Lecture 19
CO Observations of Molecular Clouds

1. CO Surveys
2. Nearby molecular clouds
3. Antenna temperature and radiative transfer
4. Determining cloud conditions from CO

References

- Tielens, Ch. 10
- Myers, "Physical Conditions in Molecular Clouds", OSPS99
- Blitz & Williams, "Molecular Clouds", OSPS99

OSPS = Origins of Stars & Planetary Systems

http://www.cfa.harvard.edu/events/crete/

Orion-Taurus-Aurigae

The location of the nearby molecular clouds.

1. CO Surveys

- There have been several surveys of CO emission of the Milky Way using the low-*J* transitions
    - ^{12}CO 1-0 at 115.271203 GHz
    - ^{12}CO 2-1 at 230.538001 GHz
    - ^{13}CO 1-0 at 110.20137 GHz
- CO surveys are the primary way of identifying giant molecular clouds and their properties
- The relatively low abundance of CO compared to H_2 is more than offset by its dipole moment (and higher Einstein *A*-values)
- CO lines can be optically thick, so the thinner lines of ^{13}CO and C^{18}O are important

Three Important CO surveys

1. <u>Goddard-Columbia-CfA</u> (Thaddeus et al.) - Dame et al. ApJ 547 792 2001, which lists earlier surveys. Carried out with two mini 1.2 m telescopes, one at CfA (originally on the top of Columbia's Pupin Hall) and the other in Chile, with angular resolution 8.5' (1 pc at the distance of Orion).
2. <u>SUNY-UMASS</u> (Solomon, Scoville, Sanders) - Scoville & Sanders, "Interstellar Processes" (1987). pp 21-50. 14 m telescope with angular resolution of 45'' (0.1 pc at the distance of Orion).
3. <u>BU-FCRAO Survey of the Outer Galaxy</u> – Heyer et al. ApJS 115 241 1998. Uses the 14-m with multi-feeds.

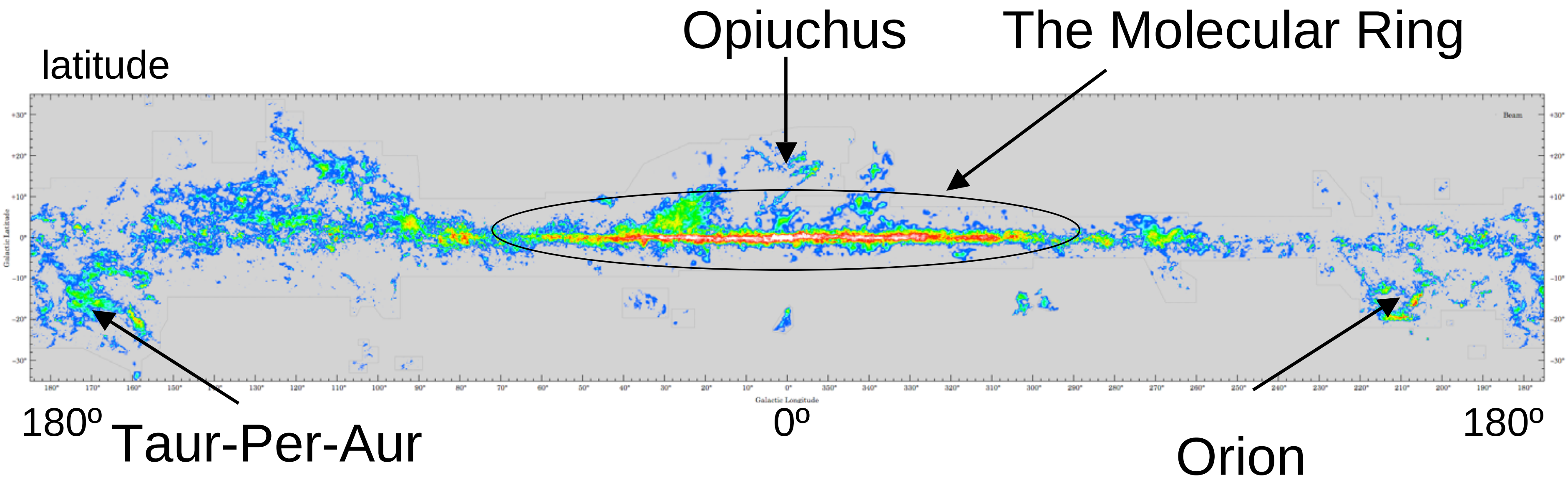
It is not just the resolution that counts, but sampling, sensitivity, & coverage. The CfA survey took 0.5M spectra; BU-FCRAO 1.7M.

A recent meeting report devoted to surveys:
"Milky Way Surveys", ASP CP317, eds. D. Clemens et al.

Overview of CO Surveys

- CO maps are clumpier and show a different global structure than the broad HI distribution
- Individual molecular clouds and cloud complexes can be identified throughout much of the galaxy (taking advantage of the variation of velocity vs. galactic radius), but clouds may be confused and ill-determined in some regions
- CO observations are crucial for studies of star formation and galactic structure: Together with radio, optical-IR observations of HII regions, OB associations and other Pop I objects, CO surveys show that virtually **all star formation occurs in molecular clouds**
- CO surveys have helped refine our knowledge of the spiral structure of the Milky Way, since clouds preferentially form in spiral arms, and their distances can be determined from associated Pop I objects

