

Interstellar Medium (ISM)

Lecture 15
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Optical Thickness of CO (J = 1-0)

- The net absorption coefficient, taking into account both absorption and stimulated emission is:

$$\kappa_\nu = n_0 \sigma_{01} \left(1 - \frac{g_0}{g_1} \frac{n_1}{n_0} \right), \quad \sigma_{01} = \frac{g_1}{g_0} \frac{c^2}{8\pi\nu_{10}^2} A_{10} \phi_\nu, \quad \frac{n_1}{n_0} = \frac{g_1}{g_0} \exp \left(-\frac{k\nu_{10}}{kT_{\text{exc}}} \right) \quad g_J = 2J + 1$$

- The optical depth of the thermally broadened CO line can be written as

$$\phi_\nu = \frac{1}{\sqrt{\pi}} \frac{\lambda}{b} e^{-\frac{v^2}{b^2}}$$

$$\tau_\nu = \int \kappa_\nu ds = \tau_0 e^{-v^2/b^2}$$

optical depth at line center =

$$\tau_0 = \frac{g_1}{g_0} \frac{c^2}{8\pi^{3/2} \nu_{10}^3} A_{10} \frac{c}{b} \left(1 - e^{-h\nu_{10}/kT_{\text{exc}}} \right) N_0$$

$$A_{10} = 7.16 \times 10^{-8} \text{ s}^{-1}$$

$$\tau_0 = 297 \left(\frac{N_{\text{H}}}{10^{21} \text{ cm}^{-2}} \right) \left[\frac{n(\text{CO})/n_{\text{H}}}{7 \times 10^{-5}} \right] \left[\frac{n(J=0)}{n(\text{CO})} \right] \left(\frac{2 \text{ km s}^{-1}}{b} \right) \left(1 - e^{-5.532 \text{ K/T}_{\text{exc}}} \right)$$

Here, N_{H} is the column density of H nucleon in the $J = 0$ rotational level. Recall that the cosmic abundance of carbon is $n_{\text{C}}/n_{\text{H}} = 2.95 \times 10^{-4}$ and a fraction $f_{\text{CO}} \approx 0.25$ of the carbon is in CO molecules.

- The above equation seems to indicate that the CO J=1-0 line is optically thick. However, we need to estimate the fraction of the CO that is in the $J = 0$ level.

- The fraction of CO in a given rotational level J will be:

$$\frac{n(\text{CO}, J)}{n(\text{CO})} = \frac{(2J + 1)e^{-B_0 J(J+1)/kT_{\text{exc}}}}{\sum_J (2J + 1)e^{-B_0 J(J+1)/kT_{\text{exc}}}} \quad E_J = B_0 J(J+1)$$

Here, B_0 is the “rotation constant.”

- We can approximate the partition function in the denominator by

$$Z = \sum_{J=0}^{\infty} (2J + 1)e^{-B_0 J(J+1)/kT_{\text{exc}}} \approx \left[1 + (kT_{\text{exc}}/B_0)^2 \right]^{1/2}$$

This approximation is exact in the limits $kT_{\text{exc}}/B_0 \rightarrow 0$ and $kT_{\text{exc}}/B_0 \gg 1$, and accurate to within 6% for all T_{exc} .

$$\tau_0 = 297 \left(\frac{N_{\text{H}}}{10^{21} \text{ cm}^{-2}} \right) \left[\frac{n(\text{CO})/n_{\text{H}}}{7 \times 10^{-5}} \right] \frac{\left(1 - e^{-5.532 \text{ K}/T_{\text{exc}}} \right)}{\left[1 + (T_{\text{exc}}/2.77 \text{ K})^2 \right]^{1/2}} \left(\frac{2 \text{ km s}^{-1}}{b} \right)$$

Here, we used $B_0/k = 2.77 \text{ K}$ for $^{12}\text{C}^{16}\text{O}$.

$$\tau_0 \approx 50 \left(\frac{N_{\text{H}}}{10^{21} \text{ cm}^{-2}} \right) \left[\frac{n(\text{CO})/n_{\text{H}}}{7 \times 10^{-5}} \right] \left(\frac{2 \text{ km s}^{-1}}{b} \right) \quad \text{for a typical CO rotation temperature } T_{\text{exc}} \approx 8 \text{ K.}$$

- Thus, **the CO 1-0 transition is expected to be often quite optically thick.**

Radiative Trapping

- ***Radiative Trapping:***
 - In many situation of astrophysical interest, there is sufficient gas present so that, for some species X, a photon emitted in a transition $X_u \rightarrow X_\ell$ will have a high probability of being absorbed by another X_ℓ somewhere nearby, and, therefore, a low probability of escaping from the emitting region.
 - This phenomenon — referred to as radiative trapping — have two effects.
 - (1) it reduces the emission in the $X_u \rightarrow X_\ell$ photons emerging from the region, and
 - (2) it acts to increase the level of excitation of species X (relative to what it would be were the emitted photons to escape freely).
 - An exact treatment of the effects of radiative trapping is a complex problem of coupled radiative transfer and excitation — *it is nonlocal*, because photons emitted from one point in the cloud affect the level populations at other points.
 - The ***escape probability approximation*** is a simple way to take into account the effects of radiative trapping.

- **Escape Probability Approximation**

- Suppose that at some point \mathbf{r} in the cloud, the optical depth $\tau_\nu(\hat{\mathbf{n}}, \mathbf{r})$ in direction $\hat{\mathbf{n}}$ and at frequency ν is known.
- We define the **direction-averaged “escape probability”** for photons with frequency ν emitted from location \mathbf{r} :

$$\bar{\beta}_\nu(\mathbf{r}) \equiv \int \frac{d\Omega}{4\pi} e^{-\tau_\nu(\hat{\mathbf{n}}, \mathbf{r})}$$

Now define the **direction-averaged and frequency-averaged escape probability**:

$$\langle \beta(\mathbf{r}) \rangle = \int \phi_\nu \bar{\beta}_\nu(\mathbf{r}) d\nu$$

Normalized line profile = $\int \phi_\nu d\nu = 1$

- Now we make two approximations:
 - (1) we will approximate **the excitation in the cloud as uniform**.
 - (2) we make the **“on-the-spot”** approximation: we assume that if a radiated photon is going to be absorbed, it will be absorbed so close to the point of emission that we can approximate it as being absorbed at the point of emission.
- ▶ These approximations replace a difficult nonlocal excitation problem with a much simpler local one! This is called the escape probability approximation.

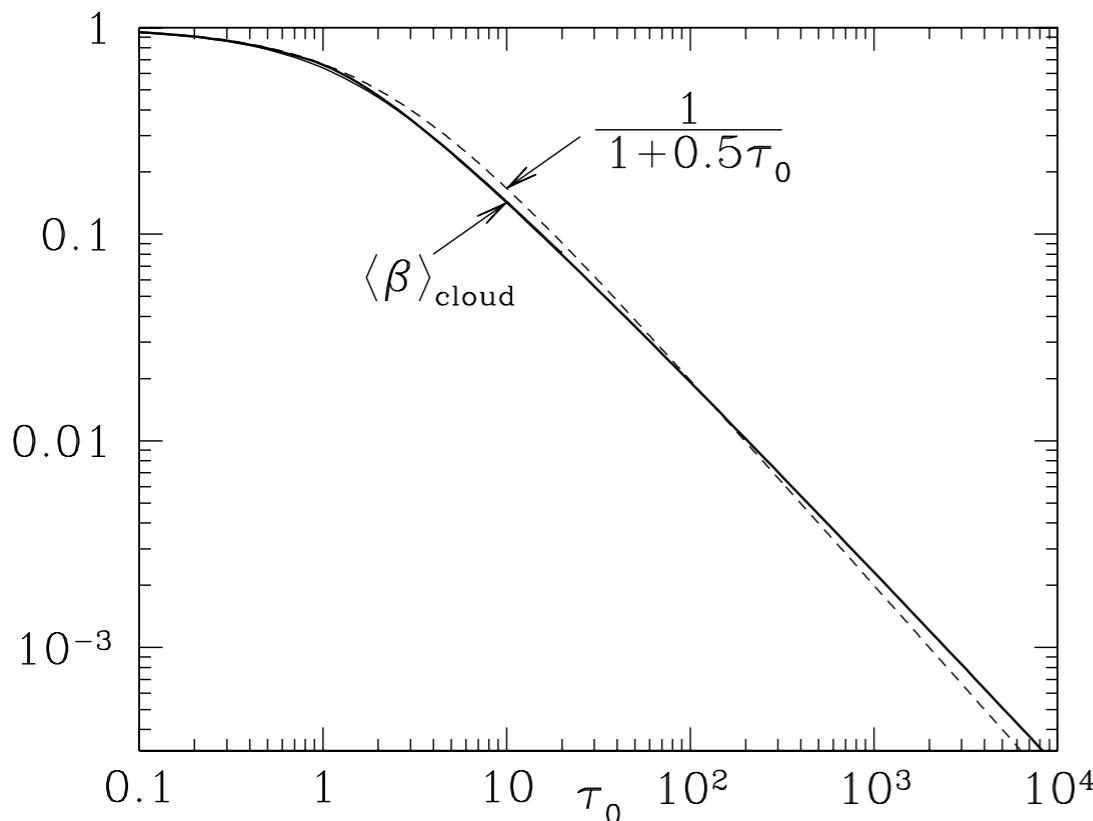
- Homogeneous Static Spherical Cloud.

- ▶ The angle-averaged escape probability $\bar{\beta}$ depends on the geometry and velocity structure of the region.

For the case of a finite cloud, $\bar{\beta}$ will depend on position — it will be highest at the cloud boundary, and smallest at the cloud center.

- ▶ We now define the escape probability averaged over the line profile and over the cloud volume. **for a uniform density spherical cloud,**

$$\langle \beta \rangle_{\text{cloud}} = \frac{1}{4\pi R^3/3} \int_0^R \langle \beta(\mathbf{r}) \rangle 4\pi r^2 dr$$



The left figure shows the mass-averaged escape probability calculated numerically for the case of a homogeneous spherical cloud, as a function of the optical depth τ_0 at line-center from the center of the cloud to the surface. The gas is assumed to have a Gaussian velocity distribution. [Fig 19.1, Draine]

A satisfactory approximation is provided by the simple fitting function.

$$\langle \beta \rangle_{\text{cloud}} = \frac{1}{1 + 0.5\tau_0}$$

Critical Density of CO (J = 1-0)

- Conditions that are favorable for formation of CO are usually favorable for the formation of H₂.
 - ▶ Therefore, the main colliders that excite and de-excite the rotational states of CO are hydrogen molecules rather than hydrogen atoms or free electrons.
 - ▶ The collisional de-excitation rate coefficient of CO (J = 1) for collisions with H₂ collisions is

$$k_{10} \approx 6 \times 10^{-11} (T/100\text{ K})^{0.2} \text{ cm}^3 \text{ s}^{-1}$$

- The Einstein A coefficient for a rotational transition J → J-1 is given by

$$A_{J \rightarrow J-1} = \frac{128\pi^3}{3\hbar} \left(\frac{B_0}{hc} \right)^3 \mu_0^2 \frac{J^4}{J + 1/2} = 7.16 \times 10^{-8} \text{ s}^{-1} \text{ for } J = 1 \rightarrow 0$$

- At the fundamental frequency, the dominant background radiation is the CMB.
 - ▶ The good news is that the 2.6 mm line of CO is radiatively excited by blackbody radiation, which is analytically tractable.
 - ▶ The bad news is that we can't use the Rayleigh-Jeans limit, as we did studying the 21 cm line.
 - ▶ The photon occupation number is: $\bar{n}_\gamma = \frac{1}{e^{5.532\text{ K}/2.725\text{ K}} - 1} = 0.151 \quad (T_{\text{rad}} = T_{\text{CMB}} = 2.725\text{ K})$
- The critical density at which collisional de-excitation equals to radiative de-excitation is given by

$$n_{\text{crit}, \text{H}_2}(\text{CO}, J = 1) = \frac{(1 + \bar{n}_\gamma) A_{10}}{k_{10}} \approx 1400(T/100\text{ K})^{-0.2} \text{ cm}^{-3}$$

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- Radiative trapping
 - ▶ The proceeding analysis has assumed that only photons from the external radiation field are used, ignoring contributions from emission line photons from the cloud material itself. This assumption is only strictly true in an optically thin cloud.
 - ▶ For lines in abundant molecular species, like the CO $J = 1-0$ line, the cloud will be optically thick, and we will have to include the effect of the radiative trapping.
 - ▶ Taking into account the radiative trapping, the actual Einstein A coefficient is replaced by an “effective” value $\langle \beta_{ul} \rangle_{\text{cloud}} A_{ul}$ (see Chap 19.1 of Draine).
 - ▶ The critical density for the CO $J = 1-0$ line is:

$$n_{\text{crit}, \text{H}_2}(\text{CO}, J = 1) = \frac{(1 + \bar{n}_\gamma) \langle \beta_{10} \rangle_{\text{cloud}} A_{10}}{k_{10}} \approx 54(T/100 \text{ K})^{-0.2} \text{ cm}^{-3}$$

$$\tau_0 \approx 50, \quad \langle \beta_{10} \rangle_{\text{cloud}} \approx 1/(1 + 0.5\tau_0) \approx 0.04$$

$$\text{for } N_{\text{H}} = 10^{21} \text{ cm}^{-2}, b = 2 \text{ km s}^{-1}, T_{\text{exc}} = 8 \text{ K}$$

- ▶ We, therefore, see that at least the $J = 1$ level of CO is expected to be thermalized in the central dense cores of molecular clouds with $n_{\text{H}} \gtrsim 10^2 \text{ cm}^{-3}$.

