Molecular Clouds (1.5 weeks)

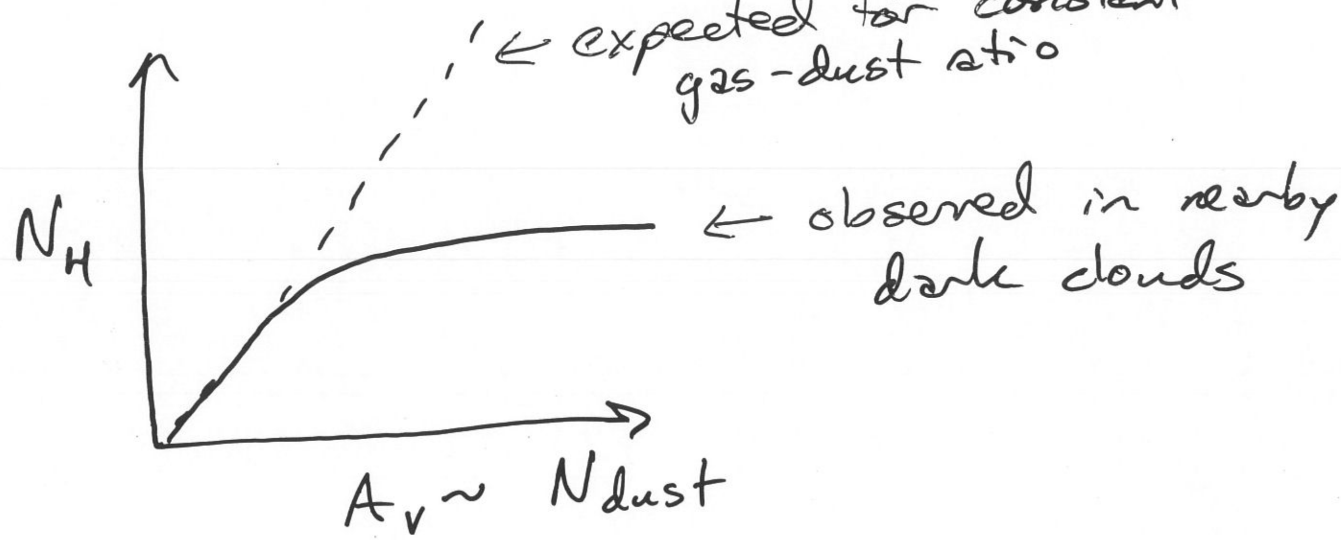
1. Overview & history
   H_2, CO
2. Observational background
3. Emission Processes
4. Giant Molecular Clouds * ~~Sept 30~~
   ~~Keith~~
5. Getting physical infor from lines
   LTE, LVG
6. Formation and destruction of molecules
7. Heating/cooling ** ~~Oct 10 - Kristen~~
8. High-Latitude Clouds, Dark Clouds (if time)

* Sanders, Scoville, & Solomon, 1985, ApJ, 289, 373

** Goldsmith-Langer 1978, ApJ 222, 881

Existence of HI in ISM known since 1951 (Ewen + Purcell); predicted ~1945

Existence of H_2 first inferred by Bok (1955) from comparing visual extinction A_V with HI column density N_{HI}



Presence of H_2 also inferred with detection of CO in ~1970

→ need $n \gtrsim 10^3$ to collisionally excite CO

→ only H_2 could contain this density (if HI, see it at 21cm)

H_2 first detected ~ 1970
- UV spectrometers above atmosphere
- nearby B stars behind cloud edge ($A_V \lesssim 2$ mag)

$\Rightarrow$ did make up missing gas

H_2 not generally observable
→ no permanent electric dipole moment
∴ → no $\Delta J = 1$ rotational transitions

