Lecture 22
Physical Properties of Molecular Clouds

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

References

Myers, "Physical Conditions in Molecular Clouds"
Blitz & Williams, "Molecular Clouds"
in Origins of Stars & Planetary Systems eds. Lada & Kylafis
http://www.cfa.harvard.edu/events/1999/crete
McKee & Ostriker, ARAA 45 565 2007
Bergin & Tafalla, ARAA 45 339 2007

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

  Self-Gravitating
  Magnetized
  Turbulent
- The central role of gravity distinguishes them from other phases of the ISM.

What is a Molecular Cloud?

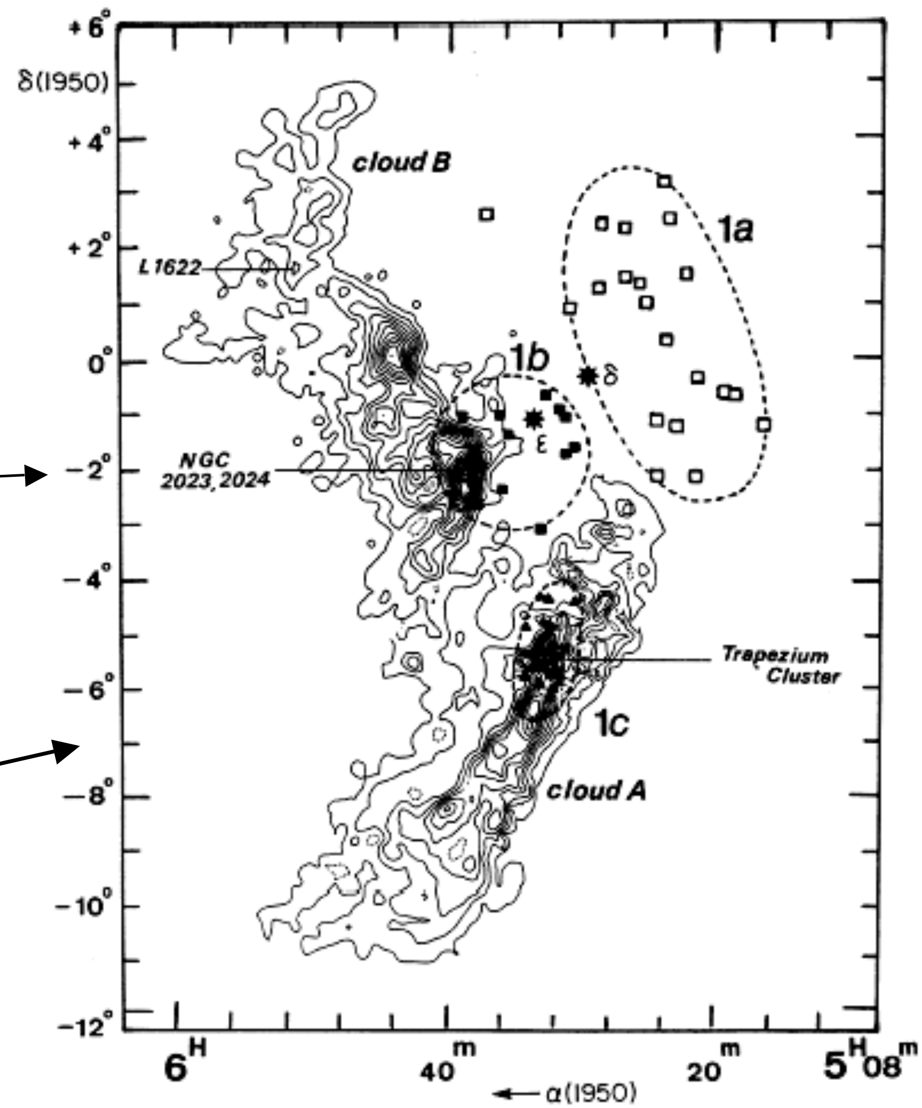
- All molecular clouds have dense regions where the gas is primarily molecular.
- *Giant molecular clouds* (GMCs) are large clouds with $10^4 M_\odot < M < 6\text{x}10^6 M_\odot$ sizes in the range 10-100 pc.
- The filing factor of GMCs is low; there about 4000 in the Milky Way). They have as much atomic as molecular gas.
- Mean densities are only ~ 100 cm^{-3}, but molecular clouds are very 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 or the action of massive stars have been suggested.

