

## Lecture 24

### CO Observations of Molecular Clouds

1. CO Surveys
2. Nearby molecular clouds
3. Antenna temperature and radiative transfer
4. Determining cloud properties from CO
5. Global distribution of molecular gas

#### 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/>

ay216

1

### Orion-Taurus-Aurigae



The location of nearby molecular clouds.

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2

# 1. CO Surveys

- There have been several surveys of CO emission of the Milky Way using the low- $J$  transitions
  - $^{12}\text{CO}$  1-0 at 115.271203 GHz
  - $^{12}\text{CO}$  2-1 at 230.538001 GHz
  - $^{13}\text{CO}$  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  $\text{H}_2$  is more than offset by its dipole moment (and higher Einstein  $A$ -values)
- CO lines can be optically thick, so the thinner lines of  $^{13}\text{CO}$  and  $\text{C}^{18}\text{O}$  are important

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3

## Three Important CO surveys

1. Goddard-Columbia-CfA (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. SUNY-UMASS (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. BU-FCRAO Survey of the Outer Galaxy – starting with Heyer et al. ApJS 115 241 1998, using the 14-m with multiple 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 2003 meeting report devoted to surveys:  
"Milky Way Surveys", ASP CP317, eds. D. Clemens et al.

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4

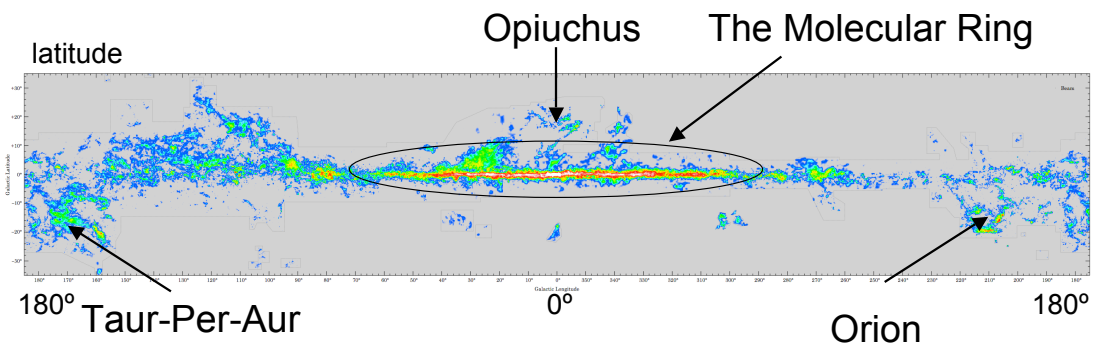
## Overview of CO Surveys

- 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: Combined 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

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5

## Distribution of CO Clouds



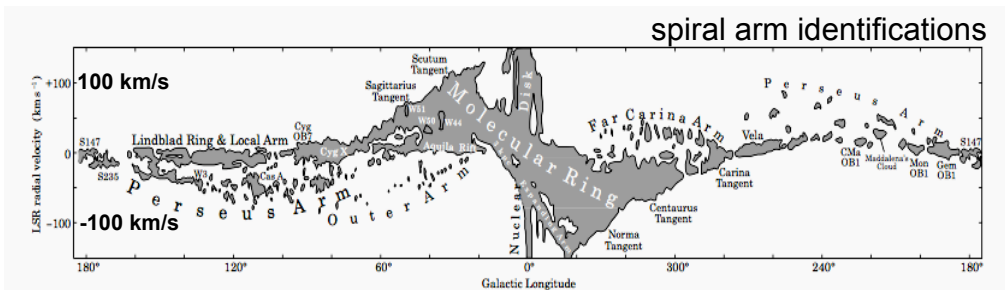
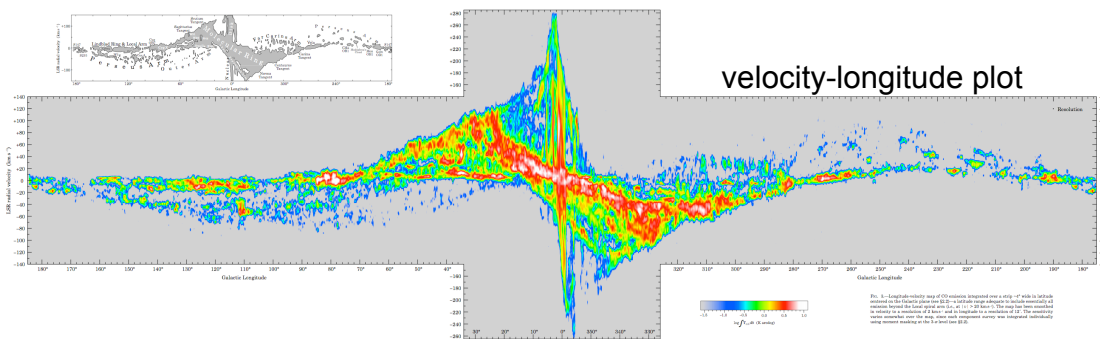
“The Milky Way in Molecular Clouds: A New Complete CO Survey”  
Dame, Hartmann and Thaddeus, ApJ 547 792 2001

