Lecture 25
Physical Properties of Molecular Clouds

1. Giant Molecular Clouds
2. Nearby Clouds
3. Empirical Correlations
4. The Astrophysics of the X-Factor

References

Blitz & Williams, “Molecular Clouds
Myers, “Physical Conditions in Molecular Clouds”
in Origins of Stars & Planetary Systems eds. Lada & Kylafis
http://www.cfa.harvard.edu/events/1999/crete
Bergin & Tafalla, ARAA 45 339 2007 - observations of cold dark clouds
McKee & Ostriker, ARAA 45 565 2007 - summary of observations and theoretical interpretations

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1. Giant Molecular Clouds

- An important motivation for studying molecular clouds is that’s where stars form
- Understanding star formation starts with understanding molecular clouds
- In addition to their molecular character, large and massive molecular clouds are dynamical systems that are

Self-Gravitating
Magnetized
Turbulent

- The central role of gravity high distinguishes them from other phases of the ISM.

What is a Molecular Cloud?

- Molecular clouds have dense regions where the gas is primarily molecular.
- *Giant molecular clouds* (GMCs) are large clouds with $10^4 M_\odot < M < 6\text{x}10^6 M_\odot$ sizes in the range 10-100 pc.
- The filing factor of GMCs is low; there about 4000 in the Milky Way). They have as much atomic as molecular gas.
- Mean densities are only ~ 100 cm^{-3}, but molecular clouds are inhomogeneous and have much higher-density regions called clumps and cores.

NB There is no accepted explanation for the sharp upper limit to the mass of GMCs; tidal disruption and the action of massive stars have been suggested.

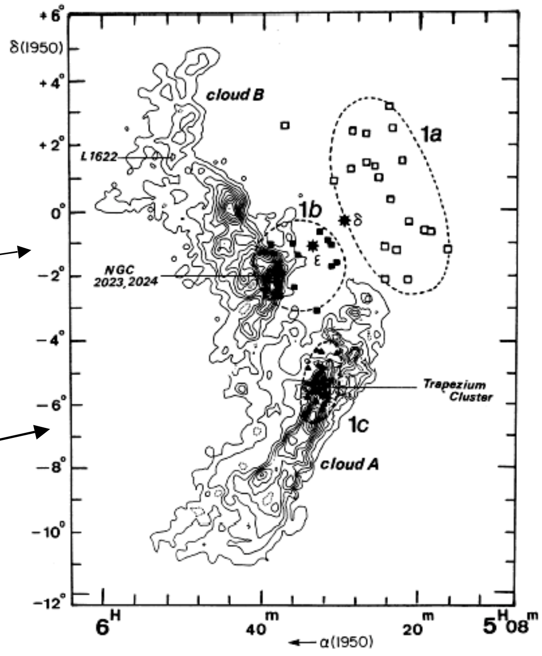
2. The Orion Molecular Cloud Complex

These clouds can't be much older than 10-20 Myr, the age of the oldest OB sub-association.

Associations older than 20-30 Myr are not associated with GMCs.