2. Nearby Orion Molecular Cloud Complex

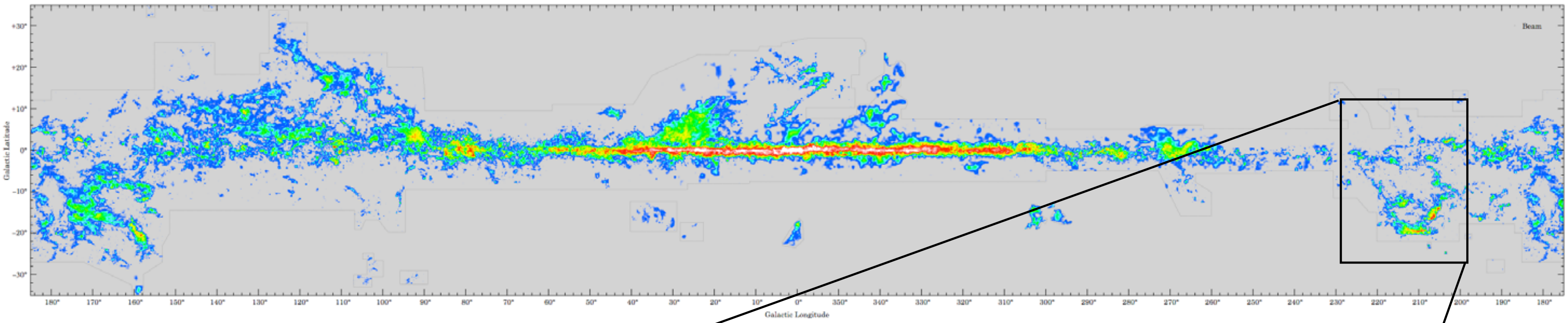
Cloud B

Cloud A

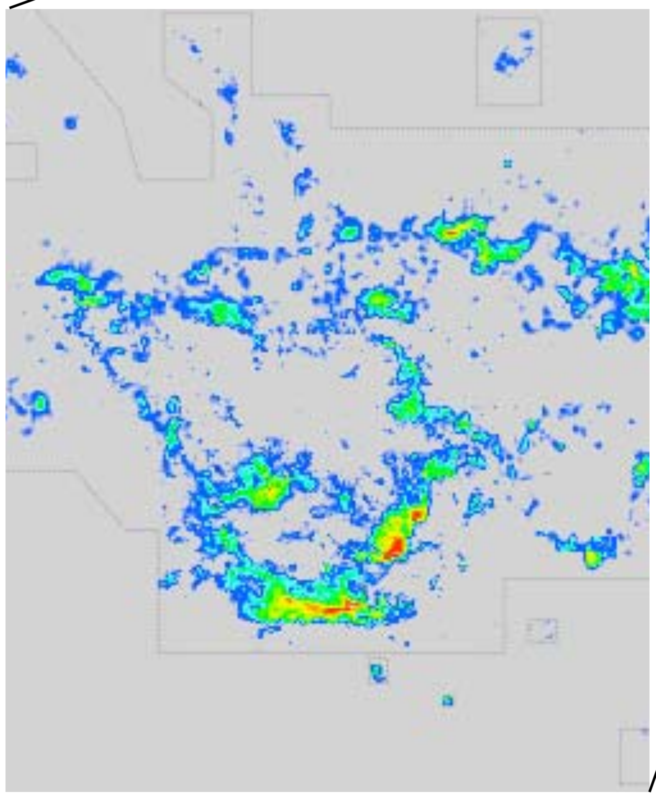


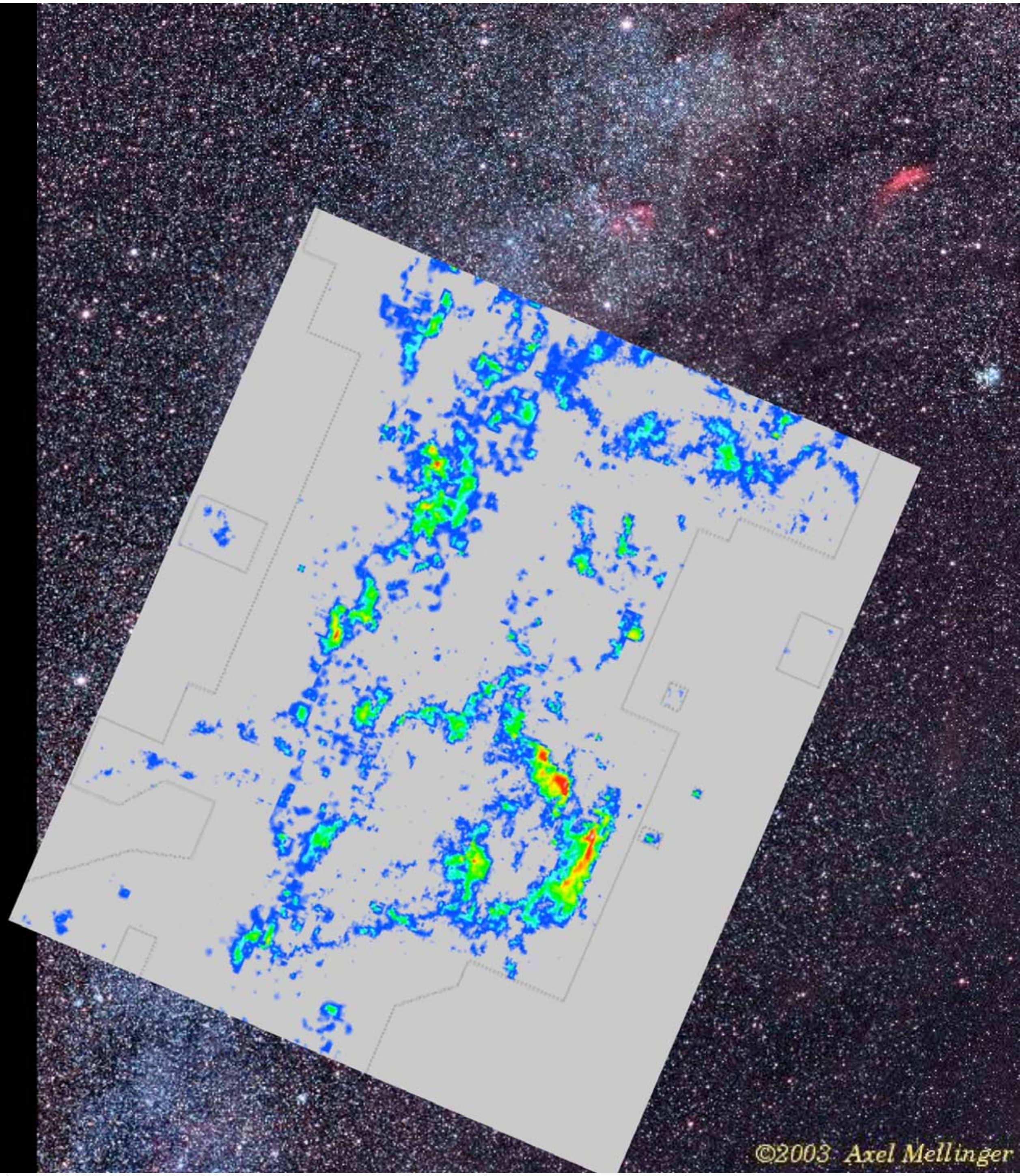
Early mini-telescope CO map

