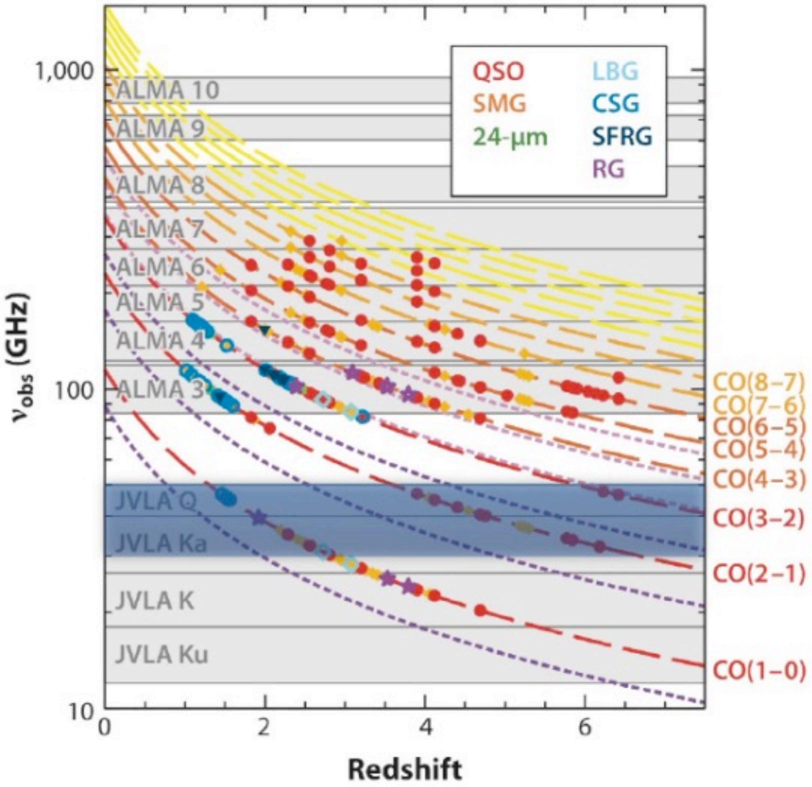
  Carbon chain chemistry toward ISM

  Direct probing first cores via CH_3OH

and many others science cases where high sensitivities are needed….



CH_3OH Transition	Frequency (GHz)	E_u (K)
$2_0\text{-}3_1$ E v_t=1	44.955778	299.624
$1_0\text{-}0_0$ E v_t=1	48.247572	294.993
$1_0\text{-}0_0$ A^+ v_t=1	48.257302	425.963
$1_0\text{-}0_0$ A^+ v_t=0	48.372456	2.322
$1_0\text{-}0_0$ E v_t=0	48.376889	7.547



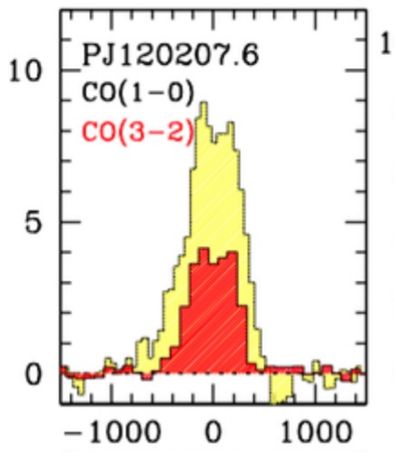
Approximate frequency (GHz)	Line ID (molecule or atom)	Transition	Exact rest frequency (MHz)	
30.00	SO	1(0) – 0(1)	30 001.547	L
31.22	H	59 α	31 223.313	S
31.95	HC_5N	12 – 11	31 951.777	L
32.85	H	58 α	32 852.196	S
33.75	CCS	3,2 – 2,1	33 751.370	L
34.60	H	57 α	34 596.383	S
34.61	HC_5N	13 – 12	34 614.385	L
35.07	CH_2NH	3(0,3) – 2(1,2) gp	35 065.545*	J
35.27	$H^{13}CCCN$	4 – 3 group	35 267.440*	L
36.17	CH_3OH	4(−1,4) – 3(0,3) E	36 169.290	L
36.39	HC_3N	4 – 3 group	36 392.365*	L
36.47	H	56 α	36 466.26	S
36.49	OCS	3 – 2	36 488.813	L
36.80	CH_3CN	2(0) – 1(0) gp	36 795.568*	L
37.28	HC_5N	14 – 13	37 276.985	L
38.47	H	55 α	38 473.358	S
38.506	CH_3CHO	2(0,2) – 1(0,1) E	38 506.035	L
38.512	CH_3CHO	2(0,2) – 1(0,1) A	38 512.081	L
39.36	CH_3CHO	2(1,1) – 1(1,0) E	39 362.533	J
39.59	CH_3CHO	2(1,1) – 1(1,0) A	39 594.292	J
39.73	NH_2CN	2(1,2) – 1(1,1), $v=0$	39 725.3811	J
39.94	HC_5N	15 – 14	39 939.574	L
40.25	CH_2CN	2 – 1 group	40 253.884*	L
40.63	H	54 α	40 630.498	S
40.88	NH_2CHO	2(1,2) – 1(1,1) gp	40 875.2766*	J
42.39	NH_2CHO	2(0,2) – 1(0,1) gp	42 386.070*	J
42.60	HC_5N	16 – 15	42 602.153	L
42.67	HCS^+	1 – 0	42 674.197	L
42.77	$HOCO^+$	2(0,2) – 1(0,1)	42 766.1975	L
42.88	^{29}SiO	1 – 0 $v=0$	42 879.922	L
42.95	H	53 α	42 951.968	S
43.42	SiO	1 – 0 $v=0$	43 423.864	L
43.96	HNCO	2(0,2) – 1(0,1) gp	43 962.998*	L
44.07	CH_3OH	7(0,7) – 6(1,6) A+	44 069.476	L
44.08	$H^{13}CCCN$	5 – 4	44 084.172	L
45.26	HC_5N	17 – 16	45 264.720	L
45.30	$HC^{13}CCN$	5 – 4	45 297.346	L
	$HCC^{13}CN$	5 – 4	45 301.707*	L
45.38	CCS	4,3 – 3,2	45 379.029	L
45.45	H	52 α	45 453.719	S
45.49	HC_3N	5 – 4 group	45 490.316*	L
46.25	^{13}CS	1 – 0	46 247.580	L
47.93	HC_5N	18 – 17	47 927.275	L
48.15	H	51 α	48 153.597	S
48.21	$C^{34}S$	1 – 0	48 206.946	L
48.37	CH_3OH	1(0,1) – 0(0,0) A+	48 372.467*	L
	CH_3OH	1(0,1) – 0(0,0) E	48 376.889	L
48.65	OCS	4 – 3	48 651.6043	L
48.99	CS	1 – 0	48 990.957	L