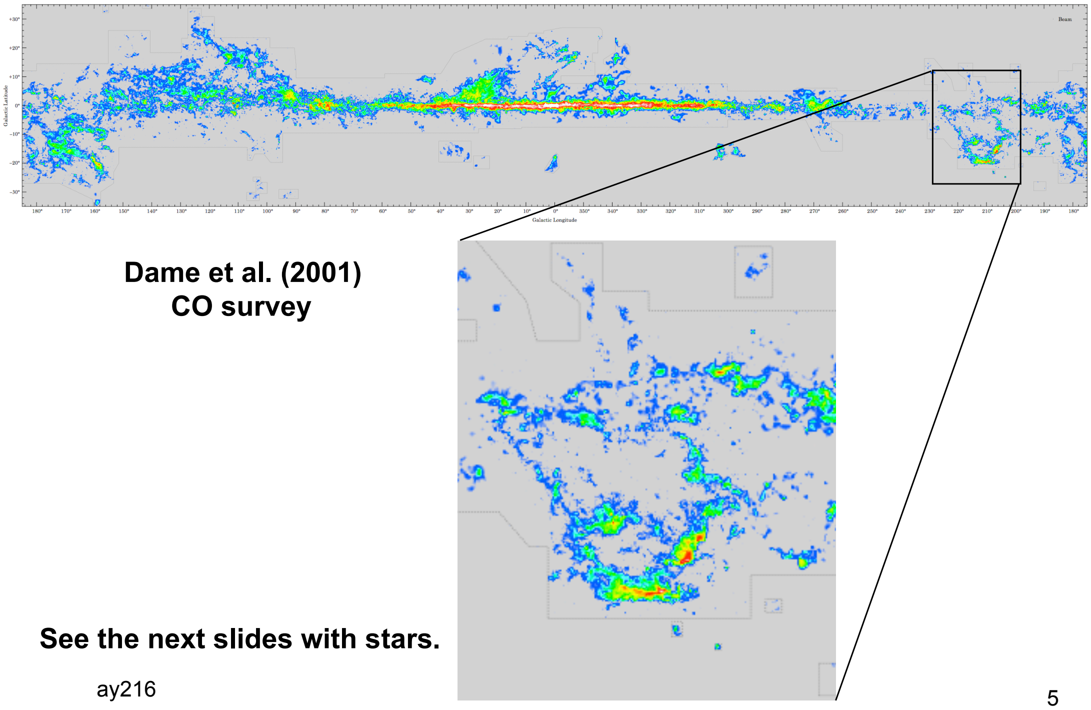
Cloud B

Cloud A



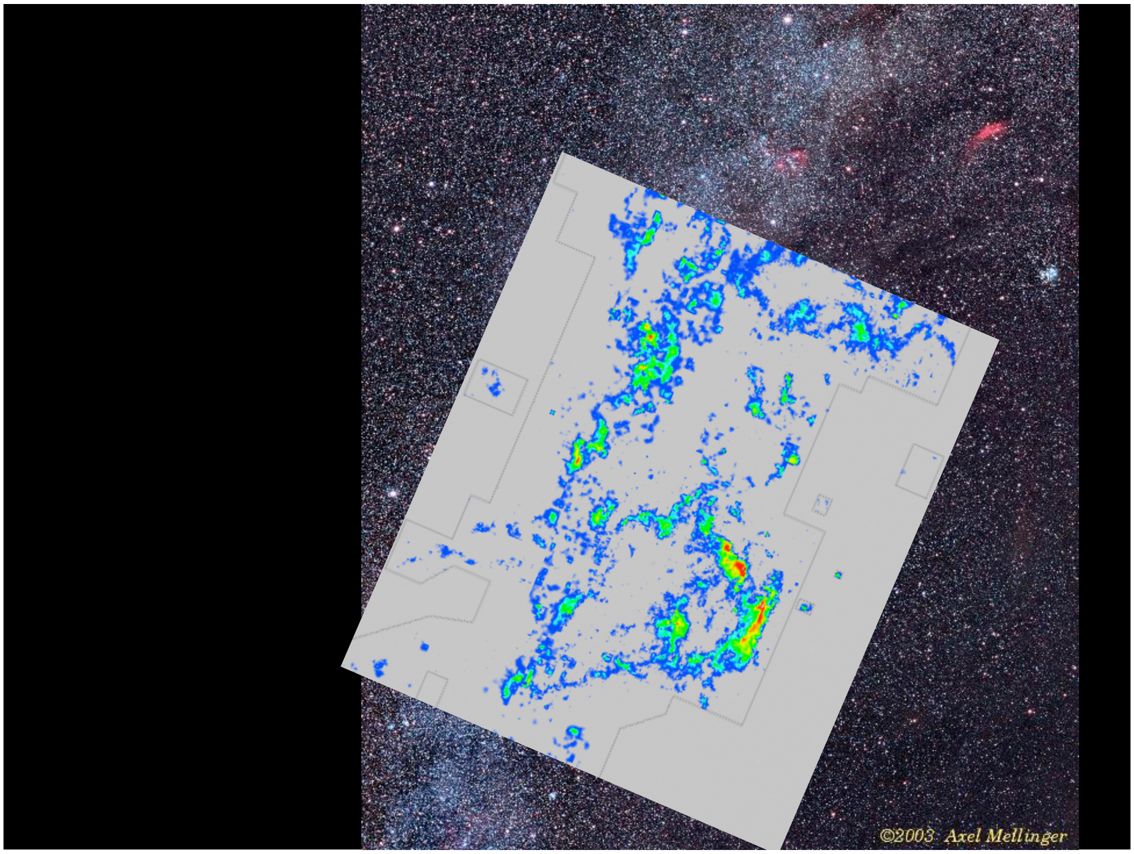
Early mini-telescope CO map

Orion: The Very Large Scale Picture



Dame et al. (2001)
CO survey

See the next slides with stars.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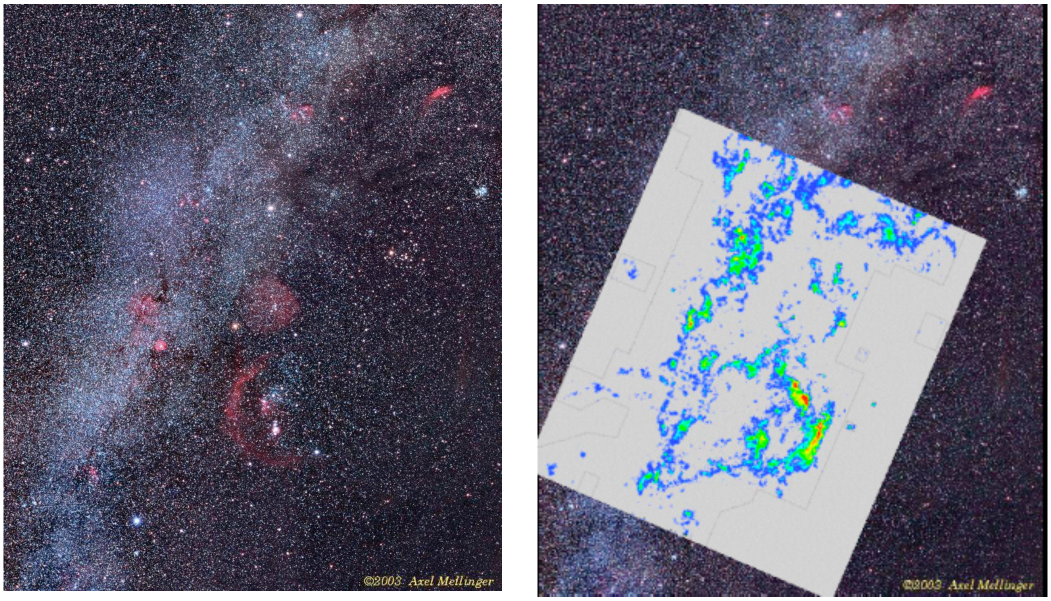
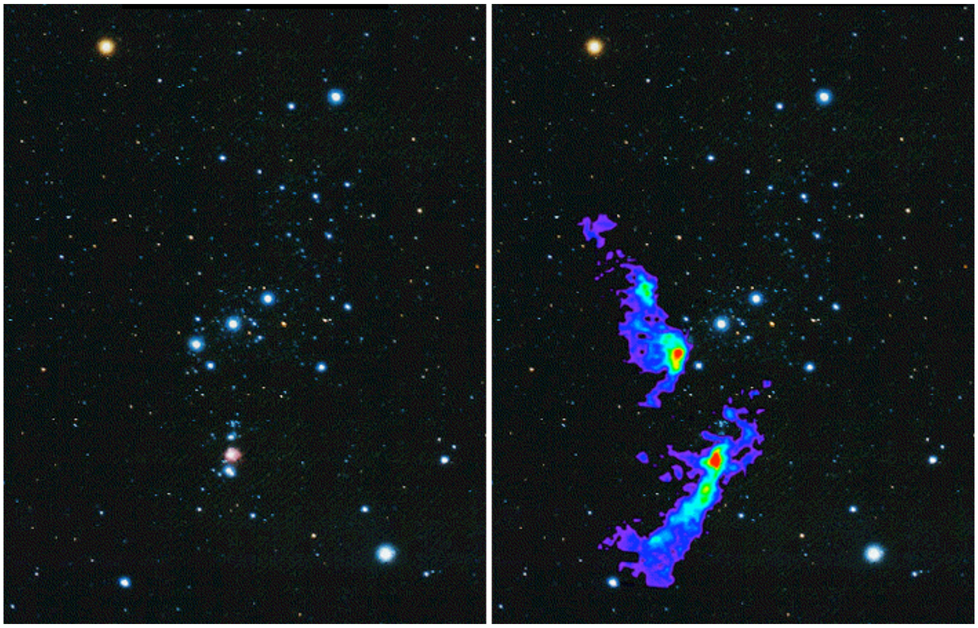
Large-scale Optical and CO Images