Orion: The Very Large Scale Picture



Dame et al. (2001)
CO survey

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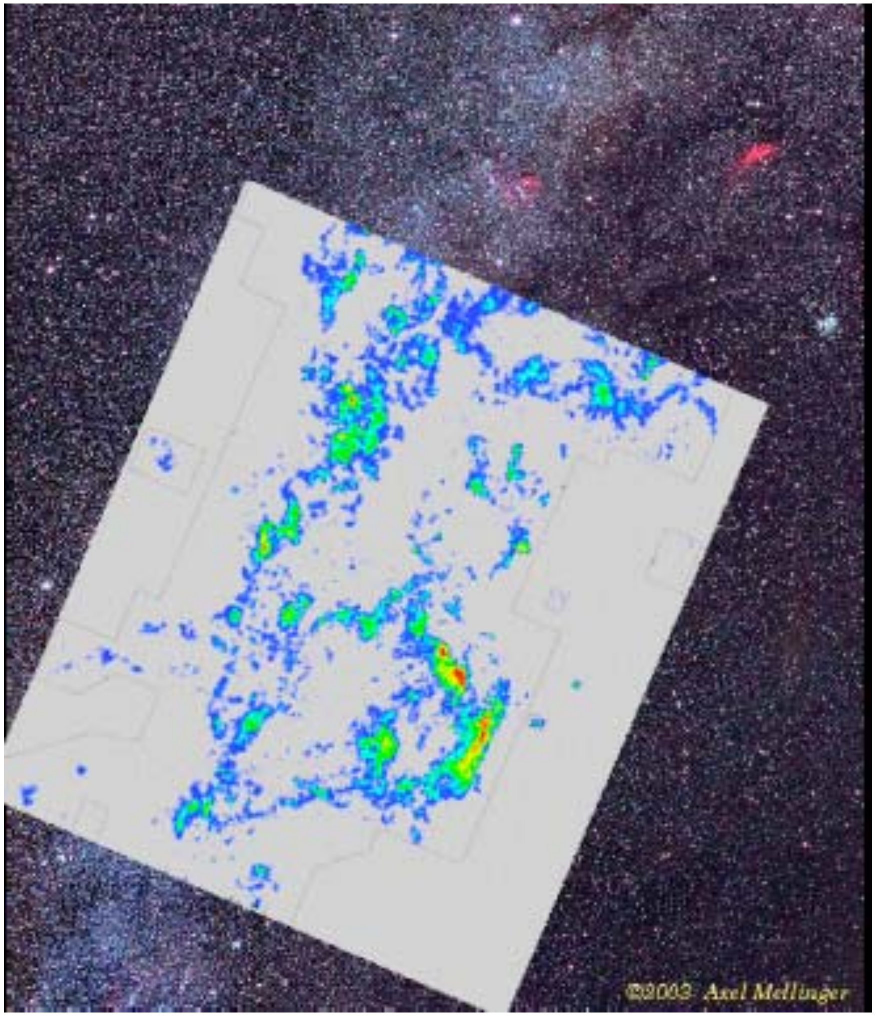
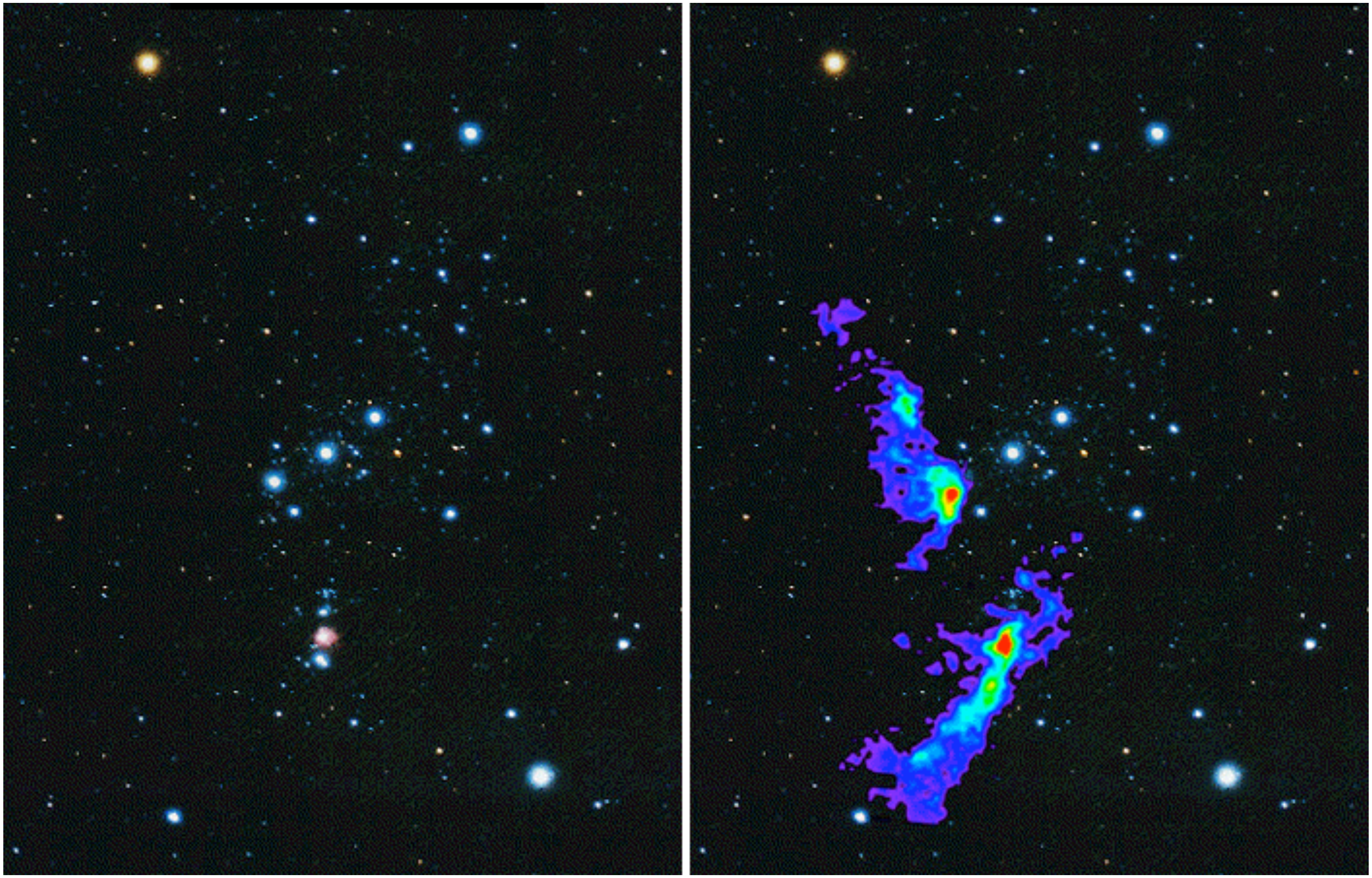
Large-scale Optical and CO Images