Extra-galactic survey –high-z CO detection

High-z CO (J=1-0) detection

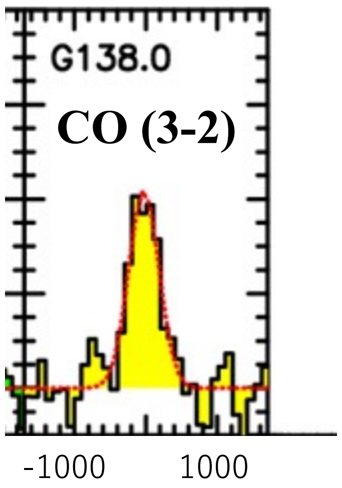
Our CO detection from high-z object

GBT 100m



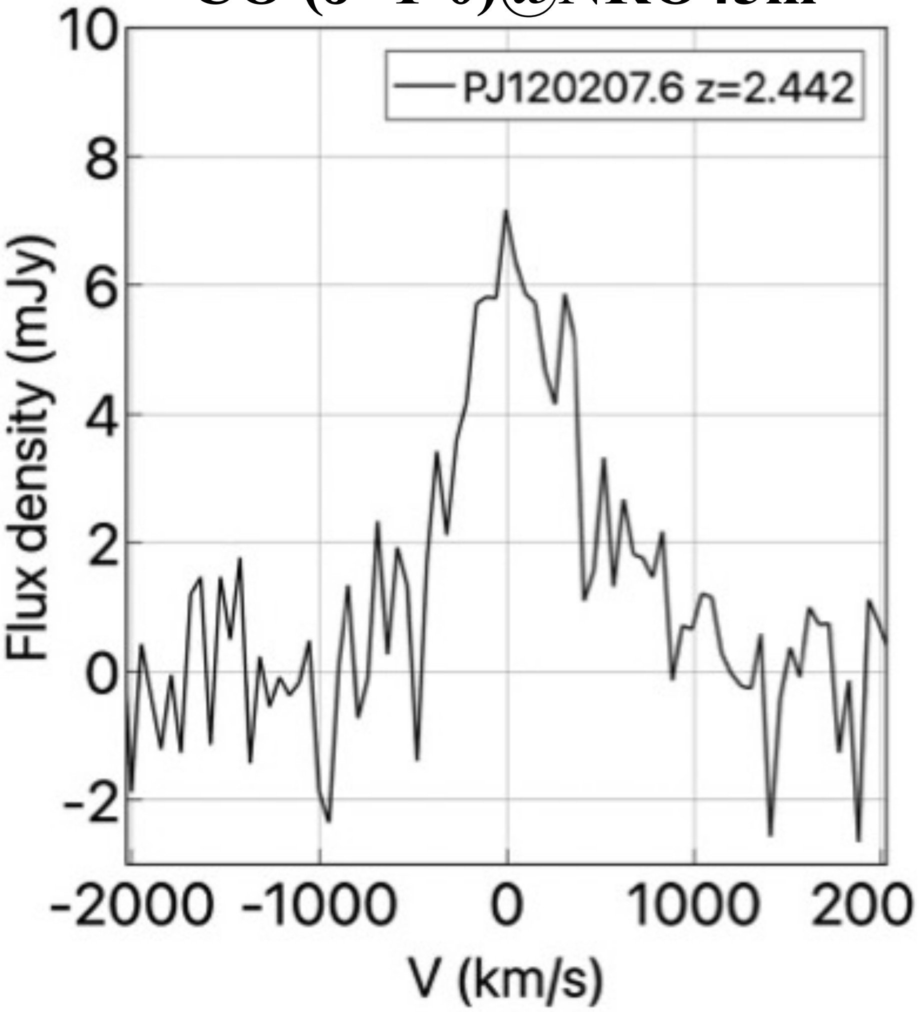
Harrington et al. (2018)

IRAM 30-m



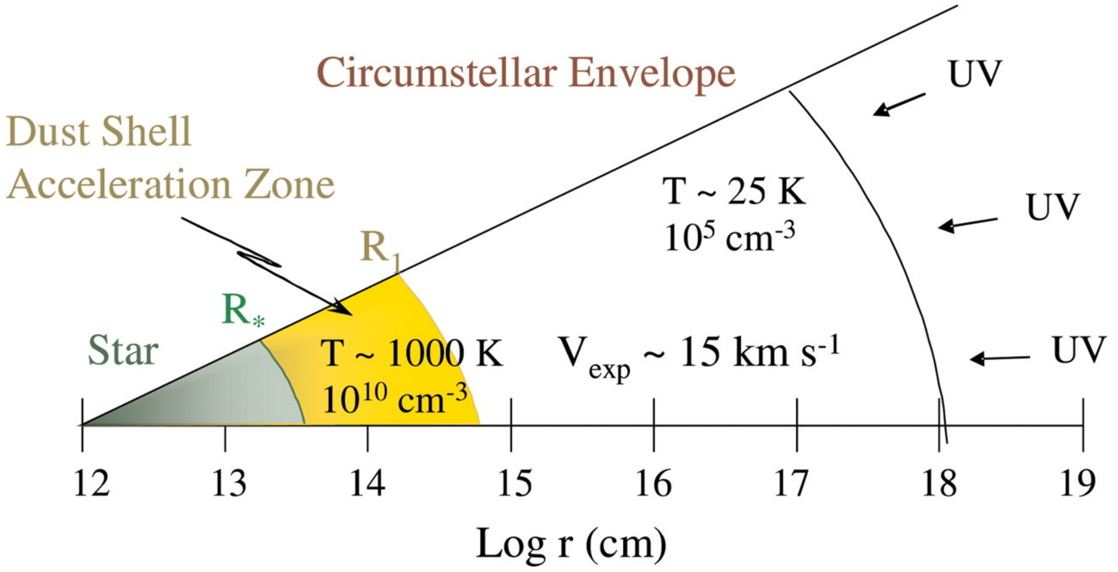
Cañameras et al. (2015)

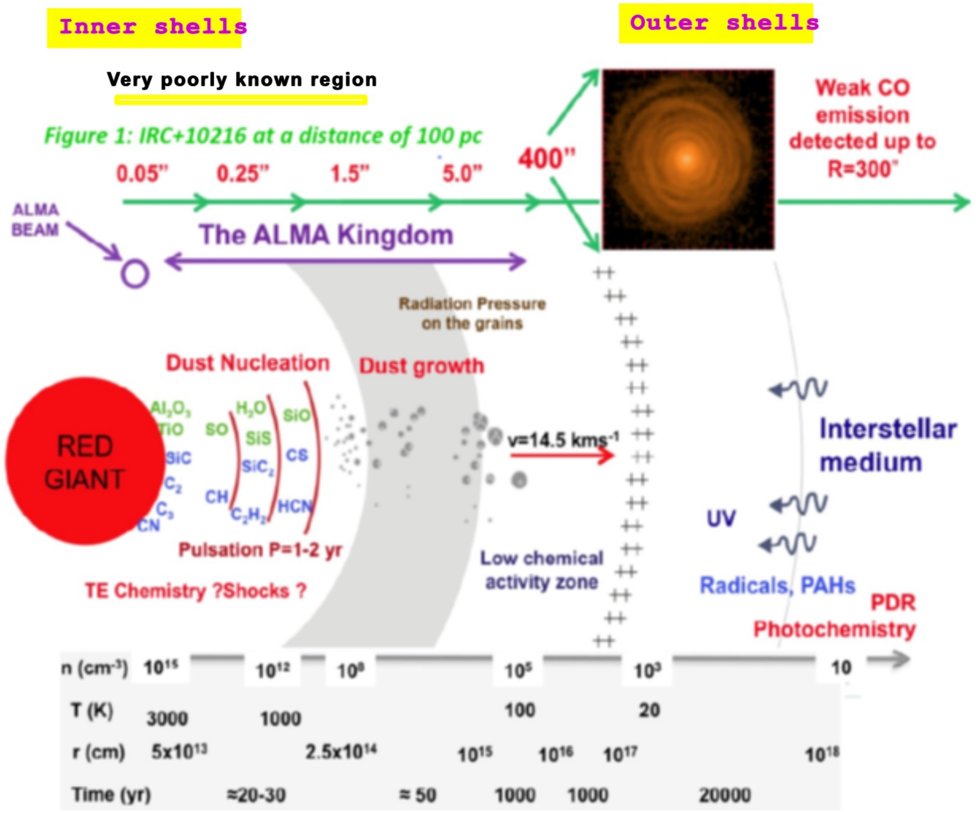
CO (J=1-0)@NRO45m



Carbon Star

A **carbon star** (**C-type star**) is typically an asymptotic giant branch (AGB) star, a luminous red giant, whose atmosphere contains more carbon than oxygen (C > O).
Important for galactic chemical evolution
Formation of dust particles (e.g., SiC) and complex organic molecules (carbon-chain molecules, HC3N, CCS,)