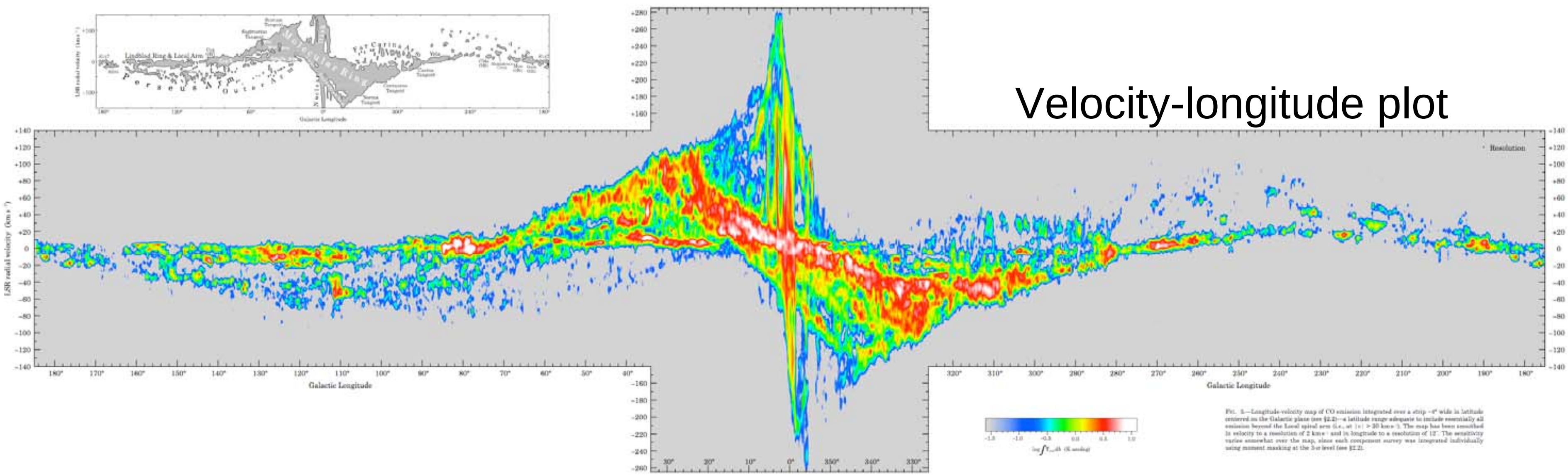
Distribution of CO Clouds



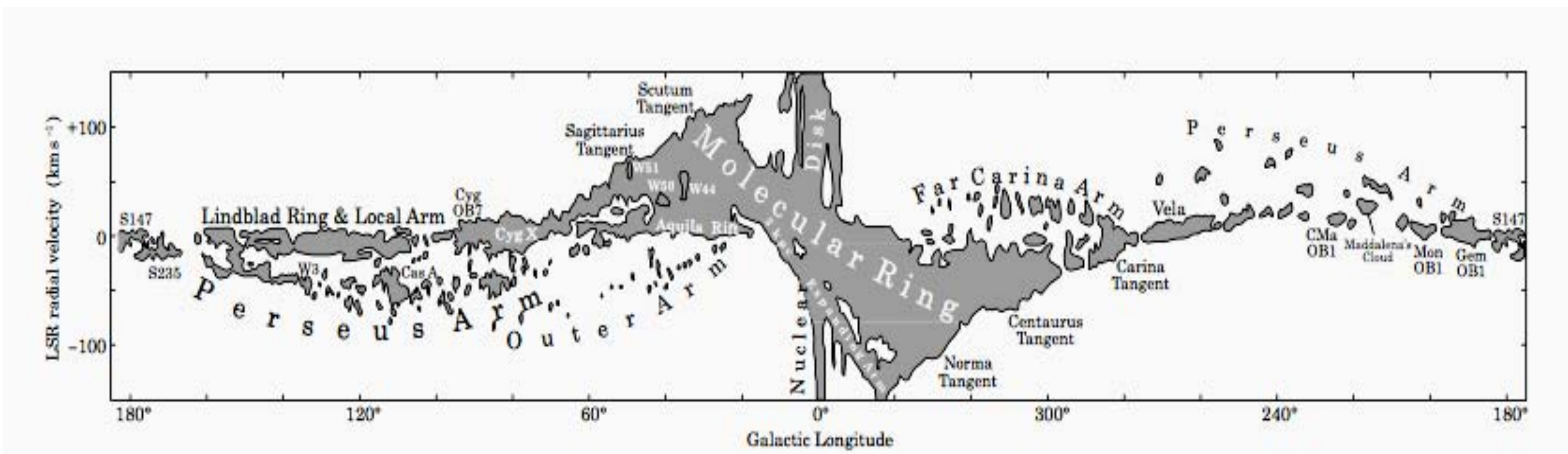
“The Milky Way in Molecular Clouds: A New Complete CO Survey”
Dame, Hartmann and Thaddeus, ApJ 547 792 2001

CO has a vertical extent ±45-75 pc over much of the disk, similar to OB associations, and flares out to ±100-200 pc.

