

# Interstellar Medium (ISM)

Week 5

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# Neutral Medium 3

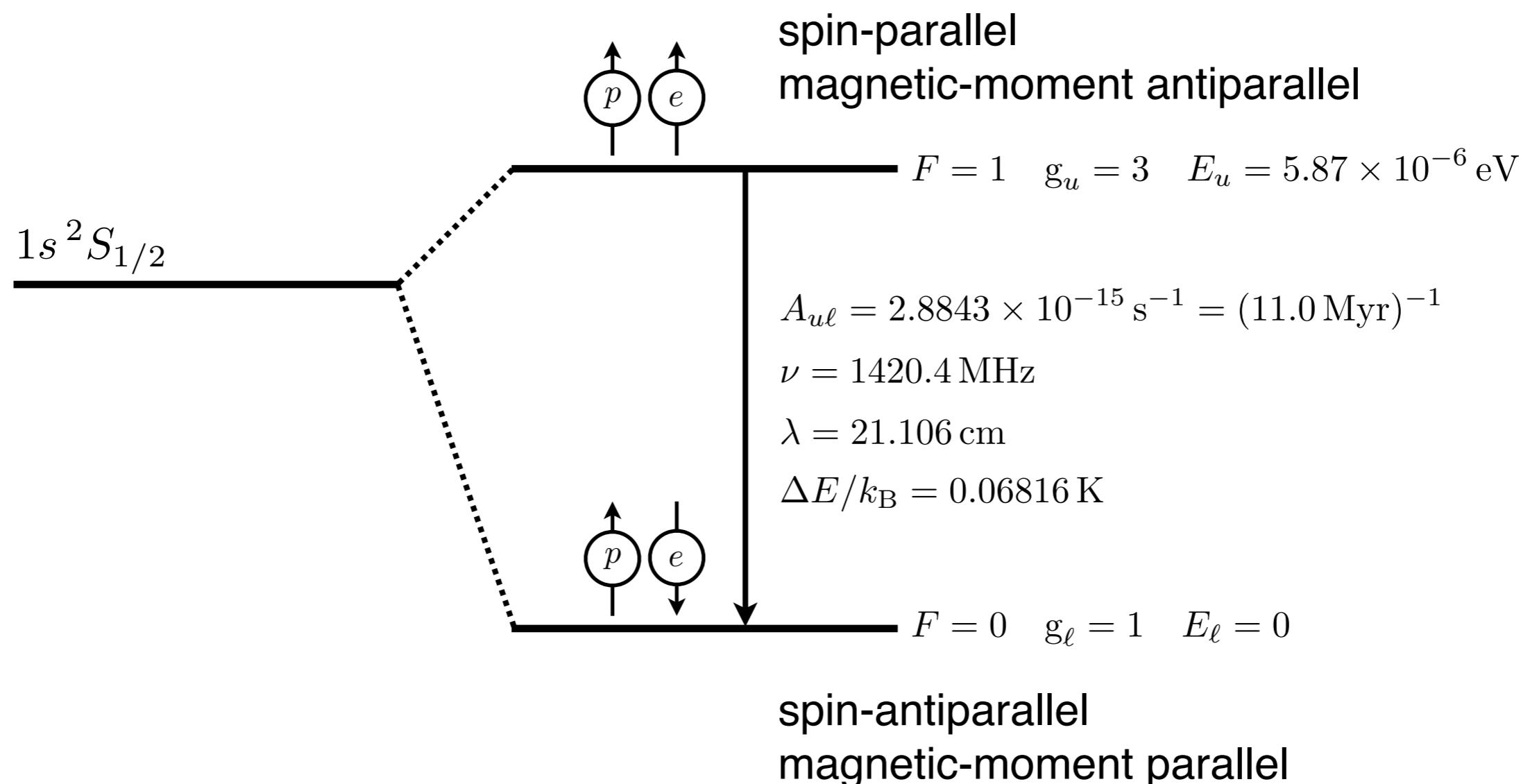
- H I 21 cm line
- Warm Neutral Medium

# 21 cm hyperfine line

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- The CNM and WNM, taken together, provide over half the mass of the ISM.
  - H is the most abundant element in the universe. In the CNM and WNM, most of the hydrogen is in the form of neutral atoms.
  - The Ly $\alpha$  line of H provides a useful probe of the properties of the CNM and WNM. However, at its wavelength the Earth's atmosphere is highly opaque, and thus observing Ly $\alpha$  absorption requires orbiting UV satellites. In addition, Ly $\alpha$  can be seen in absorption only along those lines of sight toward sources with a high UV flux.
  - To do a global survey of atomic hydrogen in the galaxy, we need some way of easily detecting radiation from hydrogen, regardless of its kinetic temperature or number density.
  - Such a way was first found in 1944, by Henk van de Hulst. He attempted to find emission lines at the wavelengths  $\sim 1$  cm to 20 m, at which the Earth's atmosphere is transparent. He then realized that the hyperfine structure line resulting from a flip of the electron spin within a hydrogen atom should have a wavelength of 21 cm. This was confirmed by Harold Ewen and Edward Purcell in 1951, when they first detected 21 cm emission from the Milky Way.

# Hyperfine splitting of the 1s ground state of atomic H



## Difference between Ly $\alpha$ and 21 cm transitions

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- The excitation energy for Ly $\alpha$  ( $E = 10.2 \text{ eV}$ ,  $E/k = 118,000 \text{ K}$ ) is much higher than the kinetic temperature of the neutral ISM.

$$\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell} \exp\left(-\frac{118,000 \text{ K}}{T}\right) \approx 1.7 \times 10^{-51} \text{ at } T = 1000 \text{ K}$$

- Collisional excitation is unimportant, and most hydrogen atoms are in the lower level of the Ly $\alpha$  transition.
- The Ly $\alpha$  has a higher energy by a factor of  $1.7 \times 10^6$  than the 21 cm.
- The excitation energy for 21 cm is  $\sim 6 \mu\text{m}$ , and its equivalent temperature  $E/k = 0.068 \text{ K}$  is much lower than the temperature of the cosmic microwave background.
  - Even the CMB is able to populate the upper level.
  - Thus, there is ample opportunity to populate the upper energy level of the 21 cm hyperfine transition. In excitation equilibrium, the level populations for the 21 cm levels.

$$\frac{n_u}{n_\ell} = \frac{g_u}{g_\ell} e^{-h\nu/kT} = 3 e^{-0.068 \text{ K}/T} \approx 3 \longrightarrow n_u \approx \frac{3}{4} n_{\text{H}}, \quad n_\ell \approx \frac{1}{4} n_{\text{H}}$$

- In fact, the hyperfine levels may not be in excitation equilibrium. Radio astronomers use the term ***spin temperature*** for 21 cm rather than the “excitation temperature.”

# Emissivity and Optical Depth

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- **Emissivity:** The upper level contains  $\sim 75\%$  of the H I under all conditions of interest, and thus the 21-cm emissivity is effectively independent of the spin temperature.

$$j_\nu = n_u \frac{A_{u\ell}}{4\pi} h\nu_{u\ell} \phi_\nu \approx \frac{3}{16\pi} A_{u\ell} h\nu_{u\ell} n_H \phi_\nu \quad \left( n_u \approx \frac{3}{4} n_H \right)$$

- **Optical depth**

$$\kappa_\nu = n_\ell \sigma_{\ell u} - n_u \sigma_{u\ell} = n_\ell \sigma_{\ell u} \left( 1 - e^{-h\nu_{u\ell}/kT_{\text{spin}}} \right)$$

Because  $h\nu_{u\ell}/kT_{\text{spin}} \ll 1$  for all conditions of interest, the correction for stimulated emission is very important!

$$\kappa_\nu \approx n_\ell \sigma_{\ell u} \frac{h\nu_{u\ell}}{kT_{\text{spin}}} \ll n_\ell \sigma_{\ell u} \quad \xleftarrow{\hspace{1cm}} \quad e^{-h\nu_{u\ell}/kT_{\text{spin}}} \approx 1 - k\nu_{u\ell}/kT_{\text{spin}}$$

$$\begin{aligned} \kappa_\nu &\approx \left( \frac{1}{4} n_H \right) \left( \frac{g_u}{g_\ell} \frac{c^2}{8\pi\nu_{u\ell}^2} A_\ell \phi_\nu \right) \frac{h\nu_{u\ell}}{kT_{\text{spin}}} \quad \left( n_u \approx \frac{1}{4} n_H \right) \\ &= \frac{3}{32\pi} A_{u\ell} \frac{hc \lambda_{u\ell}}{kT_{\text{spin}}} n_H \phi_\nu \end{aligned}$$

- The damping constant of the 21 cm line profile is extremely small, and thus we can assume that the line profile is a Gaussian.

$$a = \frac{\gamma_{u\ell}}{4\pi} \frac{\lambda_{u\ell}}{b} = 4.844 \times 10^{-20} \left( \frac{\gamma_{u\ell}}{2.8843 \times 10^{-15} \text{ s}^{-1}} \right) \left( \frac{\lambda_{u\ell}}{21.106 \text{ cm}} \right) \left( \frac{1 \text{ km s}^{-1}}{b} \right)$$

- Hence,

$$\phi_\nu = \frac{1}{\sqrt{\pi} \Delta\nu_D} H(u, a) \approx \frac{c}{\sqrt{\pi} \nu_{\ell u} b} e^{-u^2} \quad \left( u = v/b, \ b = \sqrt{2}\sigma_V = \sqrt{2kT_{\text{gas}}/m_{\text{H}}} \right)$$

$$\begin{aligned} \tau_\nu &= \kappa_\nu s = \frac{3}{32\pi} A_{u\ell} \frac{hc \lambda_{u\ell}}{kT_{\text{spin}}} N_{\text{HI}} \phi_\nu & N_{\text{HI}} \equiv \int n_{\text{H}} ds \text{ is the column density of HI.} \\ &= \frac{3}{32\pi} \frac{1}{\sqrt{\pi}} \frac{A_{u\ell} \lambda_{u\ell}^2}{b} \frac{hc}{kT_{\text{spin}}} N_{\text{HI}} e^{-u^2} & \sim 10^{21} \text{ cm}^{-21} \text{ toward the Galactic disk.} \\ &= 3.111 \left( \frac{N_{\text{HI}}}{10^{21} \text{ cm}^{-2}} \right) \left( \frac{100 \text{ K}}{T_{\text{spin}}} \right) \left( \frac{1 \text{ km s}^{-1}}{b} \right) e^{-u^2} & \text{Some lines of sight through our} \\ \text{or } \tau_\nu &= 2.201 \left( \frac{N_{\text{HI}}}{10^{21} \text{ cm}^{-2}} \right) \left( \frac{100 \text{ K}}{T_{\text{spin}}} \right) \left( \frac{1 \text{ km s}^{-1}}{b/\sqrt{2}} \right) e^{-u^2} & \text{galaxy (at high galactic latitude)} \\ && \text{are optically thin and other lines} \\ && \text{of sight (at low galactic latitude)} \\ && \text{are optically thick at 21 cm.} \end{aligned}$$

- Self-absorption in the 21-cm line can be important*** in many sightlines in the ISM.
- The optical depth is inversely proportional to the spin temperature.***

# [1] Column Density Determination

- **Radioastronomers express the line profile as a function of radial velocity rather than of frequency.** This is logical because line broadening is only caused by the Doppler effect, its natural width being extremely narrow since the lifetime of the upper level is only limited by collisions which is rare in the diffuse medium.
- We first define the column density per velocity interval.

$$\frac{dN_{\text{HI}}}{dv} = N_{\text{HI}} \phi_v = N_{\text{HI}} \frac{1}{\lambda_{u\ell}} \phi_\nu \quad \phi_\nu = \phi_v \left| \frac{dv}{d\nu} \right| = \frac{1}{\lambda_{u\ell}} \phi_\nu$$

- The column density can be written:

$$\tau_\nu = \frac{3}{32\pi} A_{u\ell} \frac{hc \lambda_{u\ell}}{kT_{\text{spin}}} N_{\text{HI}} \phi_\nu \rightarrow \tau(v) = \frac{3}{32\pi} A_{u\ell} \frac{hc \lambda_{u\ell}^2}{kT_{\text{spin}}(v)} \frac{dN_{\text{HI}}}{dv}$$

$$\begin{aligned} \frac{dN_{\text{HI}}}{dv} &= \frac{32\pi}{3} \frac{k}{A_{u\ell} hc \lambda_{u\ell}^2} T_{\text{spin}}(v) \tau(v) \\ &= 1.813 \times 10^{18} \frac{T_{\text{spin}}(v) \tau(v)}{\text{K}} \left[ \frac{\text{cm}^{-2}}{\text{km s}^{-1}} \right] \end{aligned} \quad N_{\text{HI}} = \int dv \frac{dN_{\text{HI}}}{dv}$$

- This indicates that ***we need to know not only the optical depth but also the spin temperature to evaluate the column density***. However, in an optically thin limit, we will show that the dependency on the spin temperature is removed.

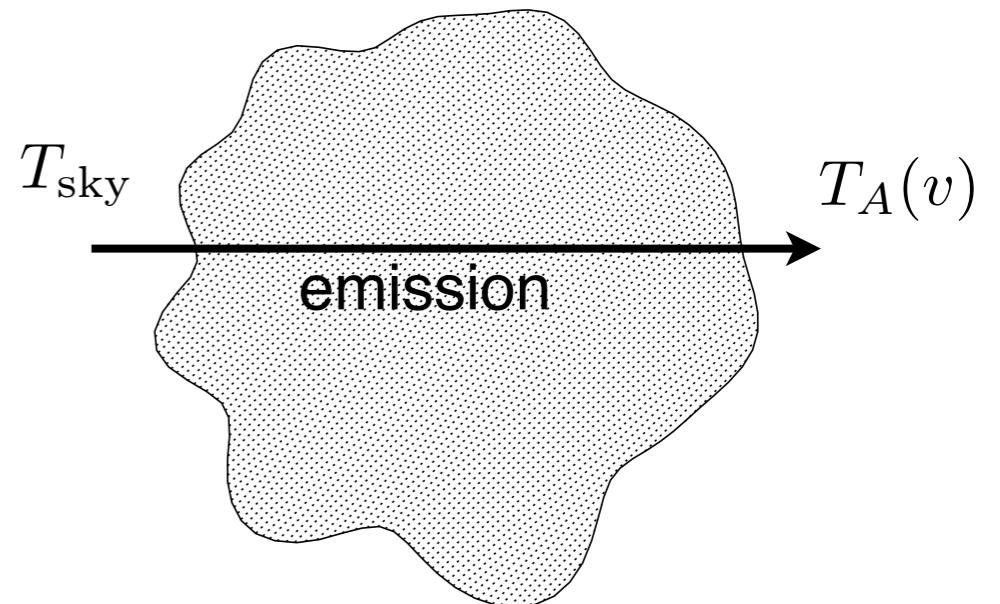
- **Optically thin case:** Suppose we are looking through an optically thin layer of neutral hydrogen toward a “**dark sky**”, which is fainter than the hydrogen cloud, with an antenna temperature  $T_{\text{sky}}$ .
  - In the optically thin limit, the RT equation becomes

$$\begin{aligned}
 T_A(v) &= T_{\text{sky}} e^{-\tau_v} + T_{\text{spin}}(v) (1 - e^{-\tau_v}) \\
 &= T_{\text{sky}} + (T_{\text{spin}}(v) - T_{\text{sky}}) (1 - e^{-\tau_v}) \\
 &\approx T_{\text{sky}} + T_{\text{spin}}(v) \tau_v \quad \leftarrow \tau_v \ll 1, \quad T_{\text{sky}} \ll T_{\text{spin}}(v) \\
 \tau(v) &\approx \frac{T_A(v) - T_{\text{sky}}}{T_{\text{spin}}(v)}
 \end{aligned}$$

- The column density per unit velocity interval is

$$\begin{aligned}
 \frac{dN_{\text{HI}}}{dv} &\approx \frac{32\pi}{3} \frac{k}{A_{u\ell} h c \lambda_{u\ell}^2} [T_A(v) - T_{\text{sky}}] \\
 &= 1.813 \times 10^{18} \frac{T_A(v) - T_{\text{sky}}}{\text{K}} \left[ \frac{\text{cm}^{-2}}{\text{km s}^{-1}} \right]
 \end{aligned}$$

$$N_{\text{HI}} = \int dv \frac{dN_{\text{HI}}}{dv}$$



We measure the antenna temperature of the dark sky from the continuum at frequencies well above and below the 21-cm emission feature.

- Therefore, the intensity integrated over the line profile gives us the total H I column density without need to know  $T_{\text{spin}}$ , provided that self-absorption is not important.