Excitation Temperature of CO (J = 1-0)

- No approximation is valid for CO.
 - ▶ We can't use the handy $kT_{\text{exc}} \ll h\nu_{u\ell}$ approximation that was useful for Ly α line.
 - ▶ Neither can we use the $kT_{\text{exc}} \gg h\nu_{u\ell}$ approximation that was used for 21-cm line.
- The radiative transfer equation is the usual

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

- ▶ Emissivity and absorption coefficient are

$$j_\nu = n_1 \frac{A_{10}}{4\pi} h\nu_{10} \phi_\nu \quad \kappa_\nu = n_0 \frac{g_1}{g_0} \frac{c^2}{8\pi\nu_{10}^2} A_{10} \phi_\nu \left(1 - \frac{g_0}{g_1} \frac{n_1}{n_0} \right), \quad \frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{k\nu_{10}}{kT_{\text{exc}}}\right)$$

- ▶ The source function can be written as

$$S_\nu \equiv \frac{j_\nu}{\kappa_\nu} = \frac{2h\nu_{10}^3}{c^2} \frac{1}{\exp(h\nu_{10}/kT_{\text{exc}}) - 1} = B_\nu(T_{\text{exc}})$$

- ▶ If the excitation (rotation) temperature is constant over the entire region of emission, we have the solution:

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

- ▶ The background radiation is the Cosmic Microwave Background: $I_\nu(0) = B_\nu(T_{\text{rad}})$

- Now, we do perform the "on" observation toward a molecular cloud, and "off" observation over to a black sky.

$$I_\nu(\text{on}) = \frac{2h\nu^3}{c^2} \left[\frac{e^{-\tau_\nu}}{\exp(h\nu/kT_{\text{rad}}) - 1} + \frac{1 - e^{-\tau_\nu}}{\exp(h\nu/kT_{\text{exc}}) - 1} \right]$$

$$I_\nu(\text{off}) = \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT_{\text{rad}}) - 1}$$

The difference between the two observations is

$$\Delta I_\nu = I_\nu(\text{on}) - I_\nu(\text{off})$$

$$= \frac{2h\nu^3}{c^2} \left[\frac{1}{\exp(h\nu/kT_{\text{exc}}) - 1} - \frac{1}{\exp(h\nu/kT_{\text{rad}}) - 1} \right] (1 - e^{-\tau_\nu})$$

- It is customary to express the intensity in terms of an antenna temperature:

$$T_A \equiv \frac{c^2}{2k} \frac{\Delta I_\nu}{\nu^2} \approx \frac{h\nu}{k} \left[\frac{1}{\exp(h\nu/kT_{\text{exc}}) - 1} - \frac{1}{\exp(h\nu/kT_{\text{rad}}) - 1} \right] \quad \text{for an optical thick cloud } \tau_\nu \gg 1.$$

We can solve this for excitation temperature:

$$\frac{5.532 \text{ K}}{T_{\text{exc}}} = \ln \left(1 + \frac{1}{T_A/5.532 \text{ K} + 0.151} \right)$$

$$h\nu/k = 5.532 \text{ K}$$

$$T_{\text{rad}} = 2..725 \text{ K}$$

$$\frac{1}{\exp(h\nu/kT_{\text{rad}}) - 1} = 0.151$$

- In our Galaxy, it is often found that $T_A \sim 5 \text{ K}$ at the line center, implying $T_{\text{exc}} \sim 8 \text{ K}$.

¹³CO Column Density

- The ¹²CO 2.6 mm line is optically thick. All the 2.6 mm emission that we see comes from a thin skin at the surface of the molecular cloud.
 - ▶ The column density of CO can be more easily derived from the optically thin ¹³CO line. The rarer isotopes will refer to gas deeper in the molecular cloud.
 - ▶ The cosmic ratio of ¹³CO to ¹²CO is ~ 0.011 . Hence, ¹³CO is optically thin.
 - ▶ The frequency of ¹³CO J = 1-0 transition is 110.20 GHz, 4.6% lower than that for ¹²CO.

ratio of the reduced masses:

$$\frac{\mu(^{13}\text{C}^{16}\text{O})}{\mu(^{12}\text{C}^{16}\text{O})} = \frac{13 \times 16 / (13 + 16)}{12 \times 16 / (12 + 16)} \approx 1.0460$$

$$\frac{B_0(^{13}\text{C}^{16}\text{O})}{B_0(^{12}\text{C}^{16}\text{O})} = \frac{\mu(^{12}\text{C}^{16}\text{O})}{\mu(^{13}\text{C}^{16}\text{O})} \approx 1 / 1.0460 = 0.9560$$

- ▶ We assume that T_{ext} of ¹³CO is the same as that of ¹²CO. This is generally a safe assumption, since the two isotopes of carbon are intermingled in the ISM.

$$T_{\text{A}}(^{13}\text{CO}) \approx \frac{h\nu}{k} \left[\frac{1}{\exp(h\nu/kT_{\text{exc}}) - 1} - \frac{1}{\exp(h\nu/kT_{\text{rad}}) - 1} \right] \tau_{\nu} \quad \leftarrow (1 - e^{-\tau_{\nu}}) \approx \tau_{\nu}$$

$h\nu/k = 5.140 \text{ K}$ for the ¹³CO J = 1-0 transition.

- ▶ The integrated line strength is then

$$\int T_{\text{A}}(^{13}\text{CO}) dv \approx 5.140 \text{ K} \left(\frac{1}{e^{5.140 \text{ K}/T_{\text{exc}}} - 1} - 0.1787 \right) \int \tau_{\nu} dv$$

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- The optical depth, integrated over the thermally broadened line, is

$$\int \tau_\nu dv = \sqrt{\pi} b \tau_0 = \frac{1}{8\pi} \frac{g_1}{g_0} \frac{c^3}{\nu^3} A_{10} \left(1 - e^{-h\nu/kT_{\text{exc}}}\right) N_0(^{13}\text{CO})$$

\uparrow

$$\tau_0 = \frac{g_1}{g_0} \frac{c^2}{8\pi^{3/2} \nu_{10}^3} A_{10} \frac{c}{b} \left(1 - e^{-h\nu_{10}/kT_{\text{exc}}}\right) N_0$$

Here, $N_0(^{13}\text{CO})$ is the column density of ^{13}CO in its rotational ground state with $J = 0$.

Note: $A_{10} = 7.20 \times 10^{-8} \text{ s}^{-1}$ for ^{12}CO
 $= 6.29 \times 10^{-8} \text{ s}^{-1}$ for ^{13}CO

$$\int \tau_\nu dv \approx 1.52 \times 10^{-15} \left(1 - e^{-5.140 \text{ K}/kT_{\text{exc}}}\right) N_0(^{13}\text{CO}) \left[\frac{\text{km s}^{-1}}{\text{cm}^{-2}} \right]$$

- Therefore, we find:

$$N_0(^{13}\text{CO}) \approx 2.9 \times 10^{14} \frac{\int T_A(^{13}\text{CO}) dv}{1 \text{ K km s}^{-1}} [\text{cm}^{-2}] \quad \text{when } T_{\text{exc}} \approx 8 \text{ K}$$

X-factor (^{13}CO to H_2)

- X-factor (^{13}CO to H_2)
 - ▶ The fraction of ^{13}CO in its rotational ground state:

$$f_{J=0} = \frac{1}{\sum_J (2J+1) e^{-B_0 J(J+1)/kT_{\text{exc}}}} \approx \left[\frac{1}{1 + \left(\frac{T_{\text{exc}}}{2.766/1.0460 \text{ K}} \right)^2} \right]^{1/2} \approx 0.314$$

- ▶ Then, we obtain the CO to H_2 ratio:

$$N(\text{H}_2) = 1.8 \times 10^6 \times \frac{1}{2} \frac{n_{\text{H}}/n_{\text{C}}}{(1/3.0 \times 10^{-4})} \frac{n(\text{C})/n(^{12}\text{CO})}{4} \frac{n(^{12}\text{CO})/n(^{13}\text{CO})}{90} \frac{N(^{13}\text{CO})/N_0(^{13}\text{CO})}{3} N_0(^{13}\text{CO})$$

$$N(\text{H}_2) \approx 5 \times 10^{20} \left[\frac{\int T_{\text{A}}(^{13}\text{CO}) dv}{1 \text{ K km s}^{-1}} \right] \text{ cm}^{-2}$$

$$X_{^{13}\text{CO}} \equiv \frac{N(\text{H}_2)}{W_{^{13}\text{CO}}} \approx 5 \times 10^{20} \left[\frac{\text{cm}^{-2}}{\text{K km s}^{-1}} \right]$$



$$W_{^{13}\text{CO}} \equiv \int T_{\text{A}}(^{12}{}^{13}\text{CO}) dv$$

X-factor (^{12}CO to H_2) - Correct Approach

(Chapter 19 of Draine's book)

- X-factor

- It would be useful if we had a reliable way to convert from something easy to measure (the antenna temperature integrated over the line of ^{12}CO) to something difficult to measure (the column density $N(\text{H}_2)$ of molecular hydrogen).

$$W_{\text{CO}} \equiv \int T_{\text{A}}(^{12}\text{CO}) dv$$

$$X_{\text{CO}} \equiv \frac{N(\text{H}_2)}{W_{\text{CO}}}$$

- If the cloud is larger than our antenna beam, we can relate W_{CO} to $N(\text{H}_2)$.
 - Recall that the optical depth at line-center from center to edge of the spherical cloud:

$$\tau_0 = \frac{g_1}{g_0} \frac{A_{10} c^2}{8\pi^{3/2} \nu_{10}^3} \frac{c}{b} \left(1 - e^{-h\nu_{10}/kT_{\text{exc}}}\right) n_0 R$$

$$\tau_0 = \frac{g_1}{g_0} \frac{A_{10} \lambda_{10}^3}{8\pi} \left(\frac{5}{2\pi G}\right)^{1/2} \frac{n_0 R^{3/2}}{M^{1/2}} \left(1 - e^{-h\nu_{10}/kT_{\text{exc}}}\right)$$

Use virial theorem:

$$b = \left(\frac{2G}{5} \frac{M}{R}\right)^{1/2}$$

- The luminosity of the cloud in a spectral line ($J = 1-0$) is:

$$\begin{aligned} L_{10} &= \int dr 4\pi r^2 n_1 A_{10} h\nu_{10} \langle \beta \rangle_{\text{cloud}} \\ &= \int dV 4\pi j_{10} \langle \beta \rangle_{\text{cloud}} \end{aligned}$$

Emissivity: $4\pi j_{10} = n_1 A_{10} h\nu_{10}$
 Escape probability averaged over the line profile and over the cloud volume:

$$\langle \beta \rangle_{\text{cloud}} = \frac{1}{4\pi R^3/3} \int_0^R \langle \beta(\mathbf{r}) \rangle 4\pi r^2 dr$$

- Using the escape probability $\langle \beta \rangle_{\text{cloud}} \approx \frac{1}{1 + 0.5\tau_0}$

$$L_{10} \approx \frac{4\pi}{3} R^3 n_1 A_{10} h \nu_{10} \frac{2}{\tau_0}$$

Here, we assume $\tau_0 \gg 1$, thus $\langle \beta \rangle_{\text{cloud}} \approx 2/\tau_0$.

$$\begin{aligned} L_{10} &\approx \frac{64\pi^2}{3} \left(\frac{2\pi G}{5} \right)^{1/2} \frac{hc}{\lambda_{10}^4} M^{1/2} R^{3/2} \frac{n_1}{n_0} \frac{g_0}{g_1} \frac{1}{1 - e^{-h\nu_{10}/kT_{\text{exc}}}} \\ &\approx \frac{64\pi^2}{3} \left(\frac{2\pi G}{5} \right)^{1/2} \frac{hc}{\lambda_{10}^4} M^{1/2} R^{3/2} \frac{1}{e^{h\nu_{10}/kT_{\text{exc}}} - 1} \end{aligned}$$

- The line luminosity per unit mass is:

$$\frac{L_{10}}{M} \approx 32\pi^2 \left(\frac{2G}{15} \right)^{1/2} \frac{hc}{\lambda_{10}^4} \frac{1}{\rho^{1/2}} \frac{1}{e^{h\nu_{10}/kT_{\text{exc}}} - 1}$$

$$M = \frac{4\pi R^3}{3} \rho$$

Note that for a give spectral line, **the luminosity per unit mass depends on the cloud density and on the excitation temperature.**

- Now, we relate (1) the mass to the average column density of hydrogen nucleon and (2) the luminosity to the average antenna (brightness) temperature.

$$\text{Hydrogen column density: } N_{\text{H}} = \frac{\Sigma}{1.4m_{\text{H}}} = \frac{\frac{M}{\pi R^2}}{1.4m_{\text{H}}}$$

Σ = surface density

Antenna temperature averaged over the projected surface area:

$$\int T_A dv \equiv \frac{\iint \frac{c^2}{2k\nu^2} I_\nu dv dA \langle \beta \rangle_{\text{cloud}}}{\int dA}$$

Here,

dA = projected area

ds = pathlength along a sightline

From the radiative transfer equation: $I_\nu = \int j_\nu ds$

$$\begin{aligned} \int T_A dv &= \frac{1}{\pi R^2} \int \left[\int \frac{c^2}{2k\nu^2} j_\nu \langle \beta \rangle_{\text{cloud}} dv \right] dV \\ &= \frac{1}{\pi R^2} \frac{1}{4\pi} \frac{c^3}{2k\nu_{10}^3} L_{10} \end{aligned}$$



$$\begin{aligned} \frac{v}{c} &\equiv \frac{\nu - \nu_{10}}{\nu_{10}} \\ j_\nu dv &= j_\nu \left| \frac{dv}{d\nu} \right| d\nu = j_\nu \frac{c}{\nu_{10}} d\nu \end{aligned}$$

- Then, we can relate the antenna temperature to the total H column density (averaged over the beam solid angle):

$$\begin{aligned} \frac{N_H}{\int T_A dv} &= \frac{8\pi k}{1.4m_H} \frac{M}{L_{10}} \\ &= \frac{1}{4\pi} \frac{k\lambda_{10}}{hc} \left(\frac{15}{2.8Gm_H} \right)^{1/2} (n_H)^{1/2} \left(e^{h\nu_{10}/kT_{\text{exc}}} - 1 \right) \end{aligned}$$

Here, we used:

$$\rho = 1.4 \times m_H n_H$$

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- If we assume $N(\text{H}_2) = N_{\text{H}}/2$, the above equation becomes:

$$\begin{aligned} X_{\text{CO}} &= \frac{N(\text{H}_2)}{\int T_{\text{A}} dv} = \frac{1}{8\pi} \frac{k\lambda_{10}}{hc} \left(\frac{15}{2.8Gm_{\text{H}}} \right)^{1/2} (n_{\text{H}})^{1/2} \left(e^{h\nu_{10}/kT_{\text{exc}}} - 1 \right) \\ &= 1.58 \times 10^{20} \left(\frac{n_{\text{H}}}{10^3 \text{ cm}^{-3}} \right)^{1/2} \left(e^{5.532 \text{ K}/T_{\text{exc}}} - 1 \right) \left[\frac{\text{cm}^{-2}}{\text{K km s}^{-1}} \right] \end{aligned}$$

- For $n_{\text{H}} = 10^3 \text{ cm}^{-3}$ and $T_{\text{exc}} = 8 \text{ K}$, this yields:

$$X_{\text{CO}} = \frac{N(\text{H}_2)}{\int T_{\text{A}} dv} = 1.56 \times 10^{20} \left(\frac{n_{\text{H}}}{10^3 \text{ cm}^{-3}} \right)^{1/2} \left[\frac{\text{cm}^{-2}}{\text{K km s}^{-1}} \right]$$

Dame et al. (2001) observationally find $X_{\text{CO}} = (1.8 \pm 0.3) \times 10^{20} \text{ cm}^{-2}/\text{K km s}^{-1}$, where infrared emission from dust (Schlegel et al. 1998) was used as a mass tracer.