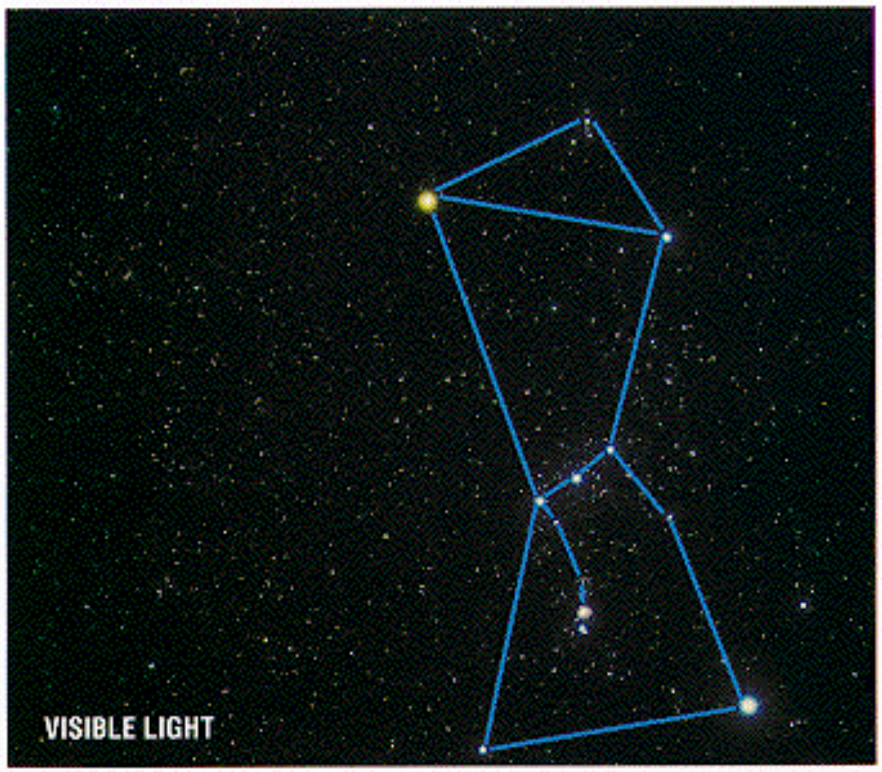
Orion Molecular Clouds A and B in CO

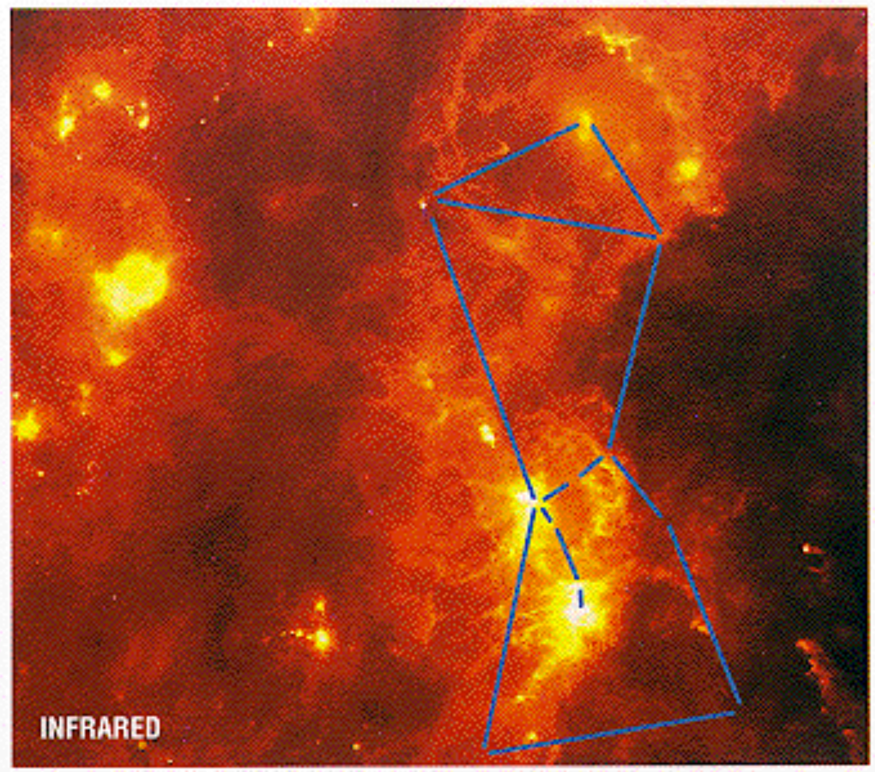
Constellation Scale Optical and CO Images

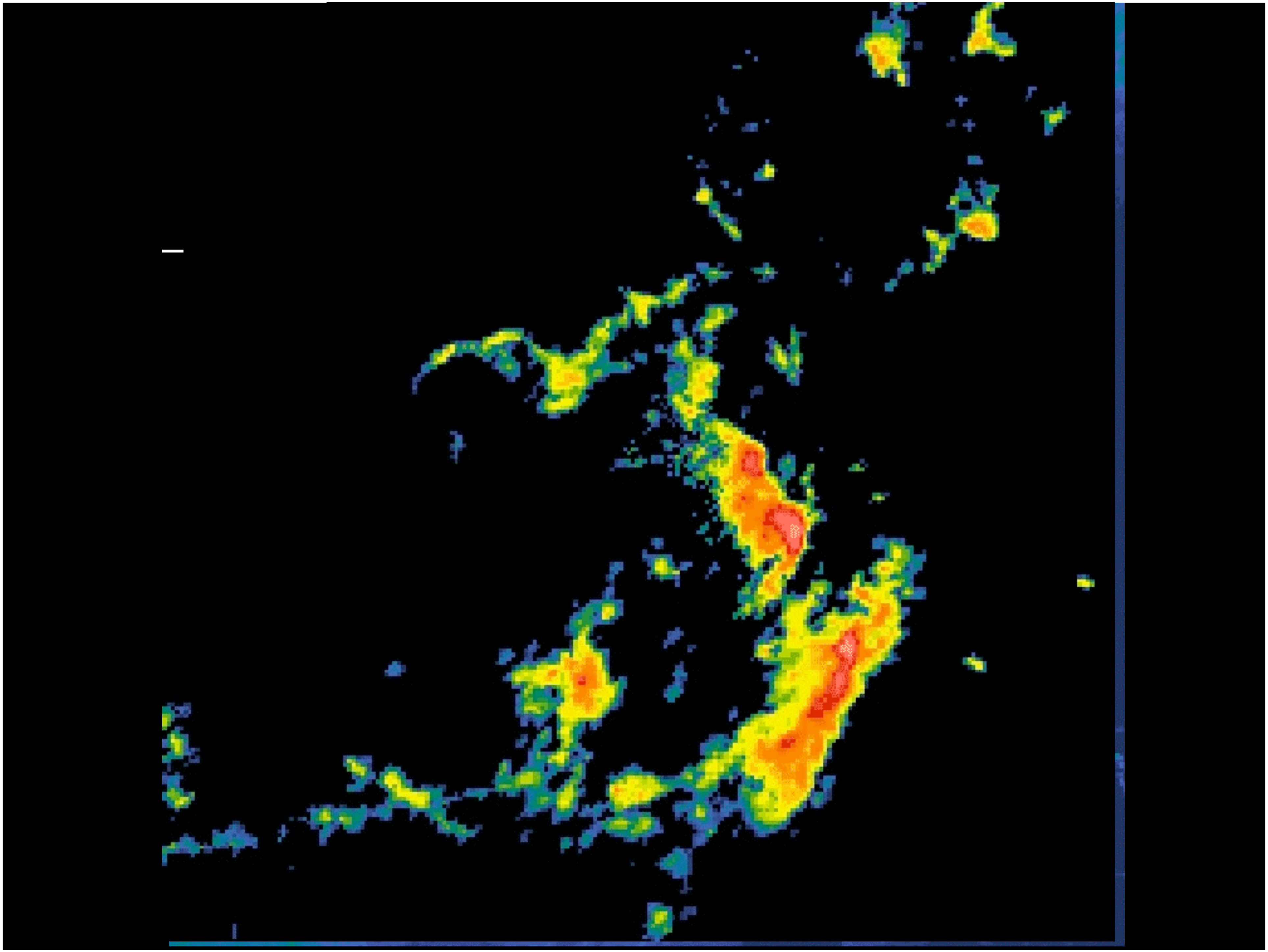


Orion Molecular Clouds A and B in IR

Constellation Scale Optical and IRAS Images







Summary for Orion GMCs

- Cloud A (L1641) exhibits typical features of GMCs:
  - elongated, parallel to the plane of the Galaxy
  - strong velocity gradient (rotation)
  - 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
- 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 linewidth, 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:

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

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

$b_{th} \approx 0.129\,(T/A)^{1/2}$ km s^{-1} (A = 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 due toSolomon, Scoville, and collaborators, is to apply the virial theorem, which assumes that