- **Alternative approach:**

- If we now neglect absorption, then

$$\begin{aligned} \frac{dI_\nu}{ds} &= -\kappa_\nu I_\nu + j_\nu & \longrightarrow & I_\nu = I_\nu(0) + \int j_\nu ds \\ &\approx j_\nu & & = I_\nu(0) + \frac{3}{16\pi} A_{u\ell} h \nu_{u\ell} \phi_\nu N_{\text{HI}} \end{aligned}$$

- Now suppose that  $I_\nu(0)$  is known independently. We can then integrate the intensity over the line

$$\int [I_\nu - I_\nu(0)] d\nu = \frac{3}{16\pi} A_{u\ell} h \nu_{u\ell} N_{\text{HI}}$$

- This can be expressed in terms of antenna temperature  $T_A$  and relative velocity  $v = [(\nu - \nu_{u\ell})/\nu_{u\ell}] c$

$$\begin{aligned} \int [T_A - T_A(0)] dv &= \int \frac{c^2}{2k\nu^2} [I_\nu - I_\nu(0)] \frac{c}{\nu_{u\ell}} d\nu \\ &\approx \frac{c^3}{2k\nu_{u\ell}^3} \frac{3}{16\pi} A_{u\ell} h \nu_{u\ell} N_{\text{HI}} \\ &= \frac{3}{32\pi} \frac{hc\lambda_{u\ell}^2}{k} A_{u\ell} N_{\text{HI}} \end{aligned}$$

- We, then, obtain the same equation as before:

$$\begin{aligned} N_{\text{HI}} &\approx \frac{32\pi}{3} \frac{k}{A_{u\ell} h c \lambda_{u\ell}^2} \int [T_A - T_A(0)] dv \\ &= 1.813 \times 10^{18} \int \frac{T_A - T_A(0)}{\text{K km s}^{-1}} dv \quad [\text{cm}^{-2}] \end{aligned}$$

- Here, we did not use the relation between the optical depth and column density.
  - In the first method, we assumed that  $\tau_\nu \ll 1$  and  $I_\nu(0) \ll S_\nu$ :

$$\begin{aligned} I_\nu &= I_\nu(0)e^{-\tau_\nu} + S_\nu (1 - e^{-\tau_\nu}) \\ &= I_\nu(0) + [S_\nu - I_\nu(0)] (1 - e^{-\tau_\nu}) \\ &\approx I_\nu(0) + S_\nu \tau_\nu \end{aligned}$$

- In the second method, we completely ignored the absorption.

$$\begin{aligned} \frac{dI_\nu}{ds} &= -\kappa_\nu I_\nu + j_\nu && \text{This may be a zeroth order approximation.} \\ &\approx j_\nu \end{aligned}$$

## [2] Spin Temperature Determination

- In cases where we have a “**bright background radio source** with a continuum spectrum (a typical radio-loud quasar or an active galactic nucleus, or a radio galaxy), we can study both emission and absorption by the foreground ISM in our galaxy by comparing “**on-source” and “off-source” observations.**
- The spectra measured on the blank sky and on the radio source are, respectively,

$$T_A^{\text{on}}(v) = T_{\text{RS}} e^{-\tau_v} + T_{\text{spin}}(v) (1 - e^{-\tau_v})$$

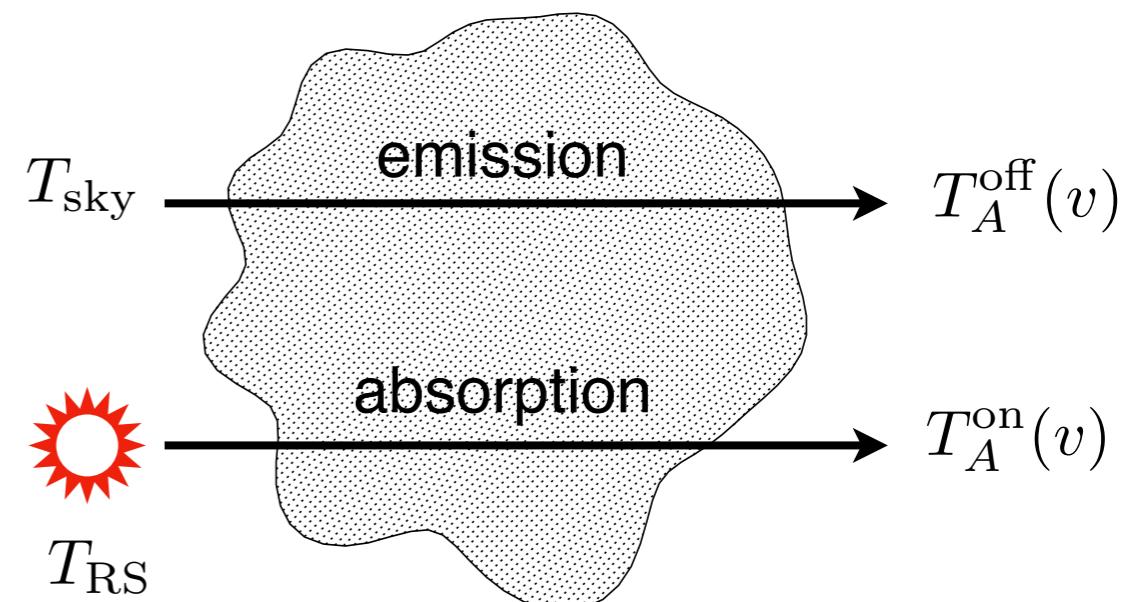
$$T_A^{\text{off}}(v) = T_{\text{sky}} e^{-\tau_v} + T_{\text{spin}}(v) (1 - e^{-\tau_v})$$

- These two equations can be solved for the two unknowns,  $\tau(v)$  and  $T_{\text{spin}}(v)$ .

$$\tau(v) = \ln \left[ \frac{T_{\text{RS}} - T_{\text{sky}}}{T_A^{\text{on}}(v) - T_A^{\text{off}}(v)} \right]$$

$$T_{\text{spin}}(v) = \frac{T_A^{\text{off}}(v)T_{\text{RS}} - T_A^{\text{on}}(v)T_{\text{sky}}}{(T_{\text{RS}} - T_{\text{sky}}) - (T_A^{\text{on}}(v) - T_A^{\text{off}}(v))}$$

- We can also derive the column density from these two quantities for an optically thick cloud.



The solution gives, in general, the spin temperature as a function of velocity.

- ***Optically thin case:*** We now consider an optically thin case where the radio source is much brighter than the spin temperature of the intervening hydrogen cloud, and assume that the spin temperature is independent of velocity.
  - The RT equation for the “on-source” and “off-source” measurements can be written:

assumptions :  $T_{\text{RS}} \gg T_{\text{spin}}$ ,  $\tau_v \ll 1$ , and  $T_{\text{spin}} = \text{constant}$

$$\begin{aligned} T_A^{\text{on}}(v) &= T_{\text{RS}} e^{-\tau_v} + T_{\text{spin}}(v) (1 - e^{-\tau_v}) \\ T_A^{\text{off}}(v) &= T_{\text{sky}} e^{-\tau_v} + T_{\text{spin}}(v) (1 - e^{-\tau_v}) \end{aligned} \quad \xrightarrow{\hspace{1cm}} \quad \begin{aligned} T_A^{\text{on}}(v) &\approx T_{\text{RS}} e^{-\tau_v} \\ T_A^{\text{off}}(v) &= T_{\text{sky}} + (T_{\text{spin}} - T_{\text{sky}}) (1 - e^{-\tau_v}) \end{aligned}$$

- Using the absorption spectrum from the “on-source” observation, we can “approximately” obtain the “velocity equivalent width.”

$$\begin{aligned} W_v &= \int dv (1 - e^{-\tau_v}) \quad \implies \quad c \int \frac{d\nu}{\nu_{ul}} (1 - e^{-\tau_\nu}) = cW \\ &\approx \int dv \left[ \frac{T_A^{\text{on}}(v) - T_{\text{RS}}}{T_{\text{RS}}} \right] \end{aligned}$$

- Rearranging the equation for the “off-source” observation, we obtain

$$\int dv [T_A^{\text{off}}(v) - T_{\text{sky}}] = (T_{\text{spin}} - T_{\text{sky}}) \int dv (1 - e^{-\tau_v})$$

- Combining this with the definition of the velocity equivalent width, we now obtain the equation for the spin temperature:

$$T_{\text{spin}} - T_{\text{sky}} = \frac{1}{W_v} \int dv [T_A^{\text{off}}(v) - T_{\text{sky}}]$$

- This equation can be converted to the column density:

$$T_{\text{spin}} \approx T_{\text{sky}} + \frac{3}{32\pi} \frac{A_{u\ell} h c \lambda_{u\ell}^2}{k} \frac{1}{W_v} \int dv \frac{dN_{\text{HI}}}{dv} \quad \leftarrow \quad \frac{dN_{\text{HI}}}{dv} \approx \frac{32\pi}{3} \frac{k}{A_{u\ell} h c \lambda_{u\ell}^2} [T_A(v) - T_{\text{sky}}]$$

- In summary, in an optically thin limit,

$$\begin{aligned} T_{\text{spin}} &\approx T_{\text{sky}} + \frac{3}{32\pi} \frac{A_{u\ell} h c \lambda_{u\ell}^2}{k} \frac{N_{\text{HI}}}{W_v} \\ &= T_{\text{sky}} + 0.5516 \frac{N_{\text{HI}}/10^{18} \text{ cm}^{-2}}{W_v/\text{km s}^{-1}} [\text{K}] \end{aligned}$$

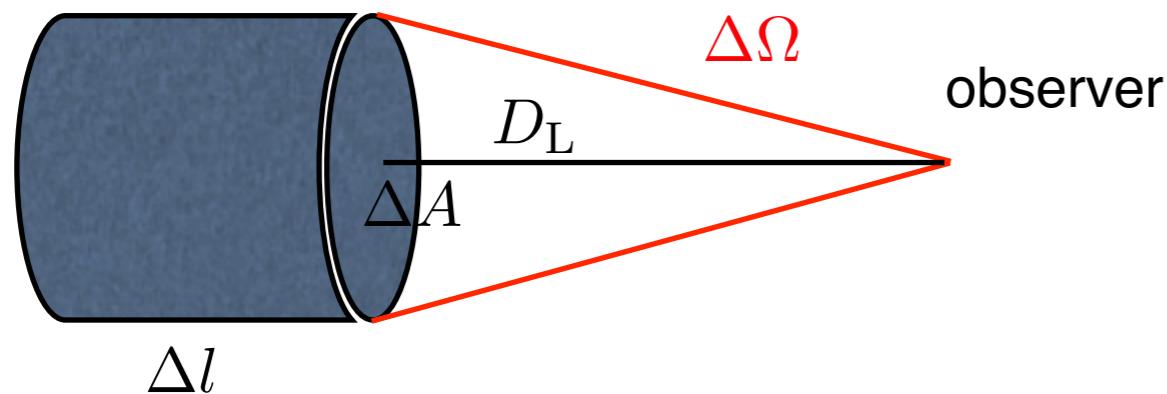
$$T_{\text{spin}} = T_{\text{sky}} + \frac{1}{W_v} \int dv [T_A^{\text{off}}(v) - T_{\text{sky}}]$$

$$\begin{aligned} N_{\text{HI}} &\approx \frac{32\pi}{3} \frac{k}{A_{u\ell} h c \lambda_{u\ell}^2} \int dv [T_A^{\text{off}}(v) - T_{\text{sky}}] \\ &= 1.813 \times 10^{18} \int dv \left[ \frac{T_A^{\text{off}}(v) - T_{\text{sky}}}{\text{K km s}^{-1}} \right] [\text{cm}^{-2}] \end{aligned}$$

$$W_v \approx \int dv \left[ \frac{T_A^{\text{on}}(v) - T_{\text{RS}}}{T_{\text{RS}}} \right]$$

# H I mass of an External Galaxy

- With the assumption that the emitting regions are optically thin, the total mass  $M_{\text{HI}}$  of H I in an external galaxy can be determined from the observed flux in the 21-cm line:



$F_\nu$  = observed flux density

$$F_{\text{obs}} = \int F_\nu d\nu_{\text{obs}} = I \Delta\Omega$$

$$I = \int I_\nu d\nu_{\text{obs}} = \frac{3}{16\pi} A_{u\ell} h \nu_{u\ell} N_{\text{HI}}$$

- Here,  $D_L$  is the luminosity distance to the galaxy.

$$n_{\text{H}} \Delta l = N_{\text{HI}}$$

$$\Delta A = D_L^2 \Delta\Omega = D_L^2 \frac{F_{\text{obs}}}{I}$$

$$\begin{aligned} M_{\text{HI}} &= m_{\text{H}} n_{\text{H}} \Delta V = m_{\text{H}} n_{\text{H}} \Delta l \Delta A \\ &= m_{\text{H}} N_{\text{HI}} D_L^2 \frac{F_{\text{obs}}}{I} \end{aligned}$$

$$\begin{aligned} \therefore M_{\text{HI}} &= \frac{16\pi}{3} \frac{m_{\text{H}}}{A_{u\ell} h \nu_{u\ell}} D_L^2 F_{\text{obs}} \\ &= 4.945 \times 10^7 M_{\odot} \left( \frac{D_L}{\text{Mpc}} \right)^2 \left( \frac{F_{\text{obs}}}{\text{Jy MHz}} \right) \end{aligned}$$

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- If the redshift of the galaxy is  $z$  :

$$\nu_{\text{obs}} = \nu / (1 + z)$$

$$d\nu_{\text{obs}} = \frac{\nu_{u\ell}}{(1 + z)} \frac{dv}{c}$$

$$\begin{aligned} M_{\text{HI}} &= \frac{16\pi}{3} \frac{m_{\text{H}}}{A_{u\ell} h \nu_{u\ell}} D_{\text{L}}^2 \int F_{\nu} d\nu_{\text{obs}} \\ &= \frac{16\pi}{3} \frac{m_{\text{H}}}{A_{u\ell} h \nu_{u\ell}} D_{\text{L}}^2 \frac{\nu_{u\ell}}{c} \frac{1}{1 + z} \int F_{\nu} dv \\ &= \frac{16\pi m_{\text{H}}}{3 A_{u\ell} h c} D_{\text{L}}^2 (1 + z)^{-1} \int F_{\nu} dv \\ &= 2.343 \times 10^5 M_{\odot} (1 + z)^{-1} \left( \frac{D_{\text{L}}}{\text{Mpc}} \right)^2 \frac{\int F_{\nu} dv}{\text{Jy km s}^{-1}} \end{aligned}$$

- Radio astronomers often report the integrated flux in “Jy km s<sup>-1</sup>.”

## Observation: Example 1

- All-sky map of H I 21-cm line intensity from the LAB survey (Kalberla et al. 2005), with angular resolution  $\sim 0.6$  deg.
  - Scale gives  $\log_{10} N(\text{HI}) [\text{cm}^{-2}]$ . The LMC and SMC are visible, with a connecting H I “bridge”.