The most recent determination using gamma rays finds

$$X_{\text{CO}} = (1.76 \pm 0.04) \times 10^{20} \text{ cm}^{-2}/\text{K km s}^{-1} \quad \text{for the Orion A GMC (Okumura et al. 2009)}$$

These results suggests that $n_{\text{H}} = 10^3 \text{ cm}^{-3}$ and $T_{\text{exc}} = 8 \text{ K}$ may be representative of self-gravitating molecular clouds in the local ISM.

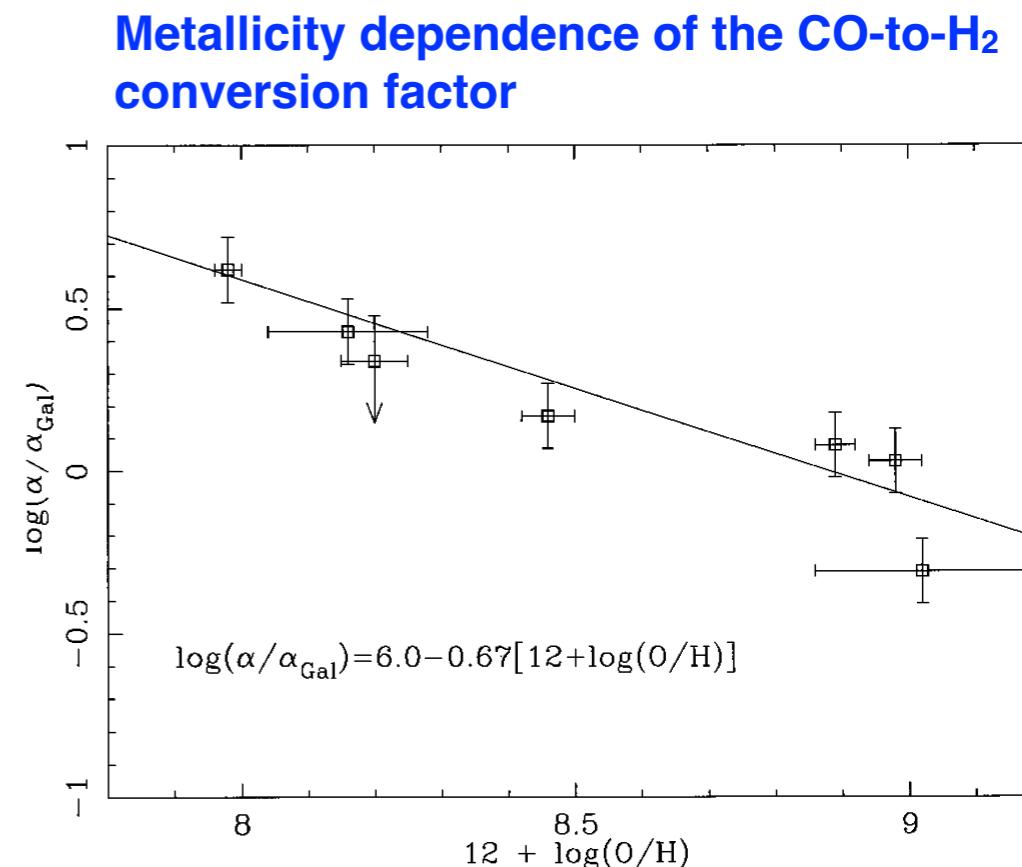
- Notes:

- ▶ *Real molecular clouds have an outer layer where the hydrogen is molecular, but where the CO abundance is very low* because it is not sufficiently shielded from dissociating radiation.
- ▶ *This does not show up in H I 21-cm or CO 1-0 surveys* — leading Wolfire et al. (2010) to refer to it as “the dark molecular gas” — but since it does contain dust, it does contribute to the Far-IR emission.
- ▶ Wolfire et al. (2010) estimate that ~30% of the molecular mass in a typical Galactic molecular cloud may be in this envelope.
- ▶ At constant n_{H} and T_{exc} , this low-CO layer will result in an increase in X_{CO} . This is in agreement with recent observations.
- ▶ **Other galaxies:** Recent observations indicates that X_{CO} in Local Group galaxies is of order
(Blitz et al. 2007)

$$X_{\text{CO}} \sim 4 \times 10^{20} \text{ cm}^{-2} / \text{K km s}^{-1}$$

with large variations from one galaxy to another.

An indirect estimate of the molecular gas mass based on modeling the IR emission from a sample of nearby galaxies also favored $X_{\text{CO}} \approx 4 \times 10^{20} \text{ cm}^{-2} / \text{K km s}^{-1}$ (Draine et al. 2007).



The average CO-to-H₂ conversion factor in five Local Group galaxies (M31, M33, IC 10, NGC 6822, SMC) is plotted as a function of the oxygen abundance.

[Fig 2, Wilson, 1995, 448, L97]

X-factor (¹²CO to H₂) - Approach of Ryden

- X-factor

- ▶ Since a typical molecular cloud is optically thick at the J = 1-0 rotational transition of ¹²CO, we use the radiative transfer solution for an opaque object:

$$I_\nu = \frac{2h\nu^3}{c^2} \left[\frac{e^{-\tau_\nu}}{\exp(h\nu/kT_{\text{rad}}) - 1} + \frac{1 - e^{-\tau_\nu}}{\exp(h\nu/kT_{\text{exc}}) - 1} \right] \rightarrow I_\nu \approx \frac{2h\nu^3}{c^2} \frac{1}{\exp(h\nu/kT_{\text{exc}}) - 1}$$

- ▶ Expressed in terms of the antenna temperature, this is

$$T_A \equiv \frac{c^2}{2k\nu^2} I_\nu \approx \frac{h\nu}{k} \frac{1}{\exp(h\nu/kT_{\text{exc}}) - 1}$$

However, this is wrong by a geometrical factor because we are dealing with a sphere. Toward outer boundary of the sphere, the optical depth will be thin.

- ▶ The observed emission lines is narrow, we can assume that $\nu = \nu_{10}$ over the entire line width.

$$\int T_A dv \approx \sqrt{\pi} b T_A(\nu_{10}) \approx \sqrt{\pi} \frac{h\nu_{10}}{k} \frac{b}{\exp(h\nu_{10}/kT_{\text{exc}}) - 1}$$

Here, we assume a Gaussian line profile
 $T_A = T_A(0)e^{-v^2/b^2}$

- ▶ Then, the X-factor is

$$X_{\text{CO}} = \frac{N(\text{H}_2)}{b} \frac{1}{\sqrt{\pi}} \frac{k}{h\nu_{10}} \left(e^{h\nu_{10}/kT_{\text{exc}}} - 1 \right)$$

- Now let's use virial theorem for a uniform, spherical cloud:

$$\sigma_v^2 = \frac{GM_c}{5R_c}, \quad b = \sqrt{2}\sigma_v \quad \rightarrow$$

$$M_c = \frac{5}{2} \frac{R_c b^2}{G}$$

$$M_c \equiv \frac{4\pi}{3} R_c^3 \rho_c \quad \rightarrow$$

$$\frac{b}{R_c} = \left(\frac{8\pi}{15} G \rho_c \right)^{1/2}$$

- Surface density:

$$\Sigma = \frac{M_c}{\pi R_c^2} \quad \xrightarrow{M_c = \frac{5}{2} \frac{R_c b^2}{G}} \quad \Sigma = \frac{5}{2\pi G} \frac{b^2}{R_c}$$

- Column density of hydrogen nucleon in terms of velocity dispersion:

$$N(\text{H}) \approx \frac{\Sigma}{1.4 \times m_{\text{H}}} = \frac{5}{2.8\pi} \frac{1}{Gm_{\text{H}}} \frac{b^2}{R_c}$$

$$N(\text{H}_2) = \frac{1}{2} N(\text{H})$$

- The X-factor is:

$$\frac{N(\text{H}_2)}{W_{\text{CO}}} = \frac{5}{2 \times 2.8\pi \sqrt{\pi}} \frac{1}{Gm_{\text{H}}} \frac{k}{h\nu_{10}} \frac{b}{R_c} \left(e^{h\nu_{10}/kT_{\text{exc}}} - 1 \right)$$

$$\frac{b}{R_c} = \left(\frac{8\pi}{15} G \rho_c \right)^{1/2} \approx \left(\frac{8\pi}{15} G m_{\text{H}} n_{\text{H}} \times 1.4 \right)^{1/2}$$

$$\frac{N(\text{H}_2)}{W_{\text{CO}}} = \frac{1}{2\pi} \frac{k}{h\nu_{10}} \left(\frac{20}{3} \frac{1}{2.8Gm_{\text{H}}} \right)^{1/2} n_{\text{H}}^{1/2} \left(e^{h\nu_{10}/kT_{\text{exc}}} - 1 \right)$$

This result gives a larger value than the correct one by a factor of $8/3 = 2.67$.

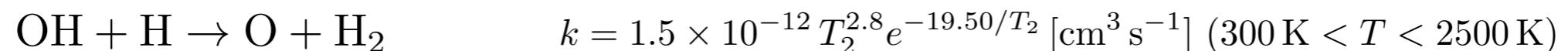
Molecular Clouds: Chemistry and Ionization

- Molecular Hydrogen
 - In the Milky Way, **~ 22% of the interstellar gas is in molecular clouds**, where the bulk of the hydrogen is in H₂ molecules.
 - H₂ is formed primarily by due grain catalysis. Destruction of H₂ is primarily due to photodissociation, but self-shielding results in very low photodissociation rates in the central regions of molecular clouds.
- Other molecules
 - Once, the H₂ has been formed, other chemistry can follow.
 - Most of the gas will be neutral, but, *because of the presence of cosmic rays, there will always be some ions present in the gas.*
 - In the outer layers of molecular clouds, there may also be sufficient UV radiation to photoionize species with ionization potentials $E_I < 13.6 \text{ eV}$.

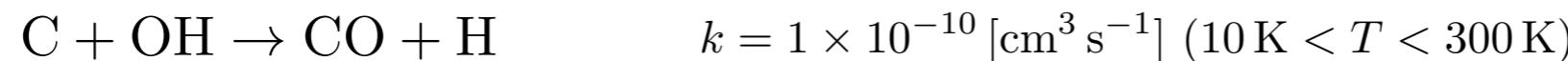
-
- Five types of reactions
 - **Photoionization:** $AB + h\nu \rightarrow AB^+ + e^-$
 - ▶ Many molecules (but not H₂) can be photo ionized by photons with $h\nu < 13.6$ eV present in the ISRF in H I or diffuse H₂ clouds.
 - ▶ The ionization threshold for H₂ is 15.43 eV, hence H₂ will not be photo ionized even in H I regions.
 - **Photodissociation:** $AB + h\nu \rightarrow (AB)^* \rightarrow A + B$
 - ▶ For some molecules (including H₂ and CO), photoexcitation leading to **dissociation occurs via lines rather than continuum**.
 - ▶ This allows such species either to self-shield (H₂), or to be partially shielded if there is accidental overlap between important absorption lines with strong lines of H₂, which will be self-shielded. This is the case with CO.
 - **Neutral-neutral exchange reactions:** $AB + C \rightarrow AC + B$
 - ▶ Most species in molecular clouds are neutral, and neutral-neutral collisions are, therefore, frequent.
 - ▶ However, even when a neutral-neutral reaction is exothermic, there will often (but not always) be an energy barrier that must be overcome for the reaction to proceed.

-
- ▶ For instance,

The following exothermic reaction has an energy barrier $E/k = 1950 \text{ K}$, which causes the reaction to be negligibly slow at $T < 100 \text{ K}$.

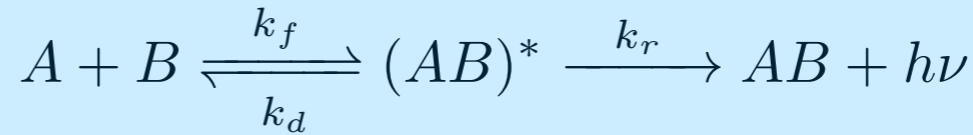


On the other hand, the reaction responsible for CO formation does not have any significant energy barrier, and can proceed at the low temperatures of molecular clouds.



- ***Ion-neutral exchange reactions:*** $AB^+ + C \rightarrow AC^+ + B$
- ▶ Ion-neutral reactions are very important in interstellar chemistry, for two reasons:
 - (1) exothermic reactions generally lack energy barriers, allowing the reaction to proceed rapidly even at low temperature, and
 - (2) the induced-dipole interaction results in ion-neutral rate coefficients that are relatively large, of order $\sim 2 \times 10^{-9} \text{ cm}^3 \text{s}^{-1}$.