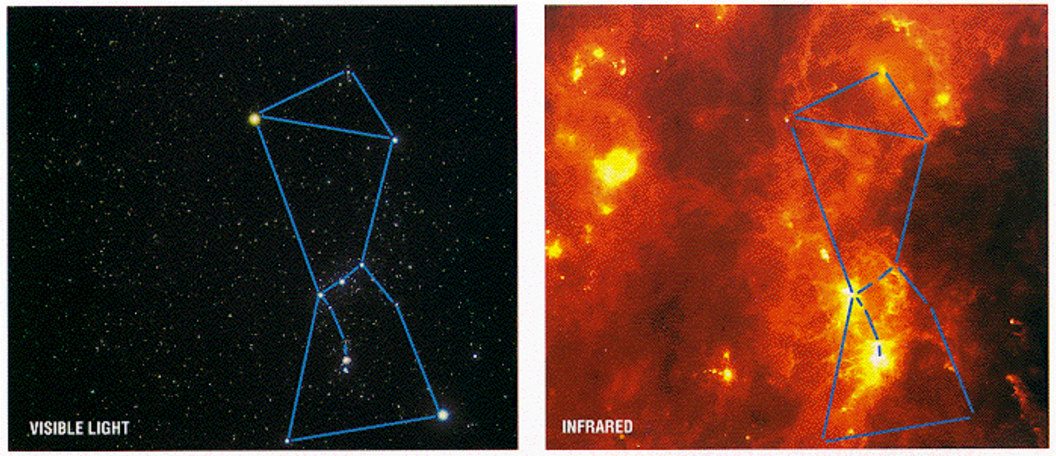
Orion Molecular Clouds A and B in CO

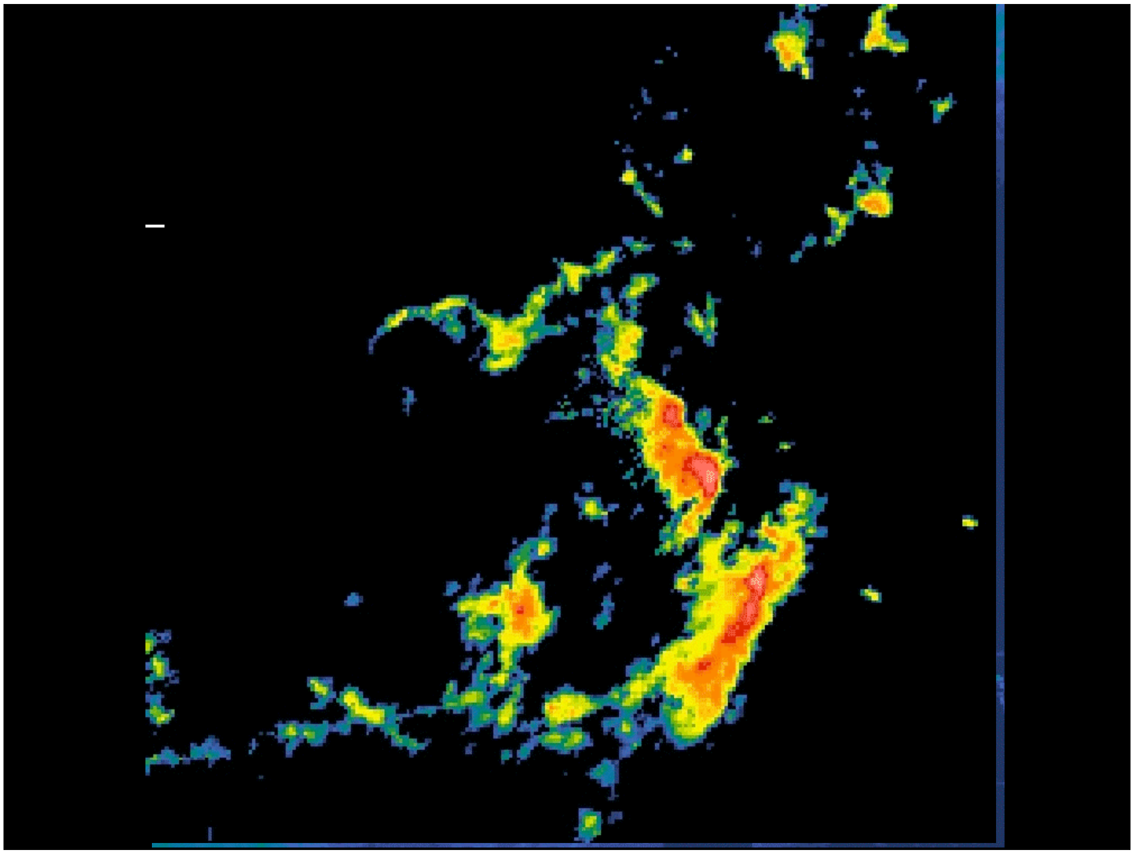
Constellation Scale Optical and CO Images



Orion Molecular Clouds A and B in IR

Constellation Scale Optical and IRAS Images





Summary for Orion GMCs

- Cloud A (L1641) exhibits typical features of GMCs:
  - fairly well defined boundaries: GMCs seem to be discrete systems
  - clumpy, but with unit surface filling factor in optically thick ^{12}CO 1-0 in low resolution maps
  - elongated, parallel to the plane of the Galaxy
  - strong velocity gradient (rotation)
- Star clusters form in GMCs
  - no local GMCs (d < 1 kpc) without star formation
  - one nearby GMC (d < 3 kpc) without star formation (Maddalena's cloud ~ $10^5\ M_{\odot}$)

Essentially all star formation occurs in molecular clouds

3. Basic Properties of Molecular Clouds

- Important deductions can be made from CO studies of molecular clouds by very direct and simple means.
- The relevant data are the line width, the integrated line strength and the linear size of the cloud.