$\Delta v = 0$ $\Delta J = 2-0$ $\lambda = 28\,\mu m$ ← bad atmosphere

$4-2$ $12\,\mu m$

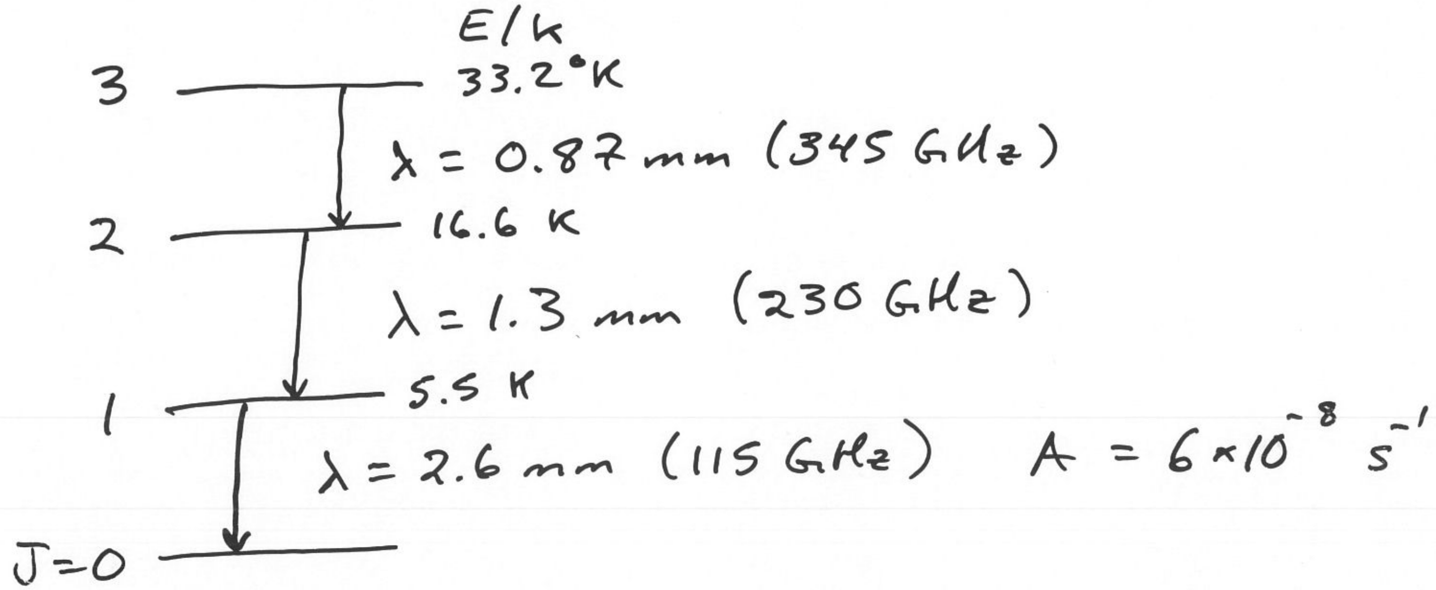
$\Delta v = 1$ $\lambda = 2\,\mu m$

↑ detected in shock heated gas
$T \sim 1000-2000$ K

→ need a more easily observed, common molecule to trace molecular gas

CO is abundant $CO/H_2 \sim 10^{-4}$ in clouds (30% of C in CO)

CO has easily observed and excited transitions



- readily excited by collisions with H_2, even at low kinetic temperature T_K

critical density $n_{H_2} \gtrsim 3000\ cm^{-3}$

BUT CO is optically thick, usually ($\tau \gtrsim 10$) $\rightarrow$ photon trapping

$A \rightarrow A\beta = \frac{A}{\tau}$ $\rightarrow n_{H_2,crit} \lesssim 300\ cm^{-3}$

^{12}CO emission is optically thick
→ not good tracer of column density

However, empirically it is found to be a good column density (+ hence mass) tracer

$$N(H_2) = \alpha \, I_{CO}$$

$$\hookrightarrow \int T(CO)\, dV$$

4 techniques

① ^{13}CO vs ^{12}CO

② ^{12}CO vs A_V

③ $L(^{12}CO)$ vs M_{vir}

④ γ-rays

$$\alpha \sim 2\text{-}3 \times 10^{20} \text{ cm}^{-2} (\text{K km/s})^{-1}$$

Key point is to estimate $N(H_2)$

① ^{13}CO → optically thin
→ derive $N(^{13}CO)$ (LTE)
→ adopt value for $^{13}CO/H_2$
→ $N(H_2)$

② A_V → assume $N(H_2)/A_V$

④ γ-rays → produced when cosmic rays collide with hydrogen

If cosmic ray density is constant, observed γ-ray flux measures
$n_H = (n_{HI} + 2n_{H_2})$ in volume

