18: Molecular Clouds

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Outline

• Famous molecular clouds
  – Orion A & B
  – Taurus, Auriga, & Perseus complex
• CO J=1-0 surveys
  – CO vs. H$_2$
• The CfA CO J=1-0 survey
Orion-Taurus-Auriga
Orion-Taurus-Auriga
Local GMCs Orion A & B

Dame et al. (2001 ApJ 547 792)
Orion in CO
Orion as Seen by IRAS
Orion Finding Chart

Fig. 3.—Schematic diagram of the molecular clouds: the lowest contour from Fig. 2. Dots with numbers, corresponding to those in Table 1, indicate locations of CO emission peaks. Some NGC numbers indicate the optically prominent objects coincident with CO peaks. The extent of UV emission from Barnard’s loop is indicated by the shaded arc (from O’Dea, York, and Henize 1967; Isobe 1973). The dashed line roughly indicates the extent of the A Orion ring of clouds.
Taurus-Perseus-Auriga
Taurus-Perseus-Auriga Complex
MOLECULAR CLOUDS IN
PERSEUS, TAURUS, AND

NGC 1333

AURIGA

NGC 1579

IC 348

TAURUS

PERSEUS

T Tau
Fig. 1.—Velocity-integrated intensity of CO emission, $W_{\text{CO}}$. The lowest contour is 0.5 K km s$^{-1}$, and the separation between contours is 1.5 K km s$^{-1}$. The border of the surveyed region is indicated by the outer, solid line; in the small regions beyond the dashed line the map is undersampled, with a spacing of 4" x 1".
TMC in $^{12}\text{CO}$

Taurus region in $^{12}\text{CO}$ & $^{13}\text{CO}$ from with the FCRAO 14-m (HPBW = 50$''$).
TMC in $^{13}\text{CO}$

Taurus region in $^{12}\text{CO}$ & $^{13}\text{CO}$ from with the FCRAO 14-m (HPBW = 50$"$).
CO Surveys

• There have been many surveys of the emission in the lower CO rotational lines
  – CO 1-0 at 115.271203 GHz
  – CO 2-1 at 230.538001 GHz
  – $^{13}$CO 1-0 110.20137 GHz

• CO surveys are the primary source for identification of Galactic giant molecular clouds and their motions
CO vs. H₂

• H₂ has no permanent electric dipole moment
  – H₂ is almost unobservable directly in the cold, obscured interstellar regions where molecules form and survive
  – Lines of site with $N_H > 10^{21}$ cm$^{-2}$ are not accessible to UV

• The low-$J$ transitions of CO, in contrast, are detectable in cool tenuous molecular gas
  – CO $J=1-0$ at 115 GHz is the molecular analog of the HI 21-cm line
CO vs. H₂

• The low abundance of CO ($n_{\text{CO}}/n_{\text{H}_2} \leq 5 \times 10^{-4}$ if all C is in CO) compared to H₂ or HI is offset by the higher Einstein $A$ values and lower excitation temperatures
  – Choose the best CO line: $J_{\text{max}} \approx (kT_{\text{rot}}/hB)^{1/2} = (T_{\text{rot}}/2.76 \text{ K})^{1/2}$
  – $^{12}$CO lines can be optically thick
  – Isotopic lines of CO are important

• The lower abundance means that $^{13}$CO or C$^{18}$O are optically thin when $^{12}$CO is optically thick

<table>
<thead>
<tr>
<th>Species</th>
<th>Transition</th>
<th>$\nu$ (GHz)</th>
<th>$E_u$ (K)</th>
<th>$A$ (s⁻¹)</th>
<th>$n_{cr}$ (cm⁻³)</th>
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<td>2.5x10⁻⁶</td>
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</table>

CO vs. $H_2$

• CO is generally the most easily observed molecular line
  – No molecular cloud free of CO emission
  – GMCs throughout the Milky Way can be detected in CO 1-0 even with a small telescope

• Independent methods show that the velocity-integrated intensity of the $J=1$-0 line measures $N(H_2)$ to $\sim x2$ or better when averaged over large region
  – Accepted value is $2-3 \times 10^{20}$ molecules cm$^{-2}$ (K km s$^{-1}$)$^{-1}$
CO & HI

• CO maps show a much clumpier morphology and different global structure than the broad HI distribution