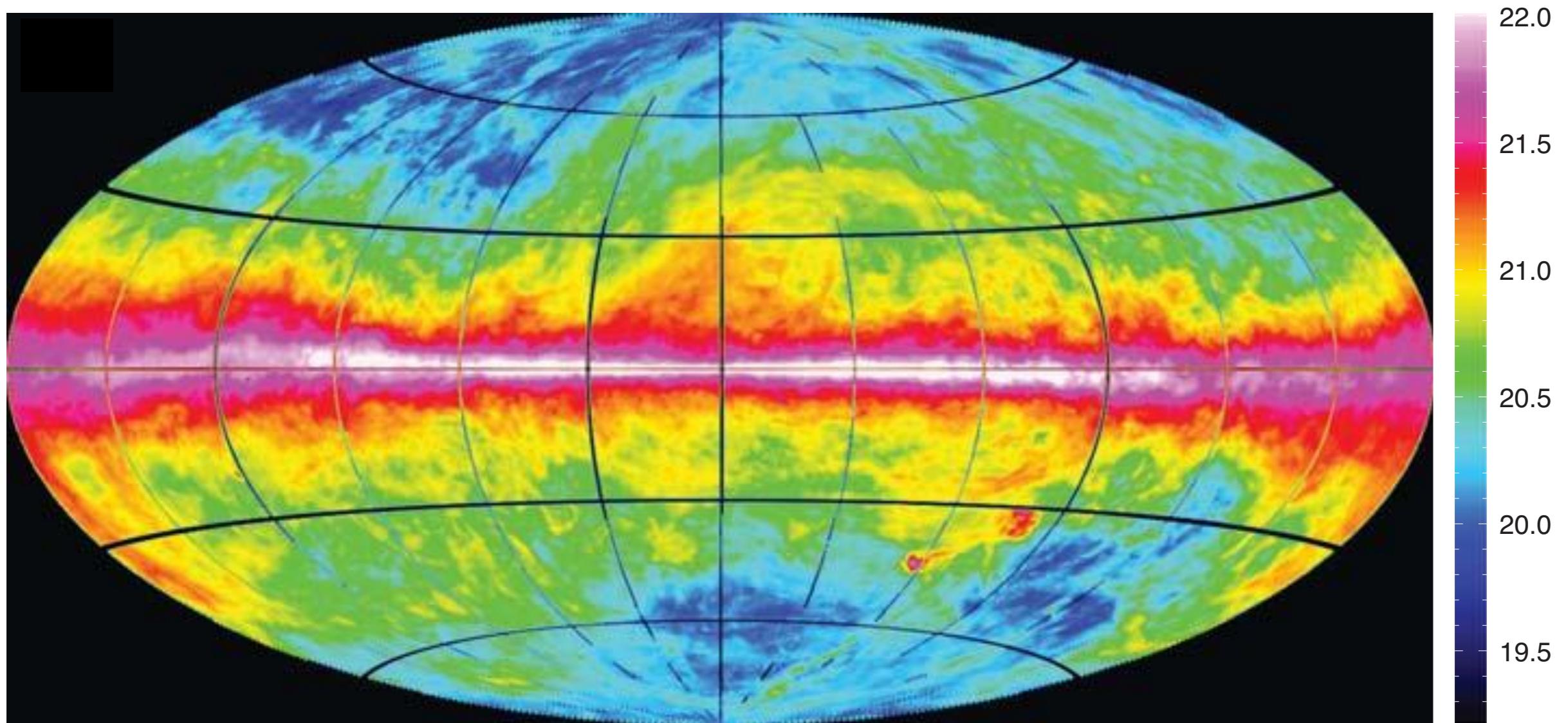
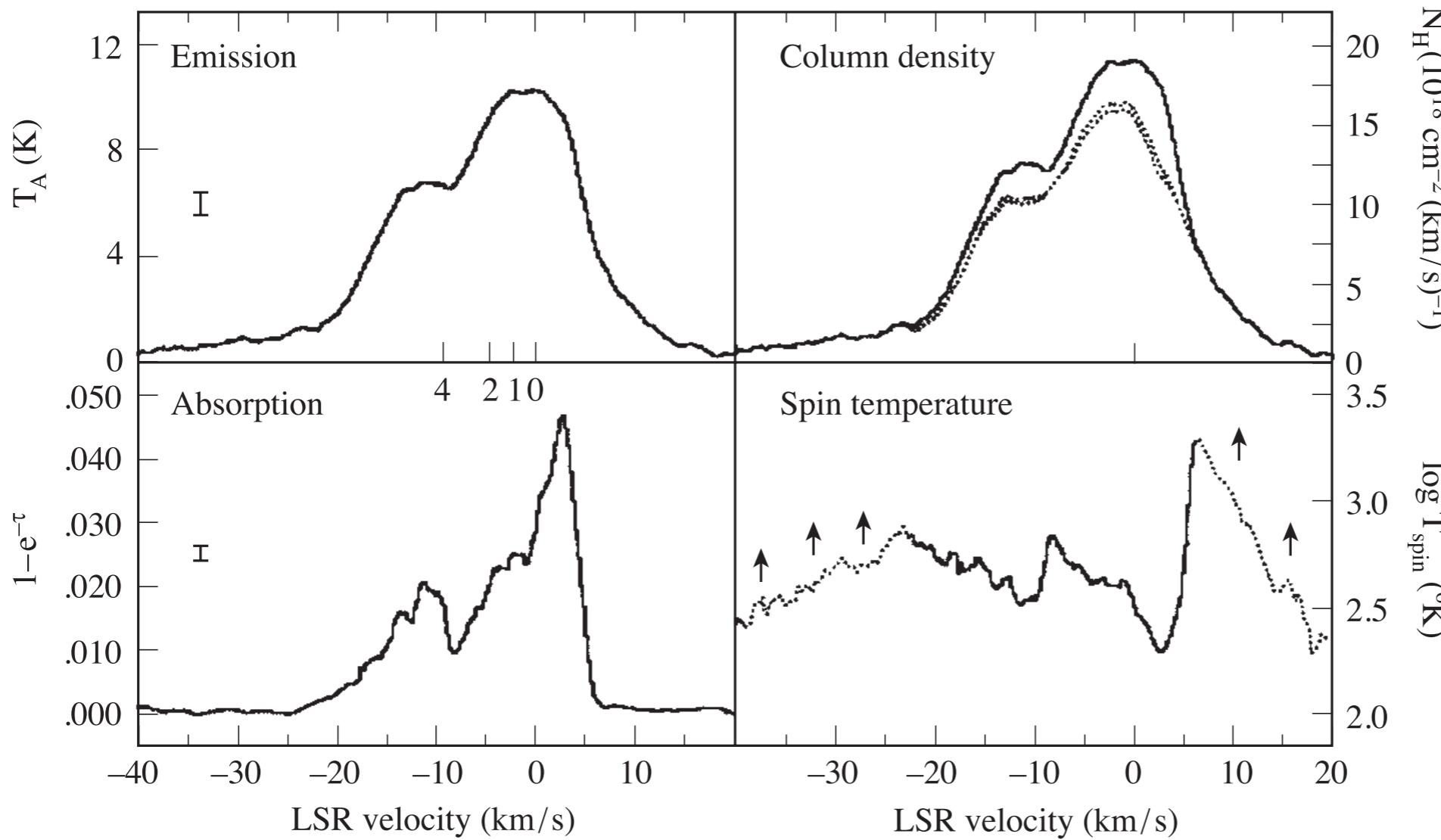


Plate 3 in [Draine]

# Observations: Example 2

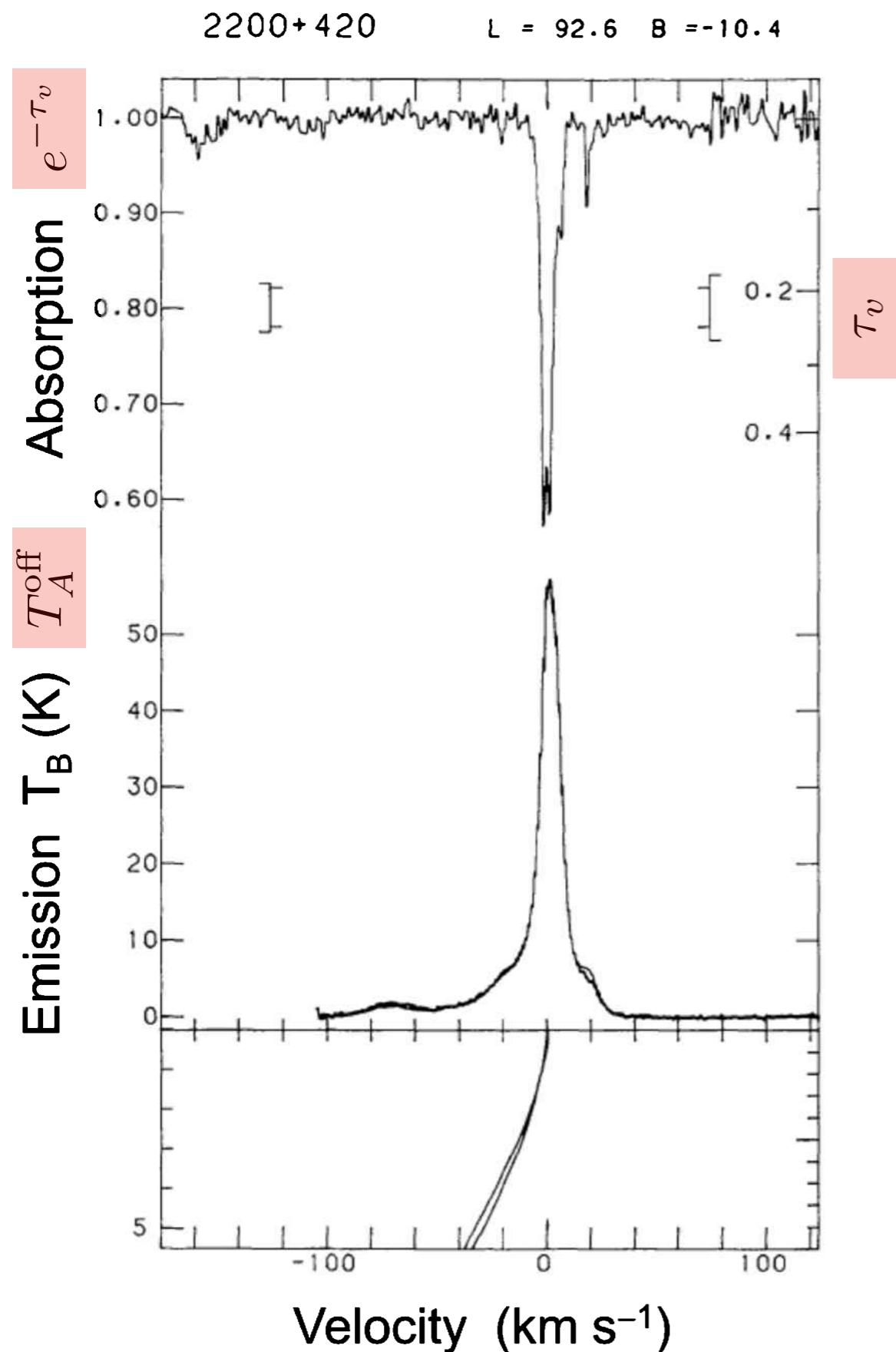
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**Figure 29.1** Left panels: Observed HI emission (off the quasar 3C48) and absorption (toward 3C48, at  $\ell = 134^\circ$ ,  $b = -28.7^\circ$ ). Lower right: spin temperature  $T_{\text{spin}}(v)$  as a function of LSR velocity. Tick marks labeled 0, 1, 2, and 4 on abscissa of left panels show the LSR velocity expected for gas at a distance of 0, 1, 2, 4 kpc (for an assumed Galactic rotation curve). Upper right:  $dN(\text{HI})/dv$  for different assumptions regarding the relative (foreground/background) locations of cold absorbing gas and warm gas seen only in emission. From Dickey et al. (1978).

[Figure 29.1 in Draine]

## Observations: Example 3



H I 21-cm absorption and emission along the line of sight towards BL Lacertae  
 [Dickey et al. 1983; Figure 3.3 in Ryden]

- maximum optical depth :  
 $\tau_v \sim 0.5$
- equivalent width of the absorption line :  
 $W_v = 7 \text{ km s}^{-1}$
- integrated line intensity of the emission line :  

$$\int \Delta T_A^{\text{off}}(v) dv \approx 930 \text{ K km s}^{-1}$$
- column density from the emission line :  
 $N_{\text{HI}} \approx 1.69 \times 10^{21} \text{ cm}^{-2}$
- Now, the spin temperature is  

$$T_{\text{spin}} = \frac{\int \Delta T_A^{\text{off}}(v) dv}{W_v} = \frac{930 \text{ K, km s}^{-1}}{7 \text{ km s}^{-1}}$$
  
 $\approx 133 \text{ K.}$

## Observation: CNM + WNM

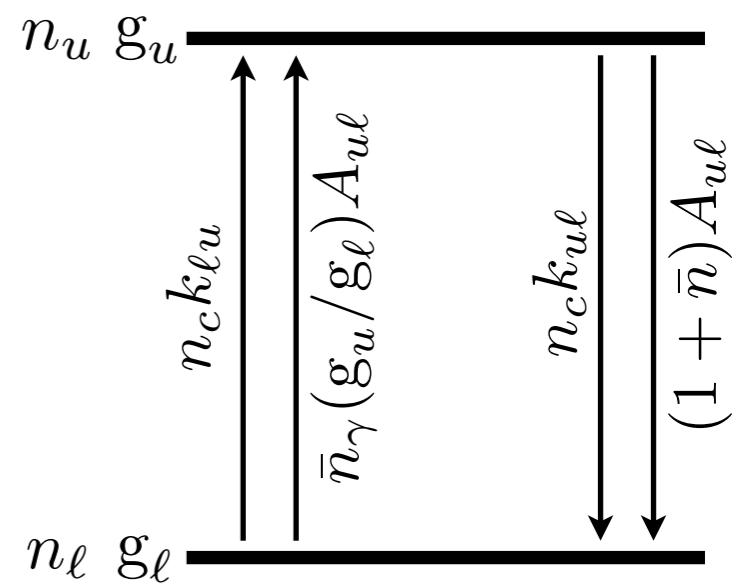
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- The most recent emission-absorption surveys (Heiles & Troland 2003) support the idea that, in the solar neighborhood (i.e., within  $\sim 500$  pc of the Sun), interstellar H I is found primarily in two distinct phases: the CNM and the WNM. About 40% of the H I (by mass) is in the CNM, with a median spin temperature  $T \sim 70$  K. The remaining 60% of the H I is in the WNM phase, which appears to have a volume filling factor  $\sim 50\%$  near the disk midplane.
- Because warm H I absorbs very weakly, for some of the WNM material it is only possible to determine a lower bound on  $T_{\text{spin}}$ . Heiles & Troland (2003) conclude that  $> 48\%$  of the WNM has  $500 < T_{\text{spin}} < 5000$  K, at these temperatures the gas is expected to be thermally unstable.

# Level Population

- In some cases, it is sufficient to consider only the ground state and the first excited state.
  - Consider collisional excitation and de-excitation by some species (e.g., electrons) with density  $n_c$ , and suppose that radiation with the energy density  $u_\nu$ .
  - The population of the excited state must satisfy:

$$\frac{dn_u}{dt} = n_\ell \left[ n_c k_{\ell u} + \bar{n}_\gamma \frac{g_u}{g_\ell} A_{ul} \right] - n_u \left[ n_c k_{ul} + (1 + \bar{n}_\gamma) A_{ul} \right]$$



photon occupation number

$$\left( \bar{n}_\gamma \equiv \frac{c^3}{8\pi h\nu^3} u_\nu \right)$$

- The steady-state solution with radiation and collision present is

$$\frac{n_u}{n_\ell} = \frac{n_c k_{\ell u} + \bar{n}_\gamma (g_u/g_\ell) A_{ul}}{n_c k_{ul} + (1 + \bar{n}_\gamma) A_{ul}}$$

Using this equation, we can calculate the excitation temperature between the two levels.