→ compare γ-ray survey + HI survey to CO surveys

③ Estimate $N(H_2)$ from virial mass and observed size

Virial Theorem for Observers

- tend to use simplest form

$$2T = \Omega$$

$2T$: kinetic energy; Ω: potential energy

$$Mv^2 = \frac{GM^2}{R} \rightarrow \Delta V = \left(\frac{GM}{R}\right)^{1/2}$$

$$I_{CO} \equiv \int T_{CO}\, dV \qquad (\mathrm{K\ km\ s^{-1}})$$

$$L_{CO} = d^2 \int I_{CO}\, d\Omega$$

$$\equiv T_{CO}\, \Delta V\, \pi R^2$$

$$\therefore L_{CO} = \left(\frac{3\pi G}{4}\right)^{1/2} \left(\frac{T_{CO}}{\rho^{1/2}}\right) M$$

α may depend on observed brightness temperature and density of gas

Emission Processes (refs Spitzer bits of Ch. 2-4)

velocity distribution of particles is Maxwellian

$$f(v) = \frac{\ell^3}{\pi^{3/2}} e^{-\ell^2 v^2}$$ velocity distribution function

$$\ell^2 = \frac{m}{2kT} = \frac{3}{2\langle v^2 \rangle}$$

→ there is a characteristic (local) kinetic temperature T_K

If we assume Local Thermodynamic Equilibrium (LTE), then relative populations of two levels $j < k$ is given by

$$\frac{n_k}{n_j} = \frac{g_k}{g_j} e^{-h\nu_{jk}/kT_k}$$ Boltzmann equation

Review of Basics of Radiative Transfer

Spitzer
Ch. 3.1

I_ν = specific intensity $\mathrm{erg\ s^{-1}\ cm^{-2}\ sr^{-1}}$

$$\frac{dI_\nu}{ds} = \underbrace{-\kappa_\nu}_{\text{absorption coefficient}} I_\nu + \underbrace{j_\nu}_{\text{emission coefficient}}$$

$$d\tau_\nu = -\kappa_\nu\, ds$$

τ_ν ← optical depth → $\tau_\nu = 0$ at observer
$\kappa_\nu > 0$, τ_ν increases towards source

Radiation received from cloud of total optical depth τ_ν

$$I_\nu = I_\nu(0)\, e^{-\tau_\nu} + \int_0^{\tau_\nu} \frac{j_\nu}{\kappa_\nu} e^{-\tau_\nu}\, d\tau_\nu$$

$I_\nu(0)$ → value of I on far side of emitting region

(i.e. a continuum source in background microwave background at 3 K)

In thermodynamic equilibrium

$$I_\nu = B_\nu(T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{h\nu/kT} - 1}$$

(T is the kinetic temperature of gas)

if I_ν = const , $dI_\nu/ds = 0$

$$\rightarrow j_\nu = K_\nu B_\nu(T)$$ Kirchhoff's law

if T is constant over path length

$$I_\nu = I_\nu(0) e^{-\tau_\nu} + B_\nu(T)(1 - e^{-\tau_\nu})$$

if $h\nu/kT \ll 1$

$$B_\nu(T) = \frac{2\nu^2 kT}{c^2}$$ Rayleigh-Jeans Law

$$\frac{h\nu}{kT} = \frac{14.39}{\lambda(\text{mm})\, T(\text{K})}$$ → not a good approximation in millimeter and submillimeter

I_ν is frequently replaced by the "brightness temperature" T_B

$$B_\nu(T_B) \equiv I_\nu$$

If Rayleigh-Jeans law applies, get

$$T_B = T_B(0)\, e^{-\tau} + T\left(1 - e^{-\tau}\right)$$

T_B: observed brightness temperature

$T_B(0)$: brightness temperature incident on far side of cloud

T: kinetic temperature of cloud

ignoring $T_B(0)$ for the moment

$\tau \gg 1 \rightarrow T_B = T$

$\tau \ll 1 \rightarrow T_B = \tau T$

Collisional Excitation

① Consider a simple, 2-level system

transition / collision rate/sec/molecule

$$C_{ul} \equiv C_{u \to l} = n\,\gamma_{ul}$$

— rate coefficient

— density (of H_2)

$$C_{lu} = C_{ul}\,\frac{g_u}{g_l}\exp\left(\frac{-h\nu}{kT_K}\right)$$

→ straightforward to calculate populations n_u and n_l ($n_{tot} = n_u + n_l$) from detailed balance, given γ_{ul}, A_{ul}, T_K, n

$$n_l\,(\gamma_{lu}\,n) = n_u\,(\gamma_{ul}\,n + A_{ul})$$

or

$$\frac{n_u}{n_{tot}} = \frac{\frac{g_u}{g_l}\exp\left(-\frac{h\nu}{kT_K}\right)}{1 + \frac{g_u}{g_l}\exp\left(\frac{-h\nu}{kT_K}\right) + \frac{n_{crit}}{n}}$$