GMCs are gravitationally bound and in virial quilibrium,

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

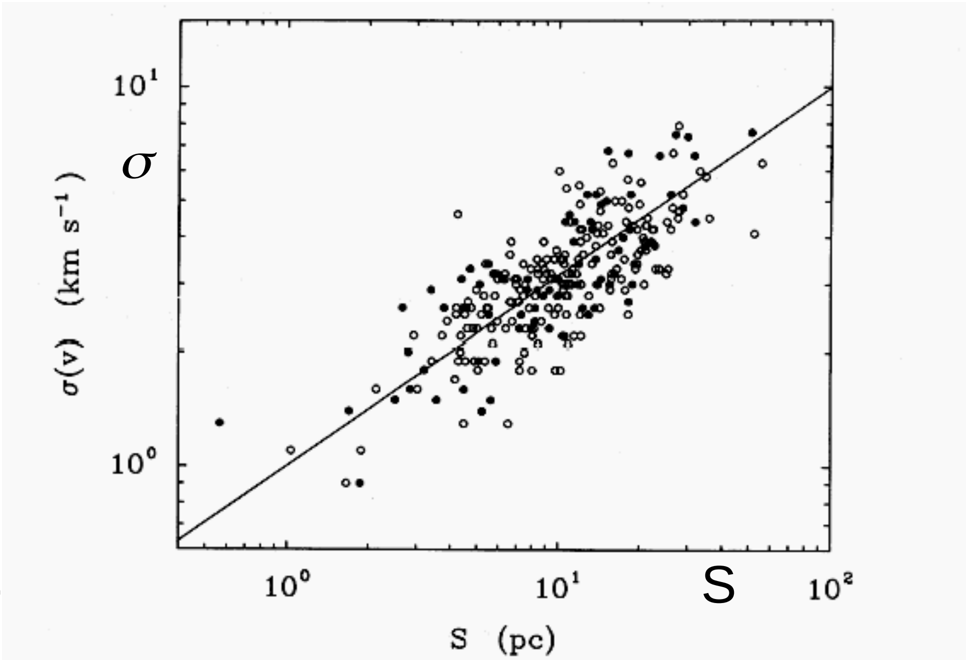
$$\boxed{M \approx \frac{R\sigma^2}{G}}$$

The Linewidth-Size Correlation

- $T_{\mathrm{kin}} \sim 20$ 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 find $\sigma \sim S^{0.5}$ (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 signatures 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

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

*** 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

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

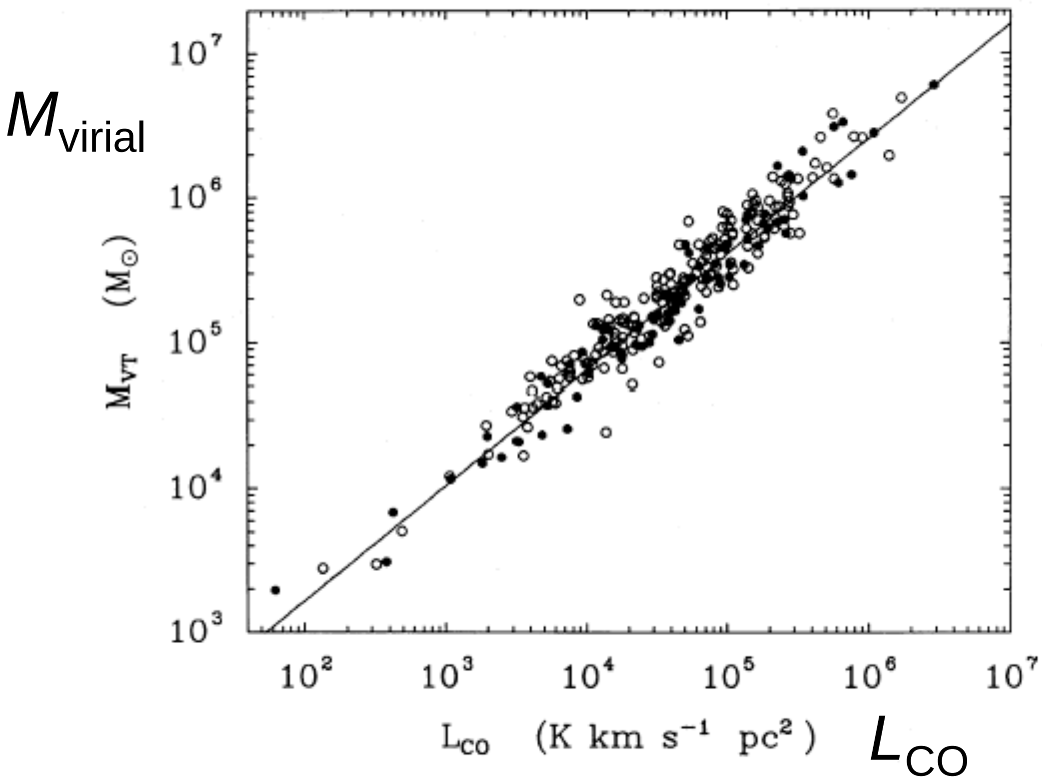
where T_{CO} is the peak brightness temperature, Δv is the velocity line width and R is the cloud radius.

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

yields

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

The Mass-CO Luminosity Correlation



Solomon et al.
ApJ 319 730 1987

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

c. Alternative Correlation Statements

We discussed two observationally based correlations for GMCs:

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

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

that lead to other statements:

$$N \approx \frac{M}{R^2} \approx \frac{\sigma^4}{R} \approx \text{constant}$$

$$\rho \approx \frac{M}{R^3} \approx \frac{1}{R^2}$$

$$M \approx \sigma^2 R \approx R^2 \text{ and } M \approx \sigma^4$$

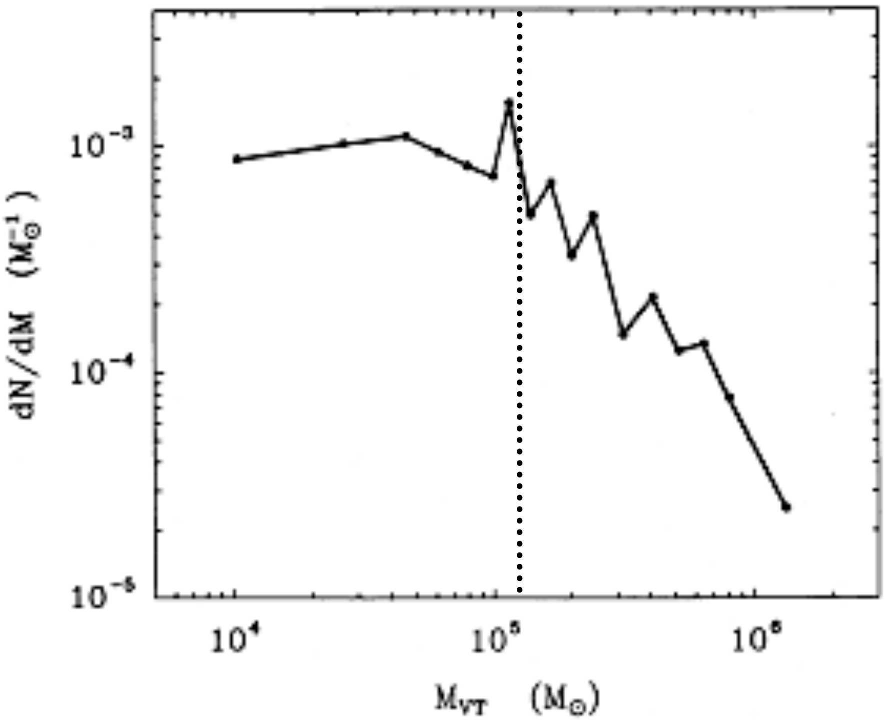
These have some independent empirical basis, and they might actually be preferred to the virial assumption if they could be better established,

