Astronomy 208 Meeting #8

Part 3 of the Course: "The ISM of the Milky Way"

3.1 Multi-phase Paradigm

3.2 The "Cold" ISM

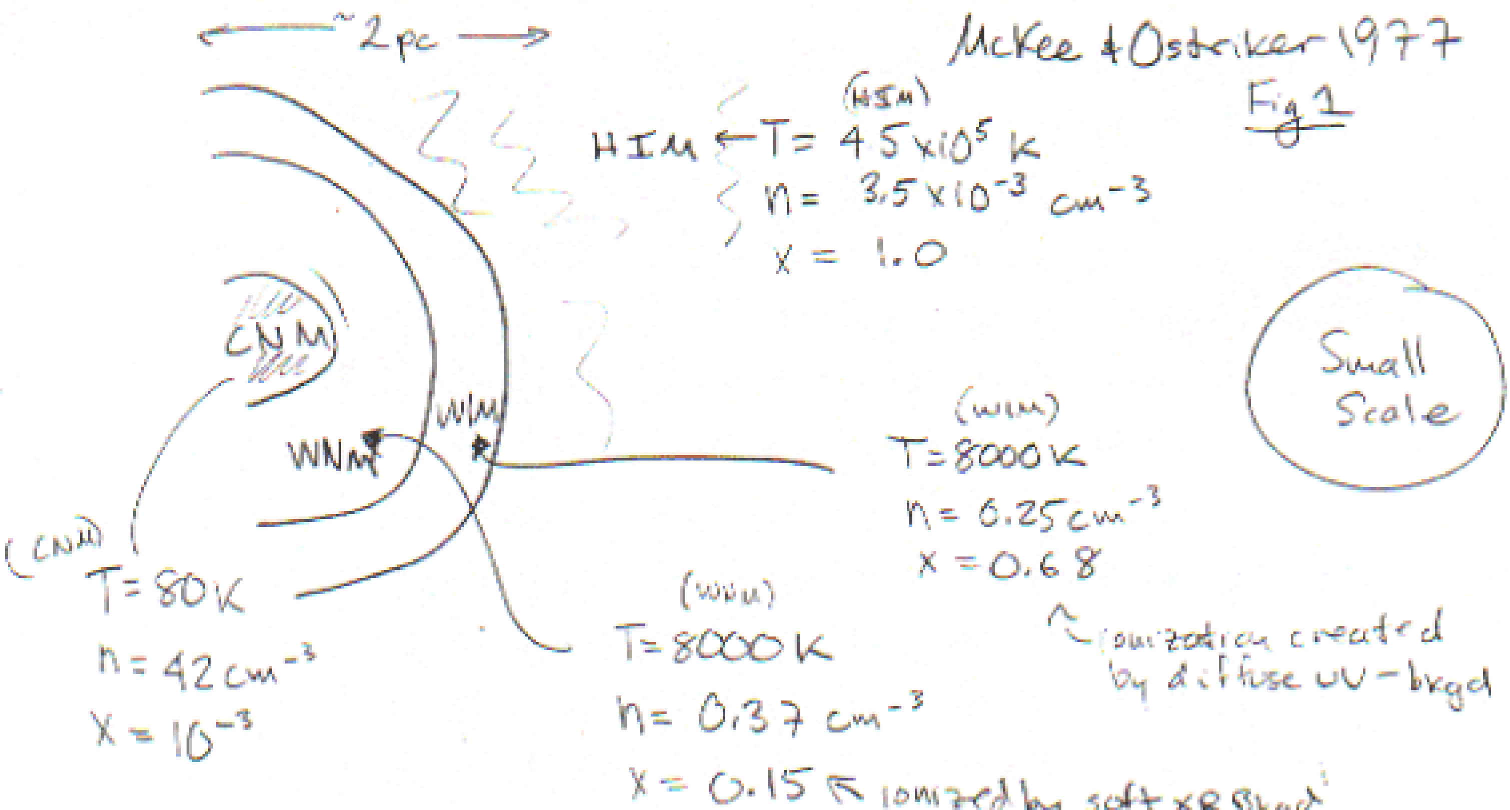
a) Atomic Gas

Origin of 21-cm Line Spin-Flip

21-cm Line Surveys