- **Radiative association reactions:**



- ▶ The reaction first creates an excited complex. The complex will fly apart in one vibrational period ($\sim 10^{-14}$ s), unless a photon is emitted first; it can be thought of as having a probability per unit time $k_d \approx 10^{14} \text{ s}^{-1}$ of spontaneously dissociating.
- ▶ If AB has an appreciable electric dipole moment (i.e., is not homonuclear), the probability per unit time that $(AB)^*$ will emit a photon in an electronic transition is $k_r \approx 10^6 \text{ s}^{-1}$. Thus, a fraction $k_r/(k_r + k_d)$ of the $(AB)^*$ complexes formed will result in formation of stable AB .
- ▶ Then, the effective rate coefficient for radiative association will be:

$$k_{\text{ra}} = \frac{k_f k_r}{k_r + k_d}$$

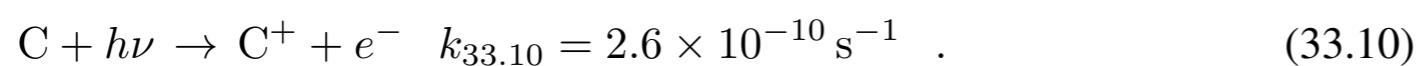
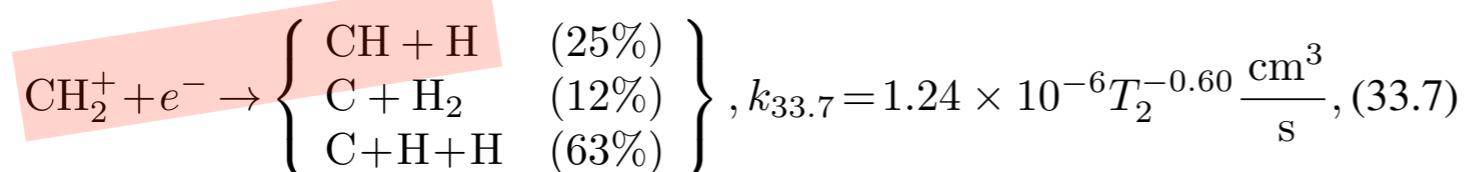
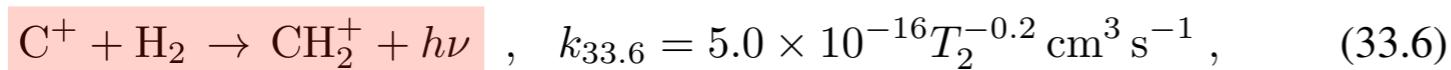
For ion-neutral reactions, the “complex formation” $(AB)^*$ is $k_f \approx 10^{-9} [\text{cm}^3 \text{ s}^{-1}]$, and hence the rate coefficient for radiative association will be $k_{\text{ra}} \approx 10^{-17} [\text{cm}^3 \text{ s}^{-1}]$.

- ▶ For example, formation of CH^+ by radiative association:



Formation of CO

- In diffuse molecular clouds, most of the gas-phase carbon is in the form of C^+ , and most of the H is in the form of H_2 .
- Carbon chemistry is initiated by the radiative association reaction of C^+ with H_2 forming CH_2^+ .
- CO is formed primarily by the sequence of the following reactions:



From page 377 in [Draine]

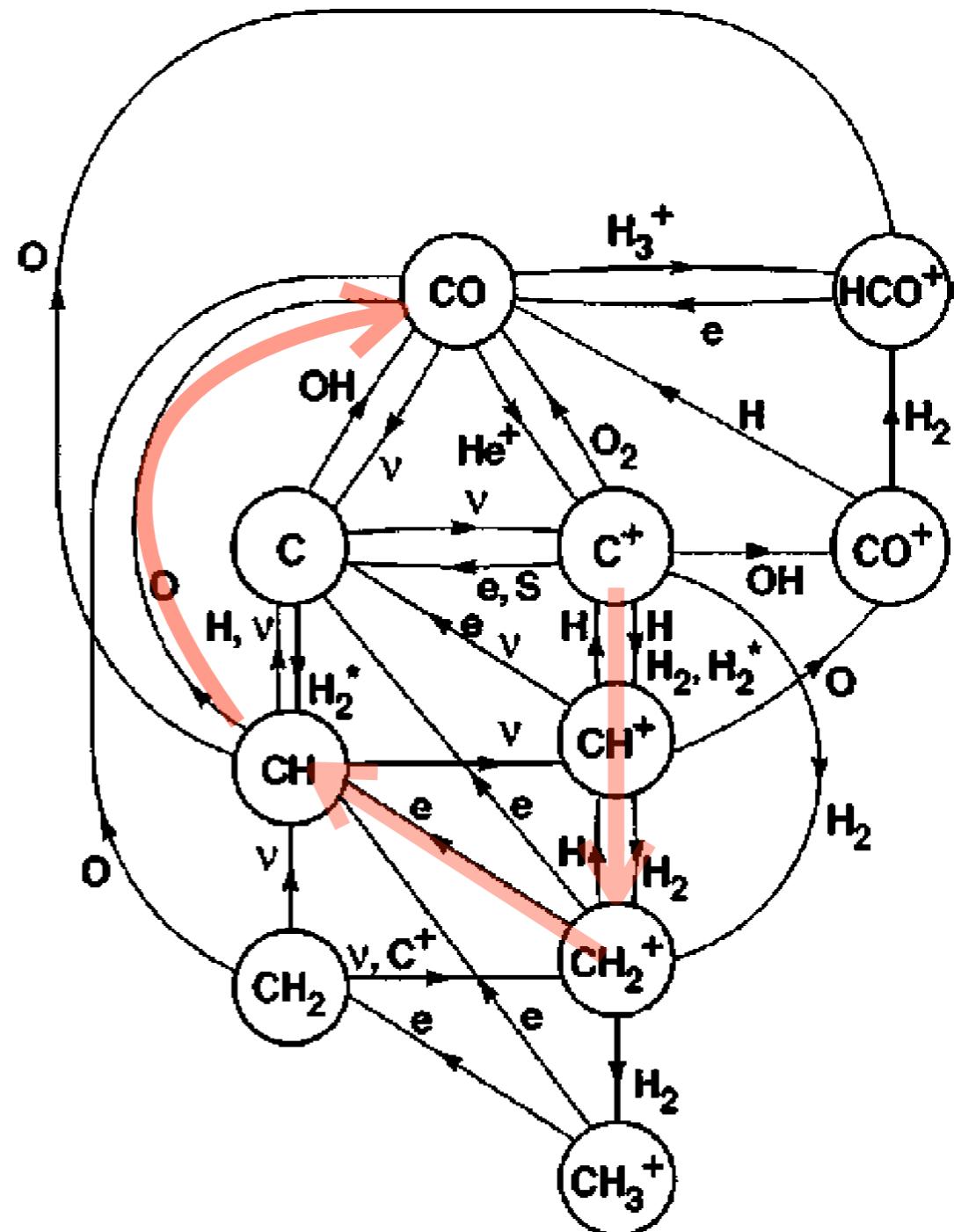


Fig 8.9, Tielens [The physics and chemistry of the interstellar medium]

Formation of OH and H₂O

- In diffuse H I clouds, cosmic-ray ionization produces H⁺ — an important starting point of the O chemistry. Charge exchange of neutral O with H⁺ yields O⁺. Reaction of O⁺ with H₂ then form OH⁺.
 - Deeper in the cloud, where H₂ is an important species, cosmic-ray ionization of H₂ leads to the formation of H₃⁺, which readily reacts with O to form OH⁺.
 - This sequence of gas-phase reaction convert the gas-phase O to H₂O, yielding: $n(\text{H}_2\text{O})/n_{\text{H}} \approx 10^{-4}$
 - However, observations indicate very low gas-phase abundance of H₂O:
- $n(\text{H}_2\text{O})/n_{\text{H}} \lesssim 3 \times 10^{-8}$
- far below the predicted abundance of H₂O.
- The gas-phase H₂O is removed by freeze-out on grains, producing H₂O ice mantles which can contain a substantial fraction of the total oxygen.

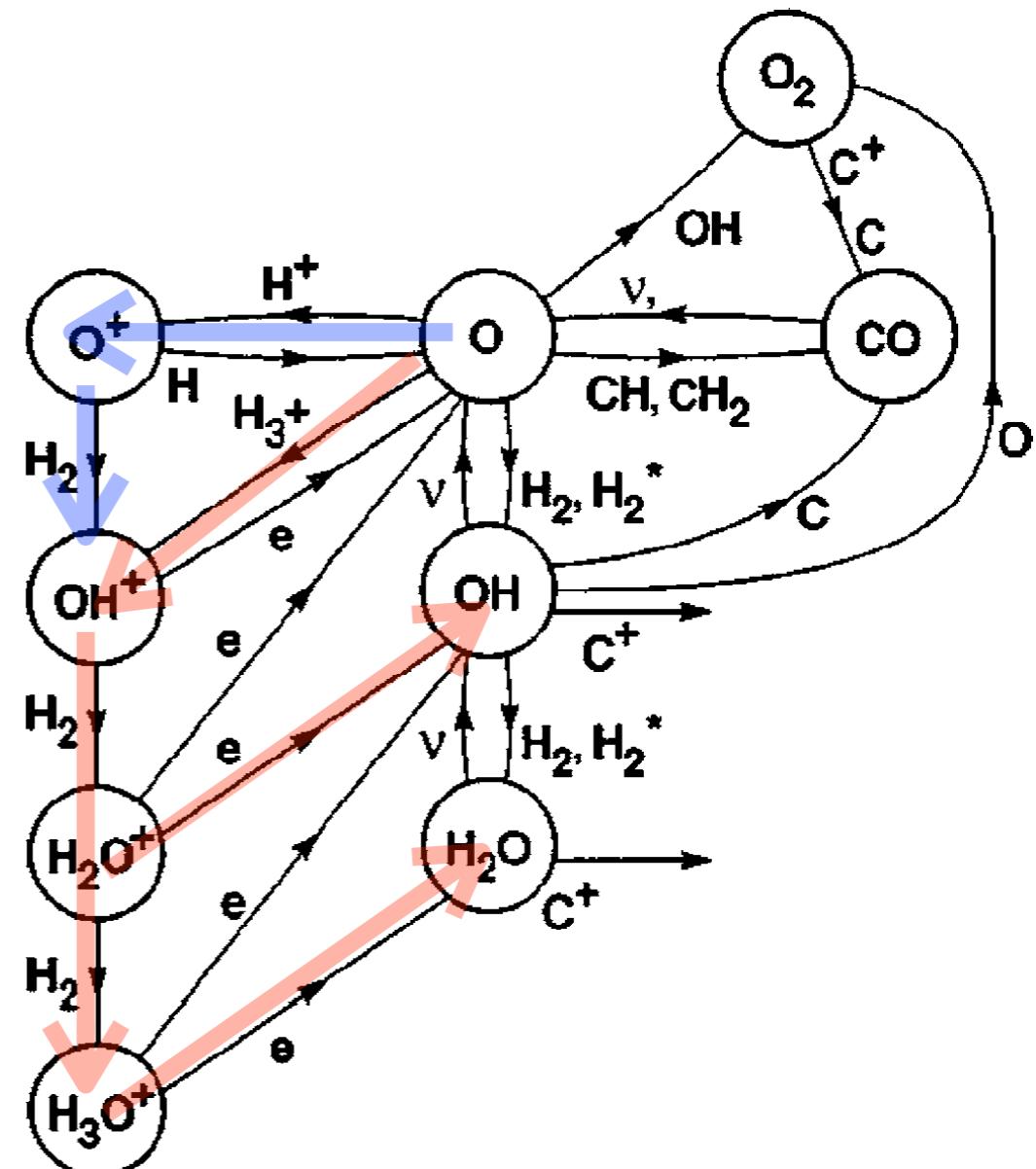


Fig 8.8, Tielens [The physics and chemistry of the interstellar medium]

Circumgalactic & Intracluster Medium Intergalactic Medium 1

- CGM (HVCs, starburst-driven galactic winds)
 - ICM (dark matter, hot diffuse ICM)
 - IGM (The Gunn-Peterson effect)
- Cosmic Recombination & Reionization

Introduction

- CGM and ICM
 - The ***circumgalactic medium*** is the diffuse gas (and some dust) that lies outside the main body of a galaxy's stellar distribution, but still lies inside the virial radius of the galaxy's dark halo.
 - The ***intracluster medium*** is the diffuse hot gas that lies inside the virial radius of a cluster of galaxies, but is not bound to any particular galaxy in the cluster.
- **Virial radius**
 - The ***virial*** radius of a galaxy or cluster is often defined as the radius inside which the virial theorem holds true, and where we can safely make a mass estimate by using:

$$M \sim \frac{\sigma_v^2 r}{G}$$

$$2 \langle K \rangle + \langle U \rangle = 0$$

Recall the virial relation for a uniform, self-gravitating system:

$$M = \frac{5\sigma_v^2 R}{G}$$

- See the previous lecture note to see the proof of the viral theorem.
- In a numerical simulation, finding the virial radius is fairly simple.
 - ▶ Just look inside a particular radius and see if the velocity dispersion, radius, and mass follow the virial relation.

- In reality, approximations must be made. The virial radius is usually approximated as ***the radius r_{vir} within the mean density $\rho(v_{\text{vir}})$ is equal to 200 times the critical density ρ_c of the universe:***

$$\rho_c \equiv \frac{3H^2}{8\pi G}$$

$$\rho(v_{\text{vir}}) = 200\rho_c$$

Here, H = the Hubble parameter
G = the Gravitational constant

- ▶ Critical density: the mean density of matter when the overall geometry of the universe is flat (Euclidean).
- ▶ From the 2015 Planck results, the current values of the Hubble parameter and the critical density are:

$$H_0 = 67.74 \pm 0.46 \text{ [kpc s}^{-1} \text{ Mpc}^{-1}\text{]}$$

$$\rho_{c,0} = (8.62 \pm 0.12) \times 10^{-30} \text{ [g cm}^{-3}\text{]}$$

Note that $\rho_{c,0}$ corresponds to 5 hydrogen atoms per cubic meter.