$n_{crit} = A_{ul}/\gamma_{ul}$ "critical density

critical density is a key parameter
→ can collisions keep up with spontaneous radiation?

$n \gg n_{crit}$ → level populations are thermalized

$$\left(\frac{n_u}{n_l}\right)_{thermal} = \frac{g_u}{g_l} \exp\left(-\frac{h\nu}{kT_K}\right)$$

below critical density, spontaneous radiative rates are faster than collisions
→ population is "subthermal"

$$\frac{n_u}{n_l} = \frac{n}{n_{crit}} \left(\frac{n_u}{n_l}\right)_{thermal}$$

For multi-level system

$$n_u \left\{ \sum_{k \neq u} \left(n \gamma_{uk} + B_{uk} U_\nu\right) + \sum_{k<u} A_{uk} \right\}$$

$$= \sum_{u \neq k} n_k \left(n \gamma_{ku} + B_{ku} U_\nu\right) + \sum_{k>u} A_{ku} n_k$$

$$u_\nu = \frac{1}{c}\int I_\nu \, d\omega$$ energy density per unit frequency

If the emission from a line is optically thick, then the level populations may be thermalized at lower densities due to photon trapping

photon escape probability $\beta \sim \frac{1}{\tau}$

$\tau \ll 1 \rightarrow I_{thin} \propto n_u V A$

$\tau \gg 1 \rightarrow I_{thick} \propto n_u V A \beta$

ie, effectively

$$A \rightarrow A\beta \sim \frac{A}{\tau}$$

The velocity dispersion σ is plotted logarithmically ... given in Table 1. A well-defined includes all of the objects for which a mass estimate is given in Table 1. A well-defined correlation between $\log \sigma$ and $\log L$ is seen, and within the scatter it is well represented by the eye-fitted dashed straight line, whose equation is

!

$$\sigma(\mathrm{km\,s^{-1}}) = 1.10\, L\,(\mathrm{pc})^{0.38}. \quad (1)$$

The rms deviation of $\log \sigma$ from this relation is 0.14, corresponding to a factor of 1.38 in σ. Equation (1) holds for $0.1 \lesssim L \lesssim 100$ pc, and is almost identical to the relation $\sigma = 1.1\, L^{0.3}$ found by Larson (1979) for interstellar motions on somewhat larger length scales, $1 \lesssim L$ 1000 pc; this earlier study included fewer data on molecular clouds, but some data on H cloud velocities and larger-scale streaming motions. The present result strengthens the conclusion that the velocity dispersion of interstellar motions shows a general power-law correlation with region size, and extends it to smaller length scales.

The data in Table 1 show, moreover, that a similar relation between σ and L often holds even within individual clouds. Fig. 2 shows the variation of σ with L in all of the clouds or complexes for which at least one subregion is listed in Table 1; in this diagram straight lines connect the symbols for each subregion and the larger cloud of which it is a part. The velocity dispersions of groups of T Tauri stars in the Taurus clouds (Table 1 and Jones & Herbig 1979) are also plotted as asterisks in Fig. 2(a). The left part of Fig. 2(b) shows additional data for several dark clouds as reproduced from Fig. 89 of Snell (1979); in this

Larson 1981

MNRAS

$\sigma \propto L^{0.38}$

(by-eye fit)