Here, by the principle of detailed balance, the upward collisional rate coefficient is given in term of the downward rate coefficient by

$$k_{\ell u} = \frac{g_u}{g_\ell} k_{ul} e^{-E_{ul}/kT_{\text{gas}}} \quad (T_{\text{gas}} = \text{gas kinetic energy})$$

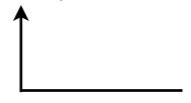
- It is instructive to examine the population equation in various limits:

- In the limit of  $n_c \rightarrow \infty$  and no radiation field  $\bar{n}_\gamma = 0$ :

$$\frac{n_u}{n_\ell} = \frac{n_c k_{\ell u}}{n_c k_{u\ell} + A_{u\ell}} = \frac{k_{\ell u}}{k_{u\ell}} = \frac{g_u}{g_\ell} e^{-E_{u\ell}/kT_{\text{gas}}} \quad \therefore T_{\text{exc}} = T_{\text{gas}}$$

- If  $n_c = 0$  and the radiation field has a brightness temperature of  $T_b = T_{\text{rad}}$  at the frequency  $\nu = E_{u\ell}/h$ :

$$\frac{n_u}{n_\ell} = \frac{\bar{n}_\gamma (g_u/g_\ell)}{(1 + \bar{n}_\gamma)} = \frac{g_u}{g_\ell} e^{-E_{u\ell}/kT_{\text{rad}}} \quad \therefore T_{\text{exc}} = T_{\text{rad}}$$


 $\bar{n}_\gamma = \left( e^{E_{u\ell}/kT_{\text{rad}}} - 1 \right)^{-1} \implies 1 + \bar{n}_\gamma = \bar{n}_\gamma e^{E_{u\ell}/kT_{\text{rad}}}$

- If we have a radiation with the brightness temperature  $T_b = T_{\text{rad}} = T_{\text{gas}}$ , then we can show that

$$\frac{n_u}{n_\ell} = \frac{n_c k_{\ell u} + \bar{n}_\gamma (g_u/g_\ell) A_{u\ell}}{n_c k_{u\ell} + (1 + \bar{n}_\gamma) A_{u\ell}} = \frac{g_u}{g_\ell} e^{-E_{u\ell}/kT_{\text{gas}}} \quad \therefore T_{\text{exc}} = T_{\text{rad}} = T_{\text{gas}}$$

# Critical Density

---

- For a collision partner c, we define the critical density  $n_{\text{crit},u}$  for an excited state  $u$  to be the density for which collisional de-excitation equals radiative de-excitation, including stimulated emission:

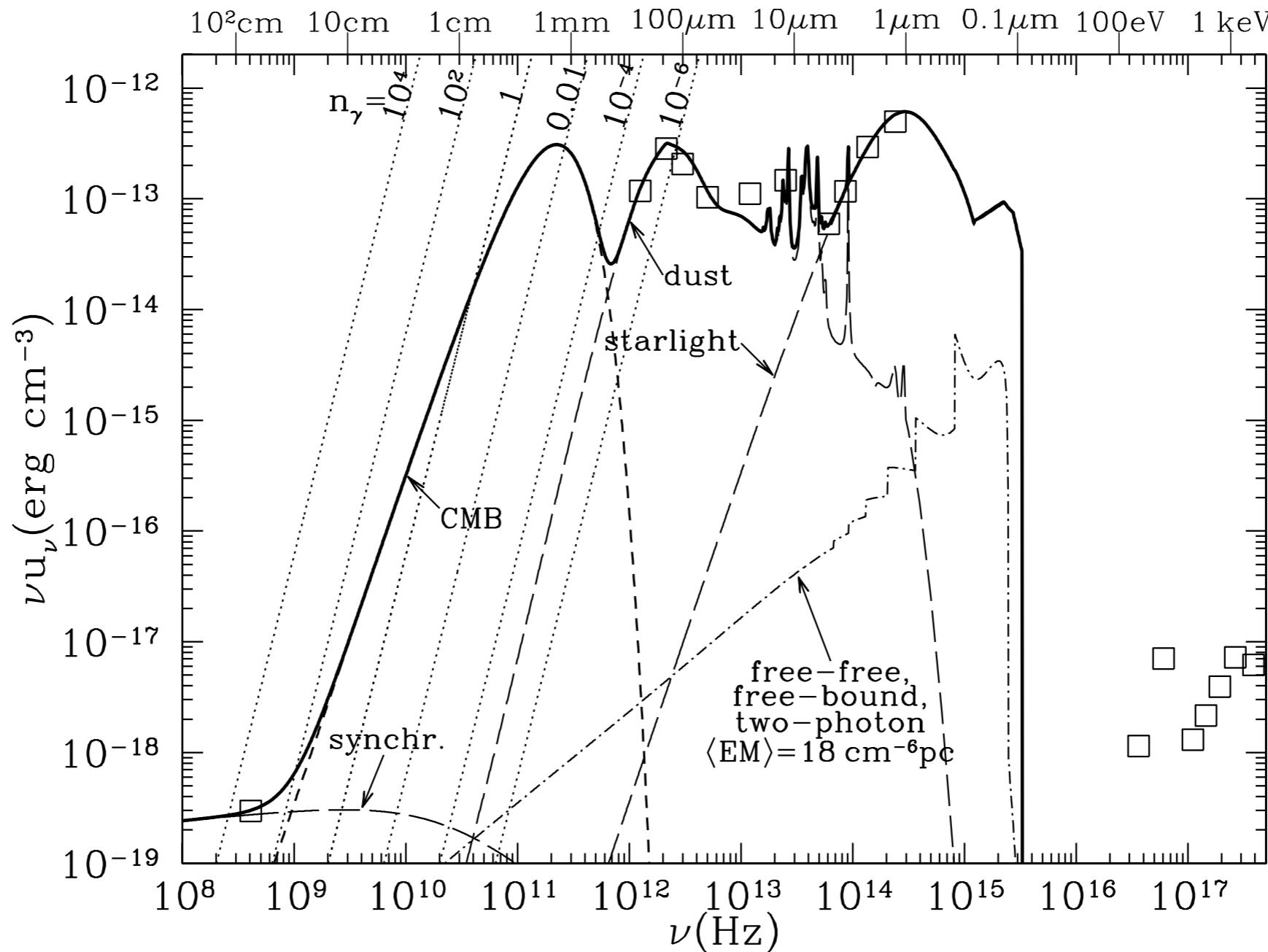
$$n_{\text{crit},u}(c) \equiv \frac{\sum_{\ell < u} [1 + (n_\gamma)_{u\ell}] A_{u\ell}}{\sum_{\ell < u} k_{u\ell}(c)}$$

- Note that this definition applies to multilevel systems, but each excited level  $u$  may have a different critical density. The critical density depends on the intensity of ambient radiation. For many transitions, the correction is unimportant, but for 21-cm line, it is important.

Critical densities for fine-structure excitation [Table 17.1 in Draine, revised for both H and  $e^-$ , errata]

Ion	$\ell$	$u$	$E_\ell/k$	$E_u/k$	$\lambda_{u\ell}$	$n_{\text{crit},u}(\text{H})$	$n_{\text{crit},u}(e^-)$
			(K)	(K)	( $\mu\text{m}$ )	$T = 100 \text{ K}$	$T = 5000 \text{ K}$
C II	$^2\text{P}_{1/2}^{\circ}$	$^2\text{P}_{3/2}^{\circ}$	0	91.21	157.74	$2.7 \times 10^3$	$1.5 \times 10^3$
CI	$^3\text{P}_0$	$^3\text{P}_1$	0	23.60	609.7	620	170
	$^3\text{P}_1$	$^3\text{P}_2$	23.60	62.44	370.37	720	150
OI	$^3\text{P}_2$	$^3\text{P}_1$	0	227.71	63.185	$2.5 \times 10^5$	$4.9 \times 10^4$
	$^3\text{P}_1$	$^3\text{P}_0$	227.71	326.57	145.53	$2.4 \times 10^4$	$8.6 \times 10^3$
Si II	$^2\text{P}_{1/2}^{\circ}$	$^2\text{P}_{3/2}^{\circ}$	0	413.28	34.814	$2.5 \times 10^5$	$1.2 \times 10^5$
Si I	$^3\text{P}_0$	$^3\text{P}_1$	0	110.95	129.68	$4.8 \times 10^4$	$2.8 \times 10^4$
	$^3\text{P}_1$	$^3\text{P}_2$	110.95	321.07	68.473	$9.9 \times 10^4$	$3.6 \times 10^4$

# Interstellar Radiation Fields



**Figure 12.1** Interstellar continuum radiation field in an HI cloud in the solar neighborhood (see text). Spectral lines are not included. Solid line is the sum of all components for  $h\nu \leq 13.6$  eV. Squares show the measured sky brightness at 408 MHz (Haslam et al. 1982), the all-sky measurements by COBE-DIRBE in 10 broad bands from 240  $\mu\text{m}$  to 1.25  $\mu\text{m}$  (Arendt et al. 1998), and all-sky measurements by ROSAT between 150 eV and 2 keV (Snowden 2005, private communication). Dotted lines are contours of constant photon occupation number  $n_\gamma$ .

# Example: H I Spin Temperature

- Collisional rate coefficients:

- Collision with other H atoms

$$\frac{n_1}{n_0} = \frac{n_c k_{01} + \bar{n}_\gamma (g_1/g_0) A_{10}}{n_c k_{10} + (1 + \bar{n}_\gamma) A_{10}}$$

(Allison & Dalgarno 1969; Zygelman 2005)

$$k_{10}(\text{H}) \approx \begin{cases} 1.19 \times 10^{-10} T_2^{0.74 - 0.20 \ln T_2} \text{ cm}^3 \text{ s}^{-1} & (20 \text{ K} < T < 300 \text{ K}) \\ 2.24 \times 10^{-10} T_2^{0.207} e^{-0.876/T_2} \text{ cm}^3 \text{ s}^{-1} & (300 \text{ K} < T < 10^3 \text{ K}) \end{cases}$$

$$k_{01}(\text{H}) \approx 3k_{10}(\text{H})e^{-0.0682 \text{ K}/T}$$

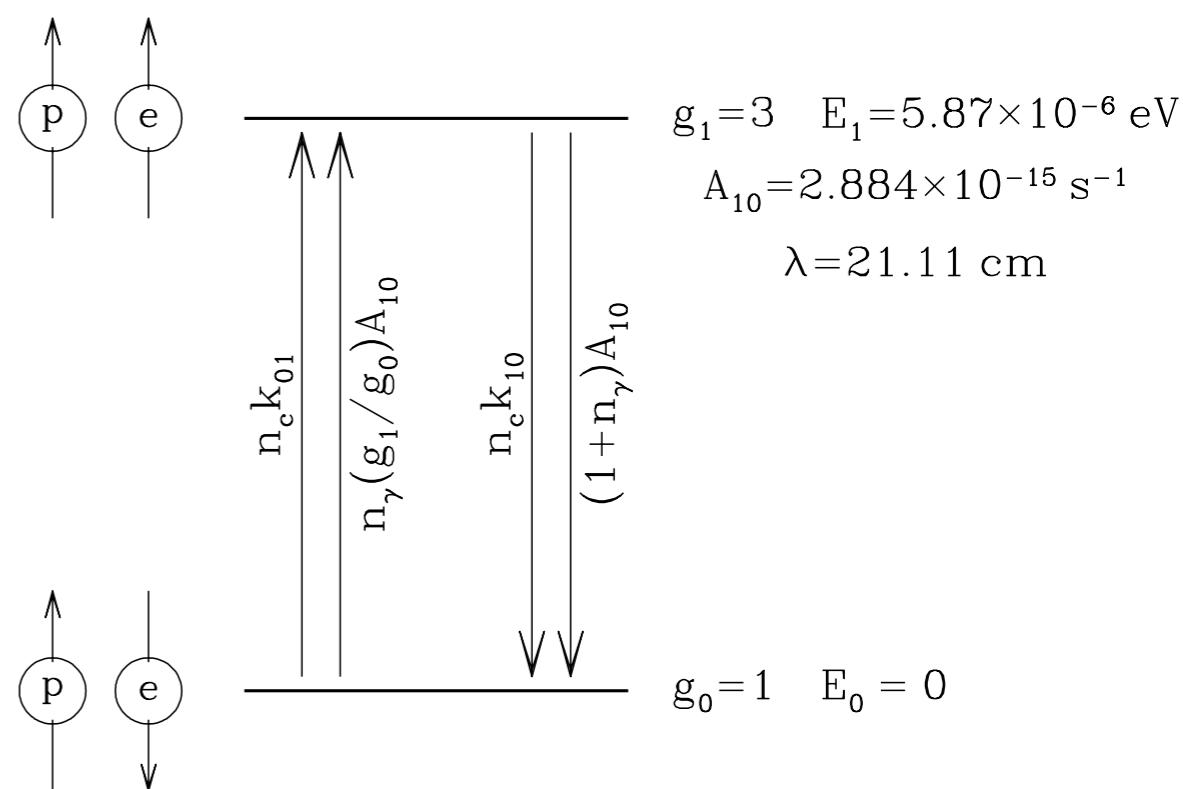
- Collision with electrons

(Furlanetto & Furlanetto 2007)

$$k_{10}(e^-) \approx 2.26 \times 10^{-9} (T/100 \text{ K})^{0.5} \text{ cm}^3 \text{ s}^{-1} \quad (1 \lesssim T \lesssim 500 \text{ K})$$

$$k_{01}(e^-) \approx 3k_{10}(e^-)e^{-0.0682 \text{ K}/T}$$

- This is a factor  $\sim 10$  larger than that for H atoms. However, ***electrons will be minor importance in regions with a fractional ionization***  $x_e \lesssim 0.03$ , such as the CNM and WNM.



- 
- Radiation Field strength
    - The radiation field near 21 cm is dominated by the cosmic microwave background plus Galactic synchrotron emission. The antenna temperature is

$$T_A \approx T_{\text{CMB}} + T_{\text{syn}} = 2.73 \text{ K} + 1.04 \text{ K} = 3.77 \text{ K}$$

- Photon occupation number:

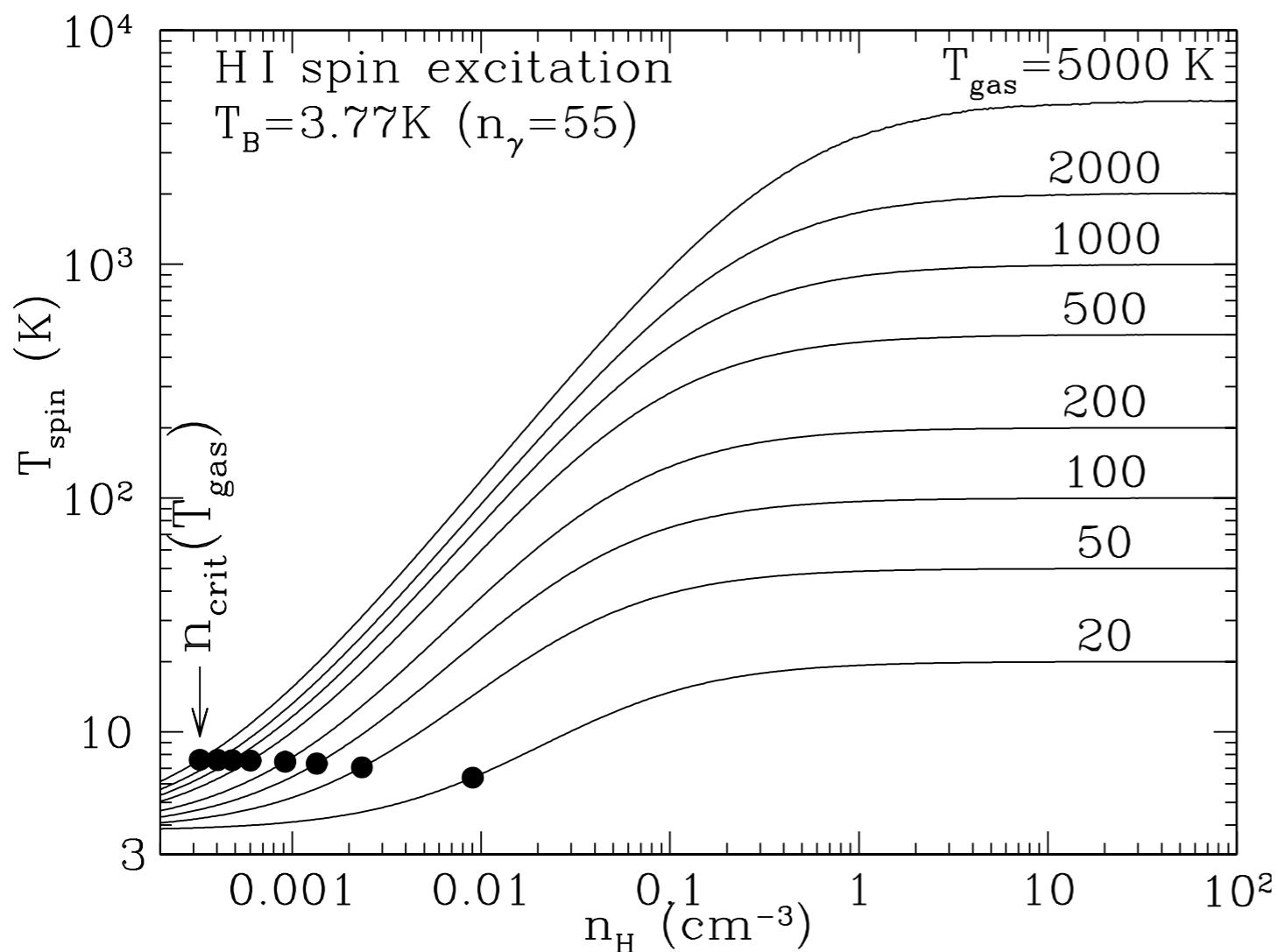
$$\bar{n}_\gamma = \left( e^{h\nu/kT_B} - 1 \right)^{-1} \approx \frac{kT_A}{h\nu} \approx \frac{3.77 \text{ K}}{0.0682 \text{ K}} \approx 55$$

- The critical density is then

$$n_{\text{crit}}(H) \approx 1.7 \times 10^{-3} (T/100 \text{ K})^{-0.66} \text{ cm}^{-3}$$

$$\begin{aligned} n_{\text{crit}} &\approx 0.07 \text{ cm}^{-3} \text{ at } T \sim 10 \text{ K} \\ &\approx 6 \times 10^{-4} \text{ cm}^{-3} \text{ at } T \sim 1000 \text{ K} \end{aligned}$$

- H I spin temperature as a function of density  $n_H$ , including only 21 cm continuum radiation and collisions with H atoms. Ly $\alpha$  scattering is not included.
  - Filled circles show  $n_{\text{crit}}(H)$  for each temperature.
  - It is important to note that one requires  $n \gg n_{\text{crit}}$  in order to have  $T_{\text{spin}}$  within, say, 10% of  $T_{\text{gas}}$ , particularly at high temperatures.