Kinematics of CO Clouds

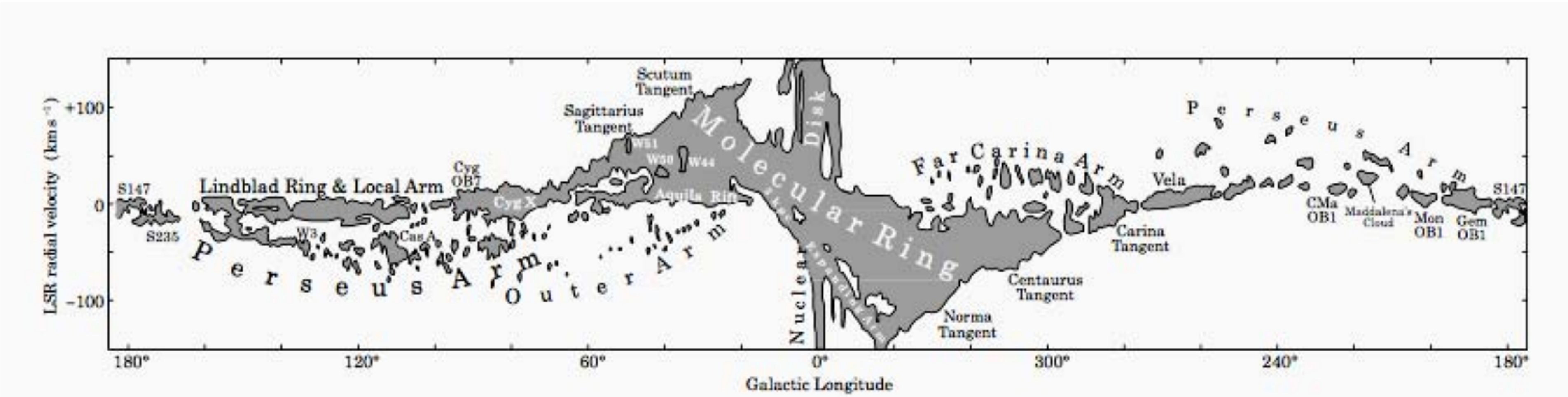


Velocity-longitude plot



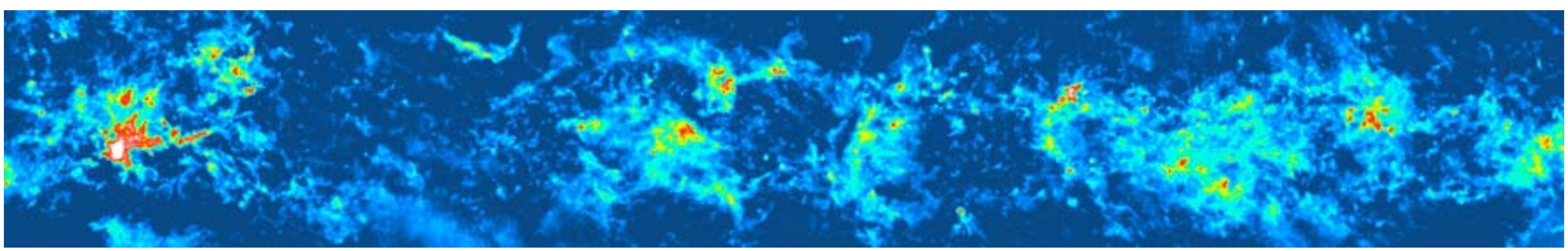
Dame et al. ApJ 547 792 2001

Kinematics of Molecular Clouds



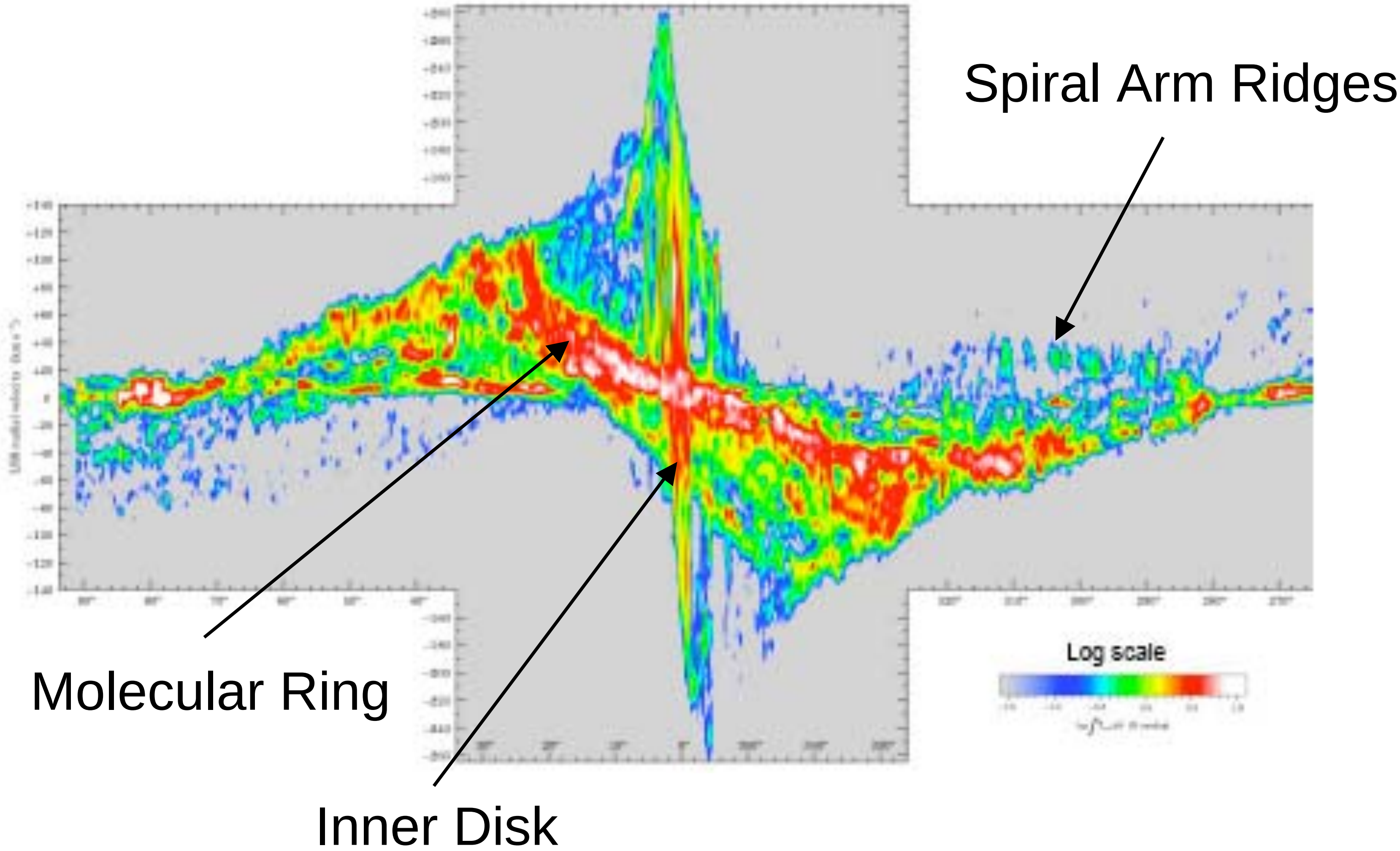
CfA survey Dame et al. 2001

- Inner (250-750 pc) disk/ring of high surface density expanding/rotating ~ 240 km/s
- Molecular ring between 3-8 kpc ("5 kpc ring")
- Spiral arms and discrete OB associations



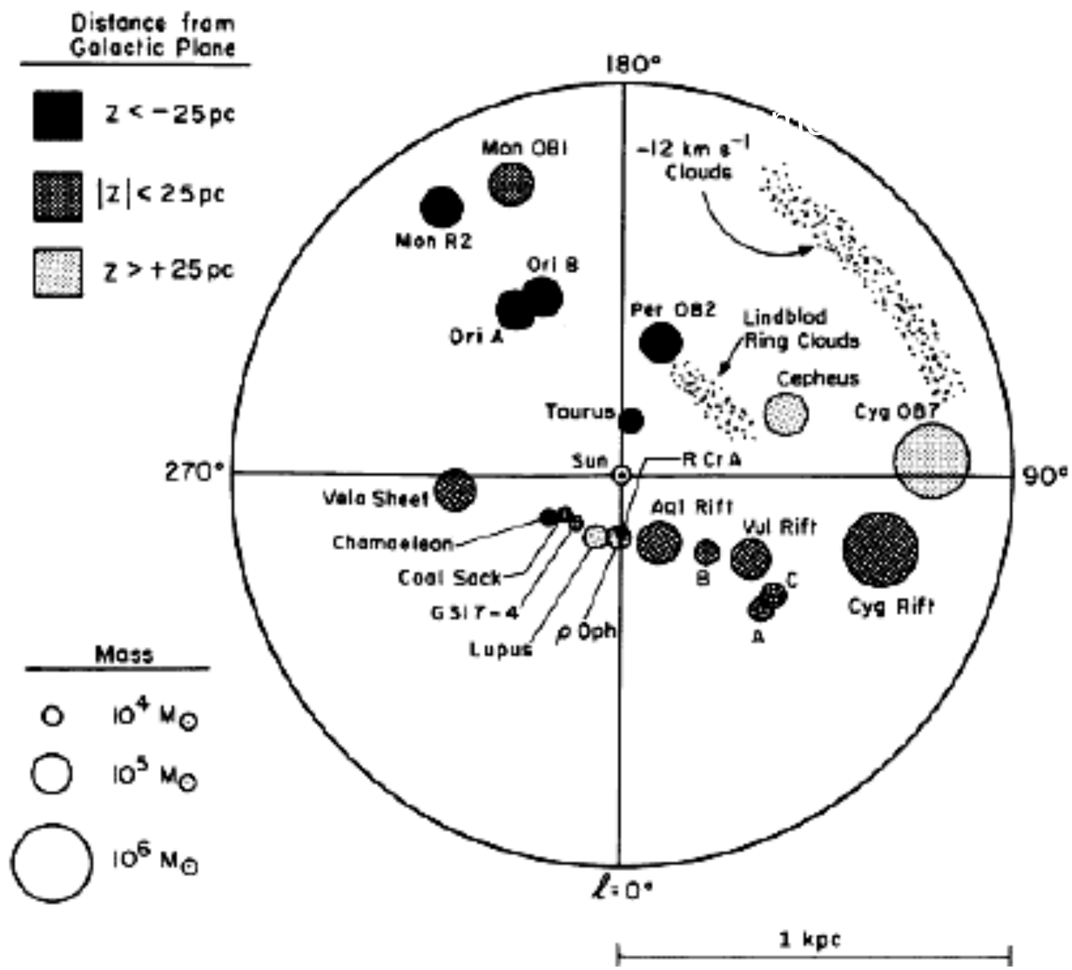
^{13}CO Galactic Ring Survey (46'' resolution) www.bu.edu/galacticring