• Individual molecular clouds and cloud complexes can be identified over much of the Galaxy
  – Although CO lines are often optically thick there are different velocities for different Galactic radii and so we can find clouds over a large section of the Galactic disk
  – In some regions the clouds complexes are confused, and there is no definitive picture of the structure in these lines of sight
Utility of CO J=1-0 Observations

• Crucial for studies of star formation & Galactic structure
  – High-resolution CO observations of dense cloud cores and molecular outflows revolutionized our understanding of how stars form

• Together with radio & O/IR, observations of H II regions, OB associations, and other Pop I objects, CO surveys show that virtually all star formation occurs in molecular clouds
Utility of CO $J=1-0$ Observations

• CO surveys have refined our knowledge of the spiral structure of our system
  – GMCs preferentially form in the arms of spiral galaxies
  – The kinematic distance ambiguity in the inner Milky Way can be broken by associating clouds with Pop I objects

• The precise kinematic information from CO surveys has also been of great value in the interpretation of Galactic continuum surveys from satellite observatories such as $\gamma$-ray (GRO) and IR (COBE)
Distribution of Molecular Clouds

  - CO 1-0 @ 7.5’–15’ angular resolution
  - Complete in longitude, variable in latitude
  - \( N(H_2) = 1.8 \pm 0.3 \times 10^{20} \text{ cm}^{-2} \text{ K}^{-1} \text{ km s}^{-1} \)
    - Detected column ranges from 0.02 –3 \( \times 10^{22} \text{ cm}^{-2} \)

- The CO distribution is thin
  - Vertical extent ±45-75 pc over much of the disk
  - Similar to that of OB associations
  - Flares out to ±100-200 pc
Kinematics of Molecular Clouds

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

- Thin intense ridge extending ±60° from the Galactic center
  - (l,ν) map shows that this results from the superposition of multiple clouds in the “molecular ring”
  - Broad ring of molecular gas that peaks ~ half way between the Galactic center and the sun
  - Multiple ridges may indicate multiple inner spiral arms

- Stark contrast in the density of molecular clouds between the inner Galaxy (l = 270°–90°) and the outer Galaxy (l = 90° – 270°) is evident in non local gas (|ν| > 20 km/s)
The Molecular Ring

Inner galaxy/outer galaxy

Local gas

$R > R_\odot$

$R < R_\odot$

$R > R_\odot$
Nuclear Disk & Inner Spiral Arm Ridges
Giant Molecular Complexes

• The strong (red-white) peaks in the \((l, v)\) maps are *giant molecular complexes*
  – \(M \approx 10^5 \text{ – } 10^6 \, \text{M}_\odot\)
  – \(\sigma \approx 15 \, \text{km/s} \text{ or larger}\)

• Appear to be well defined, coherent structures
  – A large fraction of the total molecular gas is contained within such structures

• Nearby examples include W44 (3kpc) and the cloud associated with the Cas A SNR
Nearby GMCs

Cas A cloud

W44
Nearby Molecular Clouds

- Taurus is the nearest molecular cloud
  - Site of low mass star formation
- Nearest site of OB star formation is Orion
- Nearest cloud complex is the Cygnus rift/Cygnus OB7
Local Spiral Arms

• Large scale coherent lanes are spiral arms
  – Local gas within 1 kpc appears at $|v| < 20$ km/s
  – Reflects organization into the local spiral arm
  – Appears well separated from the Perseus arm
CO & Spiral Arms

• CO traces spiral arms
  – Quantitative agreement lacking
    • Disagrees with Georgelin & Georgelin (1976 AA 49 57)
  – Clouds have random velocities and non-circular velocities adding uncertainties to kinematic distances

• Milky Way is not unique
  – NGC 891 (Scoville et al. 1993 ApJL 404 59)
What is a Molecular Cloud?

• Molecular clouds:
  – Contain molecules (but don’t forget HI)
  – Self-gravitating
  – Magnetized
  – Turbulent
    • The central role of gravity, not their molecular composition, that distinguishes them from any other phase of the ISM

• Stars form only in molecular clouds
  – Understanding star formation starts with understanding molecular clouds
Giant Molecular Clouds

• Definition is problematic because of the apparent lack of a physical scale
  – The mass spectrum is a power law with no natural size or mass
  – By convention $M > 10^5 \, M_\odot$ is a molecular cloud
    • Definition starts to get fuzzy at $\sim 10^4 \, M_\odot$
    • Some small $10^2 \, M_\odot$ high latitude molecular clouds

• GMCs found in CO surveys and those found by studying regions of star formation are indistinguishable
  – Results of detailed studies of local clouds are likely to be of general applicability
  – Star formation is the normal state of GMCs
Spatial Structure