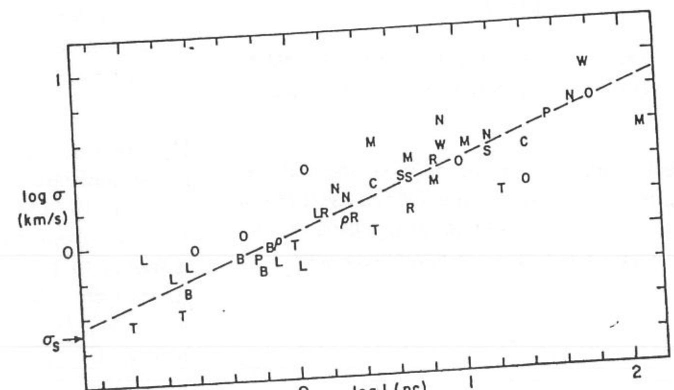


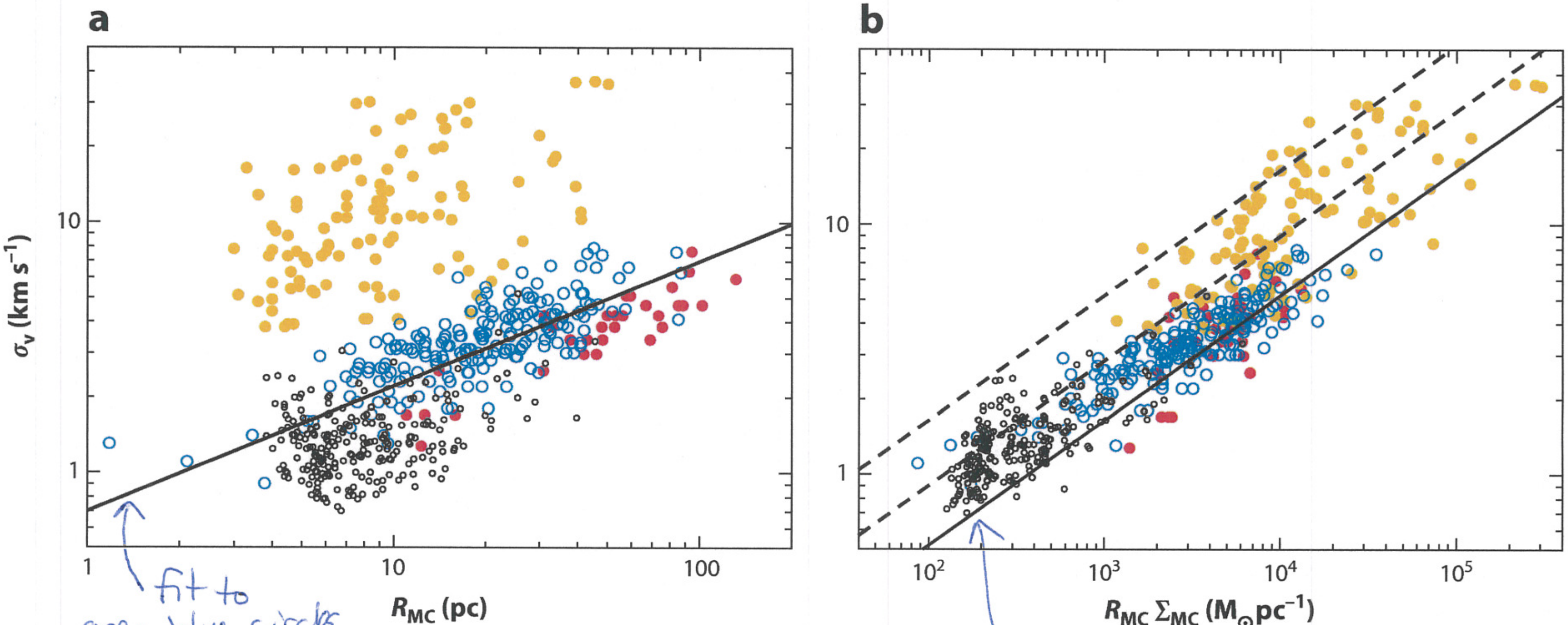
Figure 1. The three-dimensional internal velocity dispersion σ plotted versus the maximum linear dimension L of molecular clouds and condensations, based on data from Table 1; the symbols are identified in Table 1. The dashed line represents equation (1), and σ_s is the thermal velocity dispersion.

compare to

Kolmogoroff law $\sigma \sim L^{1/3}$

(subsonic turbulent flows)