Inner Galaxy in CO



2. Nearby Molecular Clouds

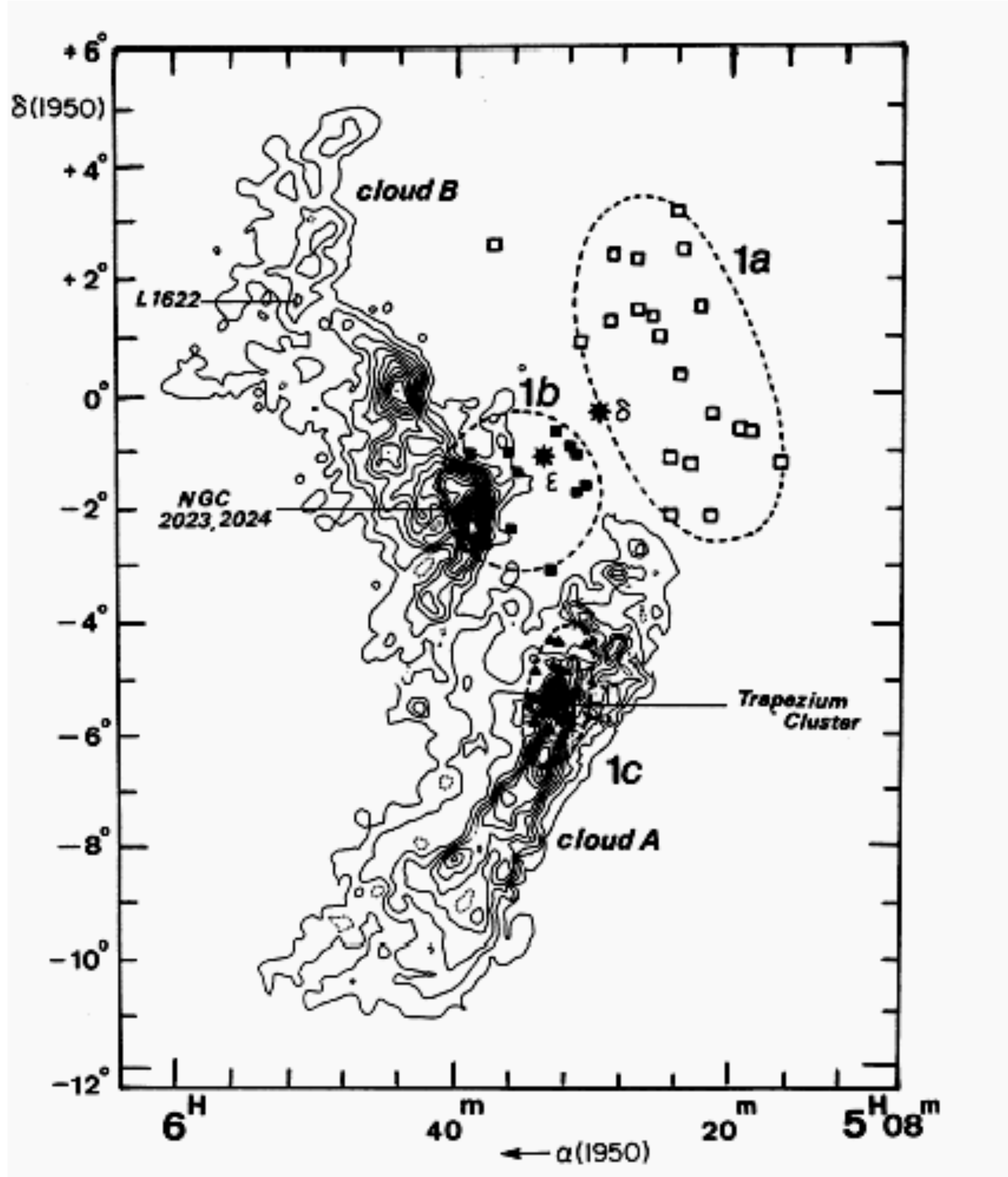
- Taurus is the nearest and the site of low-mass star formation
- Closest site of massive star formation is Orion
- Nearest large cloud complex is Cygnus rift/Cygnus OB7



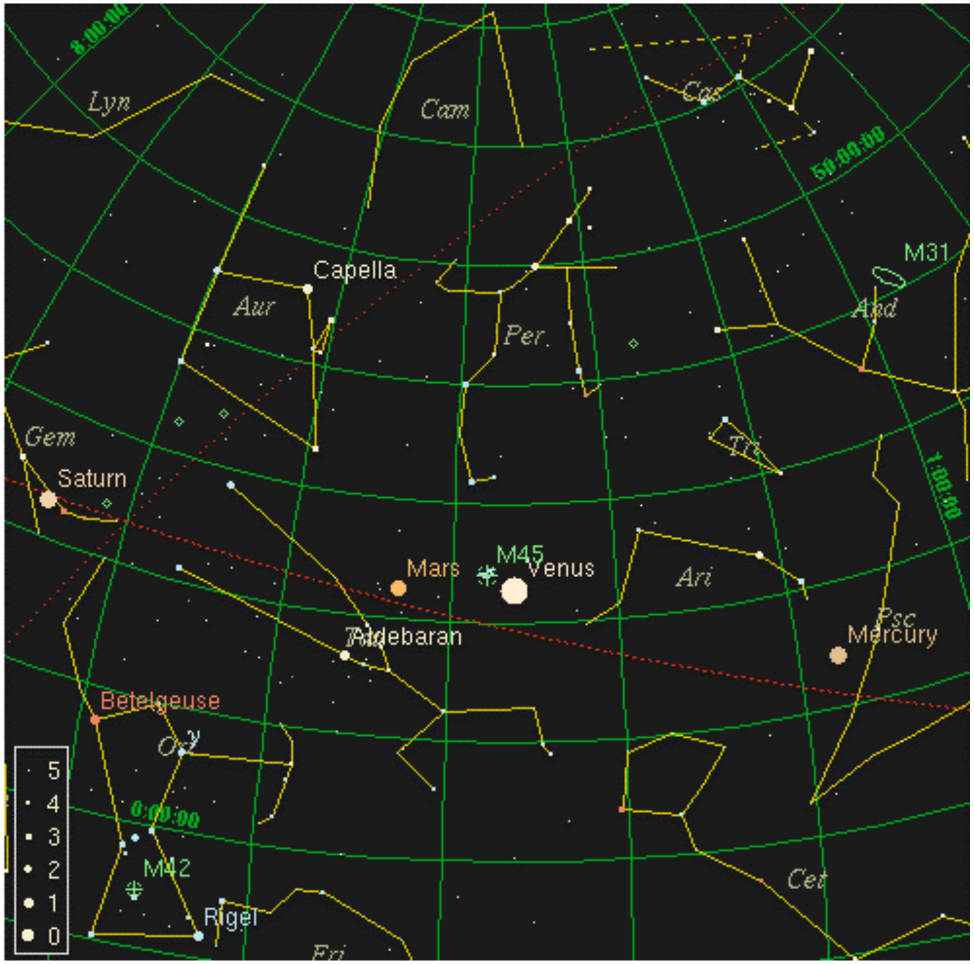
Early CO map of Orion by the Goddard-Columbia 1.2 m mini-telescope plus Blaauw's OB associations