IRC+10216

CIT6

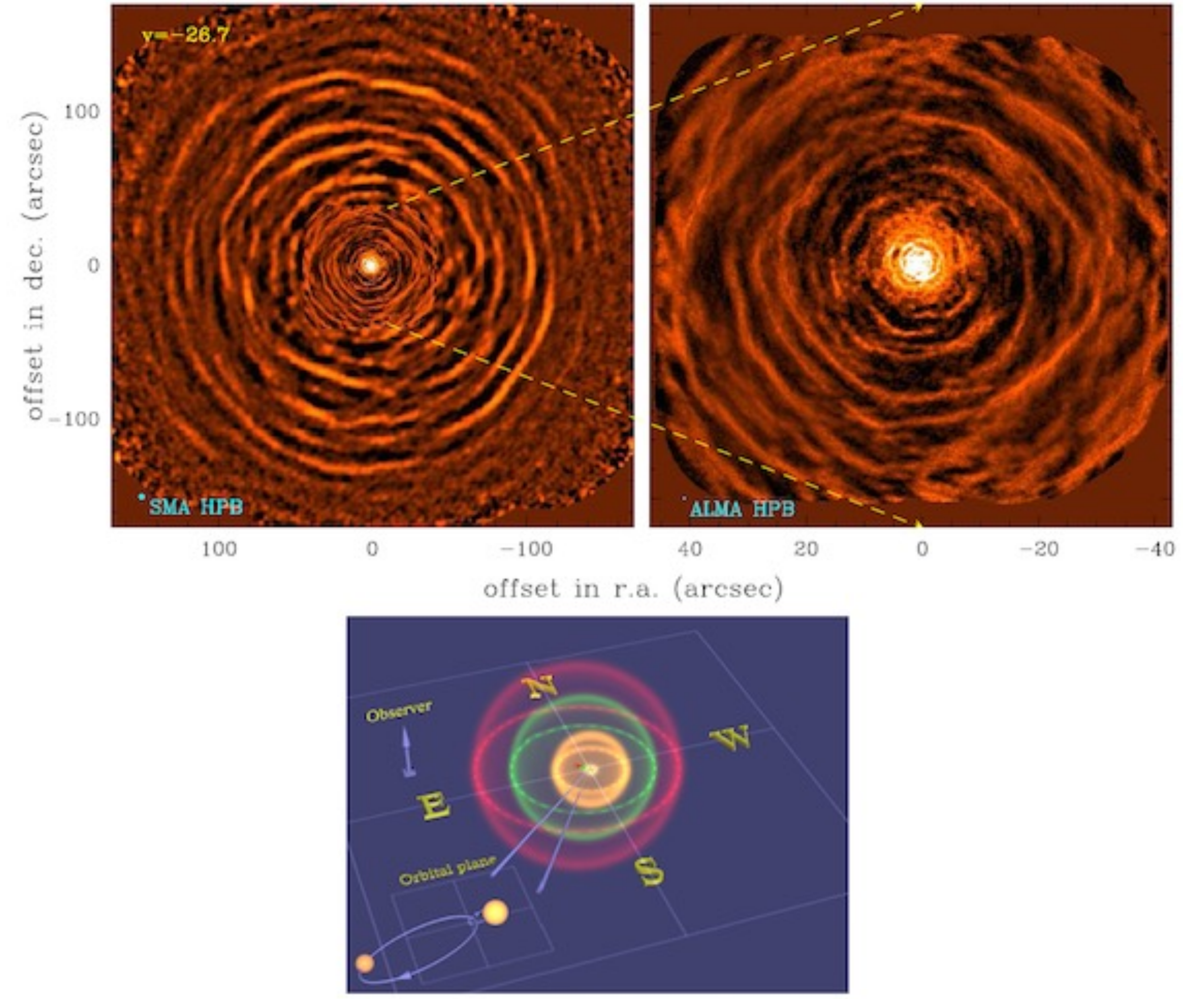