(a) FCRAO 14 m

(b) CfA 1.2 m
# Dense Gas Tracers

<table>
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<tr>
<th>Molecule</th>
<th>Transitions</th>
<th>Frequency (GHz)</th>
<th>E/k (K)</th>
<th>$n_{\text{crit}}$ (cm$^{-3}$) @ 10 K</th>
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<tr>
<td>$^{12}\text{C}^{16}\text{O}$</td>
<td>1-0</td>
<td>115.2</td>
<td>5.5</td>
<td>1100</td>
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<td>2-1</td>
<td>230.5</td>
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<td>6700</td>
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<td>3-2</td>
<td>345.7</td>
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<td>$2 \times 10^4$</td>
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<td>CS</td>
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<td>98.0</td>
<td>7.1</td>
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<td>$\text{NH}_3$</td>
<td>(1,1)</td>
<td>23.7</td>
<td>1.1</td>
<td>$1.8 \times 10^3$</td>
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<td>(2,2)</td>
<td>23.7</td>
<td>42</td>
<td>$2.1 \times 10^3$</td>
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</table>
Density Structure in Molecular Cloud Cores

Fig. 1. — Half-maximum intensity contours of 16 dense cores in dark clouds, in the 1.3 cm \((J, K) = (1,1)\) lines of NH\(_3\), from Benson & Myers (1989), and in the 3.0 mm \(J = 2 \rightarrow 1\) line of CS, and the 2.7 mm \(J = 1 \rightarrow 0\) line of \(^{13}\)CO, from Fuller (1989). For each map, North is up, East is left, and the linear scale 0.2 pc is indicated. A cross indicates an associated star.
What is a Molecular Cloud?

- Molecular clouds (by definition) are regions where the mass is primarily molecular
  - Much of the volume is not necessarily molecular
  - Highly structured with large range of density
    - Critical density of CO 1-0 \( \sim 1400 \text{ cm}^{-3} \)
    - Critical density of CS 2-1 \( \sim 2 \times 10^5 \text{ cm}^{-2} \)
  - Filling factor is low
    - Perhaps less than \( \sim 0.2 \)

- Most of the molecular ISM is in the form of giant molecular clouds
  - \( M \sim 10^{5-6} \text{ M}_{\odot} \) with a sharp cut off at \( 6 \times 10^6 \text{ M}_{\odot} \)
  - \( D \sim 50 \text{ pc} \)
  - \( < n_{\text{H}_2} > \sim 100 \text{ cm}^{-3} \)

- What sets the upper mass range?
  - Galactic tidal field?
  - Feedback from massive stars?
Properties of Local GMCs

<p>| | |</p>
<table>
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<th></th>
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<tr>
<td>Mass</td>
<td>$1-2 \times 10^5 , M_\odot$</td>
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<tr>
<td>Mean diameter</td>
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</tr>
<tr>
<td>Projected surface area</td>
<td>2100 pc$^2$</td>
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<tr>
<td>Volume</td>
<td>$9.6 \times 10^4 , pc^2$</td>
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<tr>
<td>Volume density ($\text{H}_2$)</td>
<td>$\sim 50 , \text{cm}^{-3}$</td>
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<tr>
<td>Mean column ($\text{H}_2$)</td>
<td>$3-6 \times 10^{21} , \text{cm}^{-2}$</td>
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<tr>
<td>Surface density</td>
<td>$\sim 4 , \text{kpc}^{-2}$</td>
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<tr>
<td>Mean separation</td>
<td>$\sim 500 , \text{pc}$</td>
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</table>
Orion A as a Typical Cloud

• Cloud A (L1641) exhibits some typical features of GMCs
  – Elongated
    • Parallel to the plane of the Galaxy
  – Strong velocity gradient (rotation)
  – GMCs have well defined boundaries
    • GMCs are discrete objects
  – Lumpy
    • Near unity surface filling factors (traced by optically thick $^{12}$CO 1-0)
  – OB associations form in GMCs
Molecular Clouds & Star Formation

- No local (d < 1 kpc) GMCs are without star formation
  - Within 3 kpc only one GMC has no star formation
    - Maddalena’s cloud
    - $10^5 \, M_\odot$
Size & Linewidth

