ISM 30-09-2019.

We have not yet discussed collissions, which we will do in a later stage
Today: atomic interstellar medium.

HI 21 cm line: hyperfine ~~splitting~~ structure in the ground state of HI (coupling of electron and nuclear spins)

~~A2 → A~~
$n=2 \rightarrow n=1$ Lyα line at 10.2 eV.
Proton and electron both have spin, so HI 21 cm is ΔE for the two states ↑↑ and ↑↓
$h\nu/k = 0.07$ K, $h\nu = 6\ \mu$eV. Ground state is antiparallel. Transition is highly forbidden and thus very unlikely.

$A_{10} = 2.9 \cdot 10^{-15}\ s^{-1}$ So lifetime is very long, $\tau = 11$ ~~10~~ ~~Gy~~ Myr. But there is so much IS Hydrogen thus we can still observe in this
HI is detected everywhere. Point sources in HI is quasars
Dark clouds in HI consists of cold and warm HI
Hole in HI in center of galaxy means that gas became molecular, e.g. HII.

Rotation curve from HI → key application.

$$I_\nu = I_0 \exp(-\tau_\nu) + \frac{j_\nu}{\kappa_\nu}(1-\exp(-\tau_\nu))$$

$$\frac{j_\nu}{\kappa_\nu} = B_\nu(T_{ex})$$

Since we're in radio regime we can use Rayleigh Jeans, and $T_{ex} = T$.

$$j_\nu = n_u \frac{A_{ul}}{4\pi} h\nu_{ul} \phi_\nu \qquad \int \phi_\nu = 1$$

$$\frac{n_u}{n_l} = \frac{g_u}{g_l} e^{-h\nu_{ul}/kT_{ex}}$$

$T_{ex} \downarrow T_s$ spin temperature (= excitation temperature of HI)

For HI we know the numbers

$$\frac{n_u}{n_l} = \frac{3}{1} \exp(-0.0682/T_s)$$

$(2S+1) = (2\frac{1}{2}+1)$

$(2S+1) = 2(\frac{1}{2}+-\frac{1}{2})+1$

We can easily show that $T_s = T_{kinetic}$, since Level populations are totally dominated by the collissions

$$= 3 e^{\left(-\frac{0.0682}{T_{kin}}\right)}$$

kinetic temperatures are mostly 50-100 K in warm neutral medium, and ~1000 K in warm neutral medium. So, $n_u/n_l = 3$ to very high precision !

$$\Rightarrow \frac{n_u}{n_l} = n_u = \frac{3}{4} n_{HI} \text{ and } n_l = \frac{1}{4} n_{HI}$$

Plugging in in j_ν

$$\hookrightarrow j_\nu = \frac{3}{16\pi} A_{UL} h\nu_{UL} n_{HI} \phi_\nu$$

$$k_\nu = n_l \frac{g_u}{g_l} \frac{A_{ul}}{8\pi} \lambda_{ul}^2 \phi_\nu (1 - e^{-\frac{h\nu_{ul}}{kT_s}})$$

$$\Rightarrow \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{kT_s} n_{HI} \phi_\nu$$

Now write down optical depth too.

$$\rightarrow \tau_s = \int \kappa_\nu \, ds = \frac{3}{32\pi} A_{ul} \phi_\nu \frac{hc\lambda_{ul}}{kT_s} N(HI)$$

$$\phi_\nu = \frac{1}{\sqrt{2\pi}} \frac{c}{\nu_{ul}} \frac{1}{\sigma_v} \exp\left(\frac{-v^2}{2\sigma_v^2}\right)$$

$$\Rightarrow \tau_v = \frac{3}{32\pi} \frac{1}{\sqrt{2\pi}} \frac{A_{ul}}{\sigma_v} \frac{hc}{kT_s} \exp\left(\frac{-v^2}{2\sigma_v^2}\right) N(HI)$$

Put in numbers to see how large this is

$$\tau_v = \cancel{2{,}190}\ 2{,}190 \ \frac{N(HI)}{10^2\,\mathrm{cm}^{-2}} \ \frac{100k}{\sigma_v} \ \frac{1\,\mathrm{km\,s}^{-1}}{T_s} \ e^{\left(-\frac{v^2}{2\sigma_v^2}\right)} \approx 2$$

τ_v can be large, but much HI is quite a lot hotter, yielding lower T.