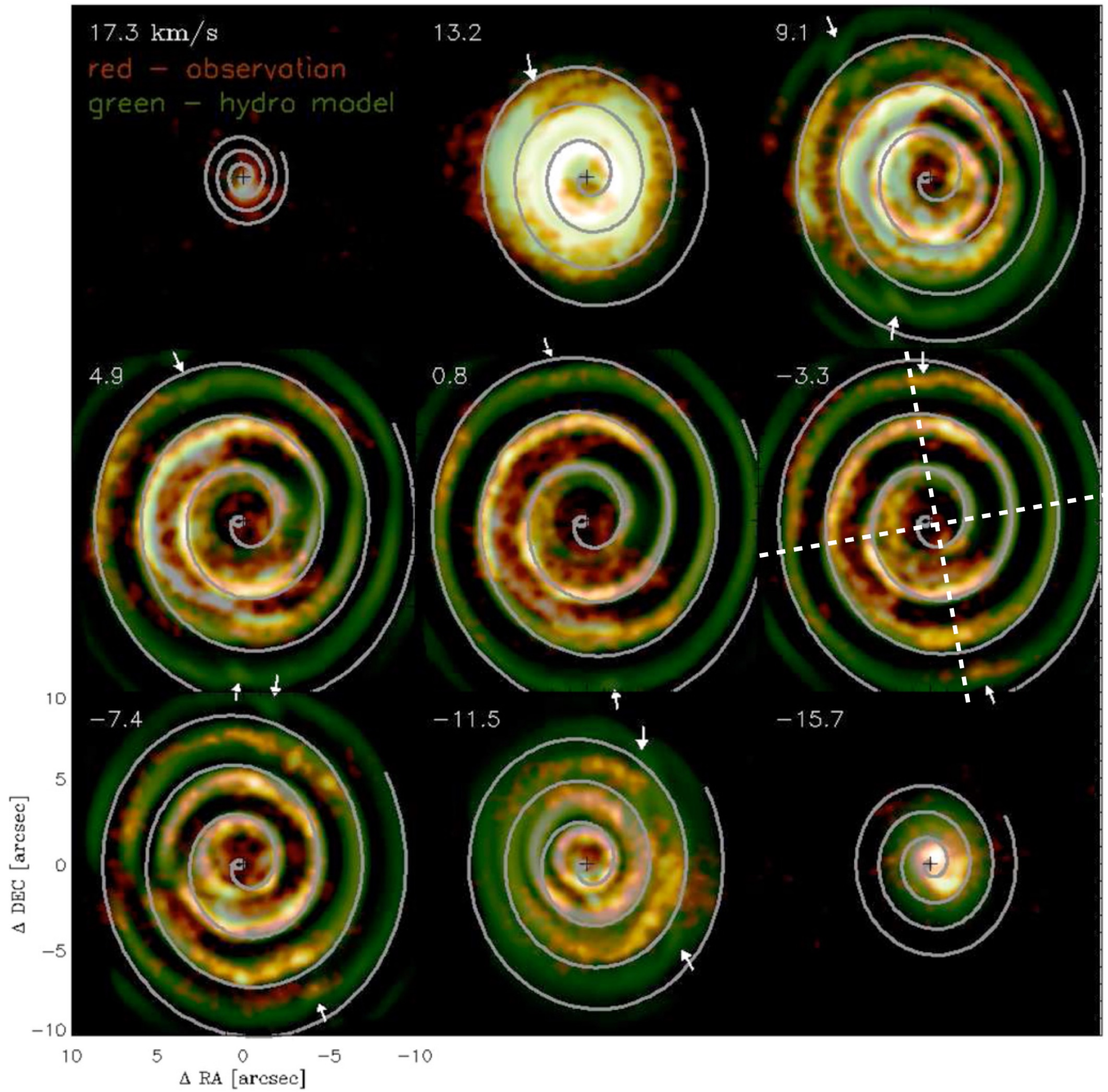
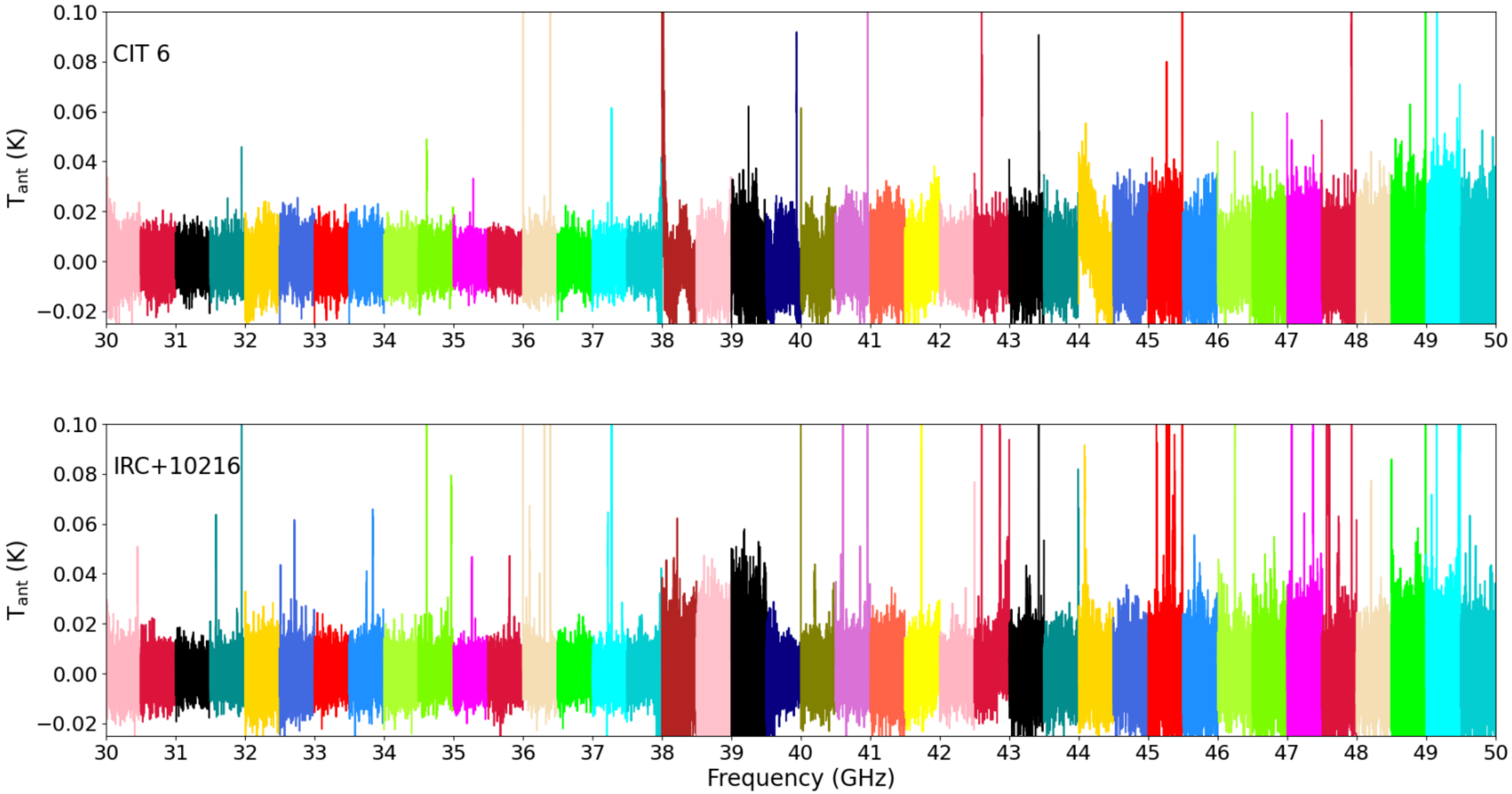