• GMCs have line widths significantly broader than thermal
• There appears to be a power law relation between sizes of molecular clouds and their velocity dispersion
  – $\sigma \sim D^{0.38}$ (Larson 1981 MNRAS 194 809)
    • Kolmogorov?
  – Various authors find $D^{0.5}$ relations
  – Could be a selection effect
Size & Linewidth

  - Line width size relation found to be $\sigma \sim D^{0.5}$
  - Virial mass estimate
    - $M \sim D \sigma^2/G$
    - Virial mass correlates with $^{12}$CO 1-0 line luminosity
    - Reasonable for a population of relaxed clouds with uniform $n$ and $T$
  - $M \sim D^2$ or constant column
    - $\Sigma \sim 170 \ M_\odot \ pc^{-2}$
    - $N(H) \sim 2 \times 10^{22} \ cm^{-2}$
    - $A(V) \sim 10 \ mag$
Origin of the $L_{CO}/$Mass Relation

- Define $I_{CO} = \int Tdv_{\text{line}}$

  CO Luminosity of a cloud at distance $d$

  $L_{CO} = d^2 \int I_{CO} d\Omega$ hence $L_{CO} \approx T_{CO} \Delta v \pi R^2$

  $T_{CO}$ is the peak brightness temperature and
  $\Delta v$ is the line width

  $R$ is the cloud size

- $\Delta v^2 \approx \frac{GM}{R}$ for virial equilibrium hence

  $L_{CO} \approx \sqrt{3\pi G/4\rho} T_{CO} M$
CO / H₂ Conversion Factor

• CO / H₂ ratio varies among and within clouds
  \[ I_{\text{CO}} = \int T \, dv \]

• \( I_{\text{CO}} \) is used to trace H₂

• Need average conversion factor between integrated CO intensity \( I_{\text{CO}} \) and H₂ column density

• Various methods used to calibrate this relation, good agreement (within factor \( \approx 2 \))
Method 1: $I_{\text{CO}}$ vs. $A_V$

- Measure $I_{\text{CO}}$ for regions with high $A_V$
- Determine $A_V$ from star counts
- Extrapolate $N_H/A_V$ from diffuse clouds
- Assume all hydrogen is molecular
- $N(\text{H}_2)/I_{\text{CO}} \approx 4 \times 10^{20} \text{ cm}^{-2}/(K^{-1} \text{ km/s})$
- Problems:
  - $A_V$ from star counts inaccurate
  - Dust properties different in dense and diffuse clouds; $N_H/A_V$ may also be different
Method 2: $^{13}$CO vs. $A_V$

- Determine $A_V$ as in method 1
- Measure $^{13}$CO line intensity
- Assume $^{13}$CO optically thin, $^{12}$CO optically thick
- Assume $T_{ex}(^{13}$CO) = $T_{ex}(^{12}$CO)
- Assume $^{12}$CO/$^{13}$CO ≈ 40 ... 60 $\Rightarrow$ $\tau(^{13}$CO) $\Rightarrow$ $N(^{13}$CO) from LTE analysis

- Problems:
  - Determination of $A_V$ inaccurate
  - Often $T_{ex}(^{13}$CO) < $T_{ex}(^{12}$CO)
Method 3: Virial Method

- Line intensity $I_{\text{CO}} \equiv I(^{12}\text{CO}) = T_A \Delta \nu$
- $N(\text{H}_2) = 2 \, R \, n(\text{H}_2)$
- Virial theorem:
  \[
  \frac{GM}{3R} = \sigma^2 + \frac{kT}{\langle m \rangle} \approx \sigma^2 = \left( \frac{\Delta \nu}{2.35} \right)^2
  \]

  \[
  M = \frac{4\pi}{3} R^3 n_{\text{H}_2} \langle m \rangle
  \]

  \[
  \frac{N(\text{H}_2)}{I_{\text{CO}}} \approx 3 \times 10^{20} \left( \frac{10K}{T_{\text{ex}}} \right) \sqrt{\frac{n_H}{1000 \text{ cm}^{-3}}} \text{ cm}^{-2} \text{ K}^{-1} / \text{ km s}^{-1}
  \]
Notes on Method 3

• Does not assume any value for \( n(\text{CO})/n(\text{H}_2) \)
• Method can be applied to any molecule
• Conversion factor depends on \( T \) and \( n \) in the cloud
  – Should be different for cold dark clouds and giant molecular clouds

• Problems:
  – Assumes virial equilibrium
  – Measures only mass within \( \tau = 1 \) surface
  – Practical difficulties in determining \(^{12}\text{CO} \) line width
Method 4: $\gamma$-Rays