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

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6

# Kinematics of CO Clouds

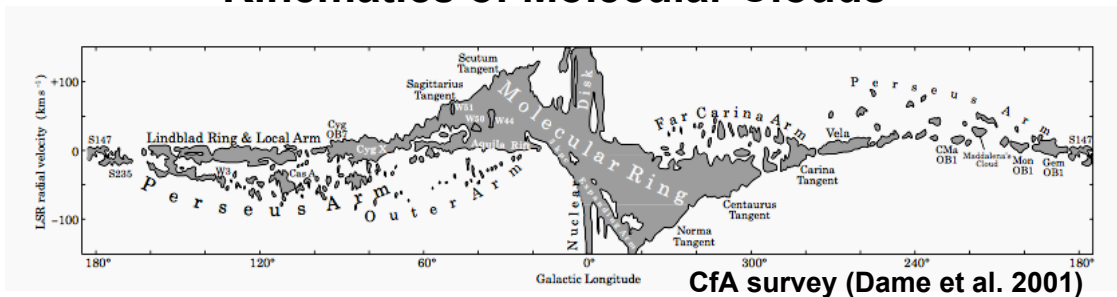


Dame et al. ApJ 547 792 2001

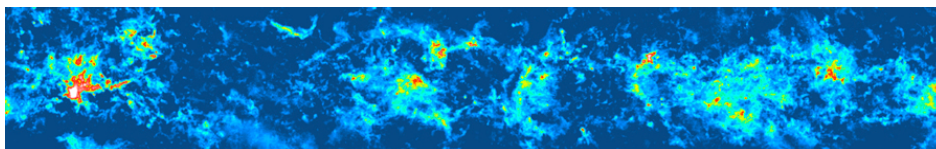
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7

# Kinematics of Molecular Clouds



- Nuclear disk/ring (250-750 pc) of high surface density expanding/rotating  $\sim 240$  km/s
- Molecular ring between 3-8 kpc (“5 kpc ring”)
- Spiral arms and discrete OB associations

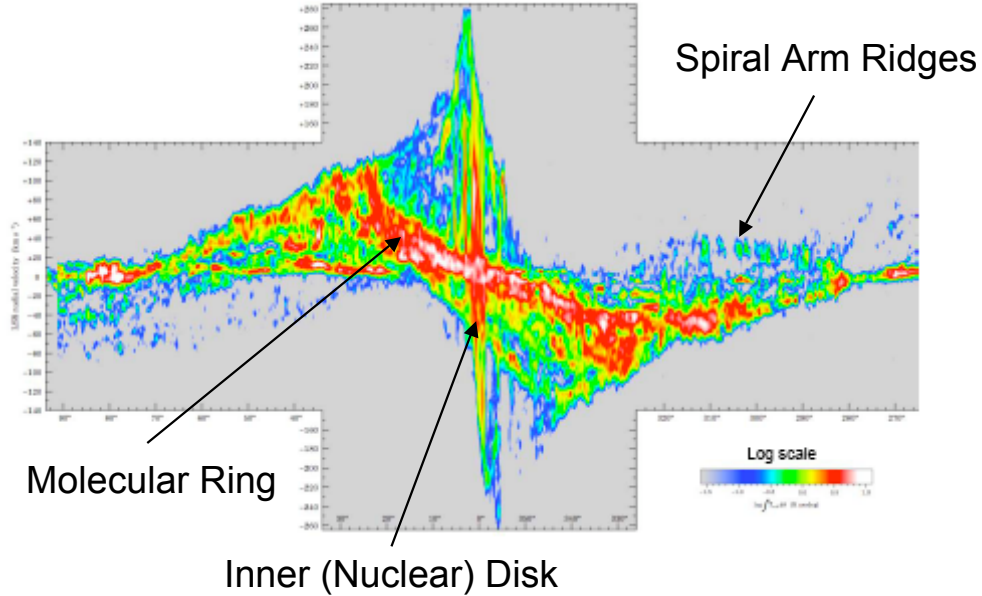


$^{13}\text{CO}$  Galactic Ring Survey (46'' resolution) [www.bu.edu/galacticring](http://www.bu.edu/galacticring)