Figure 1: The CO(2-1) emission at the star velocity (v=-26 km s^{-1}) at different scales: *left frame* 380″ × 380″ SMA map (HPBW 3″) with, at its center, the 90″ × 80″ 27 field mosaic ALMA map; *center frame* ALMA map (HPBW 0.34″×0.31″) at an enlarged scale. *right frame* Schematic view of the 3 brightest shells of the IRC+10216 envelope and (at an enlarged scale) of the binary star system with a mass ratio 4:1 and eccentricity 0.92, orbiting in the plane of the sky. The blue dots show the SMA and ALMA half-power beam widths.



Spectral line survey toward CIT6 and IRC+10216



Similar lines are detected for both stars, but the intensities tend to be higher for IRC+10216.
We detect several cyanopolyynes (HCnN)

Nguyen-Luong et al. (2024, in prep.)

Line profiles are different between IRC+10216 and CIT6

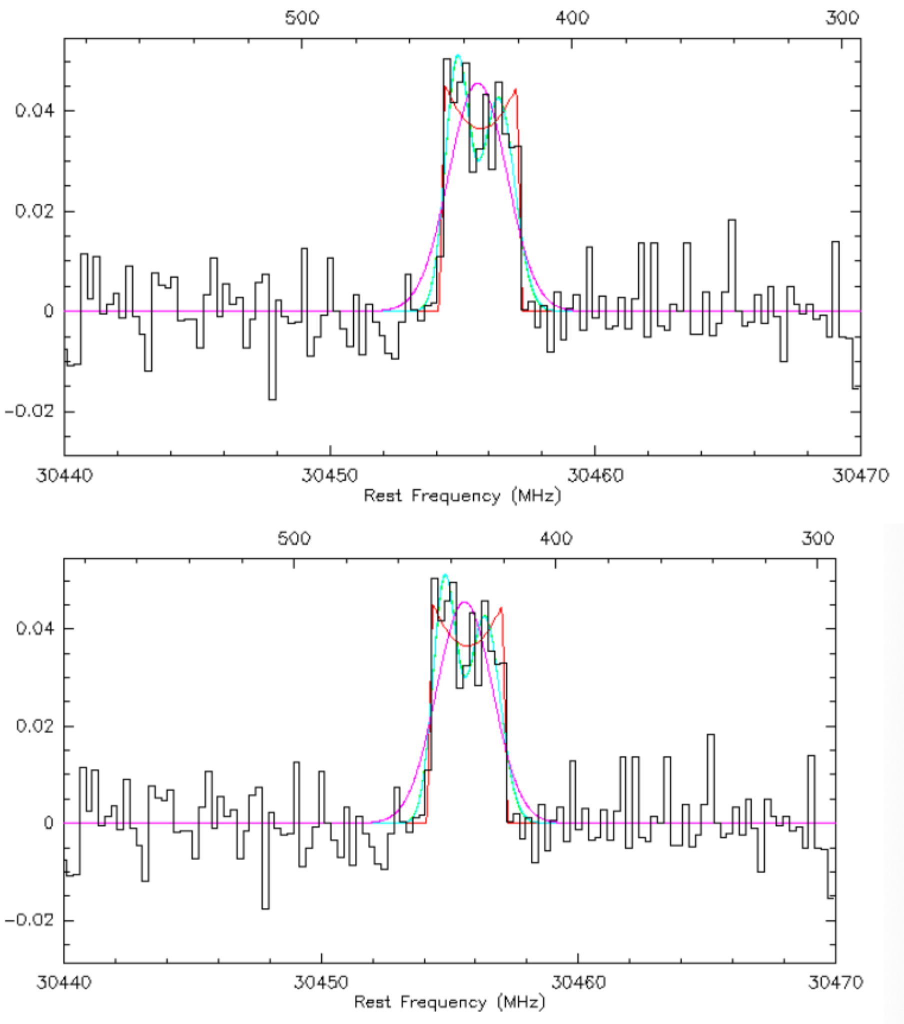
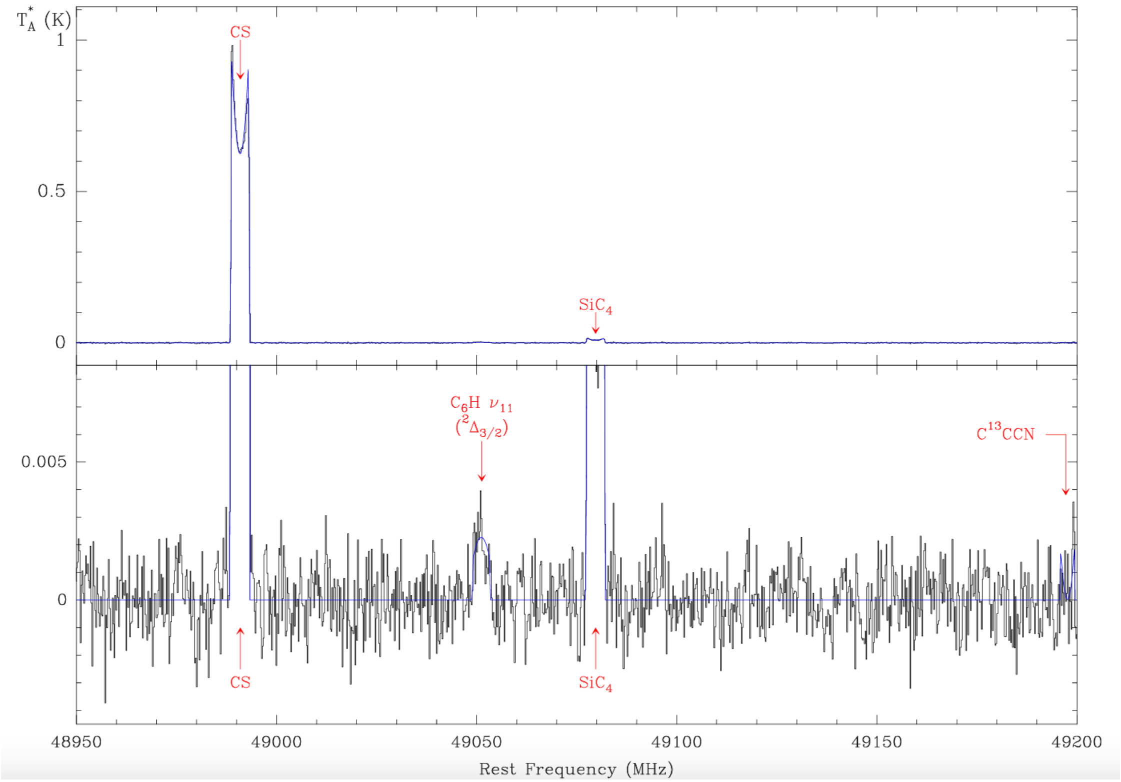


Fig. D.2. Example of line fitting using different methods: multiple Gaussian or Shell for C5H line **(a)** and HC7N **(b)**.



Extraction of physical quantities from spectral line data

- LTE analysis (analysis of optically thin molecular line)

  -Boltzmann distribution at each energy level

  -**Rotational Diagram**: Temperature, Column density

- Non-LTE analysis (analysis of optically thick lines)

  It is necessary to simultaneously solve the statistical equilibrium equation for the molecular energy levels and the radiative transfer equation.

  -RADEX (van der Tak et al. 2007, A&A, 468, 627)

  https://var.sron.nl/radex/radex.php

Rotational Diagram

Our wide bandwidth allows us to obtain multi-transition lines.

Assuming the Boltzmann distribution and optically thin

$$N_u = N_{\mathrm{tot}} \frac{g_u}{Q(T)} \exp\left(-\frac{E_u}{kT}\right)$$

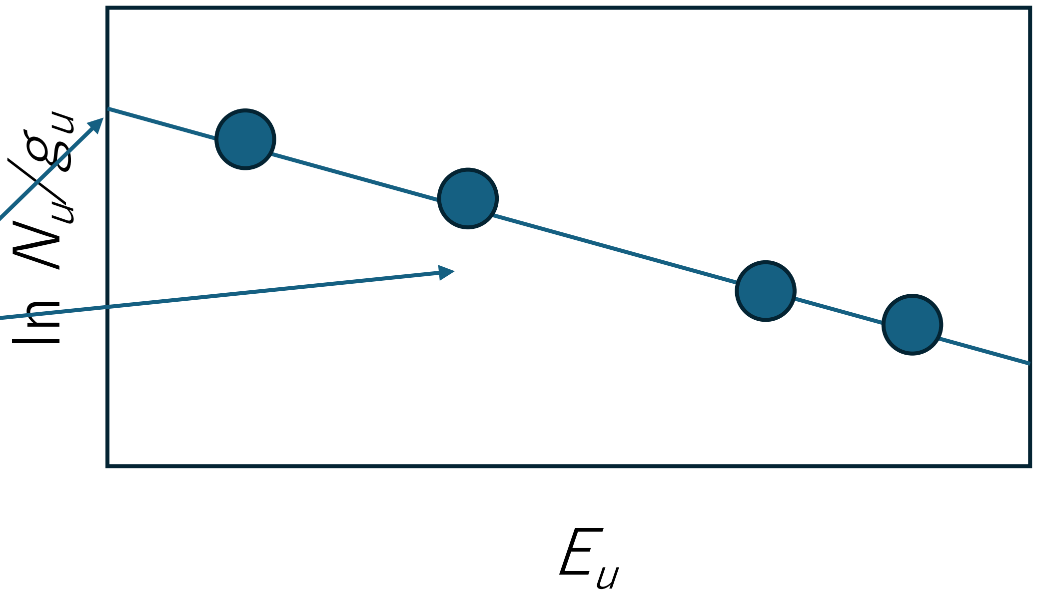
Partition function $Q(T) = \Sigma_i g_i \exp\left(-\frac{E_i}{kT}\right)$

$$\ln\left(\frac{N_u}{g_u}\right) = \ln\left(\frac{N_{tot}}{Q(T)}\right) - \frac{E_u}{k_B T}$$

$$\ln \frac{N_\mathrm{u}}{g_\mathrm{u}} = \ln \frac{3k \int T_\mathrm{S} dv}{8\pi^3 \nu \mu^2 S}$$