σ vs M implies most regions are gravitationally bound and roughly in virial equilibrium



fit to open blue circles

$\sigma_V = \left(\frac{\pi G}{5}\right)^{1/2} R_{MC}^{1/2}\ \Sigma_{MC}^{1/2}$

Heyer M, Dame TM. 2015.
Annu. Rev. Astron. Astrophys. 53:583–629

- gold dots are clouds near Galactic Center
- equation for line in right panel is virial theorem (grav and kinetic energy equipartition) + Larson's Law with exponent 0.5

Overview of Properties of Giant Molecular Clouds

see Fukui & Kawamura, 2010, ARAA, 48 547

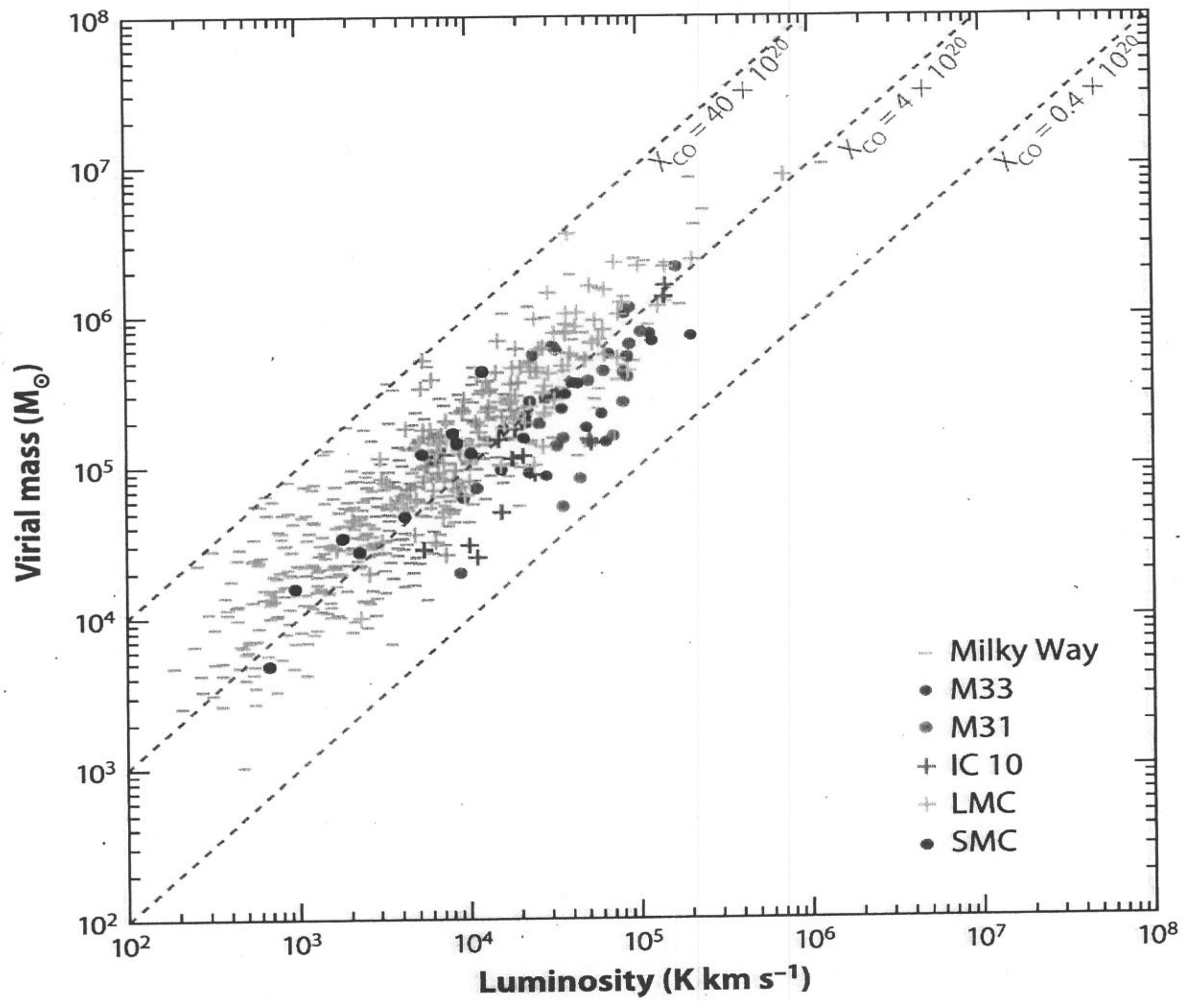
- masses from 10^4 – few $\times 10^6$ $M_\odot$
- (linewidth) $\Delta V \propto R^{0.5}$ (size)
  - → for virialized clouds implies
    $\bar{n} \propto 1/R$
    $\bar{N}$ = constant
- mass function $\frac{dN}{dm} \propto M^{-1.7}$
  - → implies most mass is in the few largest clouds