For a Gaussian line, the variance or dispersion σ is related to the Doppler parameter *b* and the FWHM as follows:

$$\phi(v) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-v^2/2\sigma^2}$$

$$\sigma = b/2^{1/2}, \quad FWHM = 2\sqrt{(2\ln 2)}\,\sigma \approx 2.355\,\sigma$$

For thermal broadening,

$$b_{th} \approx 0.129\,(T/A)^{1/2}\ \text{km s}^{-1} \quad (A = \text{atomic mass}).$$

More generally, in the presence of turbulence,

$$\sigma^2 = \frac{kT}{m} + \sigma_{turb}^2$$

Application of the Virial Theorem

A key step in the elementary interpretation of the CO observations by Solomon, Scoville, Sanders et al. uses the virial theorem, which assumes that

GMCs are gravitationally bound in virial equilibrium,

The virial theorem with only gravitational forces reads:

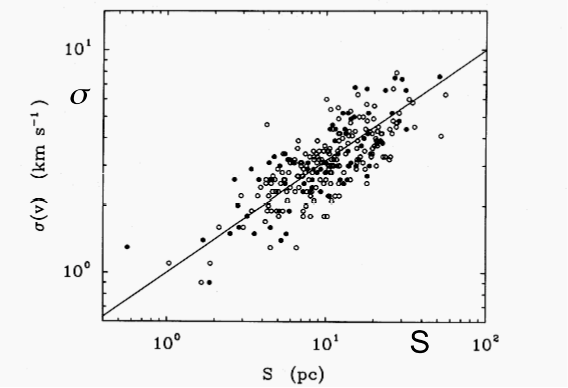
$$-\langle V\rangle = 2\langle K\rangle = \langle mv^2\rangle \qquad \text{or} \qquad \langle \frac{GM}{R}\rangle = \langle v^2\rangle = \sigma^2$$

Measurements of the size *R* and the velocity dispersion *σ* can then be used to estimate the mass of the GMC:

$$\boxed{M \approx \frac{R\sigma^2}{G}}$$

The Linewidth-Size Correlation

- $T_{\text{kin}} \sim 20$ K $\Rightarrow \sigma < 0.1$ km/s (from low-*J* CO lines*)*
- Linewidths are suprathermal
- Noticed by Larson (MNRAS 194 809 1981), who fitted
  $\sigma \sim S^{0.38}$
  close to Kolmogorov 1/3.
- Others found $\sigma \sim S^{0.5}$ (σ in km s^{-1} and *S* in pc).
- The correlation extends to smaller clouds and smaller length scales within GMCs (Heyer & Brunt, ApJ 615 L15 2004), but not to cores
- If the linewidth is a signature for turbulence*, this correlation is an ***empirical statement about turbulence in molecular clouds***.



Linewidth-size correlation for 273 molecular clouds Solomon et al. ApJ 319 730 1987

$$\sigma = (0.72 \pm 0.03)\left(R/\text{pc}\right)^{0.5\pm0.05}\ \text{km s}^{-1}$$

*** For an introduction to interstellar turbulence, see Sec 2. McKee & Ostriker (2007)**

The Luminosity-Mass Correlation

$$I_{CO} = \int_{line} T_A(v)\,dv$$

is the line integrated intensity for optically thick ^{12}CO.

The CO luminosity of a cloud at distance d is

$$L_{CO} = d^2 \int_{cloud} I_{CO}\,d\Omega\ ; \qquad \text{hence} \quad \boxed{L_{CO} \approx T_{CO}\ \Delta v\ \pi R^2}$$

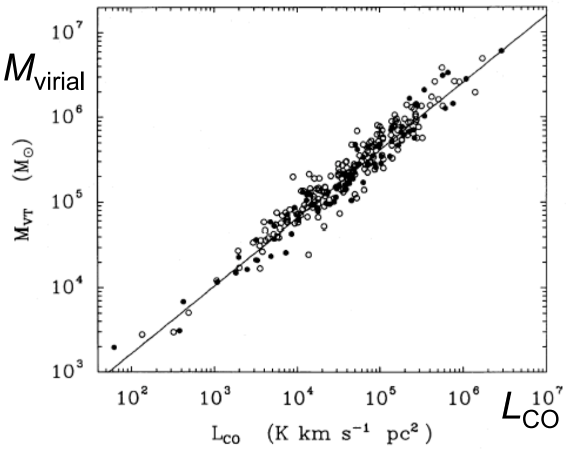
where T_{CO} is the peak brightness temperature, Δv is the velocity line width and R is the cloud radius.

Substituting $\Delta v^2 \approx \frac{GM}{R}$ (virial equilibrium) and $\mathrm{M} = \frac{4\pi}{3}\rho R^3$

yields

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

The Mass-CO Luminosity Correlation



Solomon, Rivolo, Barrett & Yahil
ApJ 319 730 1987

The good correlation over 4 dex supported the assumption that GMCs are in virial equilibrium.

M_{virial} may be an underestimate because it is based on optically thick CO. GMCs have diffuse regions that are not optically thick. And there are observational problems as well.

c. Correlations

The two observationally based correlations for GMCs are:

$$\sigma \approx R^{1/2} \qquad \text{(line width size relation)}$$

$$\frac{M}{R} \approx \sigma^2 \qquad \text{(virial equilibrium)}$$

Substitution leads to another

$$N \approx \frac{M}{R^2} \approx \frac{\sigma^2}{R} \qquad \text{(constant surface density)}$$

and as well two more

$$\rho \approx \frac{M}{R^3} \approx \frac{\sigma^2}{R^2} \approx \frac{1}{R} \quad \text{and} \quad M \approx \sigma^2 R \approx R^2 \approx \sigma^4$$

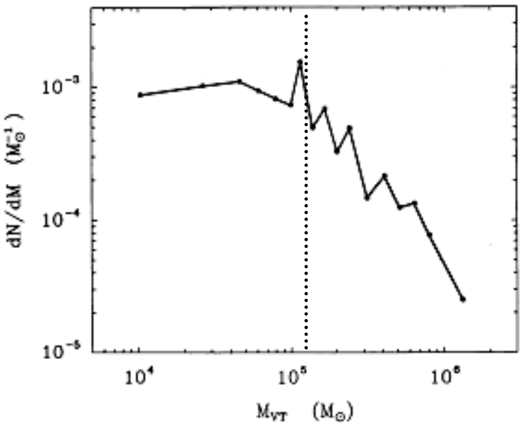
The first three are often referred to as Larson’s Laws

Is it really true that the surface densities of GMCs are all about the same? Many have so assumed following Solomon et al.:

$N_H \sim 1.5 \times 10^{22}$ cm^{-2}
$A_V \sim 10$
$\Sigma \sim 150\ M_\odot$ pc^{-2}

GMC Mass Spectrum

Solomon et al. ApJ 319 730 1987



- **The spectrum is incomplete for M < 10^5 M_{sun} (dotted line).**
- ***dN/dM* $M^{-3/2}$ for large *M***