Of special interest is that the surface densities of GMCs are all about the same to within a factor of 2:

N_H ~ 1.5 x 10^{22} cm^{-2}
A_V ~ 10
Σ ~ 150 $M_\odot$ pc^{-2}

GMC Mass Spectrum

Solomon et al. ApJ 319 730 1987

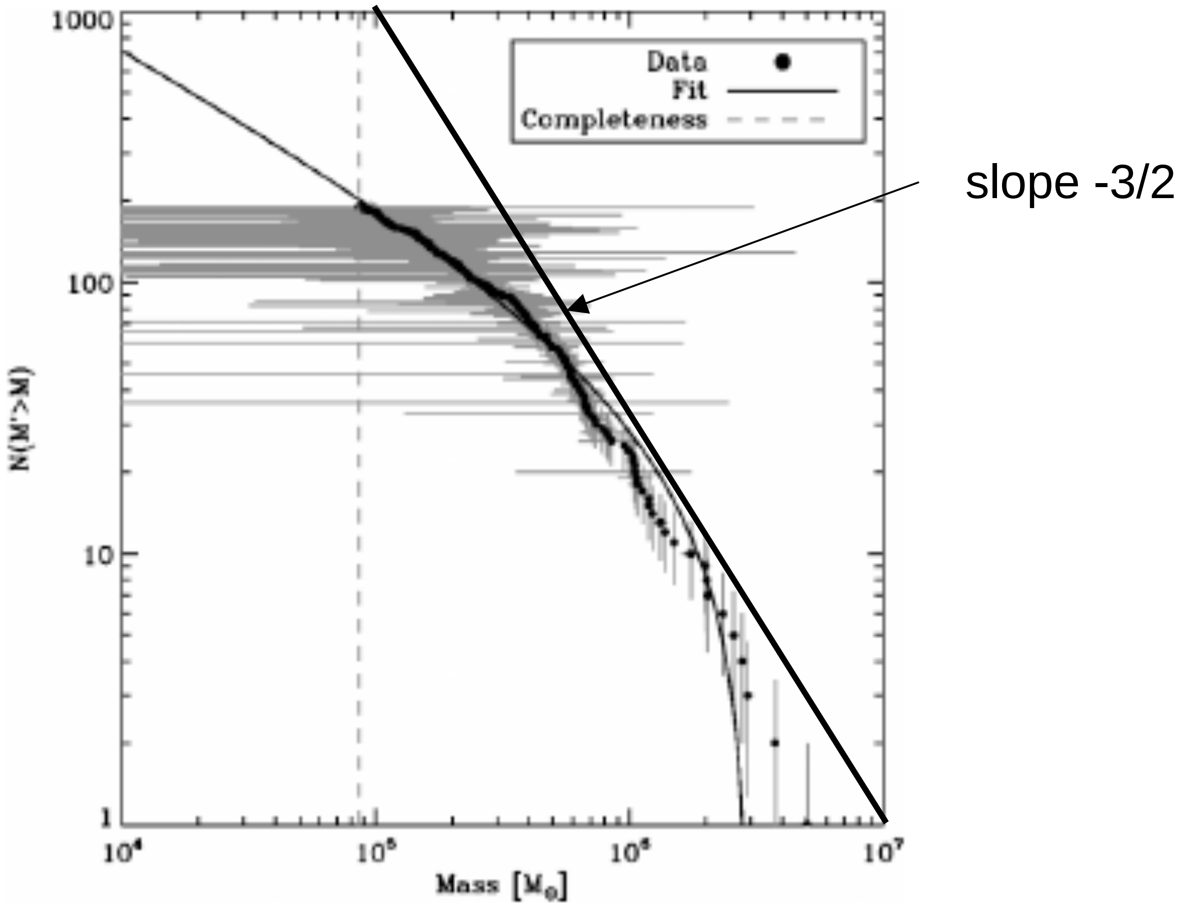


- The spectrum is incomplete for M < 10^5 M_{sun} (dashed line).
- What is the mass spectrum for clumps and cores ?
- How are cloud mass functions related to the stellar initial mass function (IMF)?

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 $\pm 24\%$. 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.

Rosolowsky PASP 117 1403 2005



There is a sharp cutoff at $M = 3\text{x}10^6\ M_{\text{sun}}$

Approximate/Typical Properties of Local GMCs

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 surface density	$1.5\ 10^{22}\ cm^{-2}$
Surface density	4 kpc^{-2}
Mean separation	500 pc

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 in molecular clouds; both are essentially invisible.
- 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 also because the CO / H_2 ratio might be expected to vary within a cloud and from cloud to cloud.
- It is also surprising that a single conversion factor between H_2 column density and I_{CO} (the so-called ***X-factor***) applies on average to all molecular clouds in the Galaxy.
- The several calibration methods agree to within factors of a few and provide insights into the properties of the clouds.

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

- Measured line intensity: $I_{CO} \equiv I(^{12}CO) \cong \langle T_A \rangle \Delta v_{FWHM}$
- $N(H_2) \cong 2\, R\, n(H_2)$
- Virial theorem: $\dfrac{GM}{R} \approx \sigma^2 = \left(\dfrac{\Delta v}{2.35}\right)^2$
- Mass estimate: $M = \frac{4\pi}{3} R^3 n(H_2) m$
- $\Delta v_{FWHM} = 2.35\, \sigma \sim (GM/R)^{1/2}$

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

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 Extincton

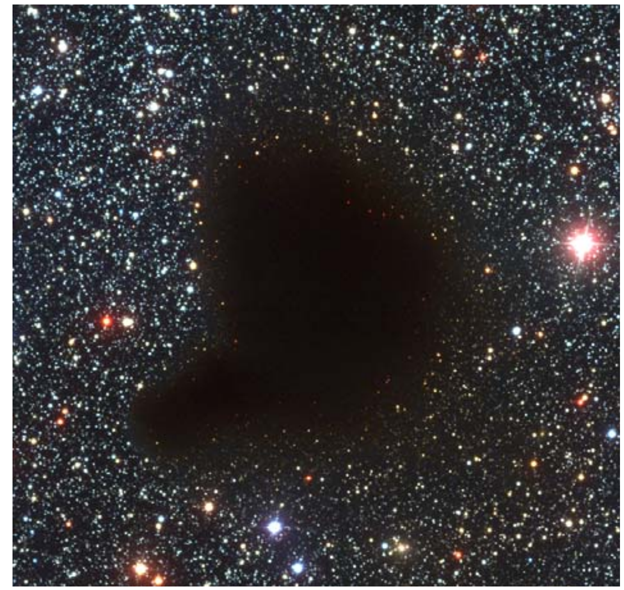
- Measure I_{CO} for regions with high A_V
- Determine A_V from IR star counts
- Extrapolate N_H/A_V from diffuse clouds
- Assume all hydrogen is molecular

Result:

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

Problems:

Inaccuracies in star-counts A_V
Variable dust properties
Variable N_H / A_V



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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:

Determination of A_V may not be inaccurate

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 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,

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

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.