Slope => $-1/k_B T$

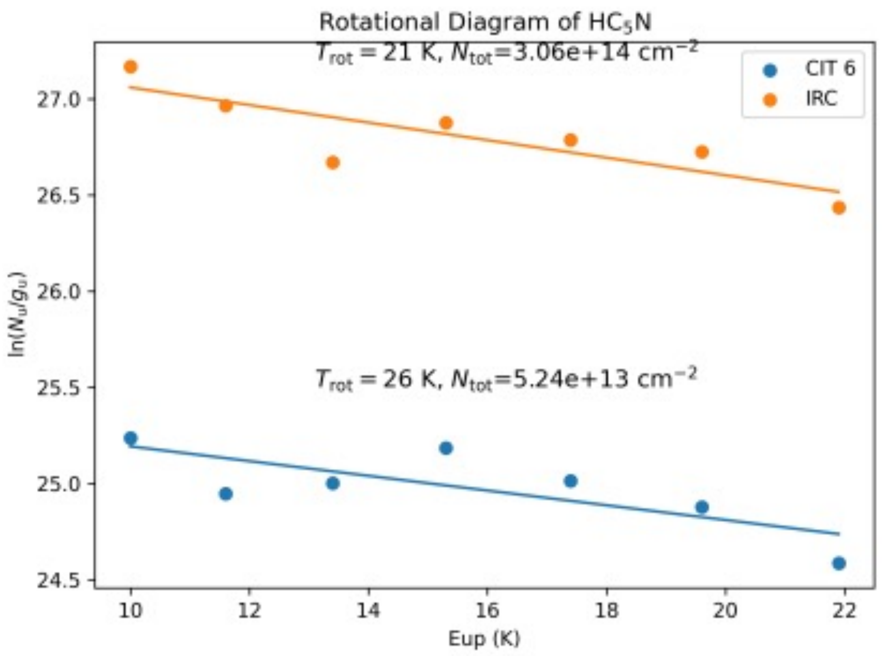
Intersept => N_{tot}

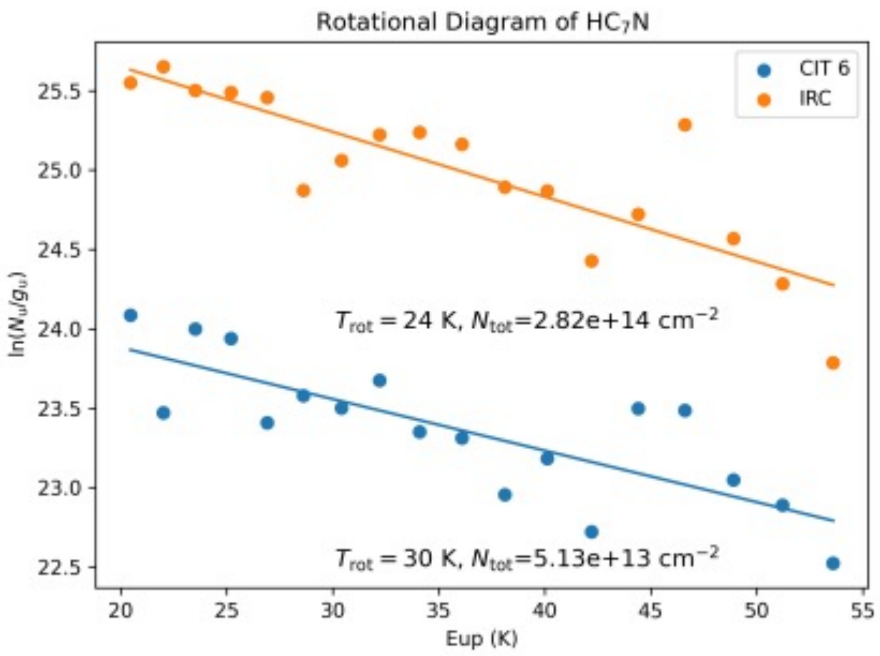


Rotational Diagram analysis

- Our wide bandwidth allows us to obtain multi-transition lines.
- Thus, we can derive the column density and temperature.

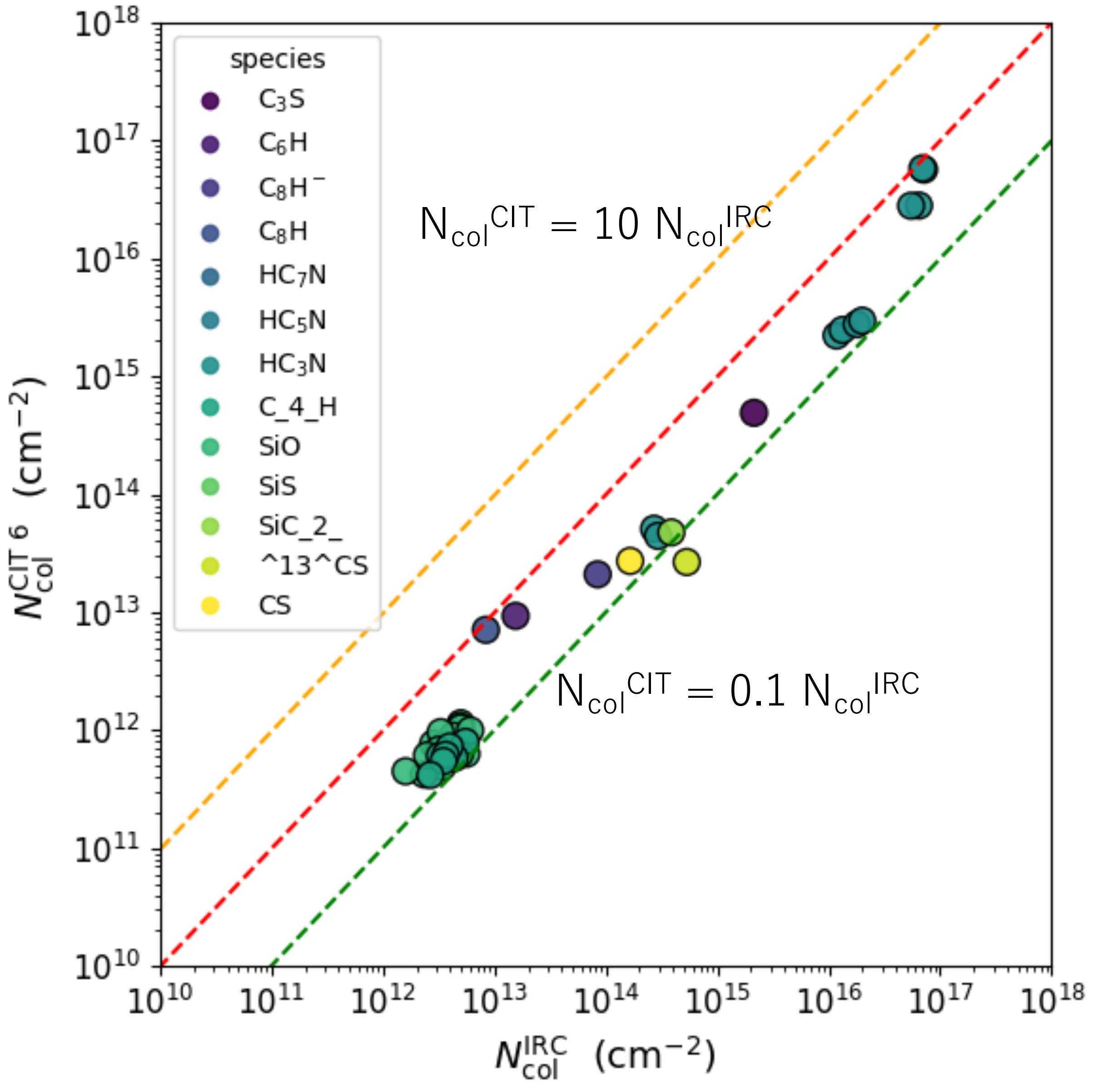
- HC5N/HC7N in CIT 6 have higher T and lower column density.