$$\Rightarrow T_s(v) = T_{0}\, e^{-\tau_v} + T_s (1 - e^{-\tau_v})$$

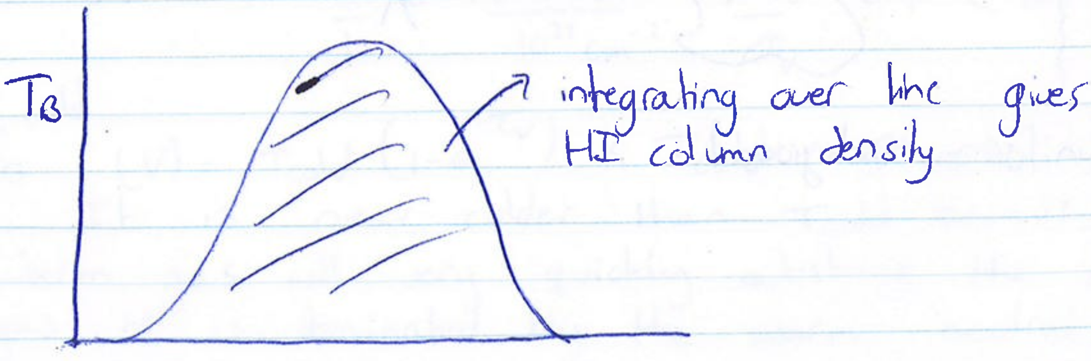
very simple in brightness units terms.

- τ small

$$T_s(v) = \tau_v T_s$$

$$\hookrightarrow \int T_B(v)\,dv = \frac{3}{32\pi} A_{ul} \frac{hc\lambda_{ul}}{k} N(HI) \int \phi \, dv$$

<u>If</u> HI is optically thin



$$\boxed{N(HI) = \frac{32\pi k}{3hc\,\lambda_{ul}^2 A_{ul}} \int T_B \, dv}$$

$\tau \ll 1$
HI emission

Optically thin observations ; directly probe HI column density!

$$\boxed{\tau_v \propto \frac{N(HI)}{T_s}}$$

specific to HI. Most cases have $\tau_v \propto N$, not T_s

↑ not general! But for long wavelength emission lines probably often valid

Insert some numbers:

$$n_{HI}\,[cm^{-2}] = 1.813 \cdot 10^{18} \frac{\int T_B \, dv}{K\,km s^{-1}}$$

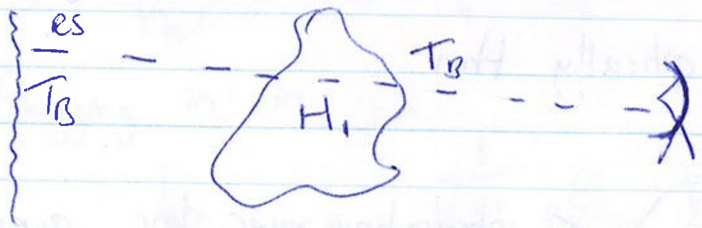
Now to mass density

$$M_{HI} = \frac{16\pi m_H}{3 A_{ul} h c} D^2 \int S_v \, dv$$

↳ $A = d\Omega D^2$

$$\hookrightarrow m_{HI} = \frac{2.343 \cdot 10^5}{M_\odot} \left(\frac{D}{Mpc}\right)^2 \frac{\int S_v \, dv}{Jy\,km s^{-1}}$$

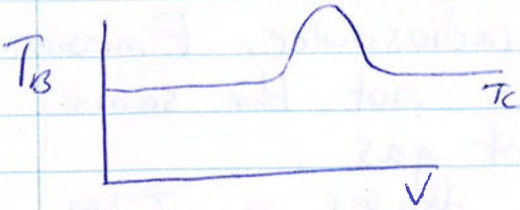
With $\tau \gg 1$, can no longer look through cloud thus numbers become smaller.