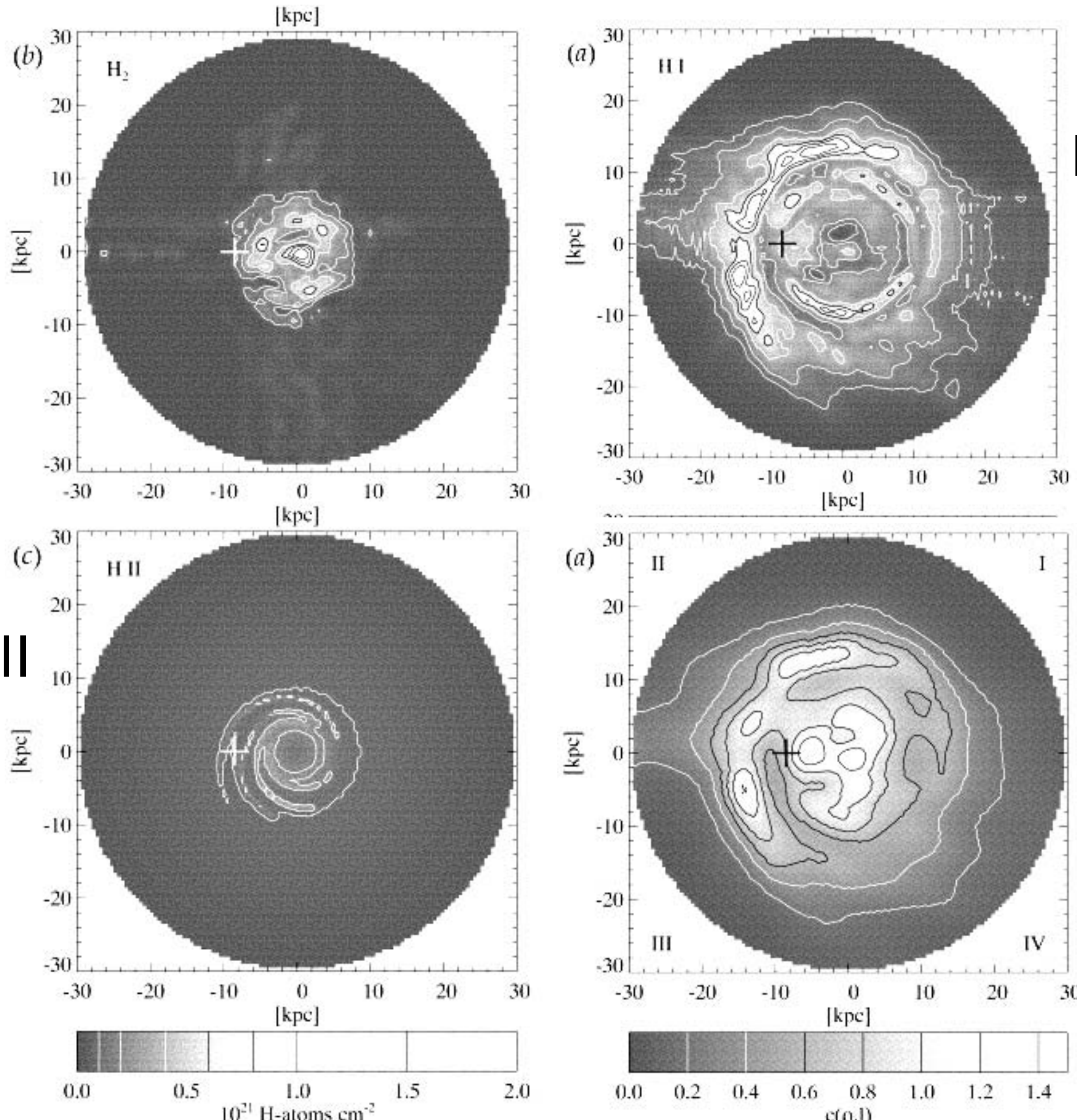
Hunter et al. ApJ 481 205 1997

H$_2$

HI

HII

CR



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

CR enhancement factor varies by ~ 50%.

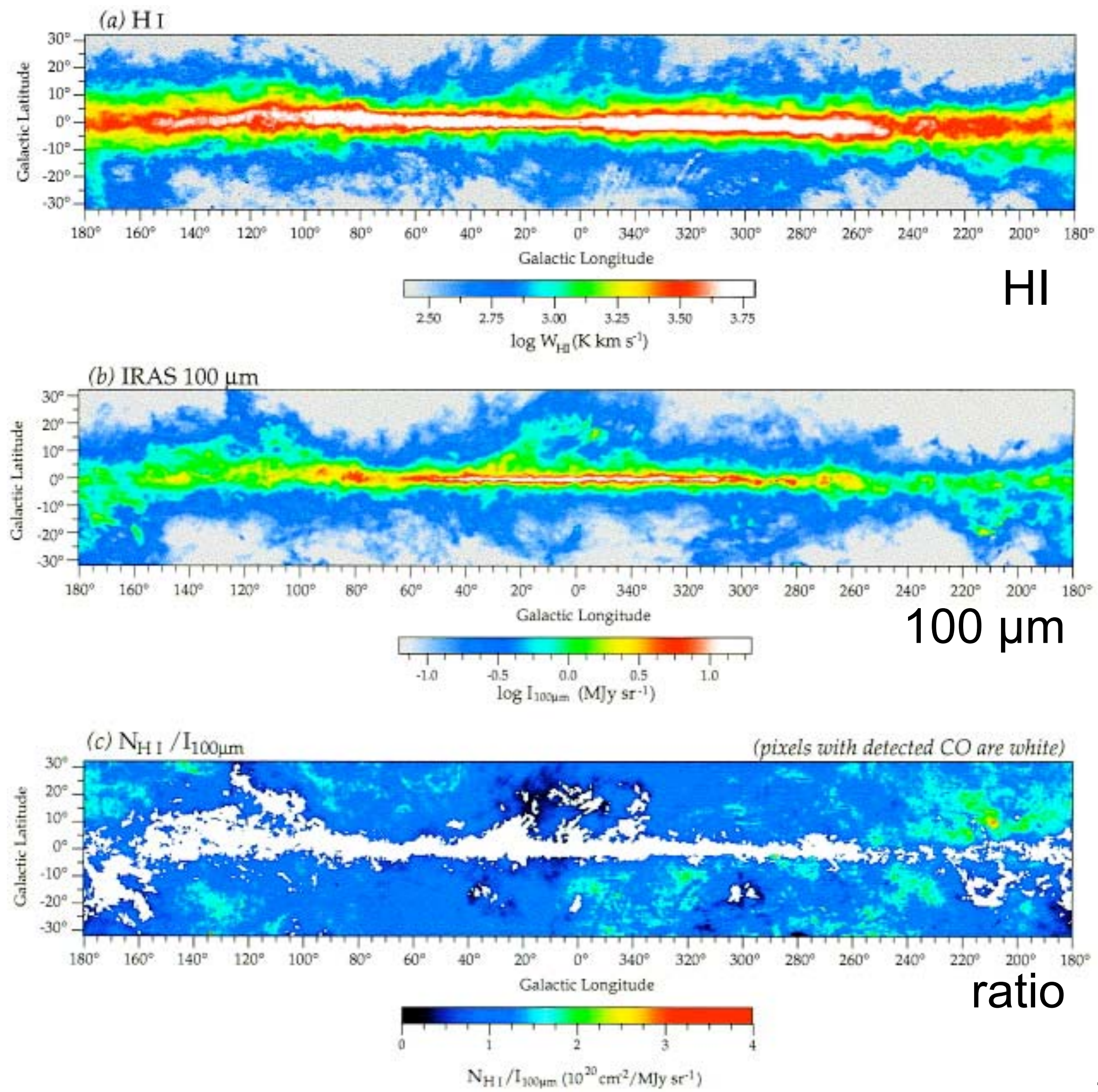
X-factor Method 5: HI/IRAS/CO

- 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 $|b| > 5^o$:

