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/

Orion-Taurus-Aurigae

The location of nearby molecular clouds.
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 $^{18}\text{O}$ are important

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).

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.
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

 Distribution of CO Clouds

“The Milky Way in Molecular Clouds: A New Complete CO Survey”

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


Kinematics of Molecular Clouds

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

13CO Galactic Ring Survey (46" resolution) www.bu.edu/galacticring
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
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

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.
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")

Notice the greater detail compared to the CO map.

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

Taurus region in $^{13}\text{CO}$ (FCRAO 14-m, HPBW = 50").
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

$$\frac{dl_v}{d\tau_v} = B_v(T_{ex}) - I_v, \quad d\tau_v = \kappa_v ds$$

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

$$\frac{n_u}{n_i} = \frac{g_u}{g_i} e^{-\tau_{ul} / T_{ex}}, \quad T_{ul} = E_{ul} / k_B$$

The integrating factor is $\exp(-\tau_v)$,

$$I_v = e^{-\tau_v} \Xi_v \quad \Rightarrow \quad e^{-\tau_v} \frac{d\Xi_v}{d\tau_v} = B(T_{ex}) \quad \Rightarrow$$

$$\Xi_v(\tau_v) - \Xi_v(0) = (e^{-\tau_v} - 1)B(T_{ex}) \text{ for constant } T_{ex}$$

Next slide for final result

Solution of the Equation of Transfer

The solution to the equation of transfer is now

$$I_v(\tau_v) = (1 - e^{-\tau_v})B_v(T_{ex}) + e^{-\tau_v}I_v(0)$$

We may think of $I_v(\tau_v)$ as the measured intensity of a uniform slab of thickness $\tau_v$, where $I_v(0)$ is the incident intensity, e.g., the CBR at frequency $v$. 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 $I_v(\tau_v) - I_v(0)$,

$$\Delta I_v(\tau_v) = I_v(\tau_v) - I_v(0) = (1 - e^{-\tau_v})[B(T_{ex}) - I_v(0)]$$

Use the Rayleigh-Jeans formula to define the brightness temperature

$$I_v \equiv \frac{2 \lambda^2}{c^2} k_B T_v^B$$

and the above solution becomes

$$\Delta T_v^B(\tau_v) = (1 - e^{-\tau_v})\left[\frac{1}{e^{T_{ul} / T_{ex}} - 1} - \frac{1}{e^{T_{ul} / T_R} - 1}\right] \quad (1)$$
Formula for the Antenna Temperature

In deriving the result,

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

we defined \( T_B = h \nu_B / k_B \) and replaced the incident field’s intensity in terms of a radiation temperature \( T_R \)

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

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

\[ \int \frac{d \nu}{\tau_v} = \frac{h \nu_{ul} (N_{ul} B_{lu} - N_{ul} B_{ul})}{c} = \frac{8 \pi^2}{g_u g_l} A_{ul} N_u (1 - e^{-T_{ul}/T_R}) \quad (2) \]

Population Calculation

The balance equation assuming adjacent ladder-rung transitions is:

\[ (A_{ul} + k_{ul} n_e + u_v B_{ul}) n_u = (k_{lu} n_e + u_v B_{lu}) n_l \]

This equation can be solved for the population ratio

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

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

\[ e^{-T_{ul}/T_R} = e^{-T_{ul}/T} \left( \frac{(e^{T_{ul}/T_R} - 1) + (n_c / n_{coll})}{(e^{T_{ul}/T_R} - 1) + (n_c / n_{coll}) e^{T_{ul}/T_R}} \right) \quad (n_c = A_{ul} / k_{ul}) \quad (3) \]

We can easily check the high and low density limits:

\[ n_{coll} >> n_c : \quad T_{ex} = T \]

\[ n_{coll} << n_c : \quad \frac{1}{T_{ex}} = \frac{1}{T} + \frac{1}{T_R} \Rightarrow T_{ex} = T \left( T << T_R \right) \text{ or } T_R \left( T >> T_R \right) \]
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 $N_i$
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 back-
ground - 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 $^{12}$CO or
$^{13}$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 Lecs 17-20 on
molecular spectroscopy to
the interpretation of the
mm observations of CO.
a. The Ground Rotational Band of CO

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

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

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

\[ \begin{array}{c|c|c|c}
J & A_{J,J-1} & 0.867 \text{ mm, 345 GHz} & f_{J,J-1} = J^4/(2J+1) \quad f_{01} = 2.8 \times 10^{-08} \\
0 & & & \\
1 & 1.30 \text{ mm, 230 GHz} & \text{approximate collisional rate coefficient for } T < 100 \text{ K:} & k_{J,J} (\text{H}_2+\text{CO}) \sim 10^{-11} \text{ T}^{0.5} \text{ cm}^3\text{s}^{-1} \\
2 & \text{2.60 mm, 115 GHz} & \text{for } |J-J'| = 1,2 & \\
\end{array} \]