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8

## Inner Galaxy in CO



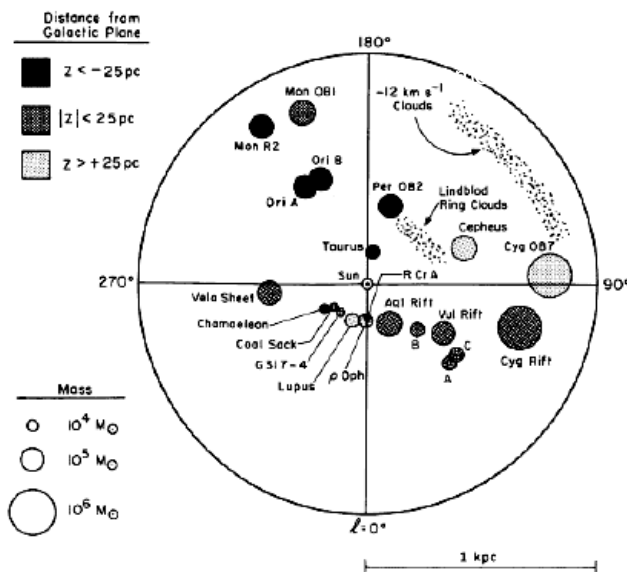
Dame et al. ApJ 547 792 2001

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9

## 2. Nearby Molecular Clouds

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



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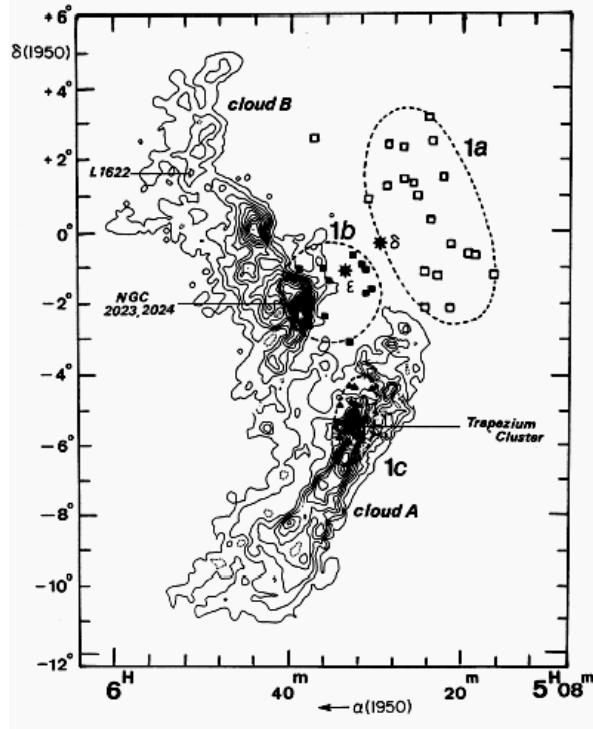
10

## Orion A and B Molecular Clouds

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

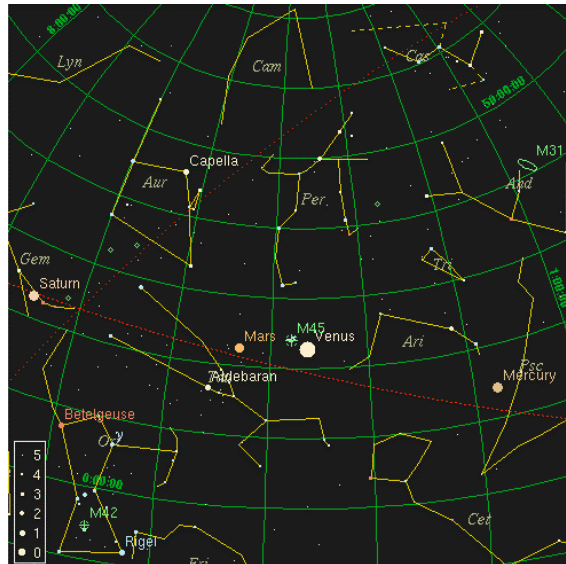
The Trapezium cluster  
has about 3500 YSOs,  
including a few O,B stars