- $\gamma$-ray emission from GeV cosmic ray protons
  \[ p + p = p + p + \pi_0, \quad \pi_0 = \gamma + \gamma \]
  - Combine COMPTON/EGRET with Columbia CO survey
  - Gamma-ray flux is a measure of total gas mass
    - Model HII, HI, H$_2$
    - Model CR density

Comparison with $I_{\text{CO}}$ gives conversion factor
- $N(H_2)/I_{\text{CO}} = (1.56 \pm 0.05) \times 10^{20} \text{ cm}^{-2} \text{ (K km/s)}^{-1}$
Method 5: HI/IRAS/CO

Dame et al. 2001 (ApJ 547 792) compared IRAS far-IR (dust), 21 cm (HI) and CO
Method 5: HI/IRAS/CO

• Dame et al. 2001 (ApJ 547 792) used IRAS far-IR as a tracer of total gas column density
  – Calibrate the Leiden-Dwingeloo 21 cm survey in regions free of CO emission
  – Total-gas map was differenced with the a HI map to obtain a complete and unbiased predicted map of $N_{\text{CO}}$
    • Close agreement between this map and observed CO implies that few molecular clouds at $|b| < 30$ have been missed by the present CO survey
  – The ratio of the observed CO map to the predicted molecular map provided a measure of the local CO-to-H2 mass conversion factor $X$.
    • Mean $X$ at $|b| > 5$ is $1.8 \pm 0.3 \times 10^{20}$ cm$^{-2}$ K$^{-1}$ km s$^{-1}$
Method 5
Method 5

- Average $X$ varies with latitude
  - High $X$ at $l \sim 0^\circ$ may be spurious since, the lack of CO-free regions toward the inner plane mean $I_{100}/N_{\text{tot}}$ cannot be properly determined
- Point-to-point dispersion is significantly larger than can be accounted for by instrumental noise
  - Excluding the plane ($|b| < 5^\circ$), where the prediction is expected to break down owing to dust temperature variations along the line of sight, the dispersion is $\approx 50\%$
  - The high dispersion may be due to variations in the gas-to-dust ratio, and by dust temperature variations not accounted for by the simple IRAS color correction
CO / H₂ Conversion Factor: Summary

- Various methods agree remarkably well
- Conversion factors apply to global scale, not locally
- Conversion factor gives no information on $N(\text{H}_2) / N(\text{CO})$
- Conversion factor should depend on $T$ and $n$ and metallicity
- Conversion factor derived for Galactic Disk is not valid for galactic nuclei (including Galactic Center region) or metal-poor systems
## CO / H₂ Conversion Factor: Summary

<table>
<thead>
<tr>
<th>Source</th>
<th>$X \times 10^{20} \text{ cm}^{-2} / \text{ K km s}^{-1}$</th>
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<tbody>
<tr>
<td>Early work</td>
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<tr>
<td>γ-rays Hunter et al. 1997</td>
<td>1.56 ±0.05</td>
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<tr>
<td>HI/IRAS/CO Dame et al. 2001</td>
<td>1.8±0.3</td>
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<tr>
<td>$A(V)$ Lada et al. 2003</td>
<td>~4</td>
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</table>
Mass Spectrum

- Statistics of the Solomon study enables an evaluation of the mass spectrum
  - $dN/dM \sim M^{-1.5}$
  - Incomplete at low masses
  - Relation to clumps in clouds & IMF?
The Rosette HII Region & Molecular Cloud
Structure of Molecular Clouds

• What is the topology of molecular clouds?
  – CO maps show that molecular gas is inhomogeneous
  • Discrete clumps?
Clumps

- Clumps can be identified within GMCs in l-b-v space
  - Williams et al (1994 ApJ 428 693) analyzed the $^{13}$CO 1-0 clump structure of the Rosette and Maddalena Cloud
Clumps

• Clumps can be identified within GMCs in l-b-v space
  – Clump masses derived using the X-factor
    • Calibrated with $^{13}$CO
    • ~ 1/2 of Galactic average
Clumps

- Spatial resolution in both clouds is similar
  - 0.7 pc
- Both clouds have similar mass ~ $10^5 \, M_\odot$
- Order of magnitude different rate of star formation
  - Traced by mid-IR dust emission
    - Rosette has ~ 17 OB stars plus embedded sources
    - G216-2.5 has no OB stars and low $L_{\text{IR}}/M_{\text{H}_2} < 0.07 \, L_\odot/M_\odot$
  - Clumps are similar
    - Clumps in G216-2.5 are bigger for a given mass & larger line widths
    - Although both clouds are bound none of the clumps in G216-2.5 are individually bound
HI and H$_2$