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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**CO rotational Frequencies and Critical Densities**

**Frequencies in GHz**

<table>
<thead>
<tr>
<th></th>
<th>CO</th>
<th>$^{13}$CO</th>
<th>C$^{18}$O</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0</td>
<td>115.271</td>
<td>110.201</td>
<td>109.782</td>
</tr>
<tr>
<td>2-1</td>
<td>230.518</td>
<td>220.4</td>
<td>219.6</td>
</tr>
<tr>
<td>3-2</td>
<td>345.796</td>
<td>330.6</td>
<td>329.4</td>
</tr>
</tbody>
</table>

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

b. Critical Densities

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

<table>
<thead>
<tr>
<th>J→J-1</th>
<th>$n_{cr}(J→J-1)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-0</td>
<td>1.4x10^3</td>
</tr>
<tr>
<td>2-1</td>
<td>2.3x10^3</td>
</tr>
<tr>
<td>3-2</td>
<td>7x10^4</td>
</tr>
</tbody>
</table>

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
\[ \tau_{J, J-1} = f_{J, J-1} \frac{\pi \epsilon^2}{m_c} \frac{\lambda_{J, J-1}}{b} N_{J-1} \text{(CO)} \left( 1 - \frac{P_J / 2J + 1}{P_{J-1} / 2J - 1} \right) \]

The stimulated emission factor is included because the transition and thermal temperatures are the same order of magnitude (10 K):
\[ 1 - \frac{P_J / 2J + 1}{P_{J-1} / 2J - 1} \approx 1 - \exp(-2.766 J / T) \]

For a constant CO abundance and excitation temperature, the column densities of the rotational levels are
\[ N_J = x(\text{CO}) P_J N_H \]

For a thermal equilibrium population but not too low \( T \),
\[ P_J \approx \frac{1}{Z} (2J + 1) e^{-J(J+1)B/kT}, \quad Z \approx \frac{T}{B} \]

Putting all the pieces together leads to:
\[ \tau_{J, J-1} \approx f_{J, J-1} \frac{\pi \epsilon^2}{m_c} \frac{\lambda_{J, J-1}}{b} x(\text{CO}) N_H \frac{2J-1}{T/B} e^{-J(J-1)B/kT} \left( 1 - e^{-2BJ/T} \right) \]

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

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

Large \( \tau_{10} \) 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 be derived from less-abundant and more optically-thin isotopes.

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

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

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

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

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

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

Under 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 with large critical densities.

<table>
<thead>
<tr>
<th>Species</th>
<th>$\mu$(D)</th>
<th>$v_{10}$(GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>.110</td>
<td>115.3</td>
</tr>
<tr>
<td>CS</td>
<td>1.96</td>
<td>48.99</td>
</tr>
<tr>
<td>HCN</td>
<td>2.98</td>
<td>89.09</td>
</tr>
<tr>
<td>HCO$^+$</td>
<td>3.93</td>
<td>89.19</td>
</tr>
<tr>
<td>N$_2$H$^+$</td>
<td>3.4</td>
<td>93.18</td>
</tr>
</tbody>
</table>

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

Note the dependence on the square of the dipole Moment.

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

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$_2$ surface density (Lecture 25)
• H$_2$ (or CO) has a ring (“5-kpc ring”) with a hole at the center (next slide).
• The total H$_2$ and HI masses are of the same order, but the ratio varies.
• Observations of external galaxies are very useful.
HI and H2 Column Densities


- H₂ has a ring with a hole at the center
- Spiral arms are not delineated clearly
- H I is more extended
- GMCs have comparable masses of HI and H₂
- Origin of HI in and near GMCs: photodissociation of H₂ or remains of GMC formation from HI?

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 H₂ arm-interarm contrast ~ 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 ~ 10⁸ yr.

Pervasive low-level CO called “chaff” may account for 10% of the total molecular gas, estimated to be 10⁹ M☉, but it may not be enough to make GMCs.
CO Emission from Spiral Arms

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 $l - c$ 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 $0 - 10$ km s$^{-1}$ and $-40$ 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.

CO and Spiral Arms in External Galaxies
Blitz and Williams (1999)

M 51 NGC 5055
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?
The Spiral Arms of the Whirlpool Galaxy

CO emission overlaid on SDSS

6” BIMA CO Survey Of Nearby Galaxies
Helfer et al. 2003 ApJS 145 259

CO emission overlaid on SDSS
CO emission
CO velocity

Courtesy of Leo Blitz