1a - 12 Myr
1b - < 1 Myr
Trapezium - < 1 Myr
1c - 2 Myr

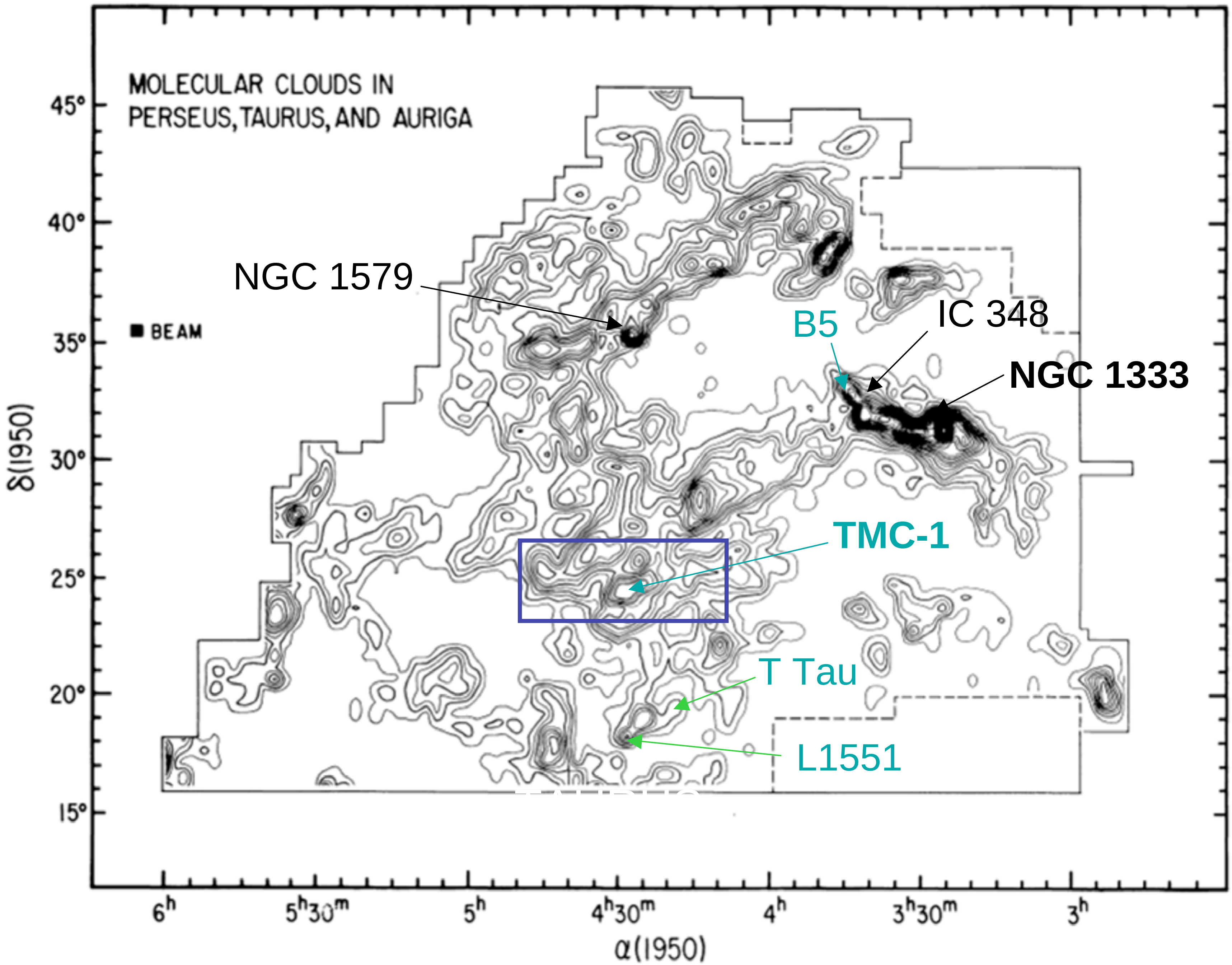
The Trapezium cluster has about 3500 YSOs, including a few O,B stars



Taurus-Perseus-Aurigae



→ Next slide: Low-mass star formation in a cloud complex, ranging from cloud cores to clusters of low-mass young stellar objects and T Tauri stars.



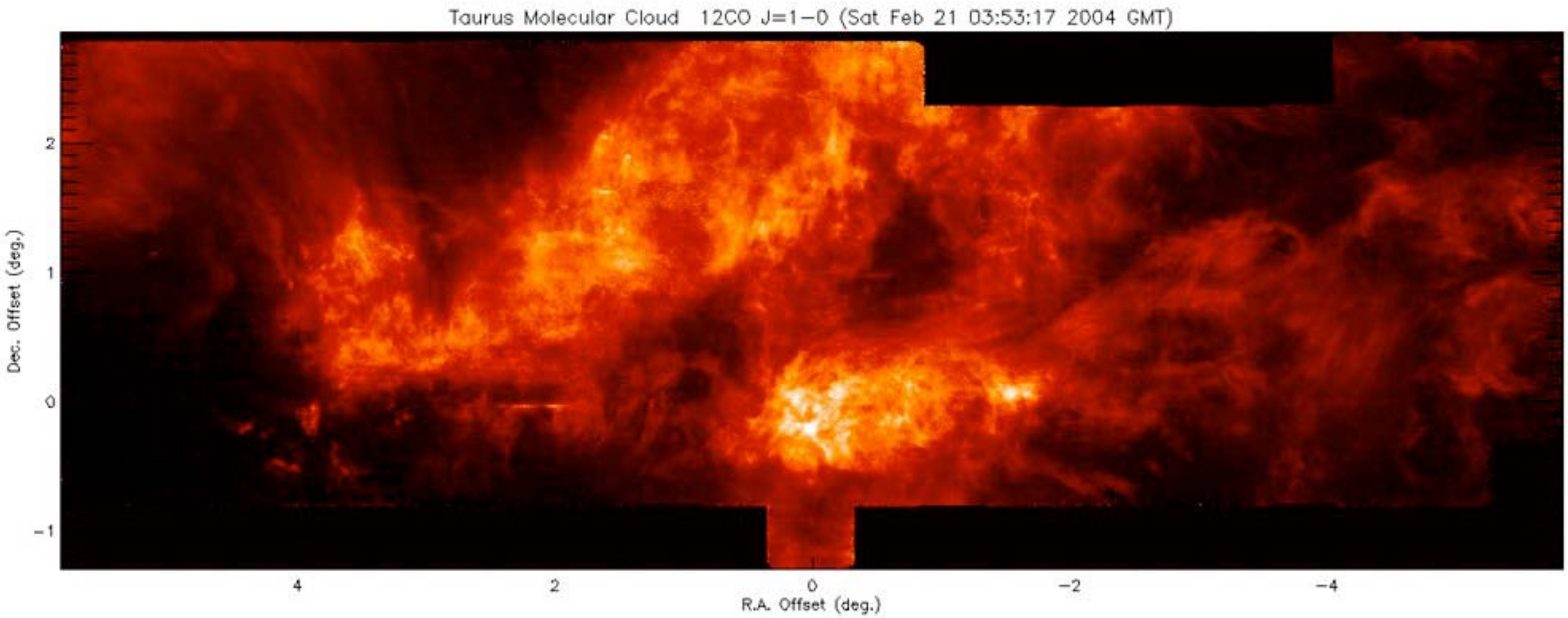
MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND AURIGA
BEAM
NGC 1579
B5
IC 348
NGC 1333
TMC-1
T Tau
L1551
45°
40°
35°
30°
25°
20°
15°
δ(1950)
6h
5h30m
5h
4h30m
4h
3h30m
3h
α(1950)