see http://cfa-www.harvard.edu/~agoodman/HI.html

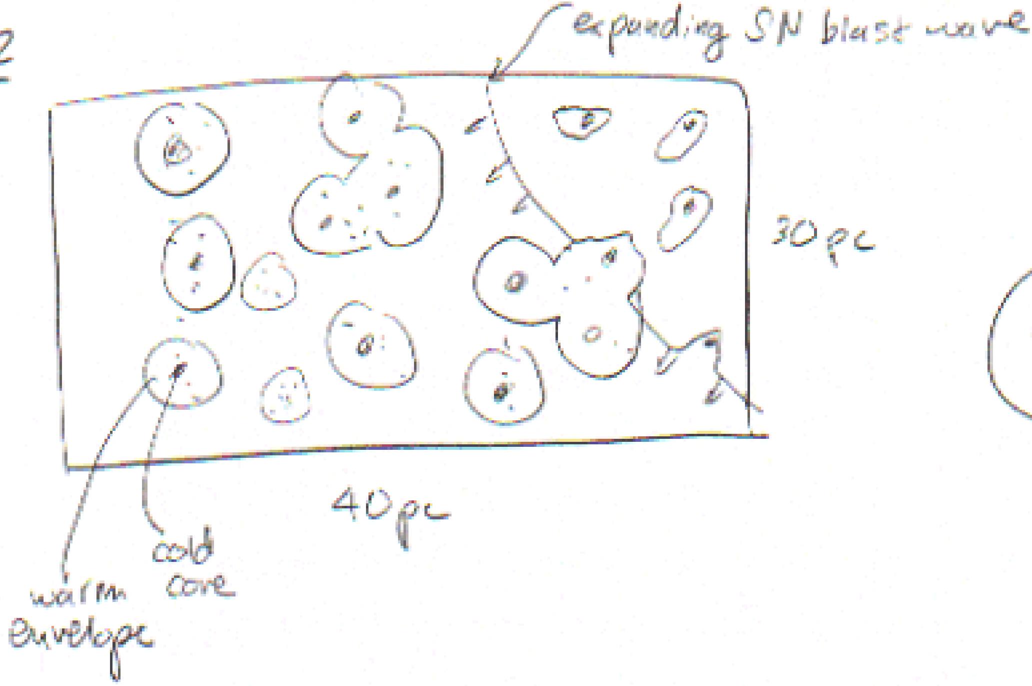
Multi-Phase Paradigm in Brief:



"Cross-section of Characteristic Small Cloud"

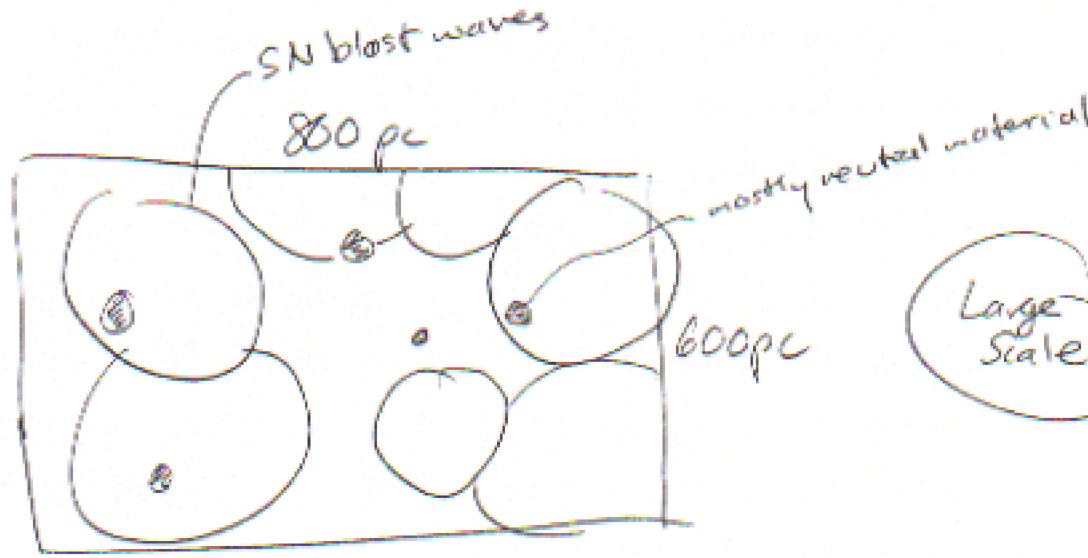
(Fig 1)