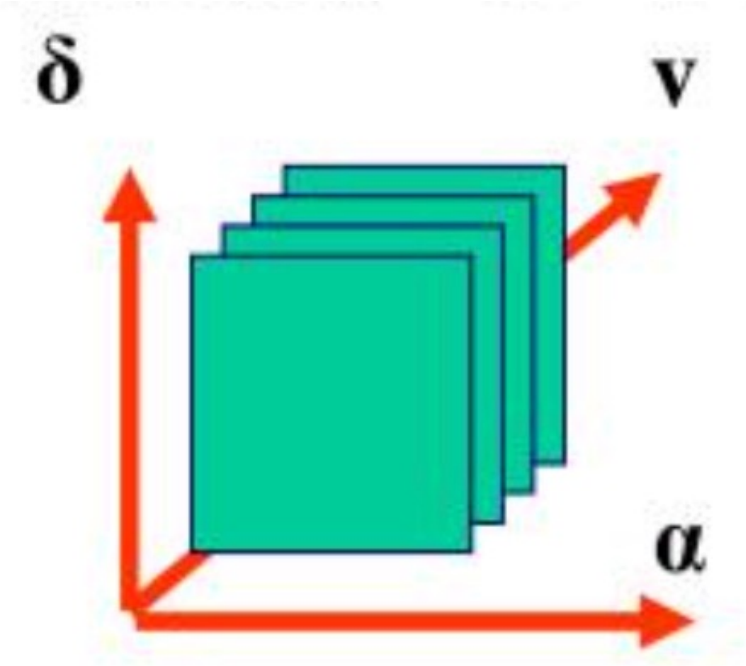




Column density distributions of carbon chain molecules

- $HC_5N/HC_7N/CS/^{13}CS$ column densities are about 5 times lower for CIT6.



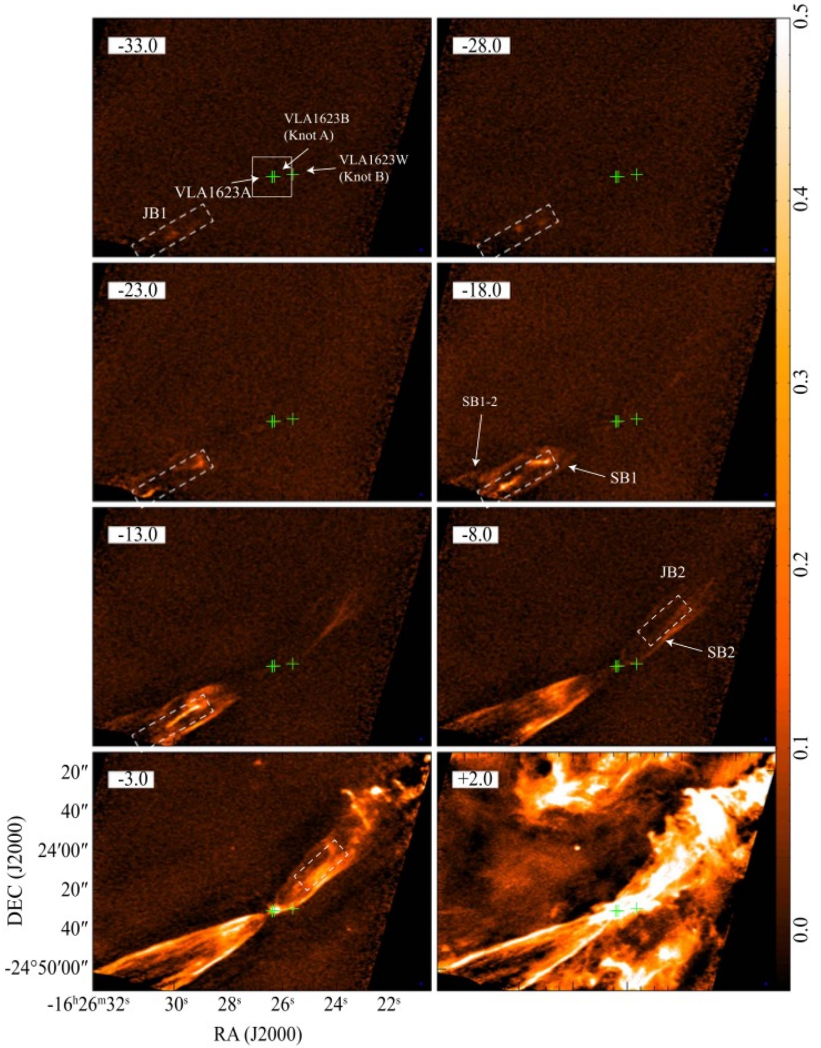


3D cube

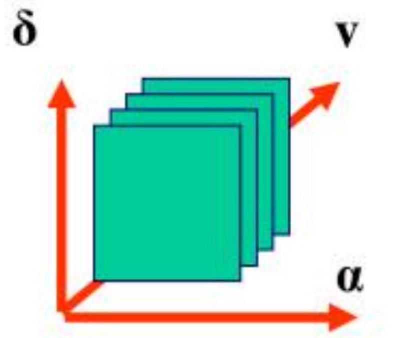
- Molecular line data are 2D position (α-δ) and 1D velocity or frequency (v) data (ppv)

- The 3D data cube is not perfectly equal to the 3D position data (ppp) but includes information of internal structure and kinematics.