[Fig. 17.2 in Draine]

Note that Ryden states that “in the CNM and WNM, we expect the hyperfine levels of atomic hydrogen to be collisionally excited, and to have a spin temperature close to the gas temperature.” based on that  $n_{\text{crit}} \sim 6 \times 10^{-4} \text{ cm}^{-3}$  at  $T \sim 1000 \text{ K}$ .

However, this is not true in the WNM.

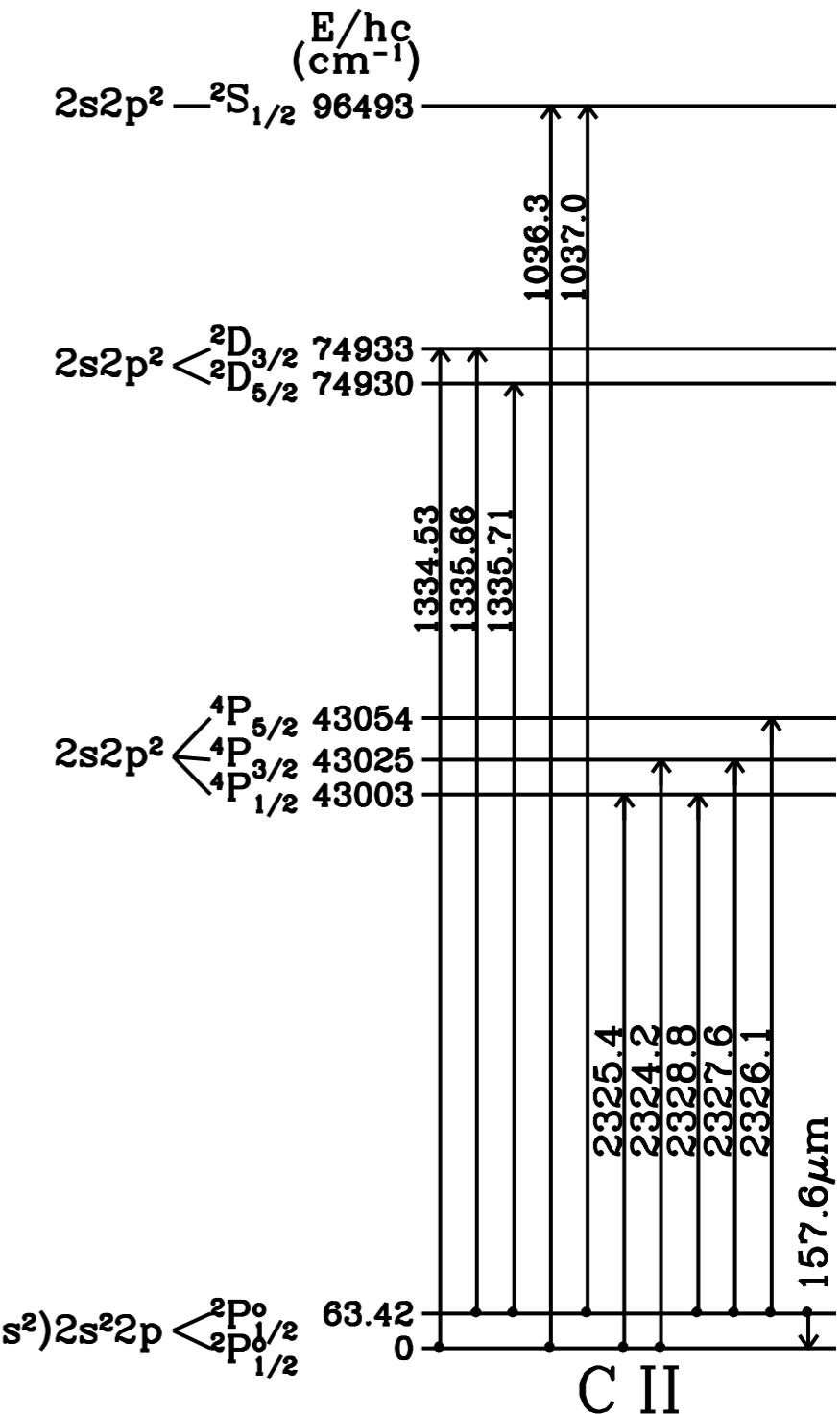
***Only in the CNM, the collisional excitation is strong enough to bring the spin temperature close to the gas kinetic temperature.***

## Example: C II Fine Structure Excitation

- The ground electronic state  $1s^2 2s^2 2p\ ^2P^o$  of C<sup>+</sup> contains two fine-structure levels.
- The electronically excited states have an excitation energy that is much higher than the kinetic temperature of the CNM.

$$2235 \text{ \AA} \rightarrow E_{ul} = 0.56 \text{ eV} \rightarrow T = 6440 \text{ K}$$

- We may, therefore, consider the two fine-structure levels in the ground electronic state to be a two level atom.
- Will the populations of these two levels be thermalized in the ISM?

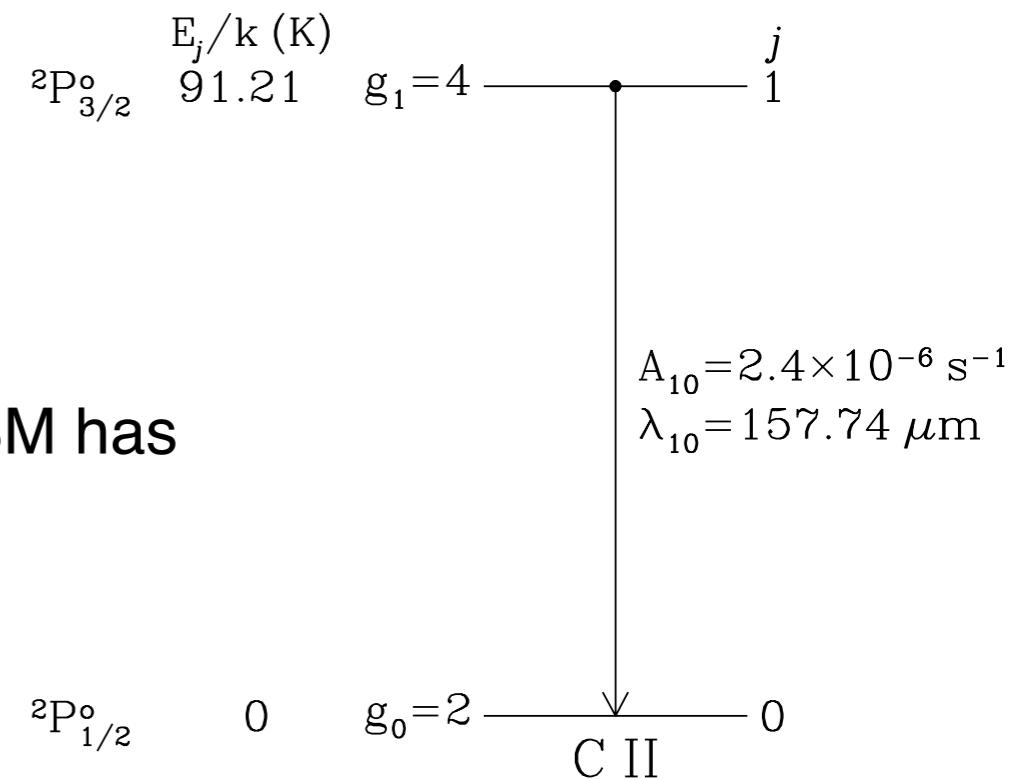


- Rate coefficients for collisional de-excitation:

$$\left\langle \Omega \left( ^2P_{1/2}^o, ^2P_{3/2}^o \right) \right\rangle \approx 2.1$$

$$k_{10}(e^-) \approx 4.53 \times 10^{-8} T_4^{-1/2} \text{ cm}^3 \text{ s}^{-1}$$

$$k_{10}(H) \approx 7.58 \times 10^{-10} T_2^{0.1281+0.0087 \ln T_2} \text{ cm}^3 \text{ s}^{-1}$$



- At  $\lambda = 158 \mu\text{m}$ , the continuum background in the ISM has

$$\bar{n}_\gamma \approx 10^{-5} \ll 1$$

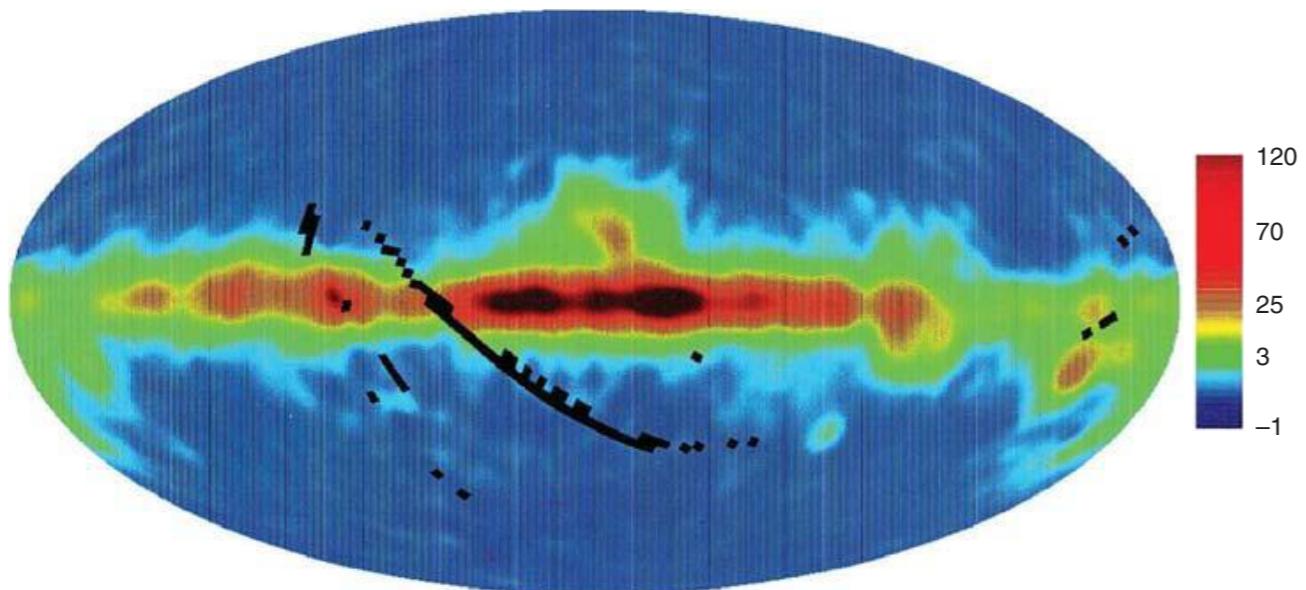
- Critical densities:

$$n_{\text{crit}}(H) \approx 3.2 \times 10^3 T_2^{-0.1281-0.0087 \ln T_2} \text{ cm}^{-3}$$

$$n_{\text{crit}}(e^-) \approx 53 T_4^{1/2} \text{ cm}^{-3} \quad (\text{Barinovs et al. 2005})$$

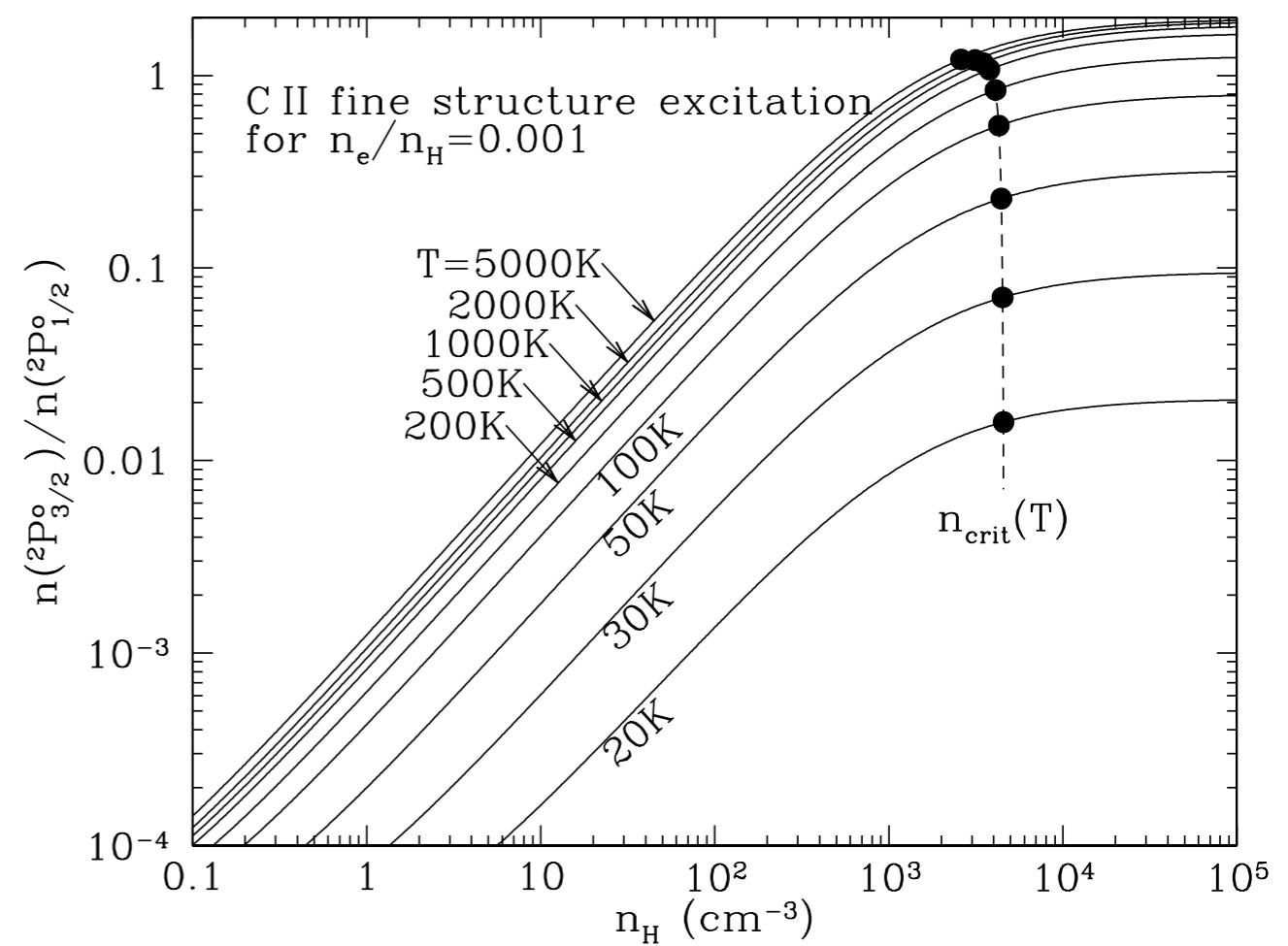
- The critical densities are much higher than the typical densities in the CNM and WNM. Thus, the C II fine-structure levels will be sub-thermally excited.

- The C II fine-structure levels will be sub-thermally excited. It follows that collisional excitations of the upper level will usually be followed by radiative decays, removing energy from the gas.
- The [C II] 158  $\mu\text{m}$  transition is the principal cooling transition for the diffuse gas in star-forming galaxies.



All-sky map of [C II] 158  $\mu\text{m}$  emission, made by Far InfraRed Absolute Spectrophotometer (FIRAS) on the COsmic Background Explorer (COBE) satellite (Fixsen et al. 1999).