Fig 2



Medium Scale

Fig 3



Large Scale

$f_{HIM} = 0.7 - 0.8$

$f_{CNM} = 0.02 - 0.04$

$f_{WIM} \sim 0.2$

+3 weeks from now – Reconsider this picture...

Key ideas: Pressure Balance – Momentum, Energy Deposition

Time Dependence

(Outflows??)

History

- spin-flip transition predicted to be detectable by van de Hulst in ~1944

~• 1951 Ewen & Purcell detect 21 cm line out window @ <u>Jefferson</u> Lab

(Dutch)
Muller & Oort were very close to doing it first, but they had a fire – they succeeded soon after, as did Australians (Christansen & Hindman)

new quest is analogous line in Deuterium @ 327 MHz not yet (quite) detected... despite some claims

21-cm line surveys

Principal Results: (see Kulkarni & Heiles 1988 in Galactic & Extragalactic Radio Astronomy, Verschuur & Kellermann ed.

HI in Milky Way ~ $4.8 \times 10^9 M_\odot$ = 4.4% of visible matter
(H_2 " " " ~ 25 to 90% as much as HI)

HI not really in "clouds" like H_2
HI filling factor ~ 20 to 90% depending where & who you believe

Some Important Definitions

"Permitted Transition" transitions which occur relatively quickly (high rate of spontaneous emission)

→ "allowed" electric dipole transitions

many selection rules are only exact in the absence of spin-orbit coupling and/or external fields and/or collisions

"Forbidden Transition" very low spontaneous emission rate

→ come from magnetic dipole or electric quadrupole transitions

collisionally excited

note: 21-cm line is a "forbidden" transition!

Note: This happens often in ISM where density is very low

"Critical Density"

$$n_{crit} = \overset{1/sec}{A_{ul}} / \underset{cm^3/sec}{\gamma_{ul}}$$

γ_{ul} = collisional rate coeff

$= \langle \sigma_{ul} v \rangle$ $\quad cm^2 \cdot \frac{cm}{sec} = \frac{cm^3}{sec}$

indicates density at which collisions can keep up with spontaneous radiative transitions

for $n < n_{crit}$ line flux $\propto n^2$

for $n > n_{crit}$ " " $\propto N$

show formally later

3.2 The Cold ISM

a) Atomic Gas

Origin of 21-cm line : "spin-flip"

transition is b/wn two hyperfine levels of $n=1$ electronic state $(1\,^2S_{1/2})$

interaction of mag mom of proton w/ spin+orbit magmom of e^-

Upper level
parallel spins

$g_u = 3$ ← note: this degeneracy removed in Zeeman splitg.

Lower level
antiparallel spins

$g_\ell = 1$

$\nu_0 = 1420.406$ MHz $\qquad \frac{h\nu_0}{k} = 0.068\,K$ very low energy!

$A_{u\ell} = 2.869 \times 10^{-15}\,s^{-1}$ (Very small!)

τ_r = rate of spontaneous decay after being excited to upper state $= \frac{1}{A_{u\ell}} \sim 10^7$ yrs!

but recall $\tau_{coll} = \frac{1}{n_H \sigma v} \cong 4 \times 10^3$ yr for $\left(\begin{array}{l} n_H = 1;\ \sigma \text{ geometric} \\ v \sim 1 \text{ km/s} \end{array} \right)$

Thus for HI in ISM

$\tau_{coll} << \tau_r$ ... see K&H handout...