Velocity channel maps of protostellar outflow



Class 0 protostellar outflow
by 12CO (J=2-1)



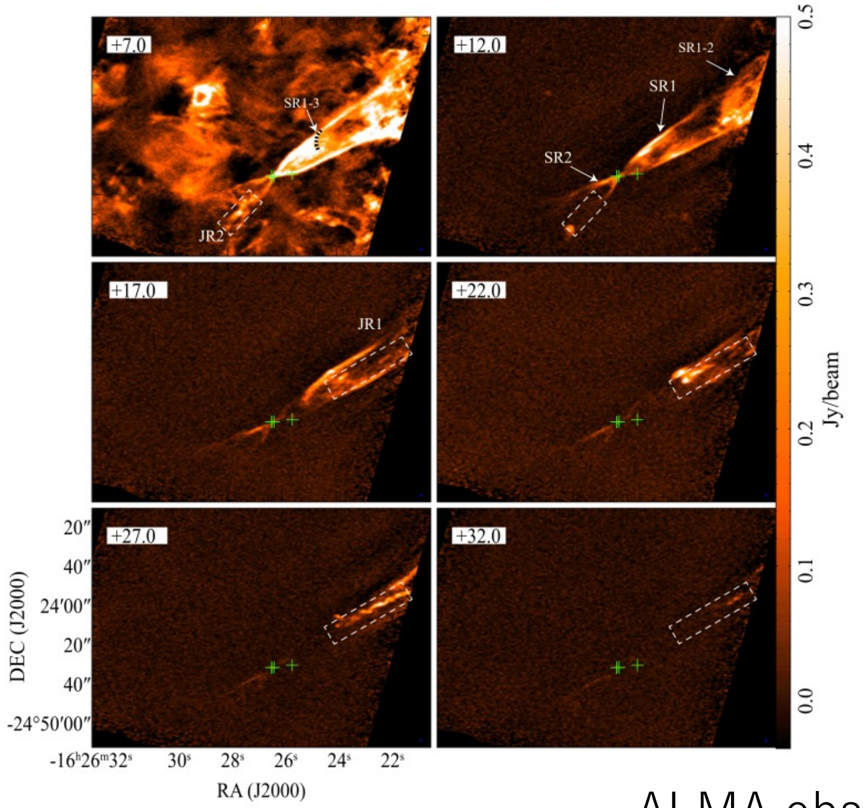
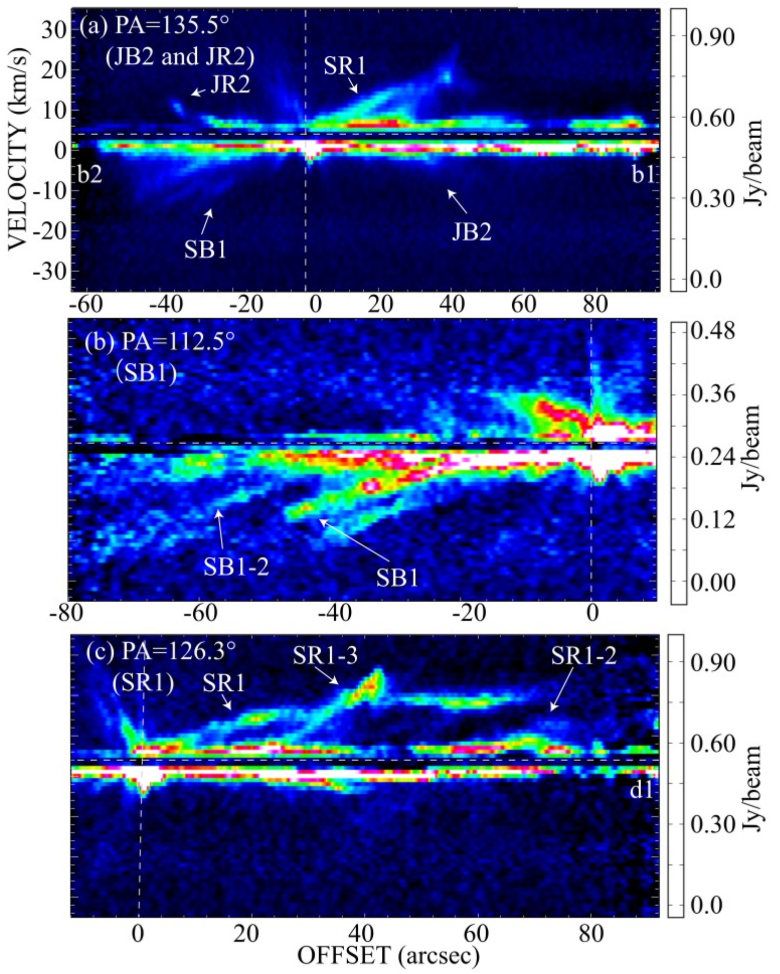
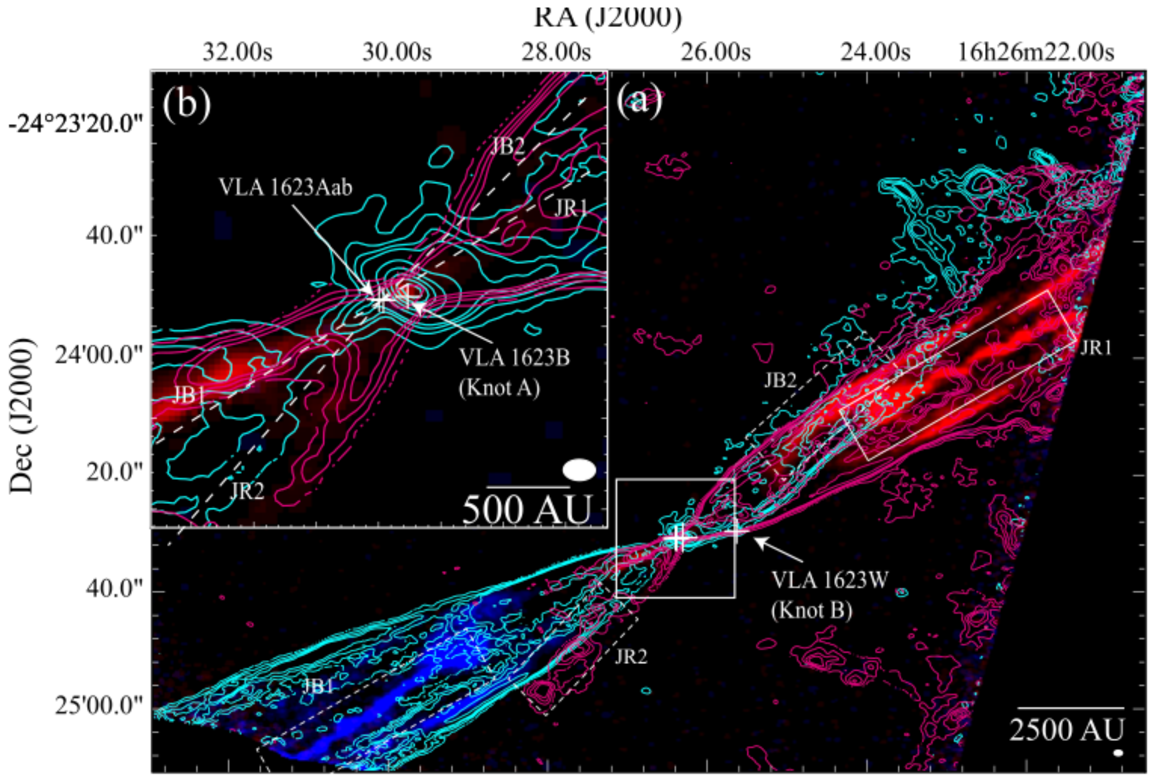


Figure 4. (Continued.)

ALMA observation Hara et al. 2018

Position-Velocity Map





Summary

- ISMs are non-uniform.
- Molecular line observations are used to understand physical conditions of ISMs such as molecular clouds, circumstellar envelopes.
- LTE/non-LTE methods are used to estimate the column density and temperature.
- Examples of molecular line observations: carbon stars and protostellar outflows.