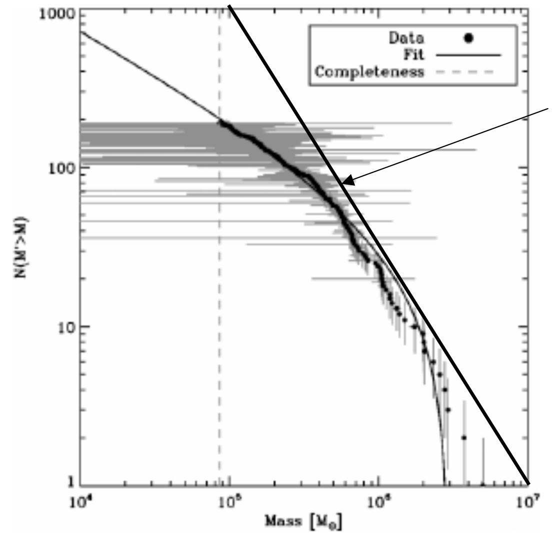
To be addressed later:

1. What is the mass spectrum for clumps and cores ?
2. How are cloud mass functions related to the stellar initial mass function (IMF)?

FIG. 3.—The molecular cloud mass spectrum dN/dM. A fit to the data above $M = 7 \times 10^4\ M_\odot$ gives $dN/dM \propto M^{-3/2}$. There are 15 clouds in each bin and the standard deviation is ±24%. The turnover at low mass is due to undercounting of smaller clouds in the more distant parts of the galactic disk.

Reanalysis of Solomon et al. (1987)

Rosolowsky PASP 117 1403 2005



slope -3/2

There is a sharp cutoff at $M = 3\times10^6\ M_{\rm sun}$

Typical Properties of Local GMCs

Based on Solomon et al. (1987)

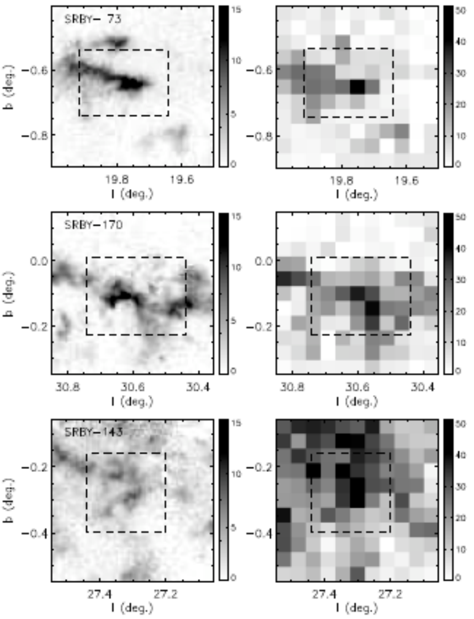
Number	4000
Mass	$2 \times 10^5\ M_\odot$
Mean diameter	45 pc
Projected surface area	2000 pc^2
Volume	$10^5\ pc^3$
Volume density (H_2)	300 cm^{-3}
Mean mass surface density	$1.5\ 10^{22}\ cm^{-2}$
Number surface density	4 kpc^{-2}
Mean separation	500 pc

Re-examining Larson's Laws

Based on the UMASS-BU Galactic Ring Survey of ^{13}CO (1-0)
Heyer et al. arXiv:0809:1397v1

Left side: UMass-BU ^{13}CO (1-0) maps Heyer et al 2009

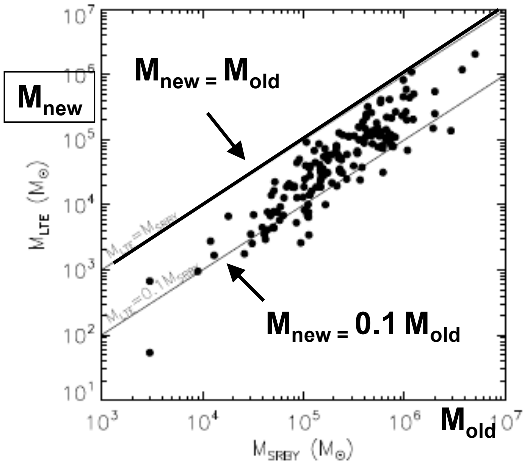
Right side: UMass-SUNY ^{12}CO (1-0) defined GMCs (dashed lines) Soloman et al 1987



New data:
- **better resolution**
- **densely sampled**
- **more optically thin**
- **sensitive to lower T_A**

NEW AND OLD GMC MASSES

Using Solomon definition of GMCs

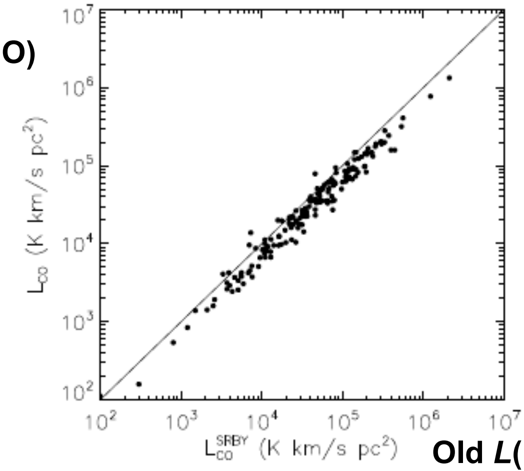


Old = Solomon et al. (1987) New = Heyer et al. (2009)

New GMC masses are ~ factor of 5 smaller than the old virial theorem masses

NEW AND OLD CO LUMINOSITIES

New L(CO)



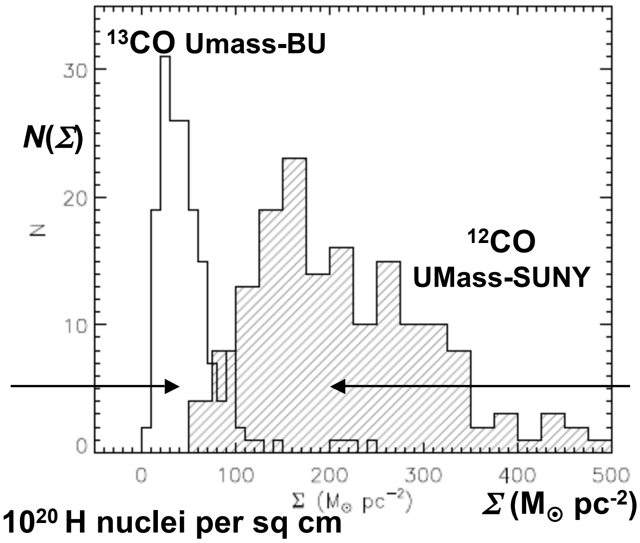
Heyer et al. (2009)