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11

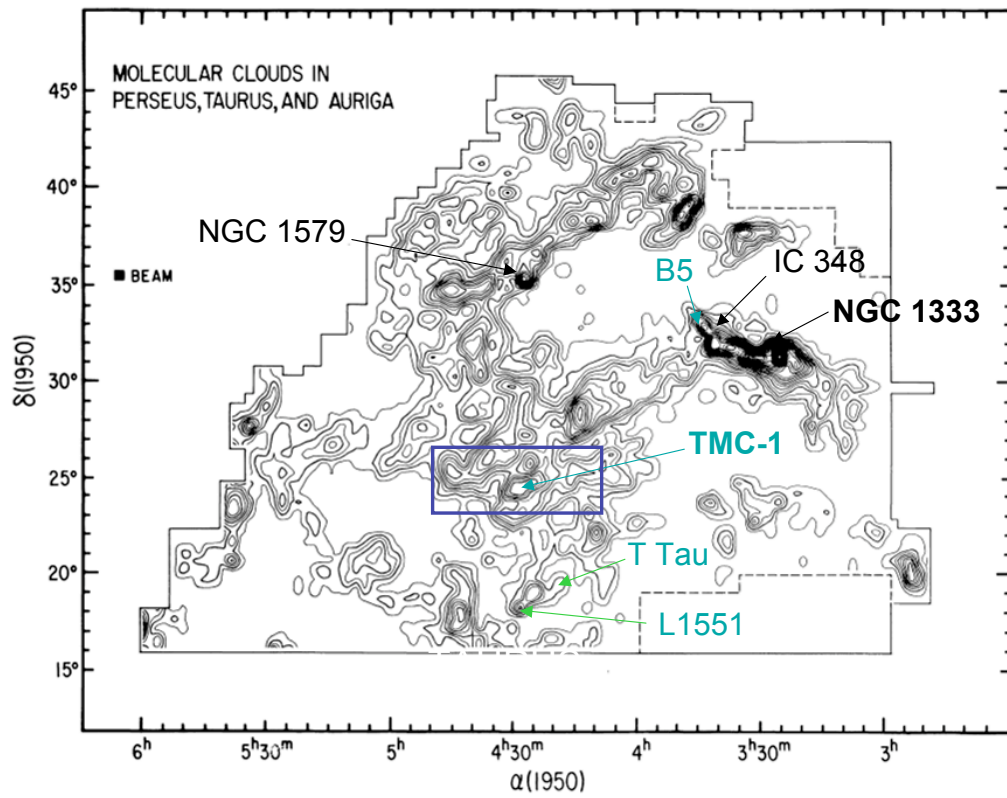
## Taurus-Perseus-Aurigae



→ 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.

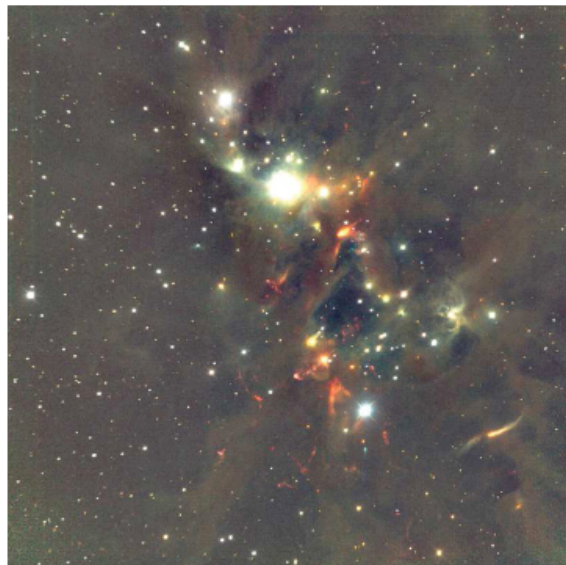
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12



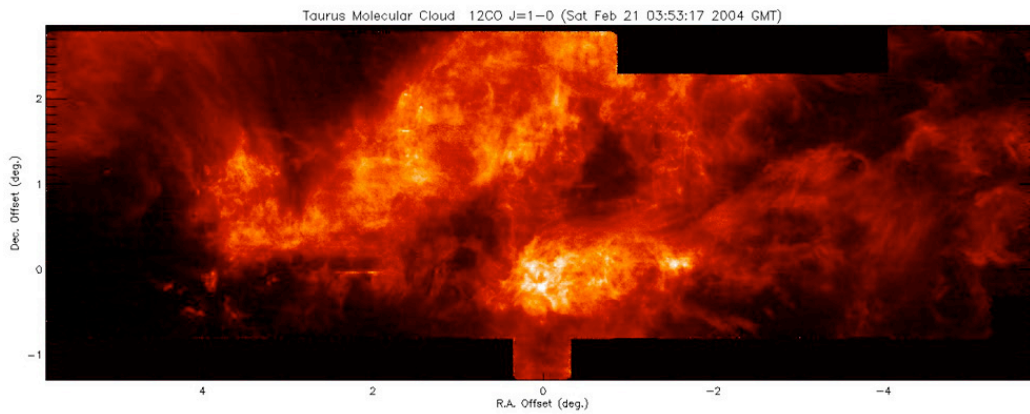
## Very Young Proto-Cluster in Perseus

NGC 1333, Lada & Lada, ARAA 41 57 2003



Notice the many outflows and jets characteristic of young protostars.

## TMC in $^{12}\text{CO}$

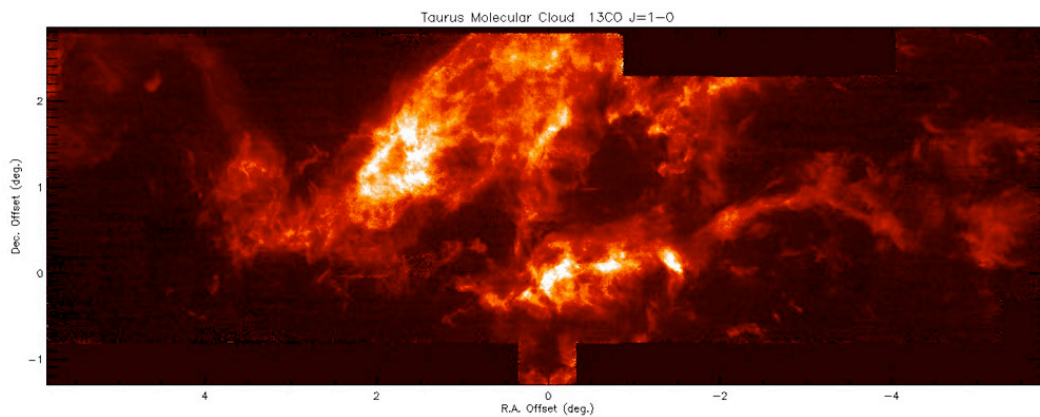


Taurus region in  $^{12}\text{CO}$  (FCRAO 14-m, HPBW = 50")