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

Method 5: HI/IRAS/CO

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

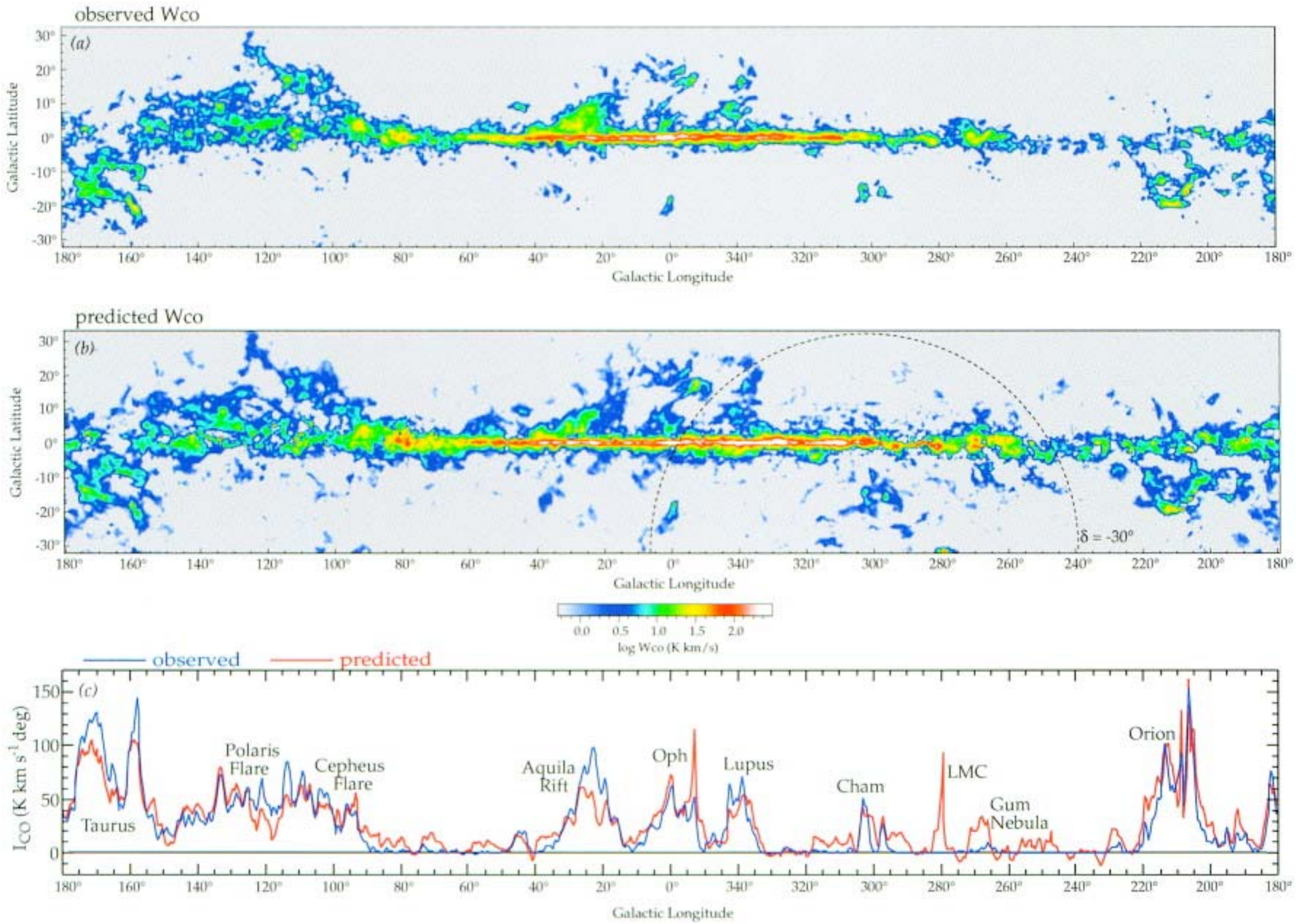


HI

100 μm

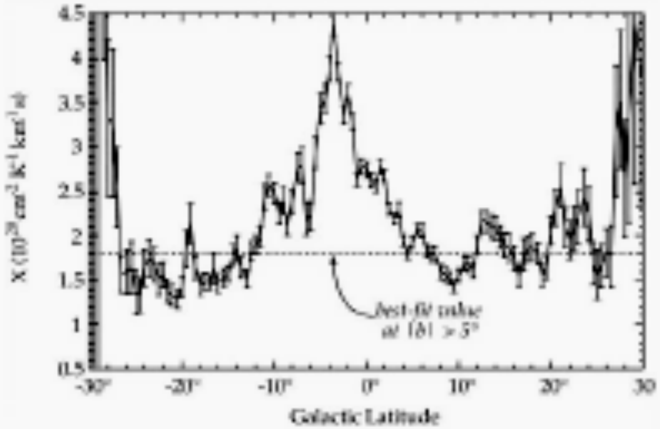
ratio

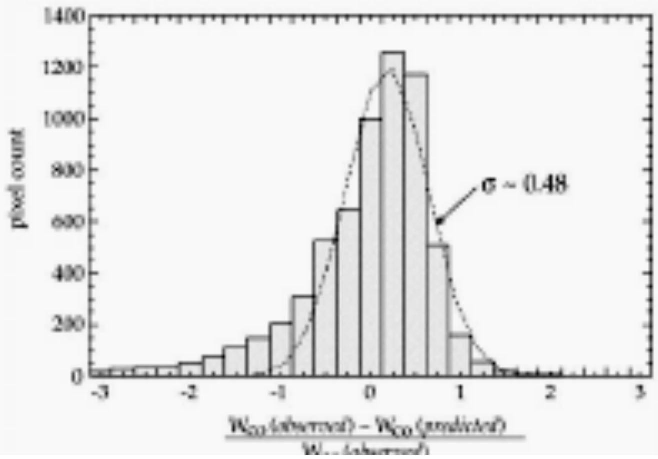
Verification of Method 5



Critique of Method 5

- Average X varies with latitude
  - High X at $l \sim 0^o$ 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 ($|b| < 5^o$), 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 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 5 members of the local group, but not the SMC, where $X_{CO} \approx 13.5 \times 10^{20}$ cm^{-2} (K km s^{-1})$^{-1}$.

CO/H_2 Conversion Factor: Summary

Source	X
Early work	2-5
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}