Old L(CO)

~ 50% overestimate by Solomon et al. indicates that their extrapolation below the detectable brightness temperature over-estimates the luminosity

Surface Density Distribution of GMCs

Heyer et al. (2009)



^{13}CO Umass-BU

$N(\Sigma)$

^{12}CO UMass-SUNY

median: 42

median: 206

Σ (M$_\odot$ pc^{-2})

1 M$_\odot$ pc$^{-2} \approx 10^{20}$ H nuclei per sq cm

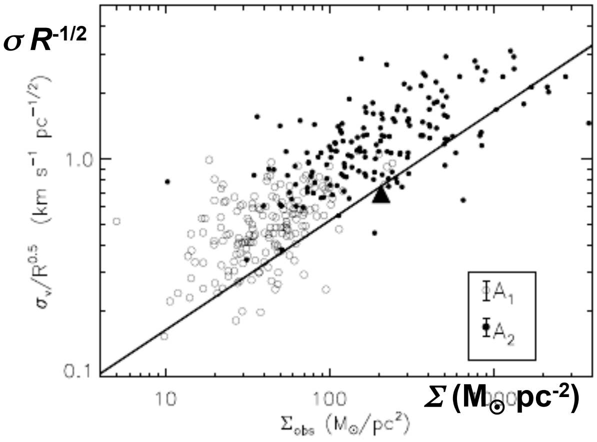
Not only is there is a factor of 5 difference in the medians, but *GMCs do not all have the same surface densities.*

Alternate Approach to Correlations

Start with the virial mass relation and the definition of surface density (with $N = \Sigma$), rather than with Larson's law, and then:

$$\text{substitute } N \approx \frac{M}{R^2} \text{ into } \frac{M}{R} \approx \sigma^2 \text{ to get : } \boxed{\sigma \approx N^{1/2} R^{1/2}}$$

This indeed is what's observed:



open circles: Σ from with cloud boundaries

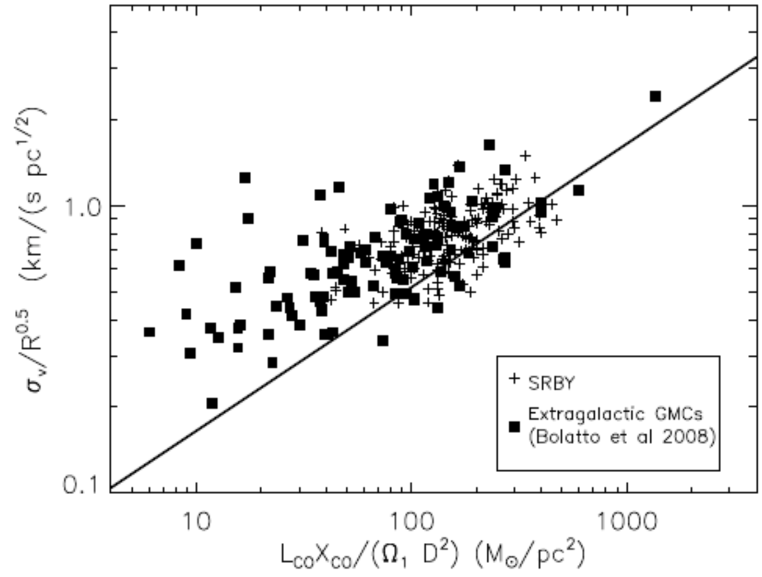
filled circles: " 1/2 maximum isophote of H_2 column

filled triangle: Solomon et al. (1987)

This is not the universal scaling law indicative of turbulence.

Similarity of the Extragalactic Correlation

Bolatto et al. IAU Symposium 255 274 2008



Understanding GMC Masses and Linewidths

1. **Observe with better resolution, sampling, and sensitivity.** See Goldsmith et al. ApJ 680 428 2008 for a 20”, 32 pixel focal plane array study of the TMC, analyzed with a variable CO abundance model for diffuse regions. They obtain twice the mass compared to the fixed abundance model, with half the mass in diffuse regions.
2. **Observe the HI with comparable resolution.**
3. **Observe and include magnetic fields and other measures of the velocity field in the analysis**
4. **The origin of the supersonic linewidths seen in GMCs** If it is not hydrodynamic turbulence, is it magnetic?

- We show in Lecture 27 that the magnetic virial theorem gives $M \sim BR^2$ or $\Sigma \sim B$.
- If the linewidths come from Alfven waves, $\sigma^2 \sim B^2/\rho$.
- Replace ρ by M / R^3 and use $M \sim BR^2$ to get $\sigma^2 \sim RB$, *or*

$$\sigma \sim \Sigma^{1/2} R^{1/2}.$$

This is Heyer’s result which he ascribes to Mouschovias (1987).

4. The CO / H_2 Conversion Factor

- Measuring the CO mass or column density is *not* the same as measuring the total gas, which is dominated by H_2 and He and are effectively invisible in cool clouds.
- The integrated CO intensity $I_{CO} = \int T_A(v)\, dv$ can be calibrated to yield the average H_2 column density. This is surprising because ^{12}CO is optically thick and because the CO / H_2 ratio might be expected to vary within a cloud and from cloud to cloud.
- It is surprising that a single conversion factor between H_2 column density and I_{CO} (the ***X-factor***) applies on average to all molecular clouds in the Galaxy.
- That several calibration methods agree to within factors of a few should provide insights into the properties of the clouds.