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15

## TMC in $^{13}\text{CO}$



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

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16



### 3. Radiative Transfer for Molecular Lines

Radio astronomers use the 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 Lec10-08 on the 21-cm line and solve the equation of transfer with an integrating factor

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

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

$$n_u/n_l = g_u/g_l e^{-T_{ul}/T_{ex}}, \quad T_{ul} = E_{ul}/k_B$$

The integrating factor is  $\exp(-\tau_\nu)$ ,

$$I_\nu = e^{-\tau_\nu} \mathfrak{S}_\nu \Rightarrow e^{-\tau_\nu} \frac{d\mathfrak{S}_\nu}{d\tau_\nu} = B(T_{ex}) \Rightarrow$$

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

Next slide for final result  $\longrightarrow$

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17

### 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  $\tau_\nu$  where  $I_\nu(0)$  is the incident intensity, e.g., the CBR at frequency  $\nu$ . 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  $I_\nu(\tau_\nu) - I_\nu(0)$ ,

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

Use the Rayleigh-Jeans formula to define the brightness temperature

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

and the above solution becomes

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

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18

## Formula for the Antenna Temperature

In deriving the result,

$$\Delta T^B_v(\tau_v) = (1 - e^{-\tau_v}) \left[ \frac{1}{e^{T_{ul}/T_{ex}} - 1} - \frac{1}{e^{T_{ul}/T_R} - 1} \right]$$

we defined  $T_{ul} = h\nu_{ul}/k_B$  and replaced the incident field's intensity in term of a radiation temperature  $T_R$

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

The solution above allows 3 possibilities:

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

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

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

**This result is incomplete because the optical depth and  $T_{ex}$  are both unknown; they require a calculation of the level population.**

The integrated optical depth is obtained in the usual way

$$\int_{\text{line}} d\nu \tau_v = \frac{h\nu_{ul}}{c} (N_l B_{lu} - N_u B_{ul}) = \frac{\lambda_{ul}^2}{8\pi} \frac{g_u}{g_l} A_{ul} N_u (1 - e^{-T_{ul}/T_{ex}}) \quad (2)$$

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19

## Population Calculation

The balance equation assuming adjacent ladder-rung transitions is:

$$(A_{ul} + k_{ul}n_c + u_v B_{ul})n_u = (k_{lu}n_c + u_v B_{lu})n_l$$

This equation can be solved for the population ratio

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

The excitation temperature can be expressed in terms of  $T_R$  and the density  $n_{coll}$  of colliders with the critical density,  $n_{cr} = A_{ul}/k_{ul}$ :

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

We can easily check the high and low density limits:

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

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

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20

# Summary of Radiative Transfer

We derived three equations for a single transition:

Eq, (1) -  $\Delta T^B$  in terms of  $T_{ex}$ ,  $T_R$  and  $\tau_v$

Eq, (2) -  $\tau_v$  in terms of  $T_{ex}$  and  $N_l$

Eq, (3) -  $T_{ex}$  in terms of  $T$ ,  $T_R$  and  $n_{coll}$

- There are five unknowns: kinetic temperature  $T$   
excitation temperature  $T_{ex}$   
background temperature  $T_R$   
density of the molecular carrier  $n$   
density of the collision partner  $n_{coll}$

and only one observable  $\Delta T^B$ !

- All is not lost, however, since usually more than one line and at least one isotope can be observed. If the isotope has a low enough abundance, its lines are optically thin, which simplifies the analysis.

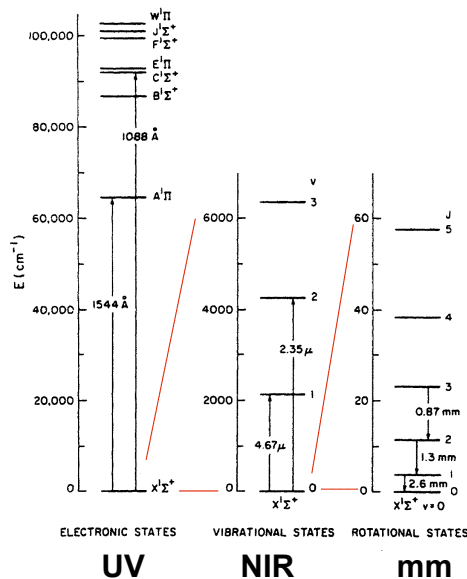
Carl Heiles pointed out that, in contrast to Slide 18,  $T_R$  refers to *any* background - not just the CMB, most importantly the diffuse line radiation from other parts of the cloud.