Very Young Proto-Cluster in Perseus

NGC 1333, Lada & Lada, ARAA 41 57 2003

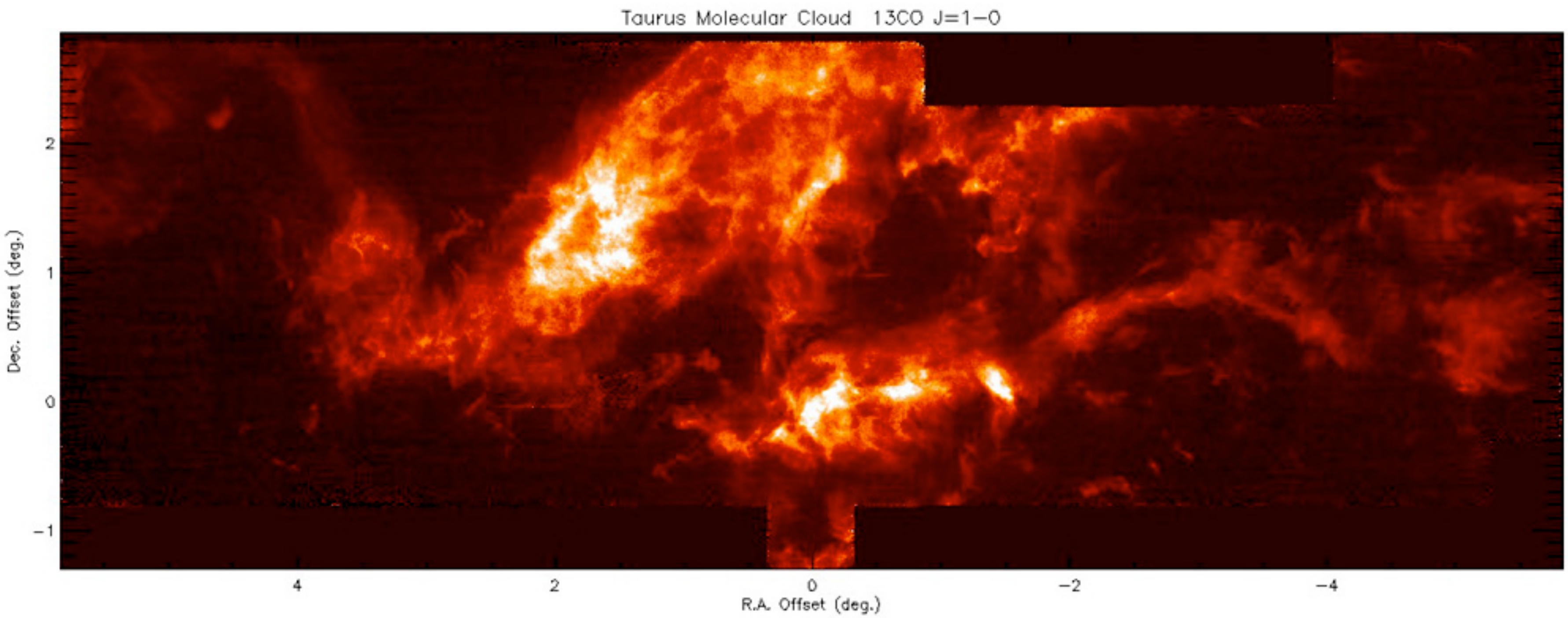
Notice the many outflows and jets, characteristic of young protostars.

TMC in ^{12}CO



Taurus region in ^{12}CO (FCRAO 14-m, HPBW = 50")

TMC in ^{13}CO



Taurus region in ^{13}CO (FCRAO 14-m, HPBW = 50”).
Notice the greater detail compared to the CO map.

3. **Antenna Temperature and Radiative Transfer**

Radio astronomers like to invoke Rayleigh-Jeans formula to describe the intensity of lines, even though it does not apply to the mm spectrum of molecules like CO.This is OK so long as the radiative transfer is done correctly.

We follow and modify the analysis of Lec10 on the 21-cm line and solve the equation of transfer with an integrating factor

$$\frac{dI_\nu}{d\tau_\nu} = B_\nu(T_{\mathrm{ex}}) - I_\nu, \quad d\tau_\nu = \kappa_\nu ds$$

where T_{ex} is the excitation of the line in question

$$n_u / n_l = g_u / g_l e^{-T_{ul}/Tex}, \quad T_{ul} = E_{ul} / k_{\mathrm{B}}$$

The integrating factor is just exp(-τ_ν),

$$I_\nu = e^{-\tau_\nu} \Im_\nu \quad \Rightarrow \; e^{-\tau_\nu} \; \frac{d\Im_\nu}{d\tau_\nu} = B(T_{ex}) \quad \Rightarrow$$

$$\Im_\nu(\tau_\nu) - \Im_\nu(0) = (e^{-\tau_\nu} - 1) B(T_{ex}) \;\text{ for constant } T_{ex}$$

Solution of the Equation of Transfer

The solution to the equation of transfer is now

$$I_\nu(\tau_\nu) = (1 - e^{-\tau_\nu})B_\nu(T_{ex}) \;+\; e^{-\tau_\nu} I_\nu(0)$$

We may think of $I_\nu(\tau_\nu)$ as the measured intensity of a uniform slab of thickness τ_ν where $I_\nu(0)$ is the incident intensity, the CBR at the frequency ν. The observations are assumed to be made in the off-on manner discussed for the 21-cm line, so the relevant quantity is the difference $I_\nu(\tau_\nu) - I_\nu(0)$,

$$\Delta I_\nu(\tau_\nu) = I_\nu(\tau_\nu) - I_\nu(0) = (1 - e^{-\tau_\nu})[B(T_{ex}) \;- I_\nu(0)]$$

Next we *define* the antenna temperature with the Rayleigh-Jeans formula as

$$I_\nu \equiv \frac{2}{\lambda^2} k_B T_\nu^{\,A}$$

and the above solution becomes

$$\Delta T_\nu^{\,A}(\tau_\nu) = (1 - e^{-\tau_\nu})[\frac{1}{e^{T_{ul}/T_{ex}} - 1} - \frac{1}{e^{T_{ul}/T_R} - 1}] \quad (1)$$