- ▶ The virial radius of a galaxy or cluster is thus defined as the radius inside which:

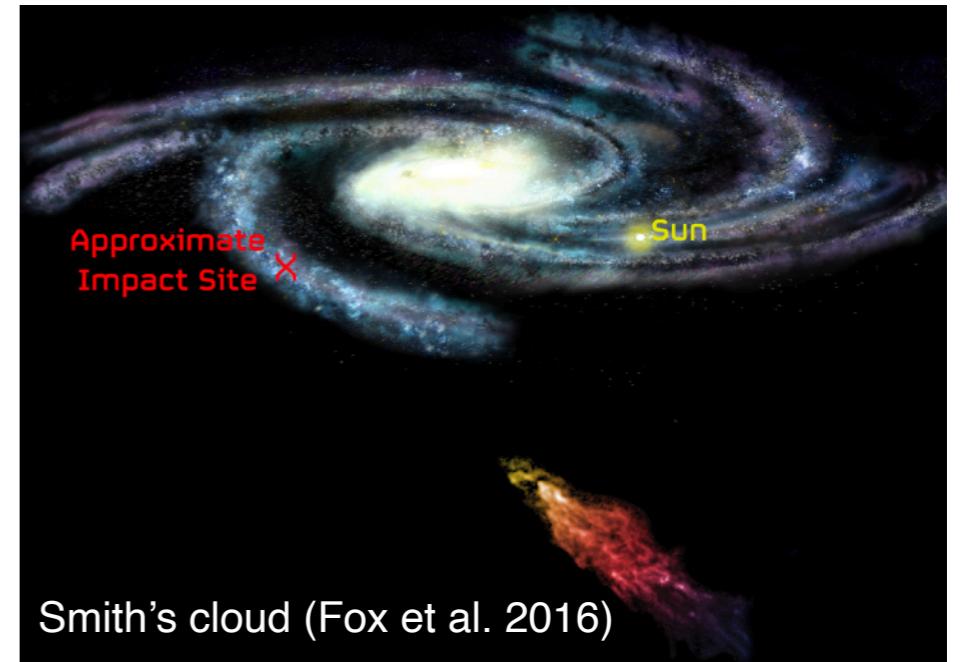
$$\rho(r_{\text{vir}}) = 200\rho_{c,0} \approx 1.7 \times 10^{-27} \text{ [g cm}^{-3}\text{]} \approx 2.5 \times 10^4 M_\odot \text{ [kpc}^{-3}\text{]}$$

- ▶ For example, $r_{\text{vir}} \sim 250 \text{ kpc}$ for the Milky Way. [Note: the scale length of the Galaxy's stellar disk $\sim 3 \text{ kpc}$.]
 $\sim 3 \text{ Mpc}$ for a cluster of galaxies (Coma Cluster).
- ▶ The virial radius is also often referred to as r_{200} .

CGM: High-Velocity Clouds

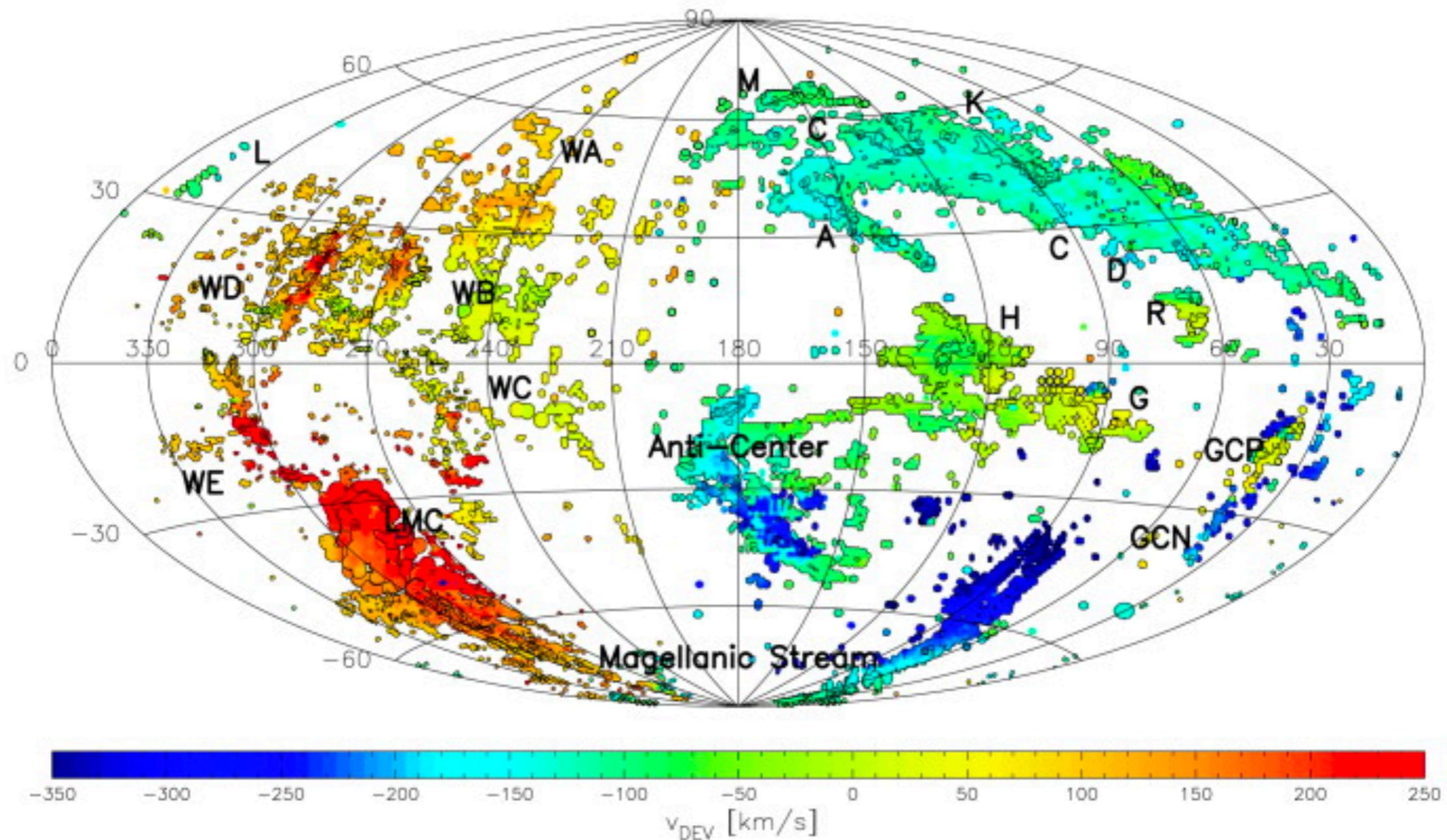
- ***H I HVCs***
 - History
 - ▶ The CGM around our galaxy was first detected in 21-cm emission (Muller et al. 1963).
 - ▶ The brightest clouds: HVC40-15+100 (Smith 1963; **Smith's cloud**), complexes A and C (Hulsbosch & Raimond 1966), “South Pole complex” (Dieter 1964), clouds M, AC I, AC II, AC III (Mathewson et al. 1966)
 - They appear to have a high radial velocity relative to the galactic disk, which is not consistent with the Galactic rotation. Hence, these fairly cool and dense gas clouds containing the neutral hydrogen are called ***high-velocity clouds (HVCs)***.
 - ▶ **Velocity:** Most of the HVCs are at galactocentric velocities between -250 km/s and +250km/s.
 - ▶ **Line broadening:** Their 21-cm emission has typical line broadening parameter $b \sim \sqrt{2}\sigma_v \sim 12 \text{ km s}^{-1}$, indicating that the emission is from a warm neutral medium with a temperature of $T_{\text{gas}} \sim 9000 \text{ K}$.
 - ▶ **Column density:** A typical HVC column density is $N_{\text{HI}} \sim 10^{19} \text{ cm}^{-2}$.
 - ▶ **Angular Size:** From enormous systems like Complex C ($90^\circ \times 20^\circ$) to subdegree-scale compact high-velocity clouds (CHVCs). Some of them are not resolved even with large single-dish radio telescopes.

- Distance
 - An upper limit to the distance of a HVC can be set by detecting absorption at the velocity of the HVC in the spectrum of a star with known distance.
 - A lower limit is set from stars not showing absorption by the HVC, with a detection limit below the expected line strength, found from an abundance determination based on an extra-galactic object.
 - Most of the HVCs are ***at distance $d < 15 \text{ kpc}$ from the Galactic center***, and are ***within $\sim 30^\circ$ of the disk plane*** as seen from the Galactic center. They reside either in the extended Galactic halo or at extragalactic (Local Group) distances.
 - For example,
 - ▶ Complex A: $2.5 \text{ kpc} < z < 6.5 \text{ kpc}$
 - ▶ Complex C: $d \sim 10 \text{ kpc}$
 - ▶ The IV arch: $z < 1.7 \text{ kpc}$
 - ▶ Complex H: $z > 3-5 \text{ kpc}$
 - ▶ Smith's cloud: $d \sim 12.4 \text{ kpc}$
- Velocity
 - The sky coverage of high-velocity gas at negative velocities is greater than that at positive velocities. (Does this mean they are mostly falling into the Galaxy?)
 - See also next slide



Velocity (north-south, east-west asymmetry)

Wakker et al. (2003, ApJS)



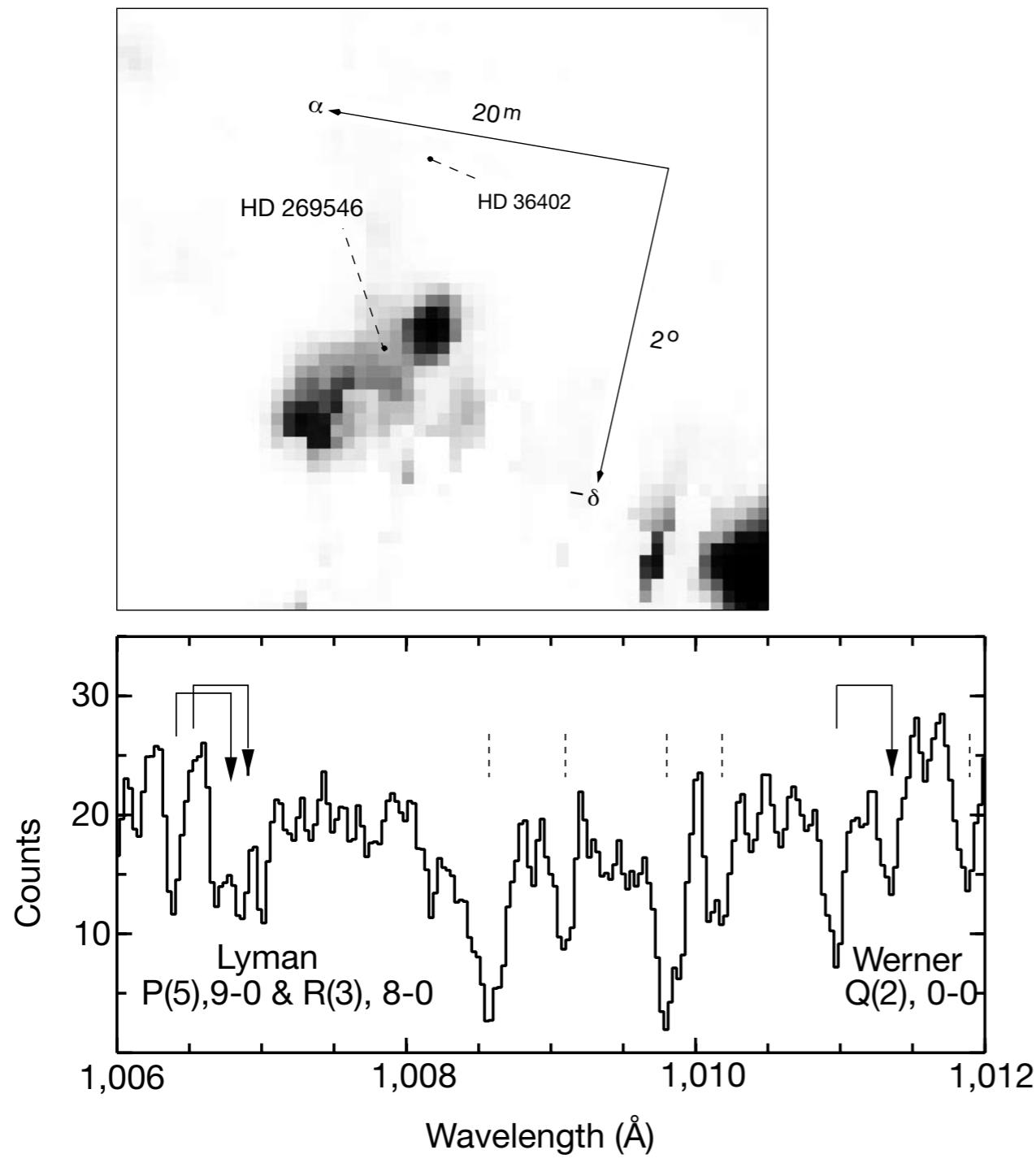
Map of the deviation velocities of the H I high-velocity gas. Data are from Hulsbosch & Wakker (1988) and Morras et al. (2000). The deviation velocity is the difference between the observed LSR velocity and the maximum velocity that can be easily understood in a simple model of Galactic differential rotation ($v_{\text{rot}} = 220 \text{ km s}^{-1}$, $R = 8.5 \text{ kpc}$, $R_{\text{MW}} = 26 \text{ kpc}$, $z_{\text{ISM}} = 2 \text{ kpc}$ at R , increasing to 6 kpc at R_{MW} , see Wakker 1991). The names of the major complexes are indicated. Contour levels are at 0.05, 0.5, and 1 K brightness temperature, or $2, 20$, and $40 \times 10^{18} \text{ cm}^{-2}$.