This is a non-local problem in more than one dimension

## 3. Determining Cloud Properties from CO

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

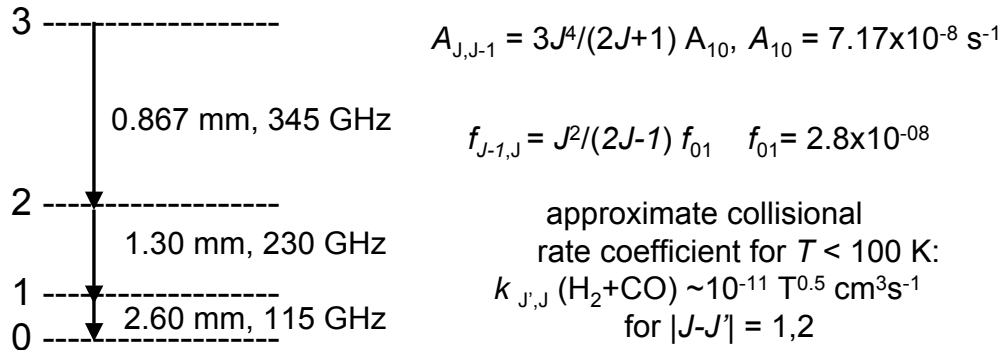
To obtain more information on the physical conditions, we apply Lects 17-20 on molecular spectroscopy to the interpretation of the mm observations of CO.



## a. The Ground Rotational Band of CO

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

$$B = 1.922529 \text{ cm}^{-1} \quad (ch/k_B) B = 2.766 \text{ K}$$



See Sec. 4 of Schoier et al. (AA 432 369 2005) for discussion of molecular collisional rate coefficients (LAMDA data base).

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23

## CO rotational Frequencies and Critical Densities

Frequencies in GHz

	CO	<sup>13</sup> CO	C <sup>18</sup> O
1-0	115.271	110.201	109.782
2-1	230.518	220.4	219.6
3-2	345.796	330.6	329.4

<http://physics.nist.gov/PhysRefData/Micro/Html/contents.html>

### b. Critical Densities

$$n_{\text{cr}}(1-0) \approx \frac{7167}{T^{0.5}} \text{ cm}^{-3} = 1.43 \times 10^3 \left(\frac{25}{T}\right)^{1/2} \text{ cm}^{-3}$$

$J \rightarrow J-1$	$n_{\text{cr}}(J \rightarrow J-1)$
1-0	$1.4 \times 10^3$
2-1	$2.3 \times 10^3$
3-2	$7 \times 10^4$

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

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24

## c. Optical Depth of the CO mm Lines

Start with the standard formula for a gaussian line

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

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

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

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

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

For a thermal equilibrium population but not too low  $T$ ,

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

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25

## CO rotational line optical depths

Putting all the pieces together leads to:

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

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

**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:

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

**Large  $\tau_{10}$  reduces the critical density.**

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26

## 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 be derived from less-abundant and more optically-thin isotopes.

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27

## Idealized Density Measurement with C<sup>18</sup>O

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

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

*Assuming* that the level population is in thermal equilibrium and that the CO abundances are constant, then:

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

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

*Under these assumptions*, the optically thin C<sup>18</sup>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  $n_{\text{H}} = N_{\text{H}}/L$ .

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28

## 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 with **large critical densities**.

Species	$\mu$ (D)	$\nu_{10}$ (GHz)
CO	.110	115.3
CS	1.96	48.99
HCN	2.98	89.09
HCO <sup>+</sup>	3.93	89.19
N <sub>2</sub> H <sup>+</sup>	3.4	93.18

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

Note the dependence on the square of the dipole Moment.

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 LAMDA and F. J. Lovas and R. A. Dragoset for microwave frequencies (c. 2002):

<http://physics.nist.gov/PhysRefData/Micro/Html/contents.html>

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29

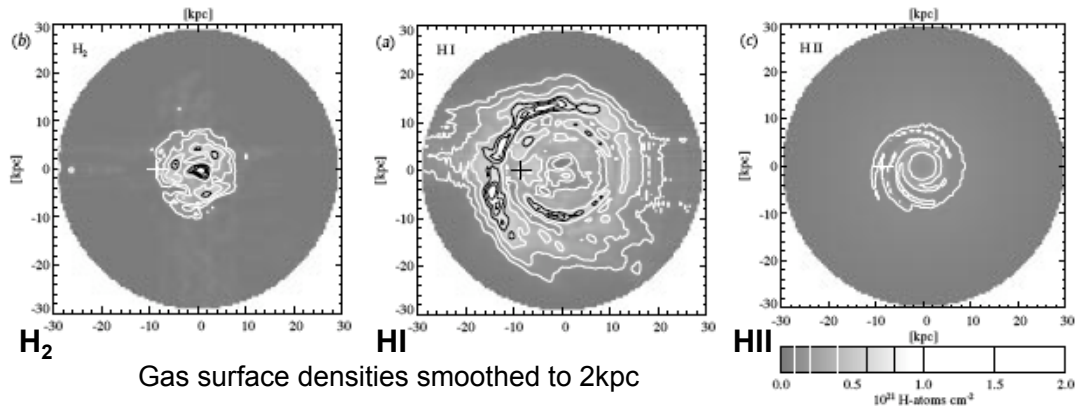
## 5. Global Distribution of Molecular Gas

- Observing from inside makes it difficult to sort out the distribution of molecular gas in the Milky Way.
- The CO emission is inhomogeneous (radially and azimuthally).
- Confusion and kinematic ambiguity make it difficult to determine whether GMCs are primarily located in spiral arms.
- An X-factor is used to obtain the H<sub>2</sub> surface density (Lecture 25)
- H<sub>2</sub> (or CO) has a ring (“5-kpc ring”) with a hole at the center (next slide).
- The total H<sub>2</sub> and HI masses are of the same order, but the ratio varies.
- Observations of external galaxies are very useful.