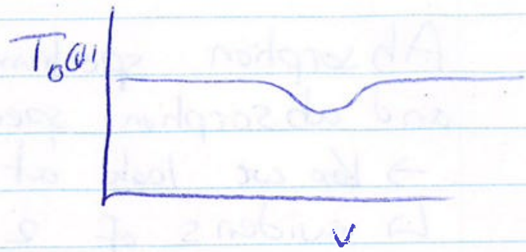


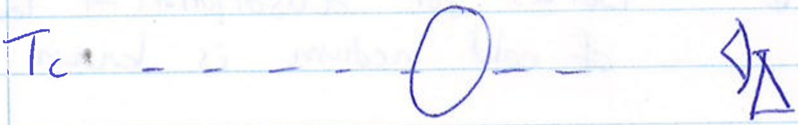
$$T_B(v) = (T_{RS} + T_{sky}) \times e^{-\tau_v} + T_s(1 - e^{-\tau_v})$$

uniform background

Absorption and emission







The radiative transfer is the same for absorption and emission.

$$T_B = T_c e^{-\tau_\nu} + T_s (1 - e^{-\tau_\nu})$$

$$T_B - T_c = (T_s - T_c)(1 - e^{-\tau_\nu})$$

$$T_s \begin{cases} T_B > T_c & \text{emission} \\ T_B < T_c & \text{absorption} \end{cases}$$

Cold cloud ; < 100 k τ_ν high

warm " " : $\sim$ few 10^3 k τ_ν low

$$\tau_\nu \propto \frac{N(HI)}{T_s}$$

$$T_B^{warm}(\nu) = \frac{3}{32\pi} A_{UL} \frac{hc \lambda_{UL}}{k} N(HI) \phi_\nu$$

$$= \frac{220}{k} \frac{N(HI)}{10^{21} cm^{-2}} \frac{km s^{-1}}{\sigma_\nu} \exp\left(-\frac{v^2}{2\sigma_v^2}\right)$$

$$T_B^{cold}(\nu) = T_{cold}(1 - e^{-\tau_\nu}) < T_{cold} < ~~T~~ 100 k$$

It is never colder than T_{cold} becaus $\tau \gg 1$

Warm gas will very quickly outshine the cold gas. HI is dominated by the warm neutral medium. Cold medium dominates in absorption

Absorption spectrum is radiosource. Emission and absorption spectra are not the same
→ ~~Voo~~ we look at different gas.
↳ evidens of 2 atomic phases in ISM

$T_B = T_c e^{-\tau_\nu}$ works for absorption → Tem of cold medium is known

CNM : 50-100 k clouds
WNM : ~5000 k not continuous distribution
→ Question on exam

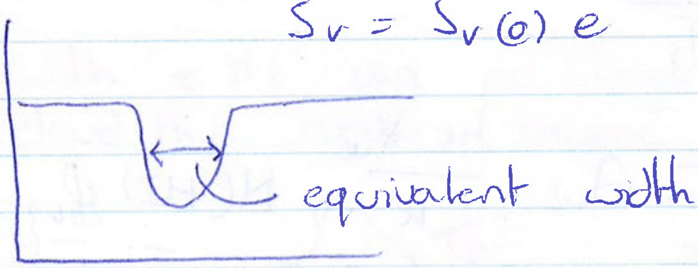
Leave radio and move to optical / UV

Radiative transfer ~~in terms of~~

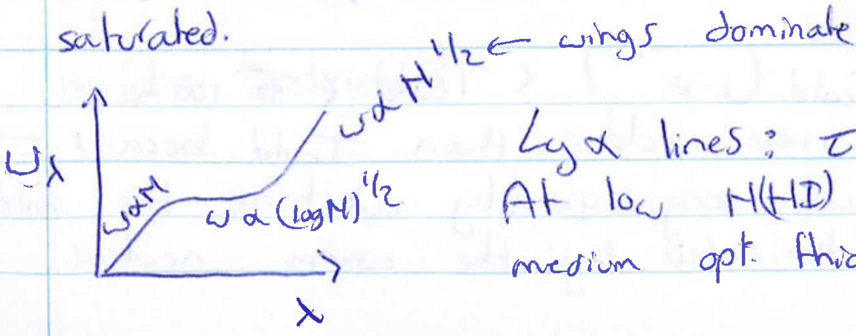
$$S_\nu = S_\nu(0)\, e^{-\tau_\nu} + B_\nu(T_{ex})\, d\Omega (1-e^{-\tau_\nu})$$

Usually non-prohibited transitions, A_{ij} is small and decay term dominates so

$$S_\nu = S_\nu(0)\, e^{-\tau_\nu}$$



τ cannot become lower then 0. It will become saturated.



Lyα lines: $\tau_0 = 0.59 \left(\frac{N(HI)}{10^{13}}\right)\left(\frac{10\,km s^{-1}}{G}\right)$
At low N(HI), ~~τ_0 large thus~~ medium opt. thick