-
- Total Mass of HVCs
 - With distances known, we can determine the physical size and mass of individual HVCs.
 - The total H I mass of the HVCs around our Galaxy is $M_{\text{HI}} \sim 3 \times 10^7 M_{\odot}$.
 - Adding in helium, metals, and ionized hydrogen, its total mass is $M_{\text{HVC}} \sim 7 \times 10^7 M_{\odot}$.
 - Ionized High-Velocity Clouds (IHVCs) invisible at 21 cm.
 - For instance, absorption lines of Si III, which traces $T_{\text{gas}} \sim 2 \times 10^4 \text{ K}$ gas, are seen over more than half the sight lines examined.
 - Absorption lines of O VI, tracing $T_{\text{gas}} \sim 3 \times 10^5 \text{ K}$ gas, are seen along more than half the sight lines.
 - The IHVCs are estimated to contain a total mass of $M_{\text{IHVC}} \sim 10^8 M_{\odot}$, comparable to the mass of the “traditional” HVCs seen in 21-cm emission.
 - Hot Circumgalactic Medium
 - HVCs are surrounded by a hot ($T_{\text{gas}} \sim 10^6 \text{ K}$) circumgalactic medium, which is detected in X-rays and in O VII and O VIII absorption lines.
 - The density of the hot CGM is $n_{\text{hot}} \sim 3 \times 10^{-5} \text{ cm}^{-3}$.
 - The hot CGM is thought to be extended $\sim 100 \text{ kpc}$ from the galactic center, with $M_{\text{hot}} \sim 10^{10} M_{\odot}$.

-
- Pressure Equilibrium between H I HVCs and the hot CGM
 - The hot CGM is of comparable temperature to the hot ISM, but its density is lower by two orders of magnitude.
 - Similarly, the temperature of H I HVCs is comparable to that of the warm ISM, but their density is lower by two orders of magnitude.
 - This suggests that HVCs are in approximate pressure equilibrium with the hot CGM.
 - Total Mass of the CGM around our Galaxy is poorly known. Simulations indicates that the total mass of the CGM is $M_{\text{CGM}} \sim 2 \times 10^{10} M_{\odot} \approx 5 M_{\text{ISM}}$.
 - Origin
 - Distance and angle from the Galactic disk indicates that ***most of the HVCs are definitely associated with the disk of our Galaxy.***
 - ***Some of the material in HVCs would be gas that has been stripped from satellite galaxies*** by ram pressure of the hot CGM (for instance, the Magellanic Stream).
 - ▶ The metallicity of the Magellanic Stream is $\sim 10\%$ of solar, consistent with the metallicity of the Small Magellanic Cloud. However, most of the HVCs can't be matched with any particular satellite galaxy.
 - ***Some of the CGM is pristine intergalactic gas falling inward*** through the virial radius.
 - ▶ Galaxy formation simulations show gas flowing inward along filaments to regions where galaxies are forming and evolving. The filamentary flow of gas tends to dilute the metallicity of circumgalactic gas.

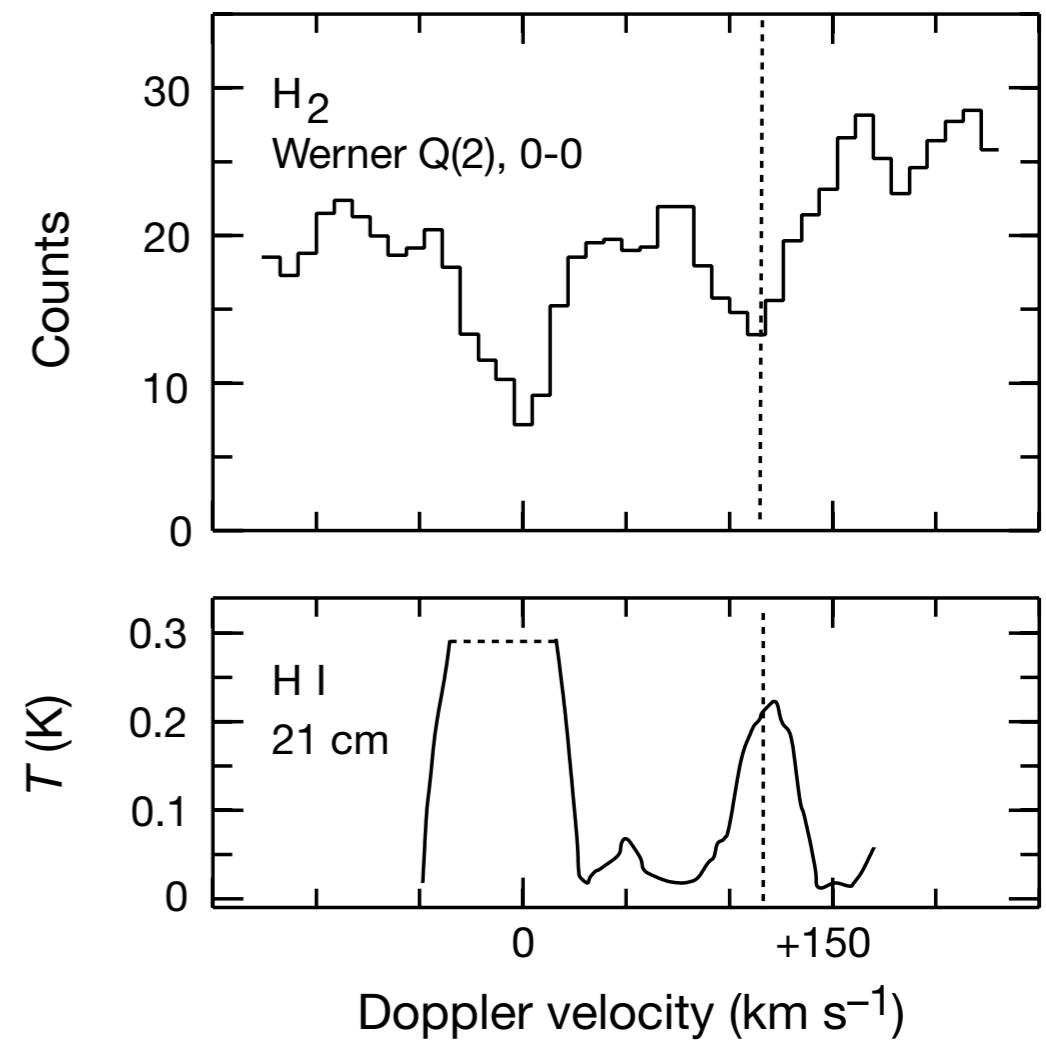
HVCs: Molecular hydrogen

- Richter (1999, Nature) detected molecular hydrogen absorption in a HVC (with +120 km/s) along the sightline to LMC, using ORFEUS.



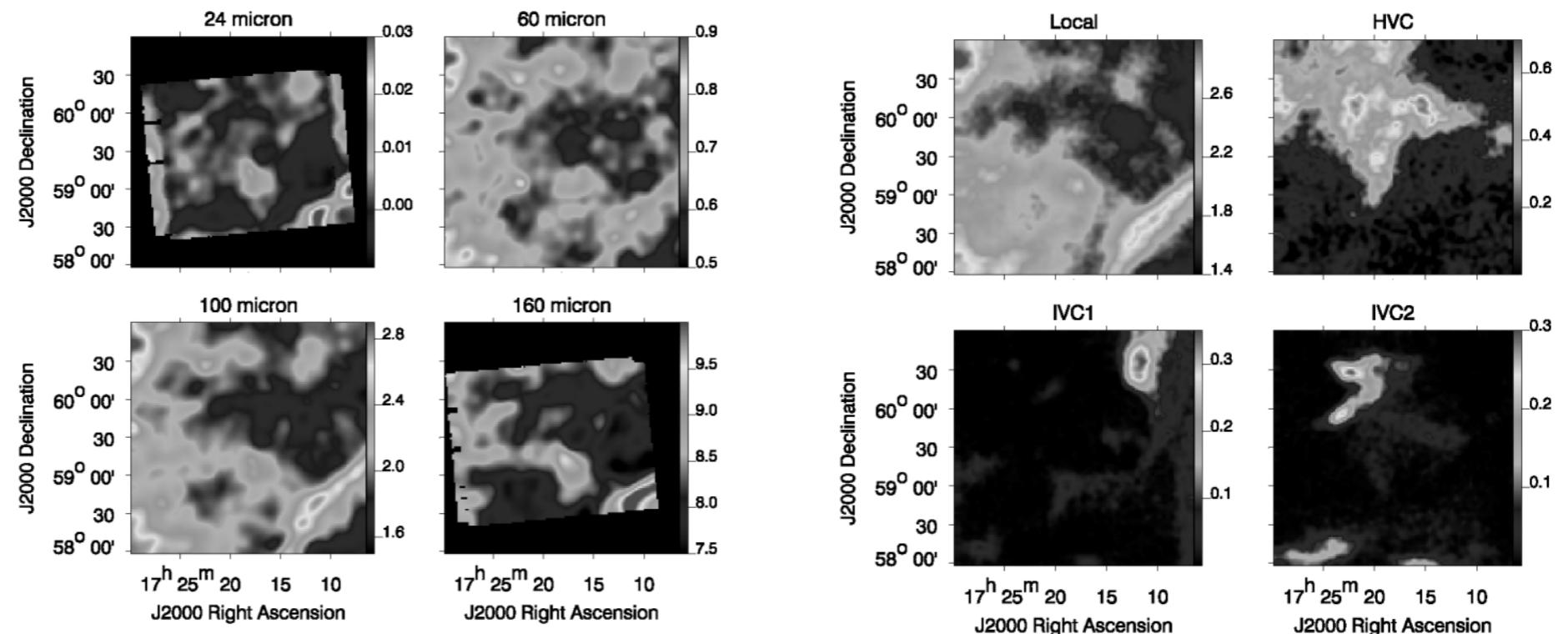
$$N(\text{H}_2) = (2.2 - 3.6) \times 10^{15} \text{ cm}^{-2}$$

$$N(\text{HI}) = 1.2 \times 10^{19} \text{ cm}^{-2}$$



HVCs: Dust

- Miville-Deschenes et al. (2005)
 - Complex C, $T \sim 10.7$ K ($T \sim 17.5$ K in the local ISM) is in accordance with its great distance from the Galactic distance.

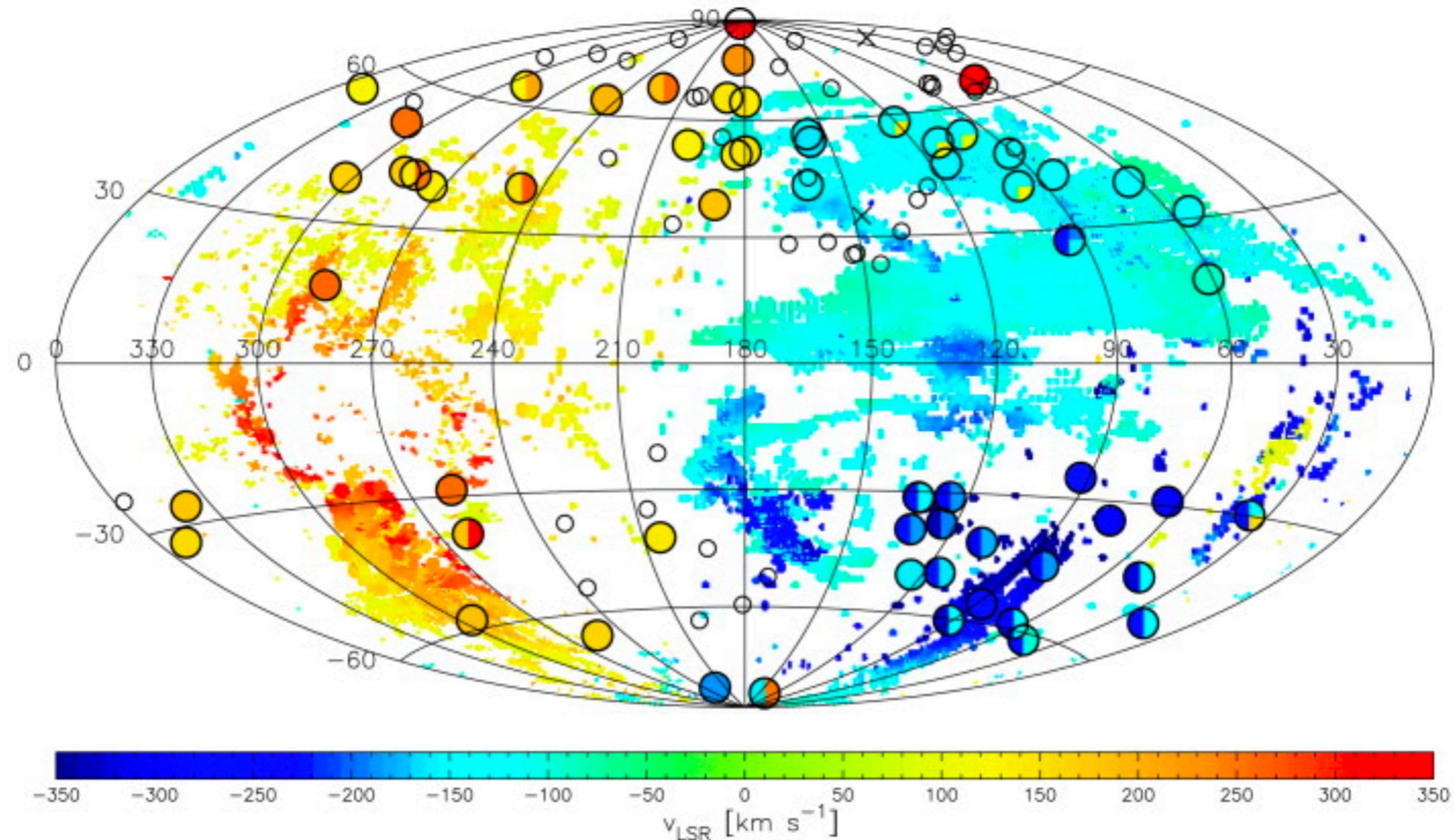


- Peek et al. (2009)
 - couldn't detect dust in Complex C, not detected dust in Complex M.
 - There exist LVCs that have extremely low dust-to-gas ratios, consistent with being in the Galactic halo
- Plank Collaboration (2011)
 - found dust in Complex C at the 3 sigma level.

HVCs: Highly ionized gas - O VI absorption

Sembach et al. (2003)

small open circles - null detection



Hammer-Aitoff projection of the high-velocity H I sky based on 21 cm emission measurements (adapted from Wakker et al. 2003). The H I data have a spatial resolution of approximately 36' and are representative of gas with $N(\text{H I}) > 2 \times 10^{18} \text{ cm}^{-2}$. Data for $|b| < 20^\circ$ have been omitted for clarity. The positions of the high-velocity O VI features listed in [Table 1](#) are denoted by the large circles, with the fill color indicating velocity on the same color scale used for the H I emission. If more than one high-velocity O VI feature is present, the circle is split and the velocities are color-coded in each section of the circle. Small open circles indicate null detections ([Table 2](#)). "X" marks indicate the locations of the two stellar sight lines in the sample.