X-factor Method 1: I_{CO} and Virial Theorem

- Measured line intensity: $I_{CO} \equiv I(^{12}CO) \cong \langle T_A \rangle \Delta v_{FWHM}$
- Virial theorem: $$\frac{GM}{R} \approx \sigma^2 = \left(\frac{\Delta v}{2.35}\right)^2$$
- Mass estimate:

$$M = \tfrac{4\pi}{3} R^3 n(H_2) m \quad \text{and} \quad N(H_2) = (\tfrac{4\pi}{3})^{-1} \frac{M/m}{R^2}$$

- $\Delta v_{FWHM} = 2.35\,\sigma \sim (GM/R)^{1/2}$

$$\boxed{\frac{N(H_2)}{I_{CO}} \approx 3 \times 10^{20} \text{cm}^{-2}\ \text{K}^{-1}\ \text{km s}^{-1}\ \frac{10\text{K}}{T} \left(\frac{n(H_2)}{1000\ \text{cm}^{-3}}\right)^{1/2}}$$

Problems:

Assumes virial equilibrium
Depends on $n(H_2)$ and T
Measures only mass within $\tau = 1$ surface

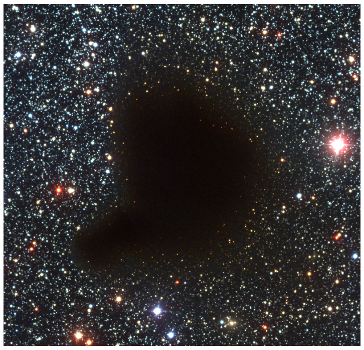
X-factor Method 2: I_{CO} and NIR Extinction

- Measure I_{CO} for regions with high A_V
- Determine A_V from IR star counts
- Extrapolate N_H/A_V from diffuse clouds
- Assume all hydrogen is molecular

Result:
$N(H_2)/I_{CO} \approx 4 \times 10^{20}$ cm^{-2} /(K km s^{-1})

Problems:

Inaccuracies in star-count A_V
Variable dust properties
Variable N_H / A_V
Best for dark clouds



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Lada et al.
ApJ 586 286 2003

X-factor Method 3: $I(^{13}CO)$ vs. A_V

- Determine A_V as in method 2
- Measure ^{13}CO line intensity
- Assume ^{13}CO optically thin, ^{12}CO optically thick
- Assume $T_{ex}(^{13}CO) = T_{ex}(^{12}CO)$
- Assume $^{12}CO/^{13}CO \approx 40 \dots 60 \Rightarrow \tau(^{13}CO) \Rightarrow N(^{13}CO)$

Problems:

Accuracy of A_V determination
Often $T_{ex}(^{13}CO) < T_{ex}(^{12}CO)$
^{13}CO may not be optically thin

X-factor Method 4: I_{CO} and γ-Rays

- High energy comic rays (> 1 GeV) produce neutral pions in collisions with protons in H and H_2, which then decay into two γ-rays

$$p + p \rightarrow p' + p' + \pi_0\,, \qquad \pi_0 \rightarrow \gamma + \gamma$$

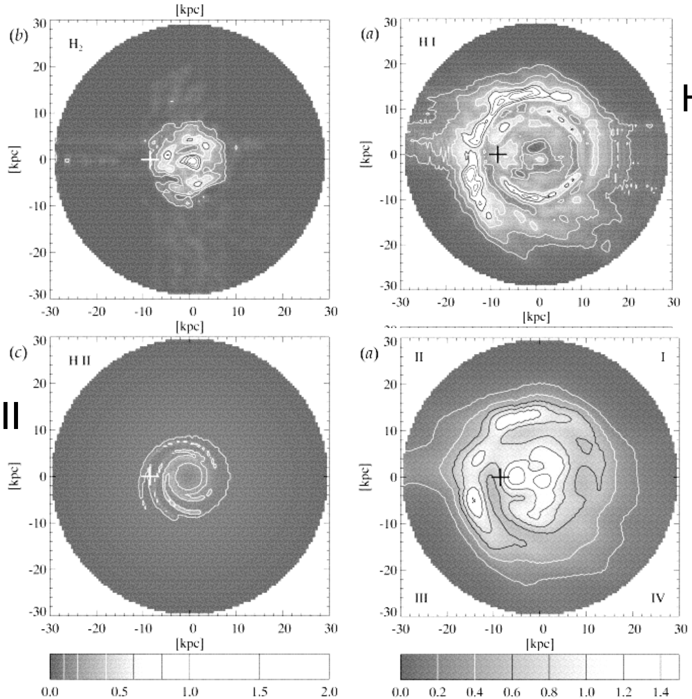
- The γ-ray emission depends on the product of the cosmic ray density and the density of all protons (n_H).
- Hunter et al. ApJ 481 205 1997 combine γ-ray measurements from COMPTON/EGRET with the Columbia-CfA CO survey and obtain,

$$\boldsymbol{N(H_2)/I_{CO} = (1.56 \pm 0.05) \times 10^{20}\ \mathrm{cm^{-2}\ K^{-1}\ kms^{-1}}},$$

presumably assuming all hydrogen is molecular.

NB The modulation correction for high energy CRs is small. Hunter et al. assume that the CR density is proportional to n_H.

Hunter et al. ApJ 481 205 1997



See also the CfA group's analysis: Digel et al. ApJ 555 12 2001

CR enhancement factor varies by ~ 50%.

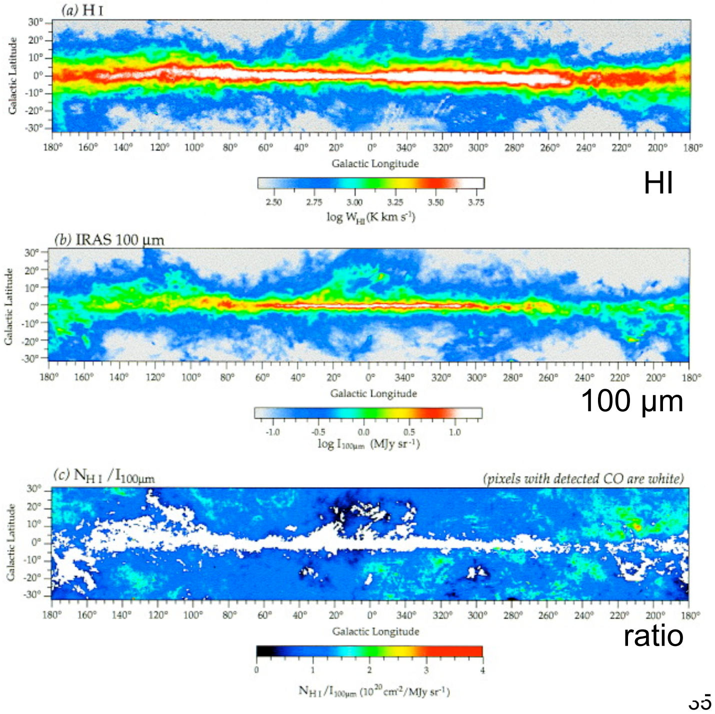
X-factor Method 5: HI/IRAS/CO

- Dame et al. (ApJ 547 792 2001) used IRAS far-IR emission as a tracer of total gas column density
- Calibrated with the Leiden-Dwingeloo 21-cm HI survey in regions free of CO emission
- Total gas map differenced with the HI map to obtain a complete and unbiased predicted map of H_2
  - Close agreement between this map and observed CO implies that few molecular clouds at $|b| < 30^o$ have been missed by CO surveys
- The ratio of the observed CO map to the predicted molecular map provides a measure of the local average X-factor for $|b| > 5^o$:

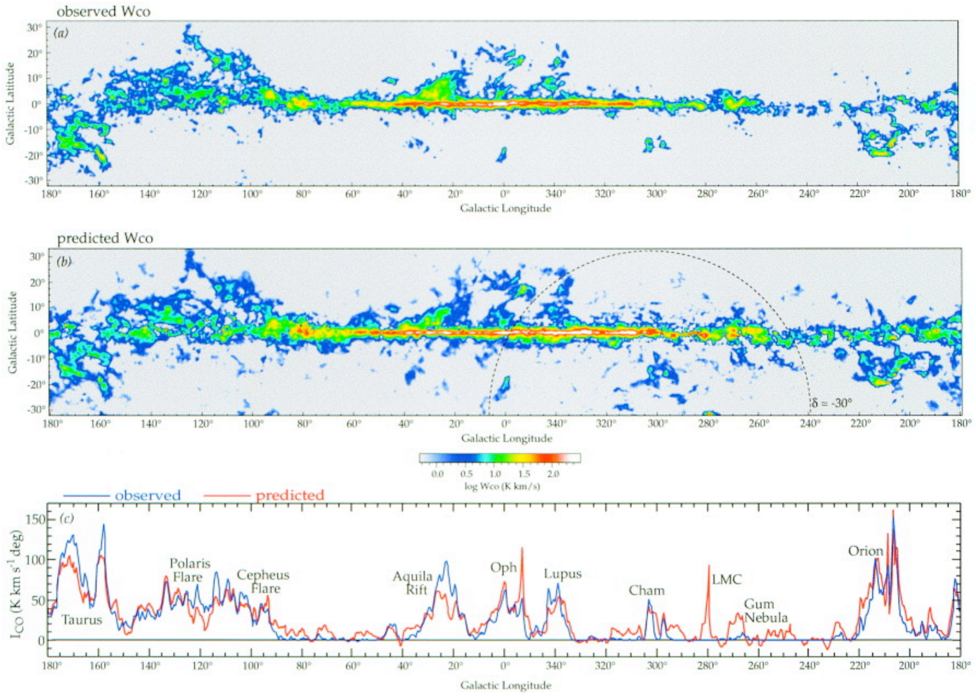
$$N(H_2)/I_{CO} = 1.8 \pm 0.3 \times 10^{20}\ \mathrm{cm}^{-2}\ \mathrm{K}^{-1}\ /\mathrm{km\ s}^{-1}$$

Method 5: HI/IRAS/CO

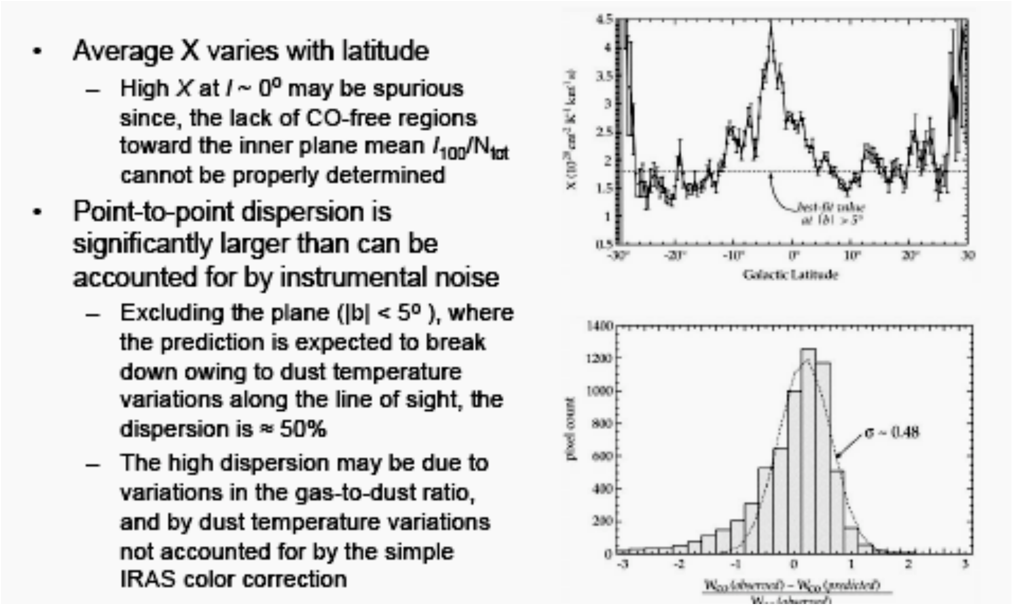
Dame et al. compared IRAS far-IR (dust). 21 cm (HI) and 2.6 mm (CO).



Verification of Method 5



James Graham’s Critique of Method 5



- Average X varies with latitude
  - High *X* at *l* ~ 0° may be spurious since, the lack of CO-free regions toward the inner plane mean I_{100}/N_{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°), where the prediction is expected to break down owing to dust temperature variations along the line of sight, the dispersion is ≈ 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

c.f. JRG Lecture 18 (2006)

CO/H_2 Conversion Factors: Summary

- Various methods agree remarkably well
- Relevant on global scales, not locally
- Limits on applicability are unclear
- No information on $N(H_2)$ / $N(CO)$ is obtained
- Conversion factors should depend on *T*, *n* and metallicity
- Conversion factor derived for Milky Way disk is not valid for galactic nuclei (including our own Galactic Center) or for metal-poor systems
- Blitz et al. (PPV) find that $X_{CO} \approx 4 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$ holds approximately for members of the local group, but not the SMC, where $X_{CO} \approx 13.5 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$. The conversion for the LMC, $X_{CO} \approx 9.0 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$, also reflects the reduced abundances of the clouds .

CO/H_2 Conversion Factor: Summary

Source	X
γ-rays (Hunter et al. 1997)	1.56 ±0.05
HI/IRAS/CO (Dame et al. 2001)	1.8±0.3
IR extinction (Lada et al. 2003)	~ 4

Units for X: 10^{20} cm^{-2} / K km s^{-1}