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30

## HI and H2 Column Densities



### Modeling of $\gamma$ -rays and CfA CO survey (Hunter et al. ApJ 2001)

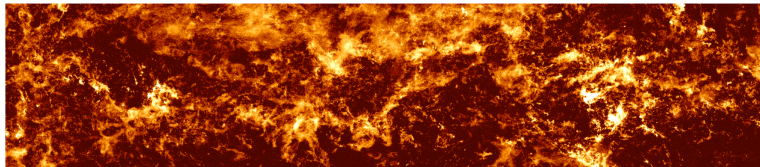
- $H_2$  has a ring with a hole at the center
- Spiral arms are not delineated clearly
- HI is more extended
- GMCs have comparable masses of HI and  $H_2$
- Origin of HI in and near GMCs: photodissociation of  $H_2$  or remains of GMC formation from HI?

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31

## FCRAO Outer Galaxy Survey

Heyer et al. ApJS 115 241 1998



- **Regions of little molecular gas**, perhaps cleared by photodissociation, stellar winds and supernova from massive stars. The last two processes can sweep up and compress gas and help make new stars.
- **CO is primarily in spiral arms**, with estimated  $H_2$  *arm-interarm* contrast  $\sim 30:1$  (the HI ratio is 2.5:1).
- **Popular old idea**: GMCs form by compression of atomic gas as it crosses the arms on the time scale of  $\sim 10^8$  yr.
- **Pervasive low-level CO** called “chaff” may account for 10% of the total molecular gas, estimated to be  $10^9 M_\odot$ , but it may not be enough to make GMCs.

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32



# CO Emission from Spiral Arms

Heyer et al. ApJS 115 241 1998

The velocity-position diagram (bottom) separates the local and nearby Perseus arms and shows that the CO emission is localized in the arms.

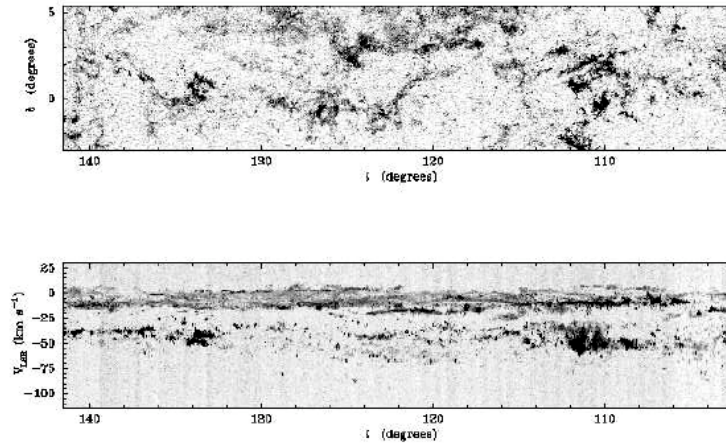


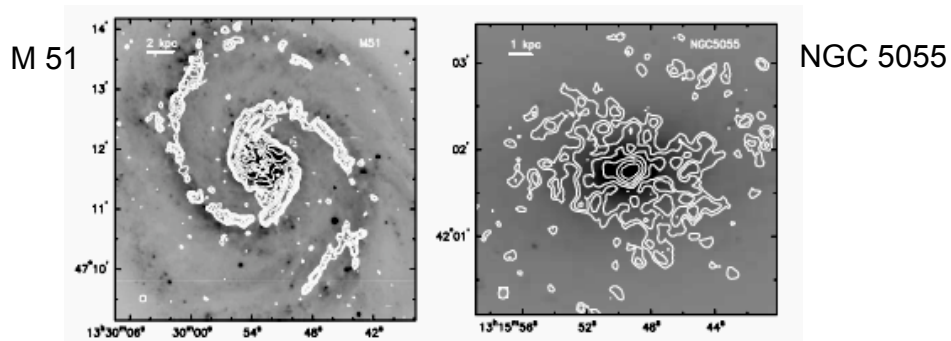
Figure 2. CO emission in the outer Galaxy (from Heyer et al. 1998). Top panel is a velocity integrated  $l-b$  plot, lower panel is a  $l-v$  plot (integrated over the latitude range of the survey) showing the local and Perseus spiral arms. Note the almost complete absence of molecular gas between the two spiral arms at about  $0 - -10 \text{ km s}^{-1}$  and  $-40 \text{ km s}^{-1}$ . The high spatial dynamic range of this survey shows the large scale distribution of molecular gas in the ISM in exceptional detail.