HI is primarily collisionally excited in CNM, but in WNM, Lyα plays role see K&H & Field 1959

Optical Depth Effects

characterizes level populations

$T_s = T_{ex}$ for spin-flip

$\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell} \exp\left(\frac{h\nu_{u\ell}}{kT_{ex}}\right)$

Recall

$$\boxed{T_B(\nu) = T_{bg}(\nu) e^{-\tau_\nu} + T_s (1 - e^{-\tau_\nu})} \quad (1)$$

(for an isolated homogeneous cloud where τ & T don't vary inside it)

Actual measurements give $\boxed{\Delta T_B = T_B - T_{bg}}$ (2)

so (1) & (2) $\rightarrow$ $\boxed{\Delta T_B = (T_s - T_{bg})(1 - e^{-\tau_\nu})}$ (3)

[Note: FYS $\tau \propto \frac{N}{T_s}$] (4) can derive this (see next page)

$\boxed{\tau \ll 1} \rightarrow \boxed{T_B = T_s \tau = N_\nu / C}$ (5) (assuming $T_{bg} \rightarrow 0$)

T_B gives column density

more stuff $\rightarrow$ more emission, linearly

$\boxed{\tau \gg 1}$ $\boxed{T_B = T_s}$ (6) only see to $\tau \approx 1$ surface

Observed brightness temp is independent of column density — only depends on temperature

Recall from eq. (31) of Meeting #7 for LTE

(Kirchoff)

(7) $$\boxed{\begin{aligned}\alpha_\nu &= \frac{h\nu}{4\pi} n_\ell B_{\ell u}\left[1-\exp\left(\frac{-h\nu}{kT_{ex}}\right)\right]\phi(\nu) \\ &= \frac{h\nu}{4\pi}\phi_\nu n_\ell B_{\ell u}\left(\frac{h\nu}{kT_{ex}}\right) \quad \text{for} \quad h\nu << kT_{ex}\end{aligned}}$$ (RJ)

$S_\nu = B_\nu(T) = \frac{j_\nu}{\alpha_\nu}$

and (8) $$\boxed{\tau_\nu(s) = \int_{s_0}^{s} \alpha_\nu(s')\, ds'}$$

So then as long as T_{ex} is independent of s $7 \,\&\, 8 \Rightarrow$

(9) $$\tau_\nu = \frac{(h\nu)^2}{4\pi}\phi_\nu B_{\ell u}\frac{1}{k}\int \frac{n_\ell}{T_{ex}}\, ds'$$

(10) and $\boxed{N = \int n\, ds}$ = column density

then $$\tau_\nu = \frac{(h\nu)^2}{4\pi k} B_{\ell u}\phi_\nu \frac{N_\ell}{T_{ex}}$$

Note: for HI

$A_{u\ell} = 2.9\times10^{-15}\ s^{-1}$

$B_{u\ell} = \frac{c^2}{2h\nu^3} A_{u\ell}$

$B_{\ell u} = \frac{g_u}{g_\ell} B_{u\ell} = 3 B_{u\ell}$

$\boxed{B_{\ell u} = 7.1\times10^{19} A_{u\ell} = 2.1\times10^{5}}$

for HI ground state

recall $\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell} e^{-h\nu/kT_{ex}}$ but $\frac{h\nu}{kT_{ex}} << 1$ so $\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell} = 3$

So $N_u = 3N_\ell$ and (11) $\boxed{N_{TOTAL} = 4N_\ell}$

And (12) $$\boxed{\tau_\nu = 5.49\times10^{-14}\, \frac{N_{TOTAL}\,\phi(\nu)}{T_{ex}}}$$

$\phi(\nu)$ in units of $cm^{-1} s$

$\int \phi(\nu)\, d\nu = 1$

$$\boxed{\tau_\nu = \frac{N_{TOT}}{C \times T_s} \qquad C = 1.82\times10^{13} \text{ for cgs}}$$