Formula for the Antenna Temperature

In deriving this result,

$$\Delta T^{A}{}_{\nu}(\tau_\nu) = (1 - e^{-\tau_\nu})\left[\frac{1}{e^{T_{ul}/T_{ex}} - 1} - \frac{1}{e^{T_{ul}/T_R} - 1}\right]$$

we defined $T_{\rm ul} = h\nu_{\rm ul}/k_{\rm B}$ and replaced the background radiation field by the BB intensity with radiation temperature T_R

$$I_\nu(0) = B_\nu(T_R)\frac{2}{\lambda^2}\frac{h\nu}{e^{T_{ul}/T_R} - 1}$$

The solution above allows 3 possibilities:

$$T_{ex} = T_R \quad \Rightarrow \text{ no line}$$

$$T_{ex} > T_R \quad \Rightarrow \text{ emission}$$

$$T_{ex} < T_R \quad \Rightarrow \text{ absorption}$$

This result is still incomplete because the optical depth and T_{ex} are both unknown; they require a calculation of the level population. The optical depth is obtained in the usual way

$$\int_{line} d\nu\, \tau_\nu = \frac{h\nu_{ul}}{c}(N_l B_{lu} - N_l B_{ul}) = \frac{\lambda_{ul}{}^2}{8\pi} A_{ul} N_u (e^{T_{ul}/T_R} - 1) \qquad (2)$$

Population Calculation

The balance equation assuming adjacent ladder-rung transitions is:

$$(A_{ul} + k_{ul}n_c + u_\nu B_{ul})n_u = (k_{lu}n_c + u_\nu B_{lu})n_l$$

This equation can be solved for the population ratio

$$\frac{n_u/g_u}{n_l/g_l} = e^{-T_{ul}/T}\,\frac{k_{lu}n_c + A_{ul}(e^{T_{ul}/T_R} - 1)^{-1}}{A_{ul} + k_{lu}n_c + A_{ul}(e^{T_{ul}/T_R} - 1)^{-1}} = e^{-T_{ul}/T_{ex}}$$

and the excitation temperature can be expressed in terms of T_R and the density n_{coll} of colliders by way of the critical density

$$e^{-T_{ul}/T_{ex}} = e^{-T_{ul}/T}\,\frac{(e^{T_{ul}/T_R} - 1) + (n_{cr}/n_{coll})}{(e^{T_{ul}/T_R} - 1) + (n_{cr}/n_{coll})e^{T_{ul}/T_R}}\quad (n_{cr} = A_{ul}/k_{ul}) \quad (3)$$

We can easily check the high and low density limits:

$$n_{coll} >> n_{cr}: \quad T_{ex} = T$$

$$n_{coll} << n_{cr}: \quad \frac{1}{T_{ex}} = \frac{1}{T} + \frac{1}{T_R} \quad \Rightarrow\ T\ (T << T_R)\ \text{and}\ T_R\ (T >> T_R)$$

Summary of Radiative Transfer

We derived three equations for one rotational transition:

Eq, (1) - ΔT_A in terms *of* T_{ex} and the optical depth
Eq, (2) - optical depth in terms of T_{ex} and N_l
Eq, (3) - T_{ex} in terms of T and n_{coll}

There are several unknowns: kinetic temperature T
excitation temperature T_{ex} of the line
density of the molecular carrier n
density of the collision partner n_{coll}

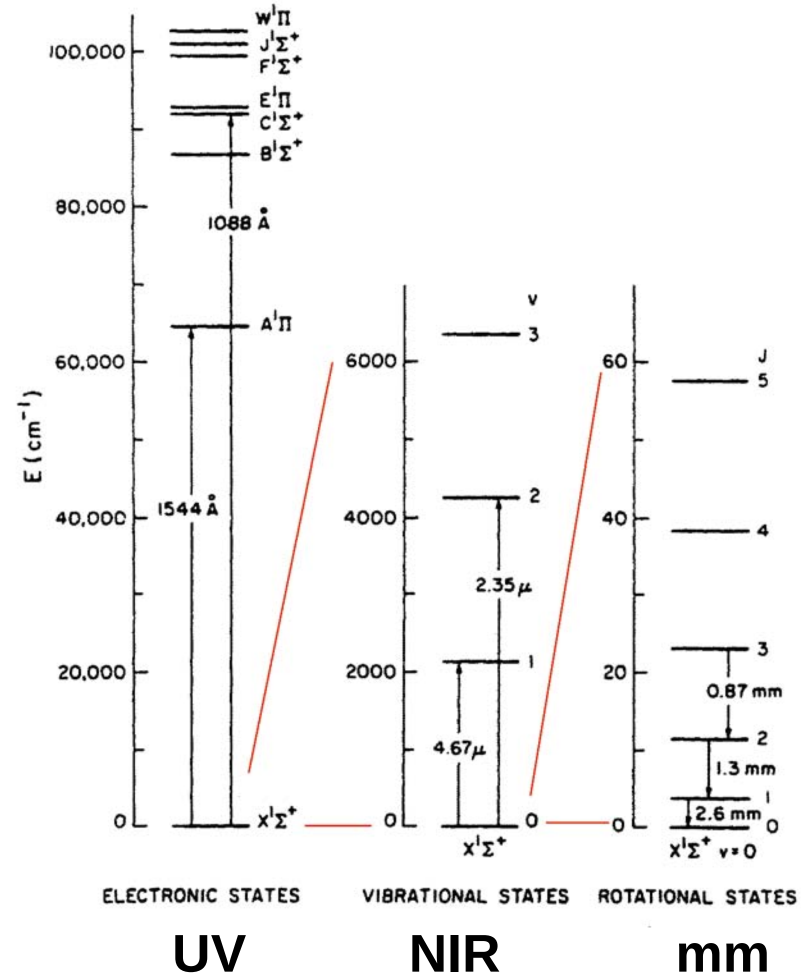
It is obvious that the three equations, containing just one observable ΔT_A, is insufficient to obtain all the desired information.

All is not lost, however, since usually more than one line and at least one isotope ca be observed. If that isotope has a low enough abundance, then one can assume that the optical depths of its lines are small, thereby simplifying the analysis.There are other tricks …

3. Determining Cloud Propeties from CO

Maps of the ^{12}CO or ^{13}CO lead to the concept of molecular clouds. The kinematics of the clouds give distances and thus the linear dimensions of the clouds.