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33

# CO and Spiral Arms in External Galaxies

Blitz and Williams (1999)

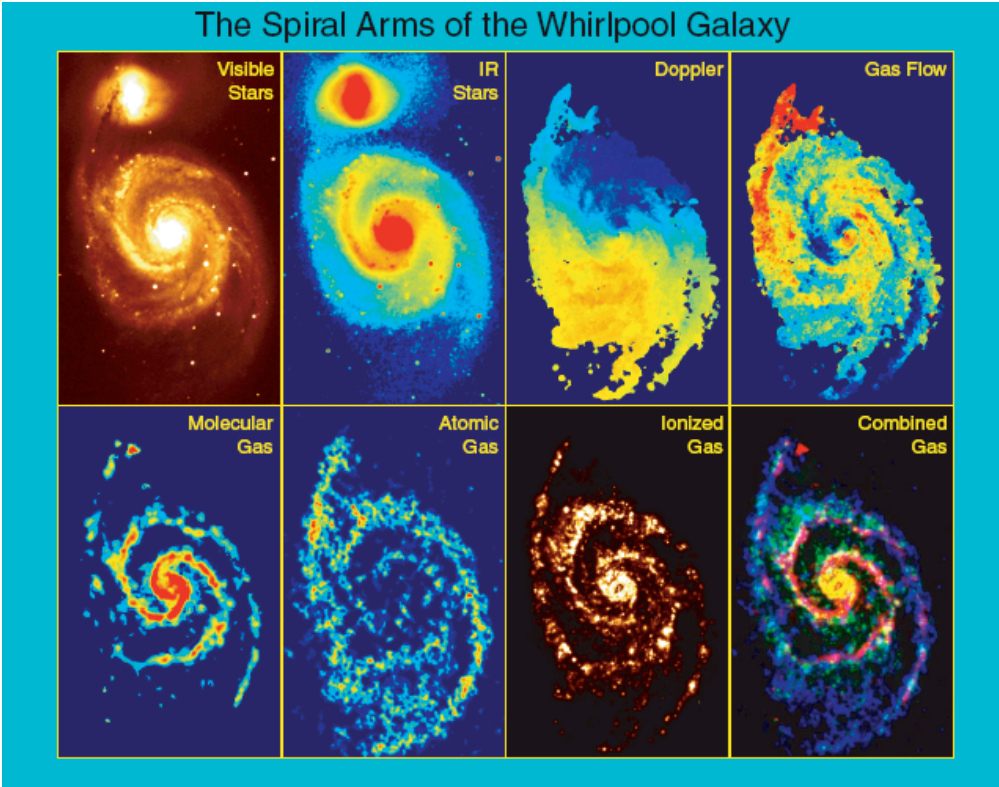


classic grand spiral      weak spiral structure  
CO emission overlaid on optical photos

Similar kinds of GMCs in galaxies with and without well-defined spiral structure. How do GMCs form in galaxies like NGC 5055 ?

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34



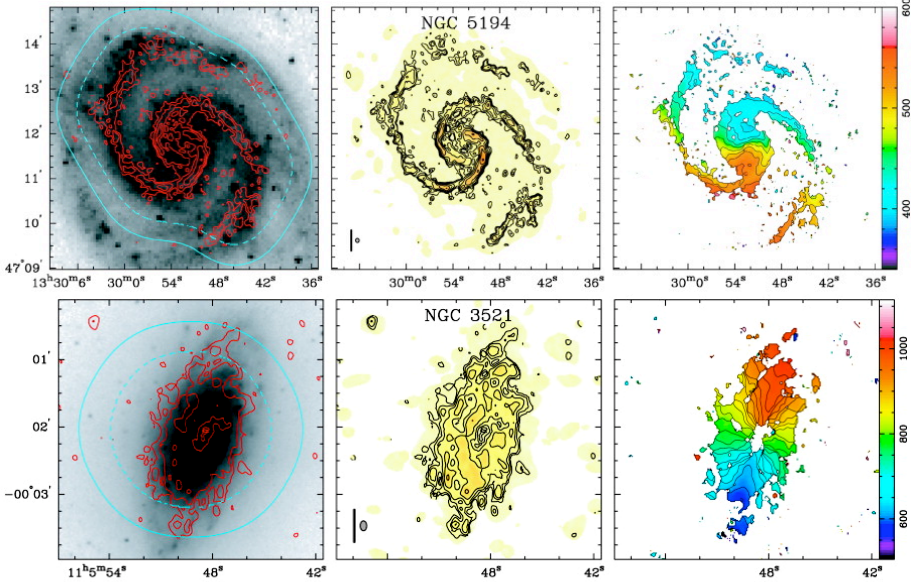
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Courtesy of Leo Blitz

35

## 6'' BIMA CO Survey Of Nearby Galaxies

Helfer et al. 2003 ApJS 145 259



CO emission overlaid on SDSS

CO emission

CO velocity

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36