[Plate 3 in Draine]



[Fig. 17.4 in Draine]

# Equation for the 21-cm Spin Temperature

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- We have derived the equation for the level populations in the presence of collision and radiation. Now, we will derive an intuitive equation for the spin temperature of the 21-cm line.

$$\frac{n_1}{n_0} = \frac{n_c k_{01} + \bar{n}_\gamma (g_1/g_0) A_{10}}{n_c k_{10} + (1 + \bar{n}_\gamma) A_{10}}$$

- Let's define the temperature corresponding to the 21-cm transition.

$$T_* = E_{10}/k = 0.0682 \text{ K}$$

- The temperatures of radiation and gas will be much higher than this:

$$T_{\text{gas}} \approx 10 - 10^4 \text{ K} \gg T_*, \quad T_{\text{rad}} = 3.77 \text{ K} \gg T_*, \quad T_{\text{spin}} \gg T_*$$

- The population ratio can be written in terms of the excitation (spin) temperature:

$$\frac{n_1}{n_0} = \frac{g_u}{g_\ell} e^{-T_*/T_{\text{spin}}} \simeq \frac{g_u}{g_\ell} \left(1 - \frac{T_*}{T_{\text{spin}}}\right)$$

- Similarly,

$$k_{01} = \frac{g_1}{g_0} k_{10} e^{-T_*/T_{\text{gas}}} \simeq \frac{g_1}{g_0} k_{10} \left(1 - \frac{T_*}{T_{\text{gas}}}\right)$$

$$\bar{n}_\gamma = \frac{1}{e^{T_*/T_{\text{rad}}} - 1} \simeq \frac{T_{\text{rad}}}{T_*}$$

- Substituting these into the population equation, we obtain

$$1 - \frac{T_*}{T_{\text{spin}}} = \frac{n_c k_{10} (1 - T_*/T_{\text{gas}}) + (T_{\text{rad}}/T_*) A_{10}}{n_c k_{10} + (1 + T_{\text{rad}}/T_*) A_{10}}$$

- Finally, we obtain the following equation:

$$T_{\text{spin}} = \frac{T_* + T_{\text{rad}} + y_c T_{\text{gas}}}{1 + y_c} \iff y_c = \frac{T_*}{T_{\text{gas}}} \frac{n_c k_{10}}{A_{10}}$$

- Ignoring  $T_*$  term, we obtain an intuitive equation for the spin temperature.

$$T_{\text{spin}} = \frac{T_{\text{rad}} + y_c T_{\text{gas}}}{1 + y_c} \iff y_c = \frac{T_*}{T_{\text{gas}}} \frac{n_c k_{10}}{A_{10}}$$

This equation was first derived by G. Field (1958).

- This equation describes the spin temperature as ***a weighted mean of the radiation and gas temperatures with weights of 1 and  $y_c$ .***
- From the equation, we can show that

$$\begin{aligned} T_{\text{spin}} &\simeq T_{\text{rad}} & \text{if } y_c \ll 1 \\ T_{\text{spin}} &\simeq T_{\text{gas}} & \text{if } y_c \gg 1 \end{aligned}$$

- A new critical density of the colliding particle may be defined:

$$y_c = 1 \implies n_{\text{crit}}^* = \frac{T_{\text{gas}}}{T_*} \frac{A_{10}}{k_{10}}$$

compare with the original definition.

$$n_{\text{crit}} \equiv \frac{[1 + (n_\gamma)_{10}] A_{10}}{k_{10}}$$

# Detectability of Hydrogen in a low density medium

- In a very low density medium (WNM, CGM, IGM), the particle collisions are very rare ( $n_{\text{HI}} \ll n_{\text{crit}}$ ).
- The radiative transition due to the CMB photons will control the relative population between the hyperfine structures.
  - This indicates  $T_s = T_{\text{CMB}}$ .
  - The RT equation in the Rayleigh-Jeans regime can be written in terms of temperature:

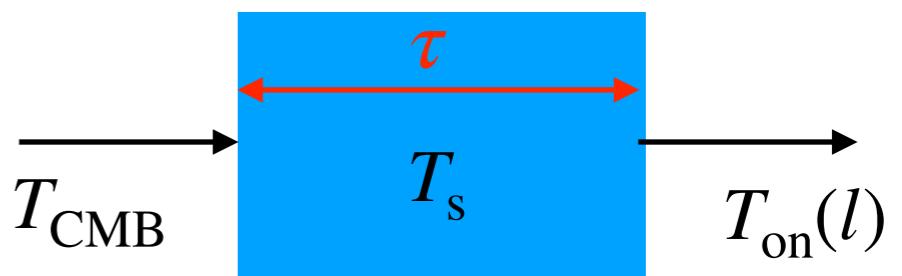
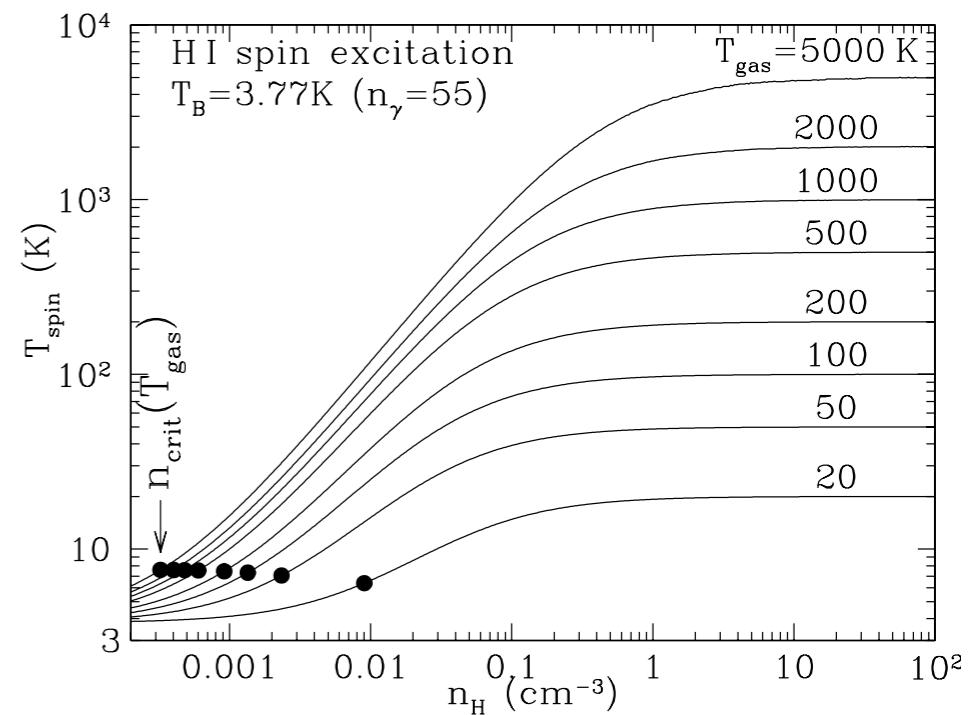
$$T_{\text{on}}(l) = T_{\text{CMB}} e^{-\tau} + T_s (1 - e^{-\tau})$$

$$T_{\text{off}}(l) = T_{\text{CMB}}$$

$$T_{\text{on}}(l) - T_{\text{off}}(l) = (T_s - T_{\text{CMB}}) (1 - e^{-\tau})$$

- Then, we have  $T_{\text{on}}(l) - T_{\text{off}}(l) = 0$
- Neither emission nor absorption feature from the hydrogen gas is detectable.***
- We need something that can make  $T_s \neq T_{\text{CMB}}$ .**

[Fig. 17.2 in Draine]



$$\frac{T_{\text{CMB}}}{T_{\text{off}}(l)}$$

# The Wouthuysen-Field effect: The Third Mechanism controlling the Spin Temperature

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- **Wouthuysen (1952, AJ, 57, 31)**

**Wouthuysen, S. A. On the excitation mechanism of the 21-cm (radio-frequency) interstellar hydrogen emission line.**

The mechanism proposed here is a radiative one: as a consequence of absorption and re-emission of Lyman- $\alpha$  resonance radiation, a redistribution over the two hyperfine-structure components of the ground level will take place. Under the assumption—here certainly permitted—that induced emissions can be neglected, it can easily be shown that the relative distribution of the two levels in question, under stationary conditions, will depend solely on the shape of the radiation spectrum in the Lyman- $\alpha$  region, and not on the absolute intensity.

The shape of the spectrum of resonance radiation, quasi-imprisoned in a large gas cloud, could only be determined by a careful study of the “scattering” process (absorption and re-emission) in a cloud of definite shape and dimensions. The spectrum will turn out to depend upon the localization in the cloud.

Some features can be inferred from more general considerations. Take a gas in a large container, with perfectly reflecting walls. Let the gas be in equilibrium at temperature  $T$ , together with Planck radiation of that same temperature. The scattering processes will not affect the radiation spectrum. One can infer from this fact that the photons, after an infinite number of scattering processes on gas atoms with kinetic temperature  $T$ , will obtain a statistical distribution over the spectrum proportional to the Planck-radiation spectrum of temperature  $T$ . After a finite but large number of scattering processes the Planck shape will be produced in a region around the initial frequency.

Photons reaching a point far inside an interstellar gas cloud, with a frequency near the Lyman- $\alpha$  resonance frequency, will have suffered on the average a tremendous number of collisions. Hence in that region, which is wider the larger the optical depth of the cloud is for the Lyman radiation, the Planck spectrum corresponding to the gas-kinetic temperature will be established

as far as the shape is concerned. Because, however, the relative occupation of the two hyperfine-structure components of the ground state depends only upon the shape of the spectrum near the Lyman- $\alpha$  frequency, this occupation will be the one corresponding to equilibrium at the gas temperature.

The conclusion is that the resonance radiation provides a long-range interaction between gas atoms, which forces the internal (spin-)degree of freedom into thermal equilibrium with the thermal motion of the atoms.

*Institute for Theoretical Physics of the City University, Amsterdam.*

“Wouthuysen” is pronounced as roughly “Vowt-how-sen.” (바우타이슨)

**From a thermodynamic argument, Wouthuysen speculated the followings:**

**A tremendous number of scattering will establish the Planck-like spectrum, at the Ly $\alpha$  line center, corresponding to the gas-kinetic temperature.**

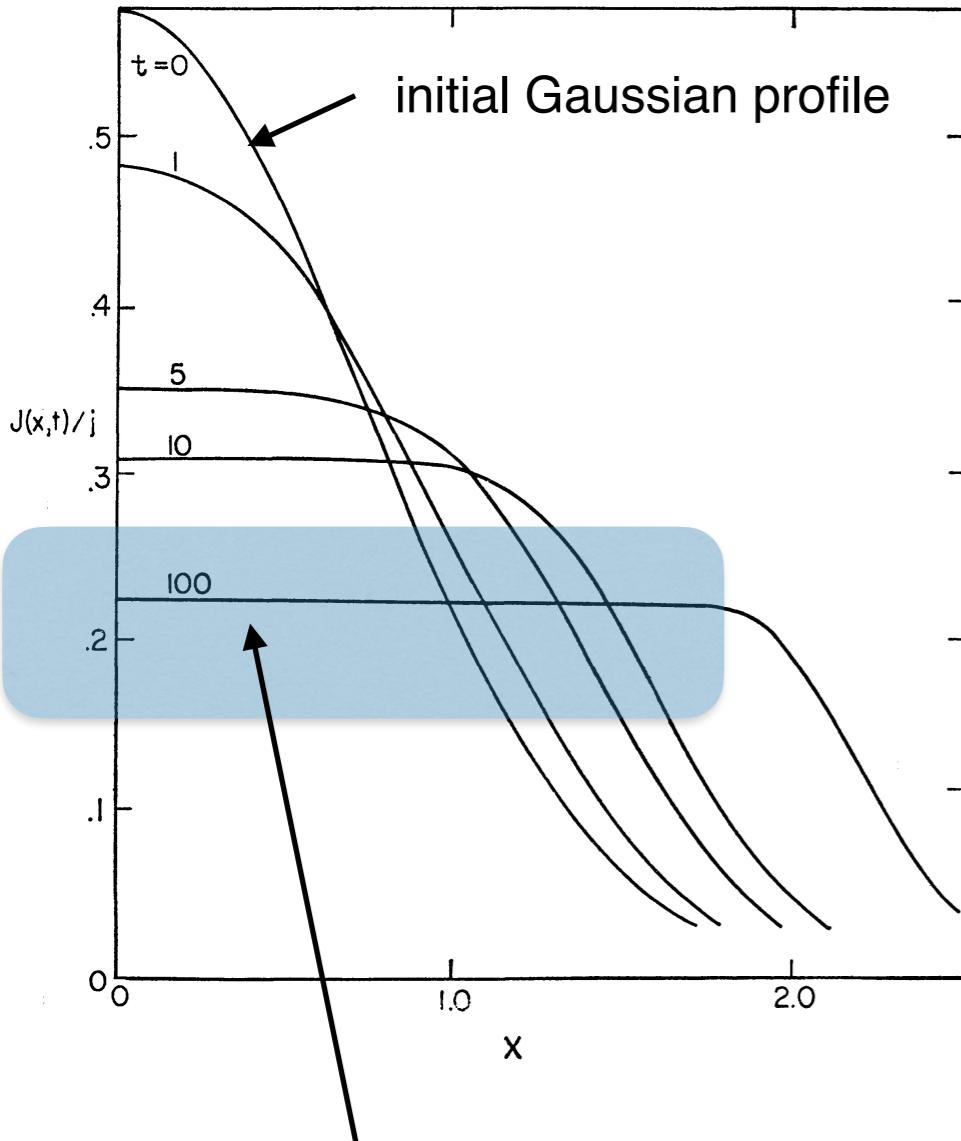
The Ly $\alpha$  radiation is coupled with the hyperfine state of the hydrogen atom.

In the end, **the 21cm spin temperature will become equal to the kinetic temperature of the hydrogen gas.**

# Relaxation of Ly $\alpha$ Profile

- Field (1958, PIRE, 46, 240; 1959, ApJ, 129, 551)

**Recoil effect = momentum transfer between H atom and photon**



spectral shape at the Ly $\alpha$  line center

**Without recoil:**

The spectral profile of Ly $\alpha$ , **within the medium**, becomes flat at the line center when the photons undergo a large number of resonance scatterings.

$$J(\nu, t \rightarrow \infty) = \text{constant}$$

**With recoil:**

Recoil of the scattering atom changes the slope of the Ly $\alpha$  central profile "**at the limit of an infinite number of scattering**" and gives a Boltzmann like (exponential) functional shape:

$$J(\nu, t \rightarrow \infty) \propto e^{-\frac{h(\nu - \nu_\alpha)}{kT_K}}$$

# Mechanisms that controls the spin temperature

---

- The spin temperature ( $T_s$ ) is determined by three mechanisms.

- (1) **Direct Radiative Transitions** by the background radiation field  
(Cosmic Microwave Background or Galactic Synchrotron)

$$I_\nu = \frac{2k_B T_R}{\lambda^2}$$

$T_R$  = brightness temperature  
= 2.73 K or 3.77 K

(Rayleigh-Jeans Law)

- (2) **Collisional Transitions** (collision with other hydrogen and electron)

$T_K$  = gas kinetic temperature

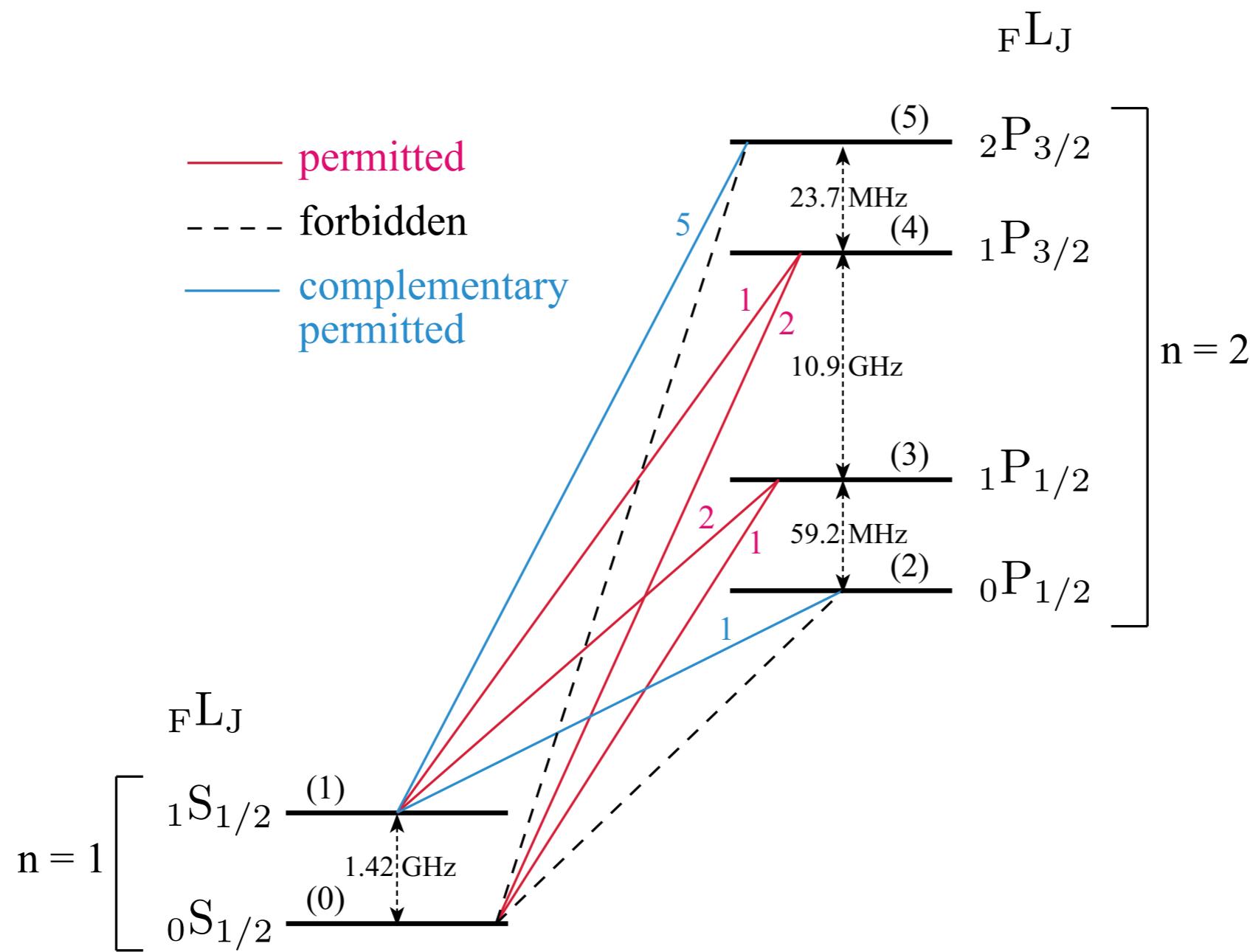
- (3) **Ly $\alpha$  pumping**: Indirect Radiative Transitions involving intermediate levels caused by Ly $\alpha$  resonance scattering