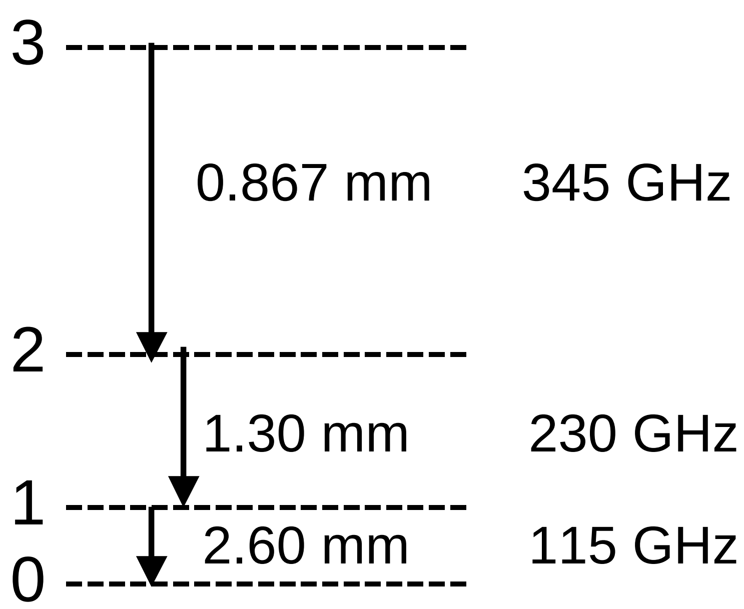
To obtain more information on the physical conditions, we apply the discussions of Lecs 13-18 on the rotational levels to the interpretation of the mm observations.



a. The Ground Rotational Band of CO

$$E_J = J(J+1)B, \quad \Delta E_J = E_J - E_{J-1} = 2BJ \quad \text{for small } J$$

B = 1.922529 cm^{-1} B/k_B = 2.766 K



$A_{J,J-1} = 3J^4/(2J+1)\, A_{10}$, $A_{10} = 7.17 \times 10^{-8}$ s^{-1}

$f_{J-1,J} = J^2/(2J-1)\, f_{01}$ $f_{01} = 2.8 \times 10^{-08}$

approximate collisional rate coefficient:

$k_{J',J}$ (H_2+CO) ~10^{-11} $T^{0.5}$ cm^{3}s^{-1}

for $|J-J'|$ = 1.2

CO rotational Frequencies and Critical Densities

Frequencies in GHz

	CO	^{13}CO	C^{18}O
1-0	115.271	110.201	219.6
2-1	230.518	220.4	219.6
3-2	345.796	330.6	329.4

See NIST /MolSpec/Diatomics

b. Critical Densities

$$n_{\mathrm{cr}}(1-0) \approx \frac{7167}{T^{0.5}}\ \mathrm{cm}^{-3} = 1.43\times 10^{3}\left(\frac{25}{T}\right)^{½}\ \mathrm{cm}^{-3}$$

$J \to J$-1	$n_{\mathrm{cr}}(J \to J$-1)
1-0	$1.4\mathrm{x}10^3$
2-1	$2.3\mathrm{x}10^3$
3-2	$7\mathrm{x}10^4$

The fundamental transition at 2.6 mm is easily thermalized, especially when line trapping is considered.

c. Optical Depth of the CO mm Lines

Start with the standard formula for a gaussian line

$$\tau_{J,J-1} = f_{J,J-1} \frac{\pi e^2}{m_e c} \frac{\lambda_{J,J-1}}{b} N_{J-1}(\mathrm{CO}) \left(1 - \frac{P_J / 2J+1}{P_{J-1} / 2J-1} \right)$$

The stimulated emission factor must be included, especially because the transition and thermal temperatures are the same order of magnitude (10 K):

$$1 - \frac{P_J / 2J+1}{P_{J-1} / 2J-1} \approx 1 - \exp(-J\ 2.766\mathrm{K} / T)$$

For a constant CO abundance and excitation temperature, the column densities of the rotational levels are

$$N_J = x(\mathrm{CO})\, P_J\, N_{\mathrm{H}}$$

For a thermal equilibrium population,

$$P_J \approx \frac{1}{Z} (2J+1) e^{-J(J+1)B/kT}, \quad Z \cong \frac{T}{B}$$

CO rotational line optical depths

Putting all the pieces together leads to:

$$\tau_{J-1,J} \cong f_{J-1,J}\ \frac{\pi e^2}{m_e c}\ \frac{\lambda_{J,J-1}}{b}\, x(\mathrm{CO}) N_{\mathrm{H}}\ \frac{2J-1}{T/B}\ e^{-J(J-1)B/T}\ (1-e^{-2BJ/T})$$

$$\Rightarrow 335\ [x(\mathrm{CO})_{-4}\ \frac{10K}{T}\ \frac{\mathrm{km\ s}^{-1}}{b}]\ \frac{mag}{A_V}\ (1-e^{-2.766/T})\quad \text{for } J=1-0$$

CO(1-0) and other low-*J* transitions can easily be optically thick

d. Further consequences of large optical depth

Consider the critical density of the CO(1-0) transition, including the effects of line trapping:

$$n_{\mathrm{cr}} \approx \frac{\beta_{10} A_{10}}{k_{10}} \approx \frac{A_{10}}{k_{10}}\ \frac{1}{\tau_{10}} = \frac{2.3\times 10^{3}\,\mathrm{cm}^{-3}}{\tau_{10}} \left(\frac{10K}{T}\right)^{1/2}$$

Large τ_{10} reduces the critical density.

Consequences of the Large CO Optical Depth

1. The case for thermalization is very strong when the line optical depth is large.
2. Low-J CO transitions provide a thermometer for molecular gas
3. Widespread CO in low density molecular regions is readily observed.
4. Optically thick line intensities from an isothermal region reduce to the Blackbody intensity $B_\nu(T)$.
5. Densities must come from the less-abundant and more optically-thin isotopes.

Idealized Density Measurement with $C^{18}O$

With its low abundance (x_{16}/x_{18} ~ 500), $C^{18}O$ may be optically thin, in which case the observed flux is (*ds* is distance along the l.o.s)

$$F_\nu = \int ds\, j_\nu\ \Delta\Omega_{\rm beam} \quad \text{with} \quad j_\nu = \frac{1}{4\pi} A_{ul}\ n_u\ h\nu_{ul}$$

Assuming that the relevant population is in thermal equilibrium, that there is no fractionation, and that x(CO) is a constant, then all the variables are known:

$$\frac{n_u}{n(\mathrm{C^{18}O})} = \frac{g_u e^{-E_{ul}/kT}}{Z} \quad \text{and} \quad n(\mathrm{C^{18}O}) = \frac{x_{18}}{x_{16}} n(\mathrm{CO})$$

$$\Rightarrow \quad F_\nu \propto N(\mathrm{CO}) \quad \text{and} \quad N_{\rm H} = \frac{N(\mathrm{CO})}{x(\mathrm{CO})}$$

Under all of these assumptions, the optically thin $C^{18}O$ flux determines the H column density. If one more assumption is made about the thickness of the cloud *L*, e.g., that it is the same as the dimensions on the sky (at a known distance), then the H volume density can be estimated as $n_H = N_H/L$.

Probes of Higher Density

Although the CO isotopes are useful for measuring the properties of widely distributed molecular gas, other probes are needed for localized high-density regions, especially cloud cores that give birth to stars. The solution is to use high-dipole moment molecules wth ***large critical densities***.

Species	μ(D)	ν_{10}(GHz)
CO	.110	115.3
CS	1.96	48.99
HCN	2.98	89.09
HCO^+	3.93	89.19
N_2H^+	3.4	93.18

$$A_{ul} = \frac{64\pi^4}{3h} \mu_{ul}^2 \nu_{ul}^3$$

See Schoier et al. A&A 432, 369 2005 for a more complete table of dipole moments and other molecular data from the Leiden data base.