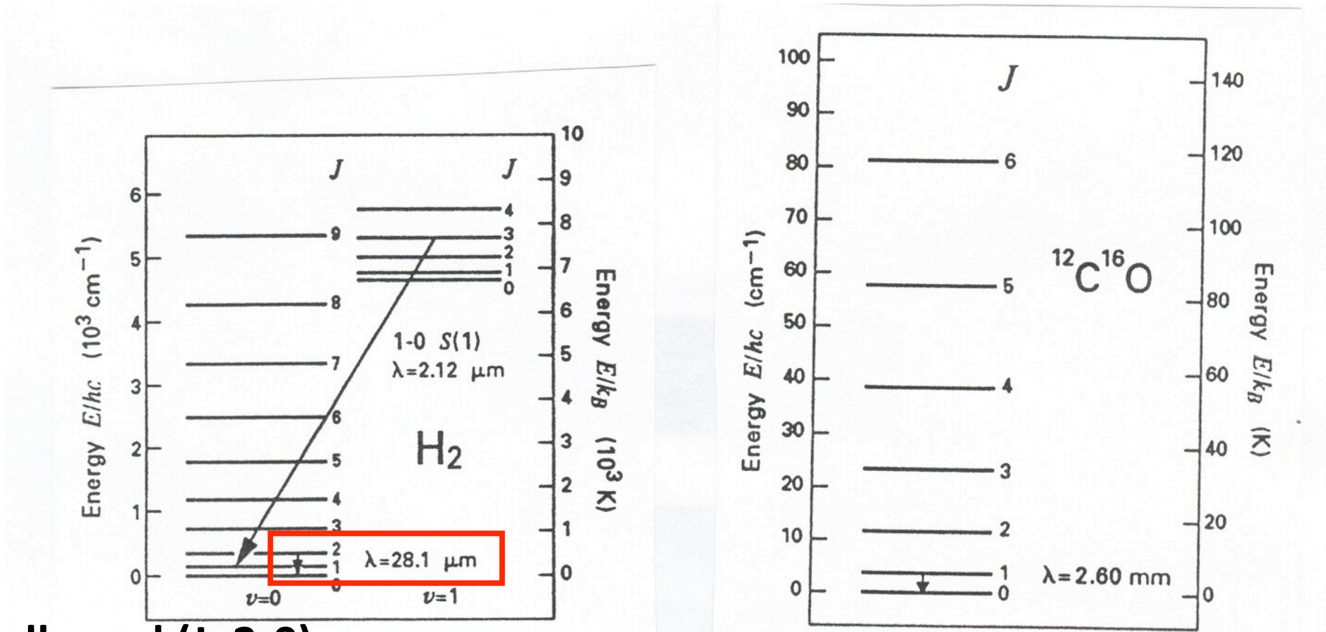
Observing molecular clouds at large



Lowest allowed (J=2-0)
ΔE = 510 K

H_2 smallest diatomic molecule: widely-spaced energy levels
Even lowest excited rot. levels too far above ground state
to be easily populated at normal molecular cloud T.
no dipole moment, hence quadrupole radiation (slow)

CO: more closely-spaced energy levels; easily populated also at low T

Deriving $N(H_2)$, total mass

1. Lines (Planck & Boltzmann)

Detection eqn., LTE, $\tau(^{12}CO) \gg 1$ ($\Rightarrow T_{ex}$), $\tau(^{13}CO) \ll 1$

$N(^{13}CO) = f(\tau_{13}, T_{ex}, \Delta v_{13}) + [H_2]/[^{13}CO] = \ldots \Rightarrow N(H_2)_{LTE}$

$^{12}C/H$, $^{12}C/^{13}C$ gradients $\Rightarrow [H_2]/[^{13}CO] = f(R)$

Non-LTE transitions: LVG model (full radiation transport eqns.)

2. Lines (empirical)

$N(H_2)/\int T(^{12}CO)\,dv \equiv X \Rightarrow N(H_2)_{Wco}$

X = constant or $f(R)$?

3. Virial theorem

Cloud radius (r), linewidth (Δv), assumptions about density distribution. For spherical cloud, $n \propto r^{-2} \Rightarrow M_{vir} = 126\, r\, \Delta v^2$

Exclude non-bound motions (e.g. outflows); actual density distribution?

4. Dust continuum

$M = (g S_\nu d^2)/\kappa_\nu B(T_{dust})$

κ_ν, T-structure, gas-to-dust ratio (g) uncertain

5. Extinction mapping $N(HI) + 2N(H_2) \approx 1.9 \times 10^{21}\ cm^{-2} A_V$, I_{CO} or $N(^{13}CO)$

$$\mathbf{N(H_2) = \boldsymbol{X_{CO}}\, W_{CO}}$$

with $W_{CO} = \int T(^{12}CO)\, dv$

$\mathbf{M_{mol} = \boldsymbol{\alpha_{CO}}\, L_{CO}}$ with L_{CO} in K km s^{-1} pc^2 ;

for $X=2\ 10^{20}$: $M = 4.3 L_{CO}\ M_{\odot}$ (Bolatto+ 2013)

The value of $\boldsymbol{X_{CO}}$ is determined by calibrating empirical N or M with other methods.

Original derivation of $\boldsymbol{X_{CO}}$ was by using diffuse γ-ray emission (Lebrun+ 1983)

Based on fact that diffuse γ-ray emission is mostly due to collisions between cosmic rays and the ISM: $I_\gamma = \varepsilon_\gamma[N(HI) + 2X_{CO}W_{CO}]$ (Bloemen 1989)
compare maps of diffuse γ-emission, HI and CO to find $\boldsymbol{X_{CO}}$.

In Milky Way $\boldsymbol{X_{CO}} = 2 \times 10^{20}$ (K $kms^{-1})^{-1}$ cm^{-2} with 30% uncertainty (Bolatto+ 2013 ARAA)

Values for other types of galaxies

* Normal galaxies: $\boldsymbol{X_{CO}} \approx 2 \times 10^{20}$ with factor 2 uncertainty

Increases sharply in systems with metallicity ca. 0.5 solar
Often smaller in central regions, as in MW

* Starbursts and other luminous galaxies: $\boldsymbol{X_{CO}} \approx 0.4 \times 10^{20}$ with factor 3 uncertainty

Antennae-values: see Zhu, Seaquist & Kuno 2003 ApJ 588, 243
$M_{tot} \sim 2 \times 10^9\ M_\odot$

See also Herrera+ 2012 A&A 538, L9 for ALMA data (3-2 instead of 1-0!)

* At high redshifts:

In massive merger-driven starbursts such as SMGs, most consistent with low $\boldsymbol{X_{CO}}$ (cf. local ULIRGs)
In blue-sequence galaxy disks, likely higher $\boldsymbol{X_{CO}}$ (cf. local disks)