$T_\alpha$  = color temperature

$$J(\nu) \propto \exp\left(-\frac{h\nu}{k_B T_\alpha}\right)$$

# Indirect Level Population by Ly $\alpha$ Scattering

**The WF effect is a mechanism that the resonance scattering of Ly $\alpha$  photons indirectly control the relative populations between the hyperfine levels in the ground state ( $n = 1$ ) via transitions involving the  $n = 2$  state as an intermediate state.**



## Line strengths

---

- Let's consider transitions from  $nJF$  to  $n'J'F'$  over all possible  $n'J'$ .
- Note statistical weight

$$g_F = 2F + 1$$

- Applying the sum rule to four sets of downward transitions from  $n=2$  to  $n'=1$ , the line strengths  $S_{ji}$  are

$$S_{51} : S_{41} + S_{40} : S_{31} + S_{30} : S_{21} = 5 : 3 : 3 : 1$$

- Applying the sum rule to four sets of upward transitions from  $n=1$  to  $n'=2$ ,

$$S_{04} : S_{14} + S_{15} = 1 : 3$$

$$S_{03} : S_{12} + S_{13} = 1 : 3$$

- Note  $S_{ij} = S_{ji}$ . Then, solving the above relations gives

$$S_{51} : S_{41} : S_{40} : S_{31} : S_{30} : S_{21} = 5 : 1 : 2 : 2 : 1 : 1$$

# Einstein A-coefficients

---

- Note

$$S_{ji} \propto g_j A_{ji} \quad \text{or} \quad \frac{S_{ji}}{S_\alpha} = \frac{g_j}{g_{\text{tot}}} \frac{A_{ji}}{A_\alpha}$$

$$S_\alpha = \sum_{j=2}^5 \sum_{i=0}^1 S_{ji} \rightarrow \text{total line strength}$$

$$g_{\text{tot}} = \sum_{j=2}^5 g_j = 12 \rightarrow \text{total statistical weight of } n = 2 \text{ level}$$

$A_\alpha$  = A coefficient for Ly $\alpha$  transition from  $n = 2$  to  $n = 1$

- From the above relations,

$$\frac{A_{20}}{A_\alpha} = \frac{A_{50}}{A_\alpha} = 0$$

$$\frac{A_{21}}{A_\alpha} = \frac{A_{51}}{A_\alpha} = 1$$

$$\frac{A_{30}}{A_\alpha} = \frac{A_{41}}{A_\alpha} = \frac{1}{3}$$

$$\frac{A_{31}}{A_\alpha} = \frac{A_{40}}{A_\alpha} = \frac{2}{3}$$

Ref: Condon & Shortley, The Theory of Atomic Spectra, Chap. IX, p236

## Equation for spin temperature (a)

---

- In stationary state, rate equation for the population of the hyperfine states 0 and 1 can be written

$$\frac{dn_1}{dt} = -\frac{dn_0}{dt} = n_0 (P_{01}^R + P_{01}^c + P_{01}^\alpha) - n_1 (P_{10}^R + P_{10}^c + P_{10}^\alpha) = 0 \quad \text{Eq (1)}$$

where

$P^C, P^R, P^\alpha$  = transition rates (per sec) caused by collisions, radio (21 cm), and Ly $\alpha$

(1) Definition of spin temperature ( $T_S$ ):

$$\frac{n_1}{n_0} = \frac{g_1}{g_0} \exp\left(-\frac{h\nu_{10}}{k_B T_S}\right) \quad \longleftrightarrow \quad T_* = \frac{h\nu_{10}}{k_B} = 0.0681 \text{ °K}$$

$$\simeq 3 \left(1 - \frac{T_*}{T_S}\right) \quad \text{Eq (2)}$$

## Equation for spin temperature (b)

---

(2) Definition of brightness temperature of radio (21 cm) radiation ( $T_R$ ) :

$$I_\nu = \frac{2k_B T_R}{\lambda_{10}^2}$$

Using this definition, we obtain the radiative transition rates due to 21 cm radiation :

$$P_{01}^R \equiv I_\nu B_{01} = I_\nu \frac{g_1}{g_0} \frac{c^2}{2h\nu_{10}^3} A_{10} = 3 \frac{T_R}{T_*} A_{10} \quad \text{Eq (3)}$$

$$P_{10}^R \equiv A_{10} + I_\nu B_{10} = A_{10} + I_\nu \frac{c^2}{2h\nu_{10}^3} A_{10} = \left(1 + \frac{T_R}{T_*}\right) A_{10} \quad \text{Eq (4)}$$

(3) From the detailed balance between the collisional excitation and de-excitation, we obtain

$$\frac{P_{01}^c}{P_{10}^c} = \frac{g_1}{g_0} \exp\left(-\frac{h\nu_{10}}{k_B T_K}\right) \simeq 3 \left(1 - \frac{T_*}{T_K}\right) \quad \text{Eq (5)}$$

( $T_K$  is the gas kinetic temperature.)

## Equation for spin temperature (c)

---

(4) Indirect excitation and de-excitation rates due to Lyman-alpha photon are given by

$$\begin{aligned}
 P_{01}^\alpha &= \sum_{j=2}^5 B_{0j} J(\nu_{0j}) \frac{A_{j1}}{\sum_i A_{ji}} \\
 &= \sum_{j=2}^5 \frac{c^2}{2h\nu_{0j}^3} \frac{g_j A_{j0}}{g_0} J(\nu_{0j}) \frac{A_{j1}}{\sum_i A_{ji}} \\
 &= \frac{c^2}{2h\nu_{0\alpha}^3} J(\nu_{0\alpha}) \left( \frac{g_3}{g_0} A_{30} \frac{A_{31}}{A_{30} + A_{31}} + \frac{g_4}{g_0} A_{40} \frac{A_{41}}{A_{40} + A_{41}} \right) \quad \leftarrow \text{ if } \nu_{0j} = \nu_{0\alpha} \\
 &= \frac{4}{3} \frac{c^2}{2h\nu_{0\alpha}^3} A_\alpha J(\nu_{0\alpha})
 \end{aligned}$$

$$\begin{aligned}
 P_{10}^\alpha &= \sum_{j=2}^5 B_{1j} J(\nu_{1j}) \frac{A_{j0}}{\sum_i A_{ji}} \\
 &= \sum_{j=2}^5 \frac{c^2}{2h\nu_{1j}^3} \frac{g_j A_{j1}}{g_1} J(\nu_{1j}) \frac{A_{j0}}{\sum_i A_{ji}} \\
 &= \frac{c^2}{2h\nu_{1\alpha}^3} J(\nu_{1\alpha}) \left( \frac{g_3}{g_1} A_{31} \frac{A_{30}}{A_{30} + A_{31}} + \frac{g_4}{g_1} A_{41} \frac{A_{40}}{A_{40} + A_{41}} \right) \quad \leftarrow \text{ if } \nu_{1j} = \nu_{1\alpha} \\
 &= \frac{4}{9} \frac{c^2}{2h\nu_{1\alpha}^3} A_\alpha J(\nu_{1\alpha})
 \end{aligned}$$

## Equation for spin temperature (d)

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$$\begin{aligned}\therefore \frac{P_{01}^\alpha}{P_{10}^\alpha} &= 3 \left( \frac{\nu_{1\alpha}}{\nu_{0\alpha}} \right)^3 \frac{J(\nu_{0\alpha})}{J(\nu_{1\alpha})} \\ &\approx 3 \frac{J(\nu_{0\alpha})}{J(\nu_{1\alpha})}\end{aligned}$$

Assume that the line profile is approximated by an exponential function:

if  $J(\nu) \propto \exp\left(-\frac{h(\nu - \nu_\alpha)}{k_B T_\alpha}\right)$  at the line center, then

$$\begin{aligned}\frac{P_{01}^\alpha}{P_{10}^\alpha} &= 3 \exp\left(-\frac{h(\nu_{0\alpha} - \nu_{1\alpha})}{k_B T_\alpha}\right) \\ &= 3 \exp\left(-\frac{h\nu_{10}}{k_B T_\alpha}\right) \\ &\approx 3 \left(1 - \frac{h\nu_{10}}{k_B T_\alpha}\right) \\ &= 3 \left(1 - \frac{T_*}{T_\alpha}\right)\end{aligned}\quad \text{Eq (6)}$$

# Equation for spin temperature (e)

Combining Eq (1) - (6), we obtain the following equation for the spin temperature in terms of the 21 cm brightness temperature, gas kinetic temperature, and Ly-alpha color temperature:

$$\begin{aligned} 1 - \frac{T_*}{T_S} &= \frac{\frac{T_R}{T_*} A_{10} + \left(1 - \frac{T_*}{T_K}\right) P_{10}^c + \left(1 - \frac{T_*}{T_\alpha}\right) P_{10}^\alpha}{\left(1 + \frac{T_R}{T_*}\right) A_{10} + P_{10}^c + P_{10}^\alpha} \\ &= 1 - \frac{A_{10} + \frac{T_*}{T_K} P_{10}^c + \frac{T_*}{T_\alpha} P_{10}^\alpha}{\left(1 + \frac{T_R}{T_*}\right) A_{10} + P_{10}^c + P_{10}^\alpha} \end{aligned}$$

$$\begin{aligned} \frac{T_*}{T_S} &= \frac{A_{10} + \frac{T_*}{T_K} P_{10}^c + \frac{T_*}{T_\alpha} P_{10}^\alpha}{\left(1 + \frac{T_R}{T_*}\right) A_{10} + P_{10}^c + P_{10}^\alpha} \\ \frac{T_S}{T_*} &= \frac{\left(1 + \frac{T_R}{T_*}\right) A_{10} + P_{10}^c + P_{10}^\alpha}{A_{10} + \frac{T_*}{T_K} P_{10}^c + \frac{T_*}{T_\alpha} P_{10}^\alpha} \\ T_S &= \frac{T_* + T_R + T_* \frac{P_{10}^c}{A_{10}} + T_* \frac{P_{10}^\alpha}{A_{10}}}{1 + \frac{T_*}{T_K} \frac{P_{10}^c}{A_{10}} + \frac{T_*}{T_\alpha} \frac{P_{10}^\alpha}{A_{10}}} \end{aligned}$$

$$T_S = \frac{T_* + T_R + y_c T_K + y_\alpha T_\alpha}{1 + y_c + y_\alpha}$$

where  $y_c \equiv \frac{T_*}{T_K} \frac{P_{10}^c}{A_{10}}$

$$y_\alpha \equiv \frac{T_*}{T_\alpha} \frac{P_{10}^\alpha}{A_{10}}$$

$$T_* = \frac{h\nu_{10}}{k_B} = 0.0681 \text{ } {}^\circ\text{K} \quad (\text{This term is negligible in the above equation.})$$

**Two requirements for the WF effect:**

- (1)  $T_\alpha = T_K$
- (2)  $y_\alpha \gg 1$  and  $y_\alpha \gg y_c$   
(Ly $\alpha$  radiation field should be strong.)

# First Requirement: Spectral Shape of Ly $\alpha$ inside the medium

With the recoil effect

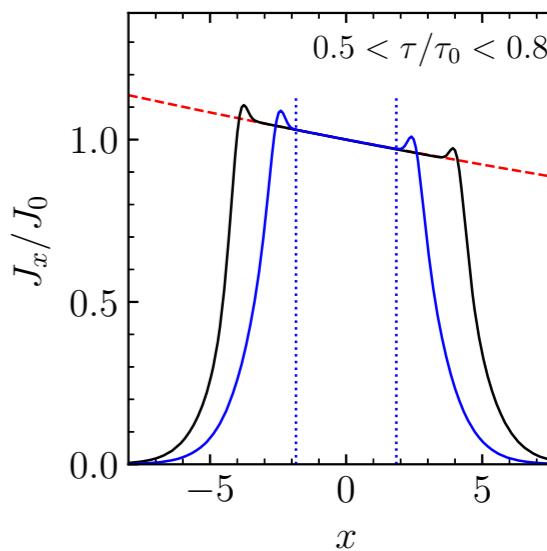
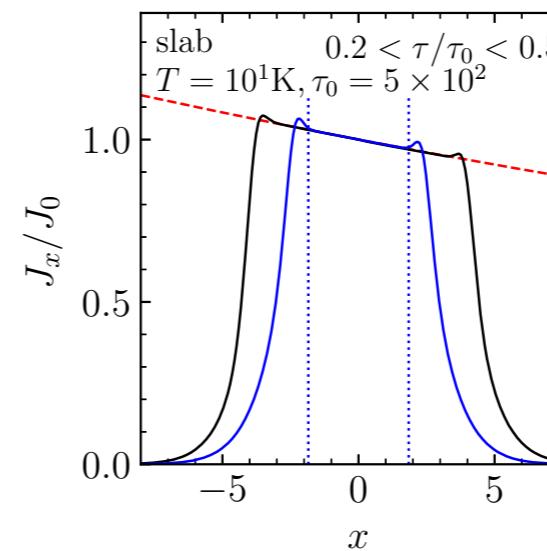
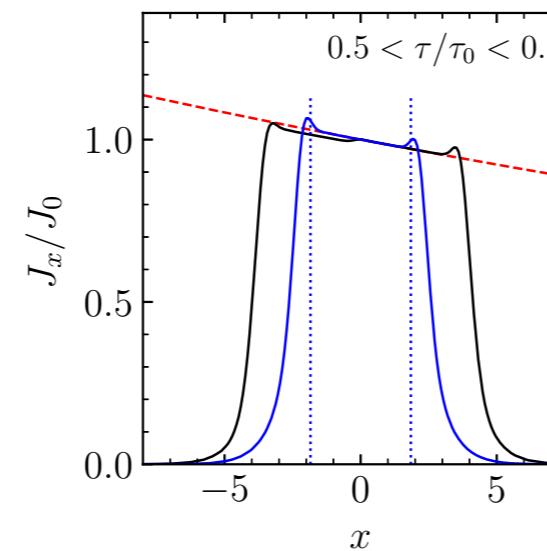
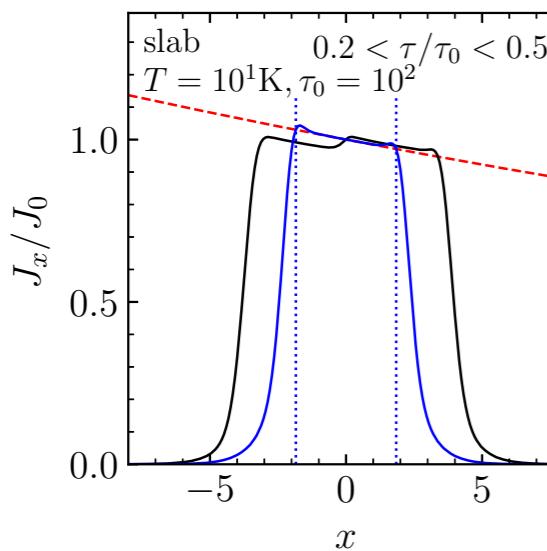
$T = 10 \text{ K}$

red dashed lines:  $J_x \propto \exp\left(-\frac{h(\nu - \nu_\alpha)}{k_B T_K}\right)$