HVCs: Ionized Gas

- Low ionized gas: Si II, Mg II
- Highly ionized gas:
 - Consideration of the possible sources of collisional ionization favors production of some of the O VI at the boundaries between cool/warm clouds of gas and a highly extended ($R > 70$ kpc), hot ($T > 10^6$ K), low- density ($n < 10^{-4} - 10^{-5}$ cm $^{-3}$) Galactic corona or Local Group medium.
- A bit low and inhomogeneous metallicity is usually found.
 - The most extended HVCs appear to be located relatively near the Galaxy, they may nonetheless be connected to extragalactic phenomena.
 - This is indicative of a combination of infalling primordial gas and outflowing enriched material.

HVCs in other galaxies

- HVCs appear to be a common feature around spiral galaxies (like M31 and M83).
- What is the origin of HVCs? There is no generally accepted theory regarding their origin.
 - cooling component of a supernova-driven “Galactic fountain”
 - inflows of neutral gas condensing from the local IGM
 - gaseous signatures of the “missing” dark matter subhalos around the Galaxy
- What is strange?
 - No stellar populations associated with HVCs have been found, unlike very low mass satellite galaxies which appear to harbor both stars and dark matter but little or no gas.
 - Aside from one case (Richter et al. 1999), HVCs appear to contain little or no molecular gas.

Galactic Wind

- The CGM is also fed by a galactic wind that blows interstellar gas outward, away from the disk.
 - M82 shows extremely strong galactic winds.
 - ▶ M82 has a star formation rate $R_{\text{SF}} \sim 10 M_{\odot} \text{ yr}^{-1}$. This high star formation rate provides a mechanism for driving the galactic wind.
 - ▶ When a large number of stars are formed within a short period of time, there will follow an epoch when multiple supernovae occur within a short period of time. The supernova remnants then merge to form a big hot bubble.
 - ▶ Active galactic nuclei can also inject large amounts of energy into the ISM, deriving a wind away from the galaxy.
 - ▶ The details of AGN physics are beyond the scope of this lecture, and we will focus on the case of the starburst-driven winds.



Optical, IR, and X-ray composite image of the starburst galaxy M81. The hot X-ray wind is in blue, the dusty outflow is red.

Fig 8.2, Ryden

Starburst-Driven Galactic Winds

- Galactic Winds
 - Starburst winds are driven by mechanical energy and momentum from stellar winds and supernovae (SNe).
 - For an instantaneous starburst, winds from OB stars dominate early on (< 3 Myr); next come Wolf-Rayet (WR) stars with mass-loss rates ~10 times higher (~3-6 Myr); and finally, core-collapse Type II SNe dominate until ~40 Myr when the least massive ($\sim 8M_{\odot}$) ones explode.
 - In the real universe, star formation episodes last for more than 40 Myr.
 - Therefore, we may ***assume a constant star-formation rate*** for a time much longer than 40 Myr.
- A Simple Model:
 - We will assume that a star formation rate $SFR = 1 M_{\odot} \text{ yr}^{-1}$ leads to a SN rate of $R_{\text{SN}} = 1/(50 \text{ yr}) = 0.02 \text{ yr}^{-1}$.
 - If each SN deposits an energy $E = 10^{51} \text{ erg}$ into the ISM, this implies an ***energy injection rate***

$$\begin{aligned}\dot{E}_* &= 10^{51} \text{ erg} \times 0.02 \text{ yr}^{-1} \left(\frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} \right) \\ &= 6.3 \times 10^{41} \text{ erg s}^{-1} \left(\frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} \right)\end{aligned}$$

- We now assume that the energy injection rate is constant with time. If the radiative losses of the overall system are negligible, the expanding bubble is energy-conserving (Sedov-Taylor solution).

- In that case, the radius of the expanding shell of shocked ISM is given by

$$r_{\text{shell}} = \xi \left(\frac{E_* t^2}{\rho} \right)^{1/5} \quad (\xi = 1.15167)$$

$$E_* = \dot{E}_* t$$

$$\begin{aligned} r_{\text{shell}} &= \xi \left(\frac{\dot{E}_* t^3}{\rho} \right)^{1/5} \\ &\approx 520 \text{ pc} \left(\frac{t}{1 \text{ Myr}} \right)^{3/5} \left(\frac{\text{SFR}}{1 M_\odot \text{ yr}^{-1}} \right)^{1/5} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-1/5} \end{aligned}$$

- The expansion rate of the shell is given by

$$\begin{aligned} v_{\text{shell}} &= \frac{dr_{\text{shell}}}{dt} = \xi \frac{3}{5} \left(\frac{\dot{E}_*}{t^2 \rho} \right)^{1/5} \\ &\approx 310 \text{ km s}^{-1} \left(\frac{t}{1 \text{ Myr}} \right)^{-2/5} \left(\frac{\text{SFR}}{1 M_\odot \text{ yr}^{-1}} \right)^{1/5} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-1/5} \end{aligned}$$

- Energy losses from the hot gas inside the bubble are negligible until the temperature behind the expanding blastwave drops below $\sim 2 \times 10^7 \text{ K}$.

- When the temperature falls to this level, we can use the cooling time scale for collisionally excited line radiation: (see Lecture 8).

$$t_{\text{cool}} \approx 0.19 \text{ [Myr]} \left(\frac{T}{10^6 \text{ K}} \right)^{1.7} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-1}$$

$$\approx 6600 \text{ [yr]} \left(\frac{v_{\text{shell}}}{100 \text{ km s}^{-1}} \right)^{3.4} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-1}$$

$$T \simeq \frac{3}{16} \frac{m}{k} V_{\text{shock}}^2$$

$$\approx 1.38 \times 10^5 \text{ K} \left(\frac{m}{0.609 m_{\text{H}}} \right) \left(\frac{V_{\text{shock}}}{100 \text{ km s}^{-1}} \right)^2$$

$$m = \frac{1.4 m_{\text{H}}}{2.3} = 0.609 m_{\text{H}} \text{ for fully ionized gas}$$

- Putting in the relation for the expansion speed of the starburst-driven bubble, we find a cooling time:

$$t_{\text{cool}} \approx 0.31 \text{ Myr} \left(\frac{t}{1 \text{ Myr}} \right)^{-1.36} \left(\frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} \right)^{0.68} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-1.68}$$

Solving the above equation for the instance when $t = t_{\text{cool}}$, we find

$$t_{\text{cool}} \approx 0.61 \text{ Myr} \left(\frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} \right)^{0.29} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-0.71}$$

- By the time $t = t_{\text{cool}}$, the bubble has expanded to a radius:

$$r_{\text{shell}} \approx 390 \text{ pc} \left(\frac{\text{SFR}}{1 M_{\odot} \text{ yr}^{-1}} \right)^{0.37} \left(\frac{n_{\text{H}}}{1 \text{ cm}^{-3}} \right)^{-0.63}$$

- The mean density of the WNM is $\sim 0.6 \text{ cm}^{-3}$, and the scale height of the WNM, in the direction perpendicular to the Galactic disk, is $\sim 350 \text{ pc}$. Thus, a superbubble is able to break free of the gaseous disk while still in its Sedov-Taylor phase.

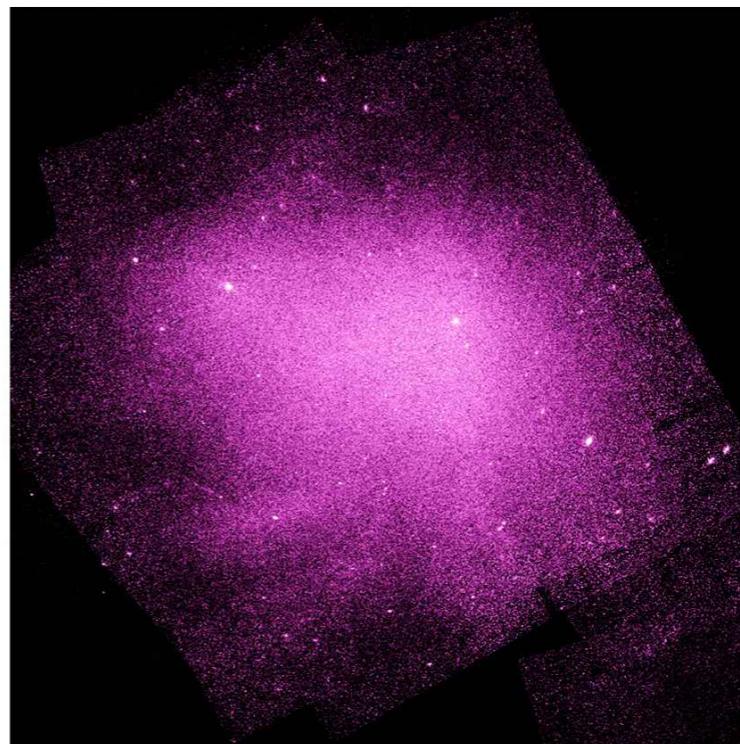
Intracluster Medium (ICM)

- **Coma Cluster**

- The Coma Cluster is a rich cluster located at a distance ~ 100 Mpc from our Galaxy; at this distance, 1 arcsec ~ 0.48 kpc (10^8 AU).
- About 1000 galaxies in the Coma Cluster have spectroscopic redshifts; taking into account of all the faint dwarf galaxies, there may be 10,000 or more galaxies in the Coma Cluster.



(a) Optical



(b) X-ray

The Coma Cluster (a) at optical wavelengths [SDSS], and (b) at X-ray wavelengths [Chandra]. Two yellowish, brightest galaxies are NGC 4889 (left) and NGC 4874 (right), which are separated by 7 arcmin, corresponding to 200 kpc.

[Fig 8.3, Ryden]

- ***Dark Matter in the Coma Cluster***

- **Virial Mass:**

- ▶ In the central regions of the Coma Cluster, the line-of-sight velocity dispersion is found to be:

$$\sigma_v \approx 800 \text{ km s}^{-1}$$

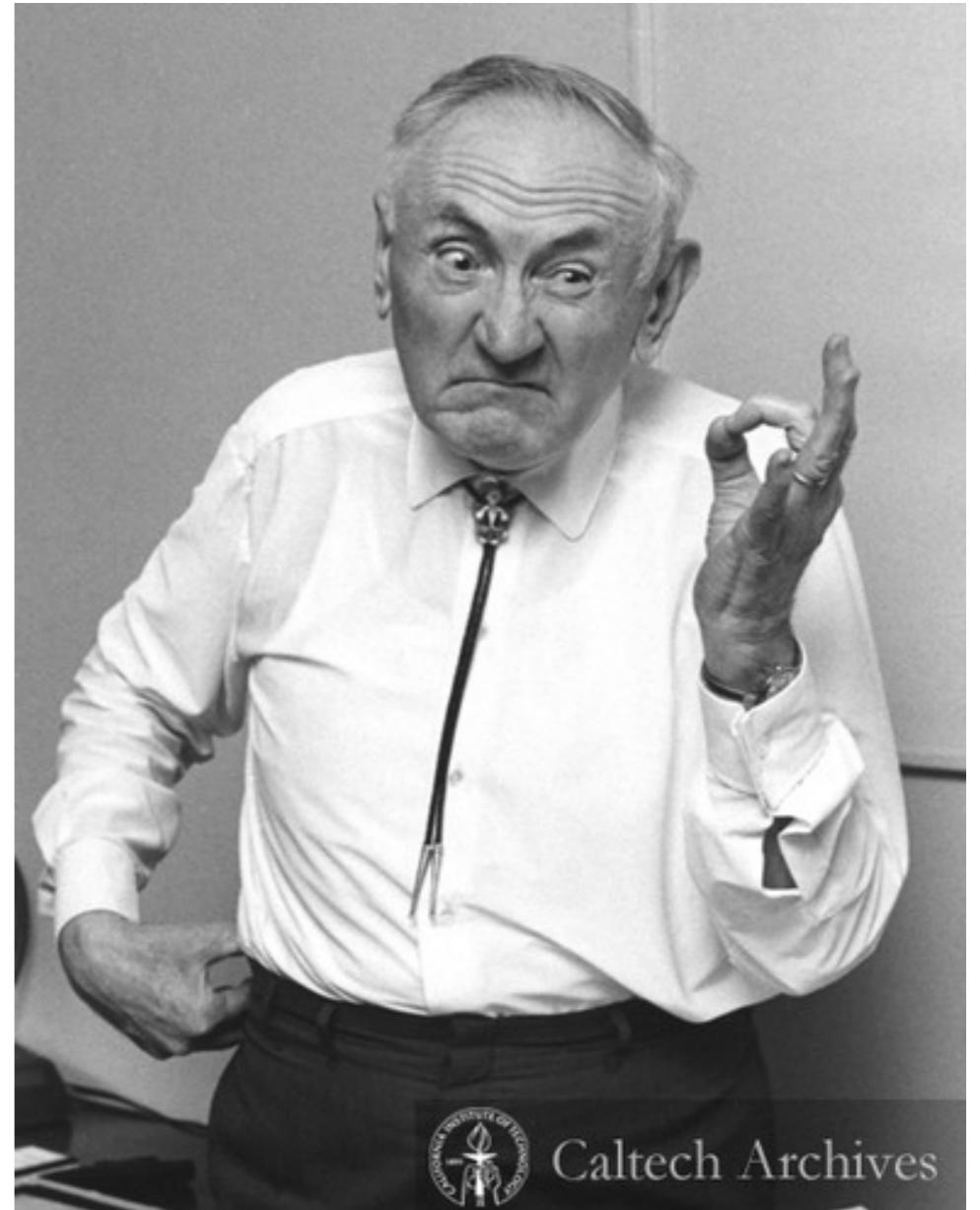
- ▶ The half-light radius, which is measured from the center of the two brightest cluster galaxies, that contains half the total flux of the galaxies in the cluster is:

$$r_h \approx 52 \text{ arcmin} \rightarrow r_h \approx 1.5 \text{ Mpc}$$

- ▶ Using the virial theorem, we can make a mass estimate for the Coma Cluster:

$$M_{\text{vir}} = 5 \frac{\sigma_v^2 r_h}{G} \approx 2.7 \times 10^{48} \text{ g} \approx 1.4 \times 10^{15} M_\odot$$

In deriving the virial equation, a constant density was assumed. But, the equation is correct within a factor of unity.