Linewidths >> thermal linewidths (1–10 km/s)

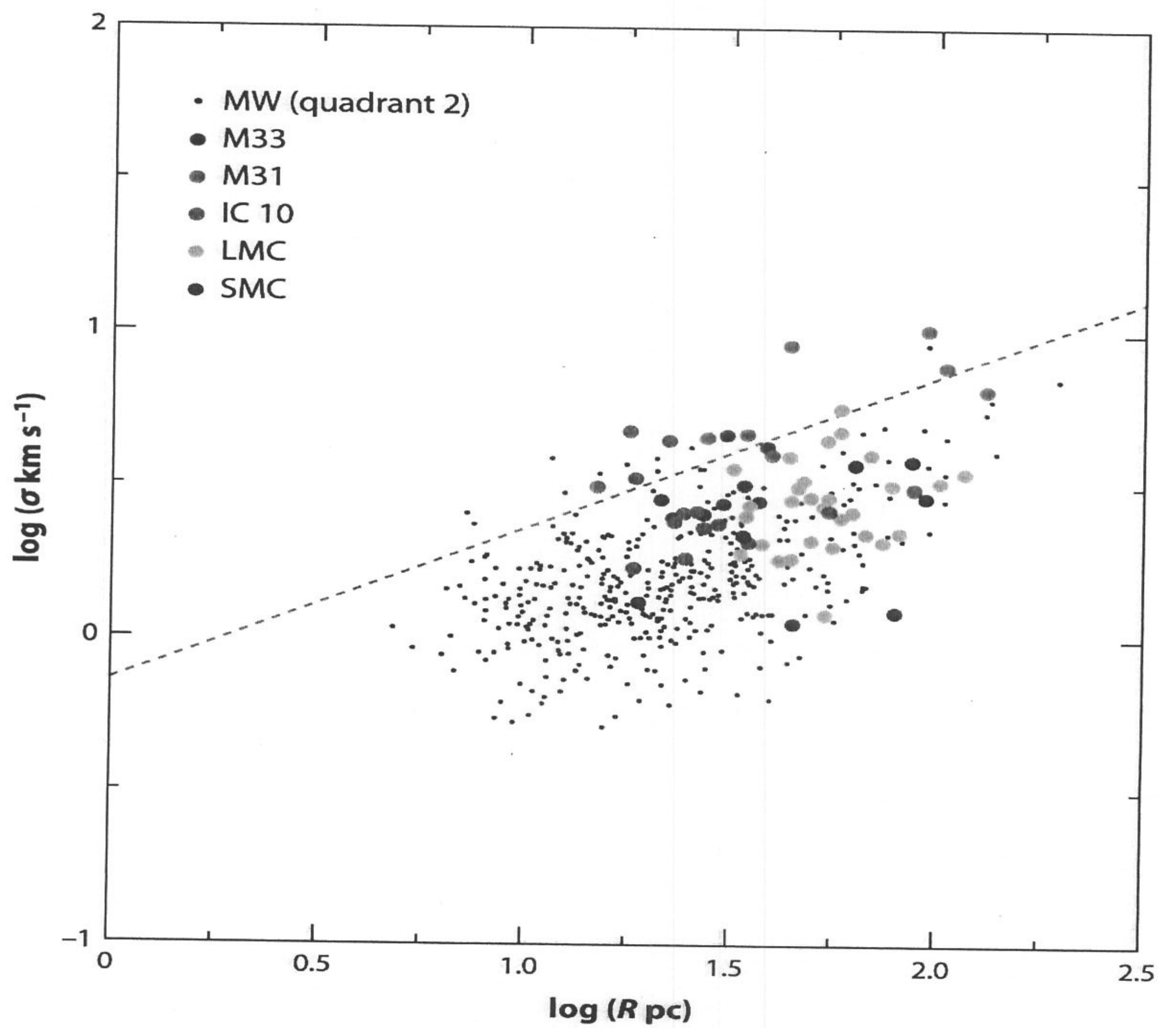
Sizes 10–100 pc

Low star formation efficiency (few percent)