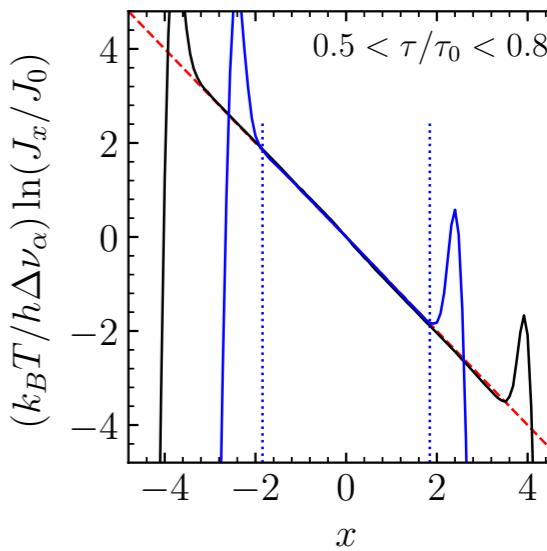
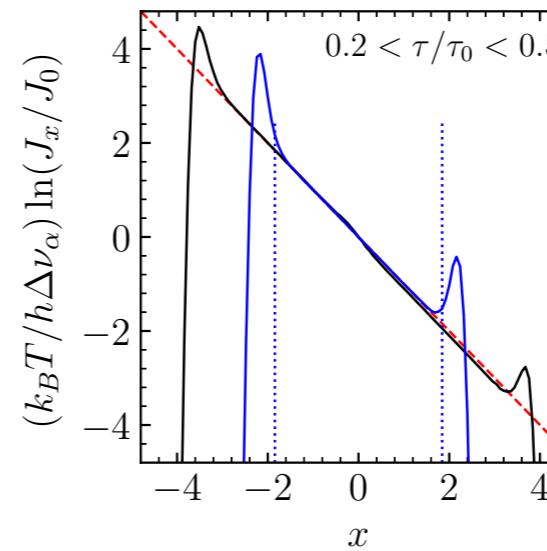
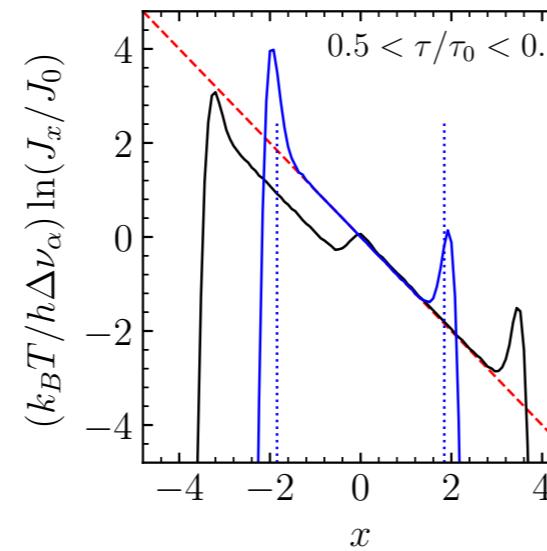
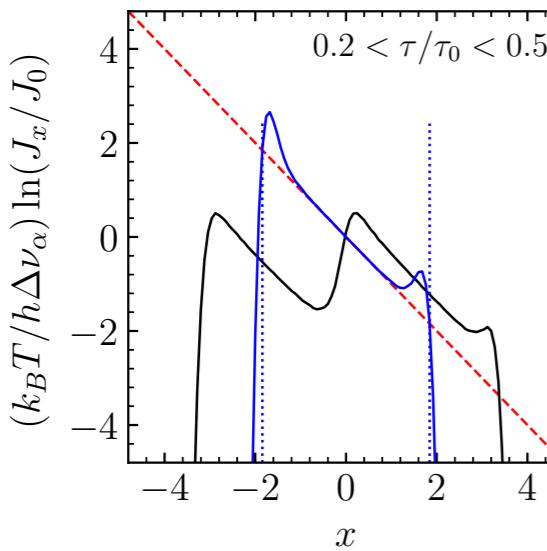
black lines: included the fine structure splitting

blue lines: ignored the fine structure

linear scale



logarithmic scale



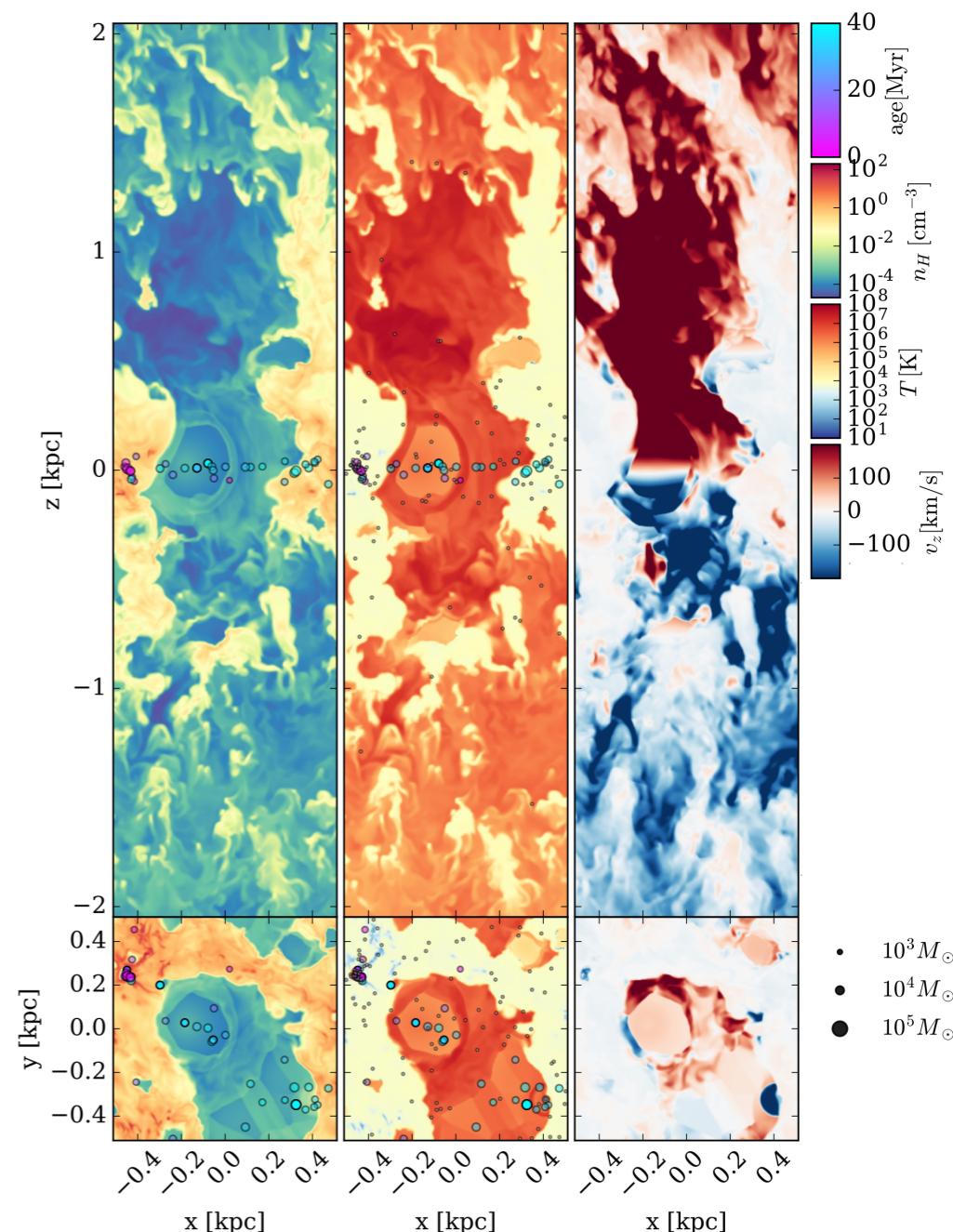
The resonance-line profile at the line center approaches to the exponential function with the gas kinetic temperature, even in a system with an optical depth as low as 100-500.

## Second Requirement: Strength of Ly $\alpha$ Radiation

- ***Is Ly $\alpha$  radiation strong enough to make  $y_\alpha$  large (in our Galaxy)?***
- We need to perform simulations in realistic ISM models to address this question.
- The TIGRESS frame work.
  - TIGRESS = Three-phase Interstellar Medium in Galaxies Resolving Evolution with Star Formation and Supernova Feedback
  - In the TIGRESS framework, the ideal MHD equations are solved in a local, shearing box, representing a small patch of a differential rotating galactic disk.
  - TIGRESS yields self-consistent 3D ISM models with self-regulated star formation.

TIGRESS

Kim & Ostriker (2017; 2018)



## Ly $\alpha$ Sources

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- ***Recombination line from H II regions (Galactic Disk)***
  - Vacca et al. (1996) gives the ionizing UV flux from 429 O- and early B-stars within 2.5 kpc of the Sun. From this, the Ly $\alpha$  production rate is calculated.

$$\psi_{\text{Ly}\alpha} = 2.52 \times 10^7 \text{ photons cm}^{-2} \text{ s}^{-1}$$

- H II regions are assumed to be distributed as follows:

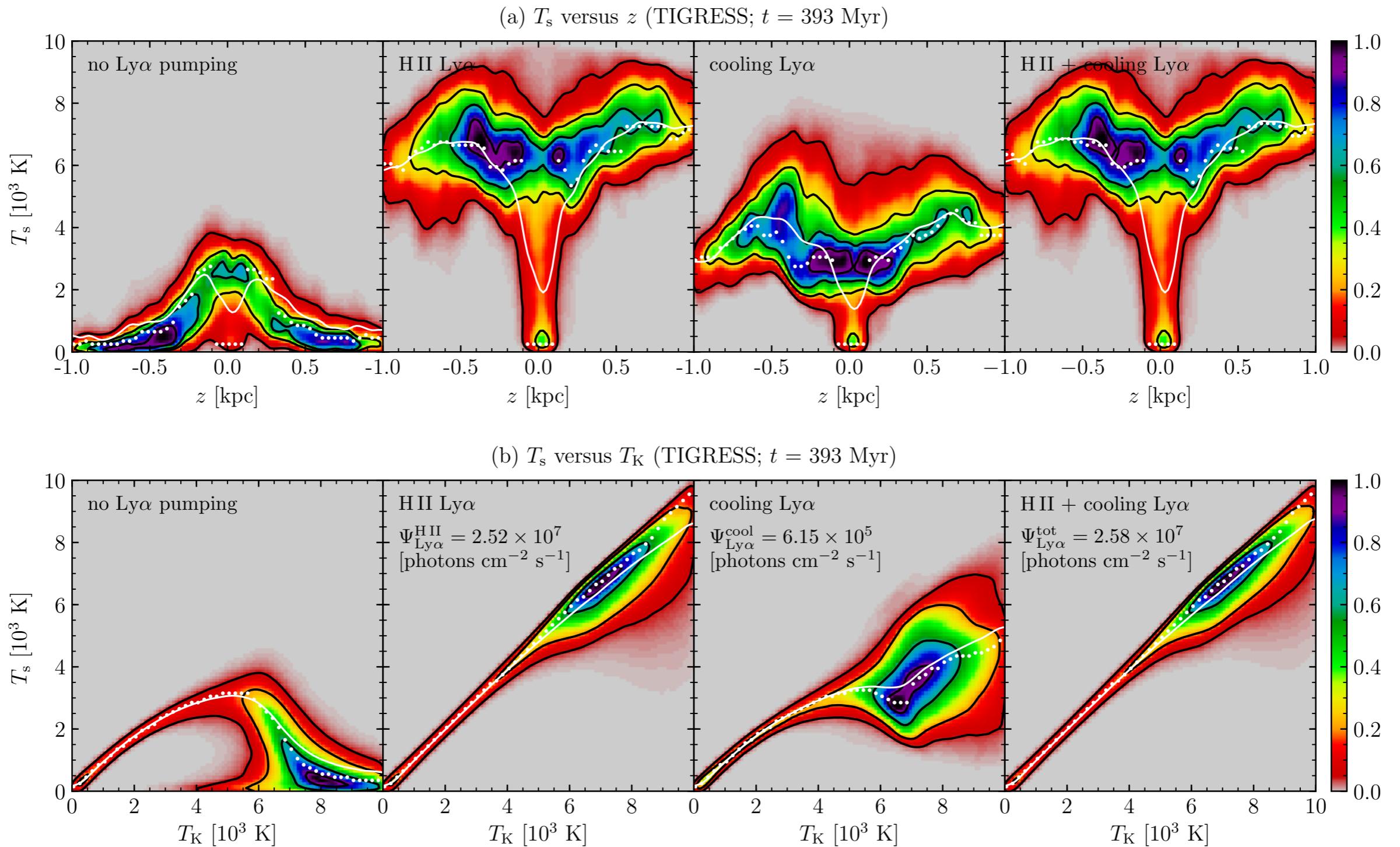
$$j_{\text{Ly}\alpha}(z) \propto \exp\left(-\frac{z^2}{2\sigma^2}\right) \text{ where } \sigma = 81 \text{ pc}$$

- ***Collisional cooling Ly $\alpha$  lines from hot gas***

- Assuming the collisional ionization equilibrium (CIE), the total Ly $\alpha$  production rate caused by the collisional excitation and ionization is calculated.

$$\frac{4\pi j_{\text{Ly}\alpha}}{h\nu_\alpha} = n_e n_{\text{H}} \frac{C_{\text{Ly}\alpha}(T)}{h\nu_\alpha} + n_e n_p \alpha_{\text{B}} P_{\text{B}}(\text{Ly}\alpha)$$

# Result: Spin vs. Kinetic Temperature



The Ly $\alpha$  radiation, at least in our Galaxy, is strong enough to thermalize the spin temperature to the gas kinetic temperature.

# Homework

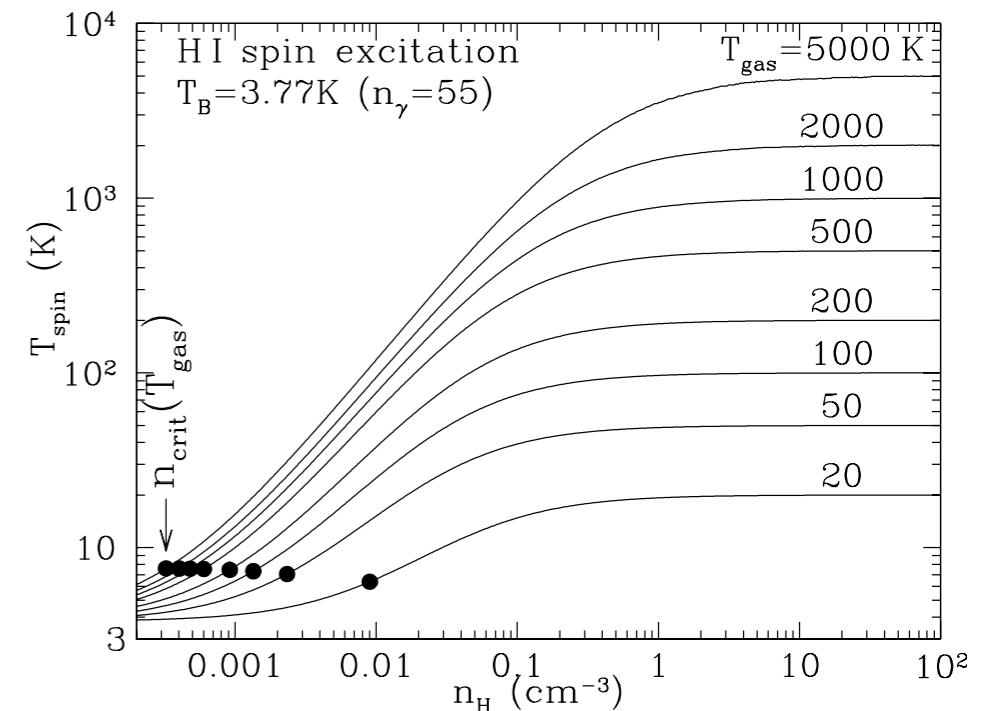
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(1) If we consider only the background radiation field and collisions with hydrogen, the spin temperature of the 21-cm transition is given by

$$T_{\text{spin}} = \frac{T_{\text{rad}} + y_c T_{\text{gas}}}{1 + y_c} \quad \text{where } y_c \equiv \frac{T_*}{T_{\text{gas}}} \frac{n_c k_{10}}{A_{10}}$$

- Using the above equation, make a plot similar to the right side figure.
- Denote the two critical densities, for each gas temperature, defined by

$$n_{\text{crit}}^* = \frac{T_{\text{gas}}}{T_*} \frac{A_{10}}{k_{10}} \quad \text{and} \quad n_{\text{crit}} = \frac{(1 + n_\gamma) A_{10}}{k_{10}}$$



(2) Discuss whether the above equation for the spin temperature for the 21-cm transition can be applied to the [C II] 158 μm or not. Explain why the equation cannot be applied?