Fritz Zwicky (1898-1974)
Photo by Floyd Clark (1971)

-
- **Stellar Mass:**
 - ▶ Integrating over the luminosity function of the Coma galaxies, the total luminosity of all the stars in all the galaxies in the Coma Cluster is found to be:

$$L_B^{\text{Coma}} \approx 8 \times 10^{12} L_{B,\odot} \sim 400 L_B^{\text{Milky Way}} \quad \text{in B-band}$$

- ▶ Most of the visible light from the Coma Cluster comes from elliptical galaxies, whose stellar populations have a ***mass-to-light ratio*** $\gamma_* \approx 5M_\odot/L_{B,\odot}$. This yields a total stellar mass for the Coma Cluster:

$$M_* = \gamma_* L_B \approx (5M_\odot/L_{B,\odot}) (8 \times 10^{12} L_{B,\odot}) \approx 4 \times 10^{13} M_\odot$$

- Thus, the total virial mass of the Coma Cluster is more than 30 times the mass of the stars that it contains:

$$\therefore M_{\text{vir}} \approx 35M_*$$

This discrepancy led Fritz Zwicky (1933) to deduce the existence of “dark matter.”

- ▶ Only eight redshifts of galaxies in the Coma Cluster were known at the time. However, it was enough for Zwicky to realize that the velocity dispersion was far too large for Coma to remain bound if stars were the only matter present.

Hot Diffuse Intracluster Medium

- Hot Diffuse ICM

- Stars provide a minority of the baryons in a rich cluster like the Coma. As seen in X-ray, the Coma Cluster is revealed as containing a hot diffuse intracluster medium.
- The X-ray spectrum has the characteristic shape of thermal bremsstrahlung, or free-free emission, with $kT \sim 10$ keV in the 2-20 keV range.

- **Cooling Time Scale:**

- ▶ For fully ionized hydrogen, the free-free emissivity is

$$j_{\nu,ff} = C_{ff} \left(\frac{m_e c^2}{kT} \right)^{1/2} n_e n_i e^{-h\nu/kT} g_{\nu,ff}$$

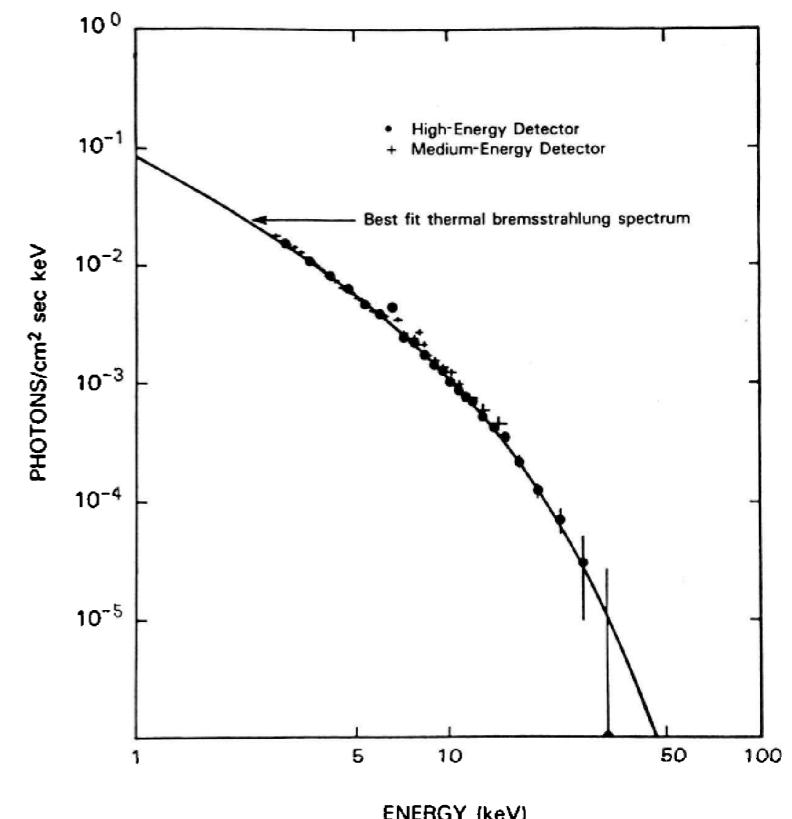
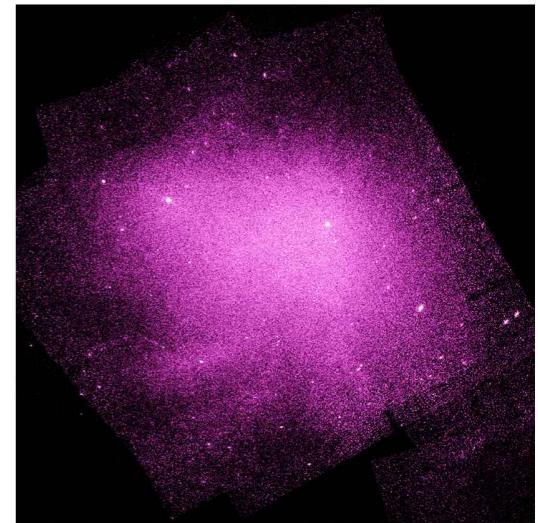
Here, $C_{ff} \equiv \frac{8}{3} \left(\frac{2\pi}{3} \right)^{1/2} \frac{e^6}{m_e^2 c^4} = 7.070 \times 10^{-44} \text{ erg cm}^3 \text{ s}^{-1} \text{ Hz}^{-1} \text{ sr}^{-1}$

Gaunt factor: $g_{\nu,ff} \approx \frac{\sqrt{3}}{\pi} \ln \left(\frac{4}{e^\gamma} \frac{kT}{h\nu} \right) \approx 0.551 \ln \left(2.25 \frac{kT}{h\nu} \right)$

for $kT \gg 13.6 \text{ eV}$ and $h\nu < kT$

(Note that the Gaunt factor has only a mild frequency dependence.)

Euler-Mascheroni constant: $\gamma = \lim_{n \rightarrow \infty} \left(-\ln n + \sum_{k=1}^n \frac{1}{k} \right) \approx 0.5772$



(top) X-ray image, (bottom) X-ray spectrum of the Coma Cluster [Henriksen & Mushotzky 1986]

$kT_{\text{gas}} \sim 7.3 \text{ keV}$ for Coma

-
- The ***power per unit volume*** produced by thermal bremsstrahlung is:

$$\mathcal{L}_{\text{ff}} = 4\pi \int j_{\nu, \text{ff}} d\nu = 4\pi C_{\text{ff}} \frac{m_e c^2}{h} \left(\frac{kT}{m_e c^2} \right)^{1/2} n_e n_i \bar{g}_{\text{ff}}$$

Here, $4\pi C_{\text{ff}} \frac{m_e c^2}{h} = 1.10 \times 10^{-22} \text{ erg cm}^3 \text{ s}^{-1}$

Frequency-averaged Gaunt factor: $\bar{g}_{\text{ff}} \approx 1.15$ (near $T \sim 10^8 \text{ K}$)

→ $\mathcal{L}_{\text{ff}} \approx 1.77 \times 10^{-29} \text{ erg cm}^{-3} \left(\frac{kT}{10 \text{ keV}} \right)^{1/2} \left(\frac{n_{\text{H}}}{10^{-3} \text{ cm}^{-3}} \right)^2$ for a fully ionized hydrogen gas

- The ***mass density*** of the ICM is:

$$\rho_{\text{ICM}} = m_{\text{H}} n_{\text{H}} \approx 1.67 \times 10^{-27} \text{ g cm}^{-3} \left(\frac{n_{\text{H}}}{10^{-3} \text{ cm}^{-3}} \right)$$

- ***Mass-to-light ratio*** for the ICM (considering only the bremsstrahlung) is:

$$\gamma_{\text{ICM}} = \frac{\rho_{\text{ICM}}}{\mathcal{L}_{\text{ff}}} \approx 180 (M_{\odot}/L_{\odot}) \left(\frac{kT}{10 \text{ keV}} \right)^{-1/2} \left(\frac{n_{\text{H}}}{10^{-3} \text{ cm}^{-3}} \right)^{-1}$$

Note that $\gamma_{\text{ICM}} \gg \gamma_{\star}$ ($\approx 5M_{\odot}/L_{\text{B},\odot}$).

The bremsstrahlung is not an efficient cooling mechanism.

- ▶ The ***thermal energy density*** of the ICM is

$$\mathcal{E}_{\text{ff}} = (2n_{\text{H}}) \frac{3}{2} kT \approx 4.81 \times 10^{-11} \text{ erg cm}^{-3} \left(\frac{n_{\text{H}}}{10^{-3} \text{ cm}^{-3}} \right) \left(\frac{kT}{10 \text{ keV}} \right)$$

- ▶ The ***cooling time*** for the ICM is then:

$$t_{\text{cool}} = \mathcal{E}_{\text{ff}} / \mathcal{L}_{\text{ff}} \approx 86 \text{ Gyr} \left(\frac{kT}{10 \text{ keV}} \right)^{1/2} \left(\frac{n_{\text{H}}}{10^{-3} \text{ cm}^{-3}} \right)^{-1}$$

- **Gas Mass:**

- ▶ The ***gas density profile*** of clusters is often expressed with a β -profile:

$$n_{\text{H}} = n_0 \left[1 + \left(\frac{r}{r_c} \right)^2 \right]^{-3\beta/2} \quad \begin{aligned} \beta &\approx 0.75 \\ r_c &\approx 0.3 \text{ Mpc} \\ n_0 &\approx 3 \times 10^{-3} \text{ cm}^{-3} \end{aligned} \quad \text{for the Coma Cluster}$$

- ▶ The amount of gas within a radius r will then be:

$$M_{\text{gas}}(r) \approx \frac{4\pi}{3(1-\beta)} m_{\text{H}} n_0 r_c^3 \left(\frac{r}{r_c} \right)^{3(1-\beta)}$$

$n_{\text{H}} \approx n_0 \left(\frac{r}{r_c} \right)^{-3\beta}$
when $r \gg r_c$ and $\beta < 1$

- ▶ We assume an abrupt cutoff at the virial radius ($r_{\text{vir}} \approx 3 \text{ Mpc}$). This gives a mass estimate:

$$M_{\text{gas}}(r) \approx 2 \times 10^{14} M_{\odot} \left(\frac{r}{3 \text{ Mpc}} \right)^{0.75} \longrightarrow M_{\text{gas}} \approx 5 M_{\star} \quad (M_{\star} \approx 4 \times 10^{13} M_{\odot})$$

- Total Mass in the hydrostatic equilibrium:

- ▶ In X-rays, the central regions of the Coma Cluster look smooth. We thus expect that Coma, at least in its central regions, is ***a relaxed cluster, in hydrostatic equilibrium.***
- ▶ Spherical objects in hydrostatic equilibrium obey the equation:

$$\frac{dP}{dr} = -\frac{GM(r)\rho_{\text{gas}}(r)}{r^2}$$

$M(r)$ is the mass of everything inside a radius r , including gas, stars, and dark mass.
 $\rho_{\text{gas}}(r)$ is the gas density.

- ▶ The ideal gas law for an ionized hydrogen gas is:

$$P = nkT = \frac{2\rho_{\text{gas}}(r)}{m_{\text{H}}} k T_{\text{gas}}(r)$$

- ▶ Combining the equation of hydrostatic equilibrium with the ideal gas law, we find the total mass M contained within a radius r :

$$\begin{aligned} M(r) &= -\frac{r^2}{G\rho_{\text{gas}}(r)} \frac{2k}{m_{\text{H}}} \frac{d(\rho_{\text{gas}} T_{\text{gas}})}{dr} \\ &= \frac{2rkT_{\text{gas}}}{Gm_{\text{H}}} \left(-\frac{d \ln \rho_{\text{gas}}}{d \ln r} - \frac{d \ln T_{\text{gas}}}{d \ln r} \right) \end{aligned}$$

- We assume that the intracluster gas is isothermal ($T_{\text{gas}} = \text{constant}$) as an first order approximation and a beta profile for the gas density:

$$\begin{aligned} M(r) &= \frac{2r k T_{\text{gas}}}{G m_H} \left(-\frac{d \ln \rho_{\text{gas}}}{d \ln r} \right) \\ n_H(r) &\approx n_0 (r/r_c)^{-3\beta} \end{aligned}$$

$$M(r) \approx \frac{6\beta k T_{\text{gas}}}{G m_H} r \approx \frac{4.5 k T}{G m_H} r \quad (\text{for } r \gg r_c \text{ and } \beta \approx 0.75)$$

If a cluster is in hydrostatic equilibrium, and has a cutoff at the virial radius, then its total mass (including everything) is:

$$M_{\text{HE}} \approx \frac{4.5 k T_{\text{gas}}}{G m_H} r_{\text{vir}} \approx 3.0 \times 10^{15} M_{\odot} \left(\frac{k T_{\text{gas}}}{10 \text{ keV}} \right) \left(\frac{r_{\text{vir}}}{3 \text{ Mpc}} \right)$$

- For the Coma Cluster, with $k T_{\text{gas}} = 7.3 \text{ keV}$ and $r_{\text{vir}} \approx 3 \text{ Mpc}$, the total mass is:

$$M_{\text{HE}} \approx 2.2 \times 10^{15} M_{\odot}$$

This is consistent with the virial estimate of $M_{\text{vir}} \approx 1.4 \times 10^{15} M_{\odot}$.

In summary,

total mass	$M_{\text{tot}} \approx 2 \times 10^{15} M_{\odot}$
stellar mass	$M_{\star} \approx 0.02 M_{\text{tot}}$
gas mass	$M_{\text{gas}} \approx 0.1 M_{\text{tot}}$