See Figures 2, 3 + 4 (not copied)



Fukui Y, Kawamura A. 2010.
Annu. Rev. Astron. Astrophys. 48:547–80



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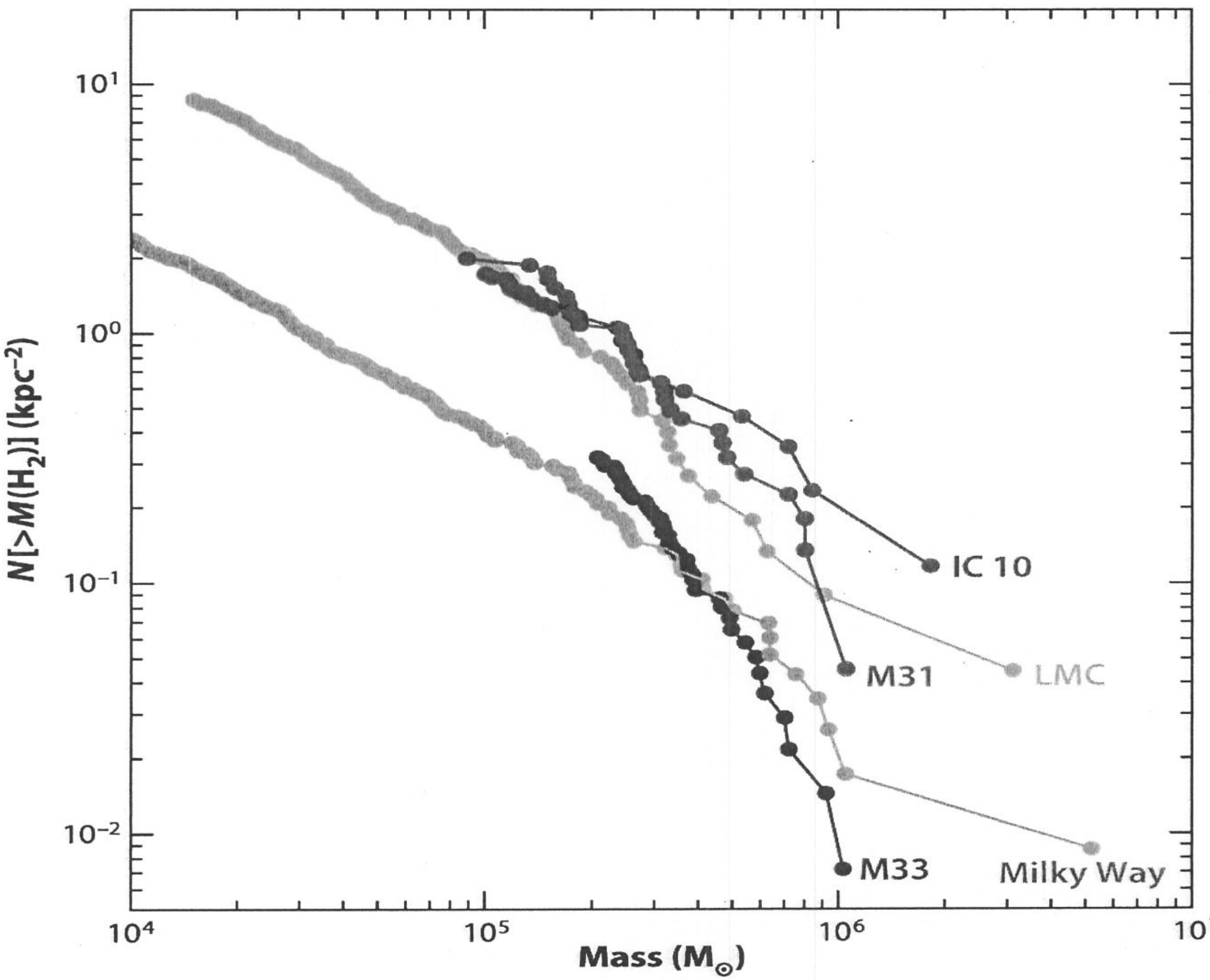

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