- HI envelope around the Rosette molecular cloud
  - Grey scale HI
  - Contours:
    - $^{12}$CO 1-0
    - $^+$ OB assoc.
- Strong HI emission lies on CO cloud boundaries forming an envelope
Interclump HI

- The HI envelopes may extend into the GMC itself & pervade the CO clumps
  - Turbulent pressure of HI and H$_2$ may be comparable
- Anti-correlation between HI & $^{13}$CO is observed suggesting that the HI is the confining medium
HI Envelopes

• HI envelopes around molecular clouds are common
  – Local GMCs have comparable masses of HI & H$_2$
  – HI is more extended
  – Chicken or egg?
    • Photoevaporated H$_2$
      – $N$(HI) $\sim$ 0.6 - 1 x 10$^{21}$ cm$^{-2}$ or $A$(V) $\sim$ 0.3 - 0.5 mag
      – Shield molecular gas
    • Remnants of condensing HI?
  – Unlikely to hold throughout the Galaxy
    • Especially in the molecular ring and the Galactic center
Where are Molecular Clouds?

- FCRAO outer Galaxy Survey (Heyer et al. 1998 ApJS 115 241)
  - No kinematic distance ambiguity & less confusion
  - Regions with little or no CO emission
    - Cleared of molecular gas by O stars
      - Photodissociation, stellar winds & supernova explosions
      - These process may sweep up molecular gas and compress it to from the next generation of stars
    - CO is exclusively found in spiral arms
      - H$_2$ Arm/interarm contrast ~ 30:1 --- HI is 2.5:1
      - Molecular clouds form in a compressed atomic medium
      - Lifetime < arm crossing time ~ 10$^7$ yr
        » Consistent with depletion rate of H$_2$ by star formation
        » Invalidates old arguments involving CO/H$_2$ conversion implying lifetimes of 10$^9$ yr (Solomon & Sanders 1980)
  - May not apply to all galaxies
    - cf. M31 and M51 vs. NGC 5055
    - Inner Milky Way? Are these clouds forming stars?
Interarm CO?

- FCRAO CO survey of the outer Galaxy
  - Local arm (0 to -10 km/s) and Perseus arm (-40 km/s)
  - No CO between
Helfer et al. 2003 ApJS 145 259
Formation of Molecular Clouds

• What is the dominant factor in the formation of molecular clouds?
  – Gravity, radiation, magnetic fields?
  – GMCs are known to be self gravitating
    • Mean internal pressures exceeds that of the ISM by ~ 10
    • GMCs are short lived
      – Minimum lifetime is ~ 20 Myr (age of oldest associated stars)
      – GMCs are older than their crossing times
    • Gravity must play a role, but there are low mass, high latitude molecular clouds that are not self-gravitating
      – $H_2$ chaff ($M < 10^3 \, M_\odot$)
Formation Mechanism

• Three categories (Elmegreen 1990, Evolution of the ISM, ASP)
  – Collisional agglomeration of smaller clouds
  – Shocks
    • Supernova remnants, galactic shocks
  – Gravo-thermal instability
Agglomeration

• If GMCs are formed from the coalescence of molecular fragments where is that gas?
  – FRCAO survey shows widely distributed, low surface brightness emission (chaff)
    • In spiral arms, in the vicinity of GMCs
    • Can this gas agglomerate to form GMCs?
Agglomeration

  - \( dN/dM \sim M^{-1.75} \)
  - Mass spectrum extends to \( 100 \, M_\odot \)
    - Incompleteness limit
  - Single power law
    - Non GMC chaff \( (M < 10^3 \, M_\odot) \) appears to belong to the same parent population
    - Same origin as self gravitating clouds?
  - The slope of \( dN/dM \) implies that most of the molecular mass is in the most massive clouds
    - \( M_{\text{chaff}} \sim 10^8 \, M_\odot \)
    - \( M_{\text{GMC}} \sim 10^9 \, M_\odot \)
  - In steady state, if the formation and destruction times are the same expect equal masses in chaff and GMCs
    - Neglects orbit crowding (even less interarm chaff)
  - GMCs must form from HI
    - \( H_2 \) Arm/interarm contrast ~ 30:1 --- HI is 2.5:1