# HI Emission and Absorption Processes

Spitzer Ch. 3

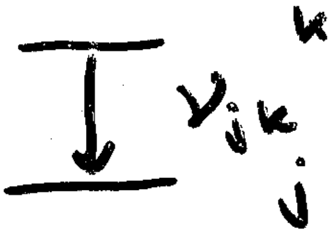
To determine $I_\nu$ (specific intensity)

need to know $j_\nu$ (emissivity)

$\kappa_\nu$ (absorption coefficient)

→ relate to particle densities in lower and upper levels of transitions involved

## (i) Emission:




$\nu_{jk}$ = freq. of line center

spontaneous emission:

Einstein coefficient $A_{kj}$

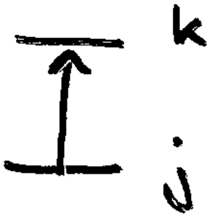
Total energy spontaneously emitted, per $cm^3$, per second, per unit solid angle, is

$$\int j_\nu \, d\nu = \frac{h\nu_{jk}\, n_k(X^{(r)})\, A_{kj}}{4\pi}$$

(element X, ionized r times)

→ $n_k$ can be determined from statistical mechanics → see Spitzer p. 29 - 35

## (ii) Absorption:




Total energy absorbed in line, per unit solid angle, per cm$^3$ per second $\equiv \int I_\nu \kappa_\nu \, d\nu$

Assume $I_\nu$ is $\approx$ constant over line width

$$\rightarrow I(\nu_{jk}) \int \kappa_\nu \, d\nu = I(\nu_{jk}) \frac{h\nu_{jk}(n_j B_{jk} - n_k B_{kj})}{c}$$

$B_{jk}, B_{kj}$ = Einstein coefficients for stimulated upward & downward transitions

## Thermodynamic Equilibrium

Rates (i) = Rates (ii)

Using $I_\nu = B_\nu(T)$ and expression for $n_j / n_k$ in equilibrium (Chapter 2)

$$\rightarrow g_j B_{jk} = g_k B_{kj} = \frac{c^3}{8\pi h \nu_{jk}^3} g_k A_{kj}$$

# Line Profiles

Let $s_\nu$ be absorption cross-section per particle, and define $s = \int s_\nu \, d\nu$
(integrated over line)

Absorption coefficient

$$K_\nu = n_j s_\nu = n_j \frac{s_\nu}{s} s \equiv n_j s \phi(\Delta\nu)$$

$$\phi(\Delta\nu) = \frac{s_\nu}{s} \qquad \Delta\nu \equiv \nu - \nu_{jk}$$

$\phi$ describes freq. distribution of $s_\nu$

depends on $\begin{cases} \text{intrinsic line width} \\ \text{distribution of Doppler shifts} \end{cases}$

i.e. if <u>entirely</u> due to Doppler broadening

$\phi(\Delta\nu)\,d\nu = P(v)\,dv$ = fraction of atoms with radial velocity in range $dv$

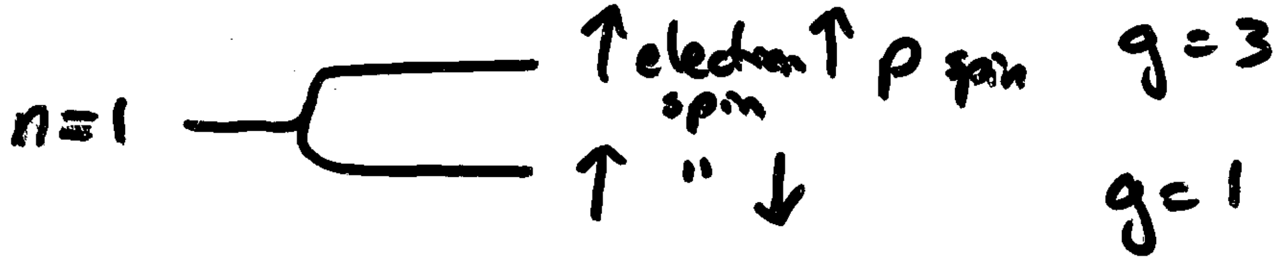
$$\frac{\Delta v}{c} = \frac{\Delta\nu}{\nu_{jk}} \quad \text{and define} \quad b \equiv \left(\frac{2kT}{m}\right)^{1/2}$$

$$\phi(\Delta\nu) = \lambda_{jk} P(v) = \frac{\lambda_{jk}}{\sqrt{\pi}\, b} e^{-(v/b)^2}$$

# The 21 cm Line

- 21 cm emission line is radiative transition between 2 hyperfine levels of ground ($n=1$) electronic state

$\lambda = 21.11$ cm




$$A_{kj} = 2.869 \times 10^{-15}\ s^{-1}$$

Typical HI atom in upper state waits 12 million years before spontaneously decaying

For $n_H > 1\ cm^{-3}$, LTE is good approx.

Then, since $h\nu_{jk} = 5.9 \times 10^{-6}$ eV $\ll kT$ for this line

$\Rightarrow$ levels populated as per statistical weight

$\rightarrow \frac{3}{4}$ of H atoms in upper state

Line profile determined by velocity $\rightarrow \phi(v)$

For 21 cm line, excitation temperature is called "spin temperature" ($\equiv T_s$)

Rayleigh-Jeans is good approx for 21cm line

$$\Delta T_B = T_B - T_B(0) = (T_s - T_B(0))(1-e^{-\tau})$$

If $T_s > T_B(0) \rightarrow$ emission line

If $T_s < T_B(0) \rightarrow$ absorption line

If $T_s = T_B(0) \rightarrow$ no net change

$$\tau_v = 5.49 \times 10^{-14} \frac{N(HI)\, \phi(v)}{T}$$

$$N(HI) = 1.823 \times 10^{18} \int T_b(v) \left( \frac{\tau_v}{1-e^{-\tau_v}} \right) dv$$

km/s

for $\tau \ll 1$, $N(HI) = 1.823 \times 10^{18} \underbrace{\int T_b\, dv}_{\text{"integrated intensity"}}$

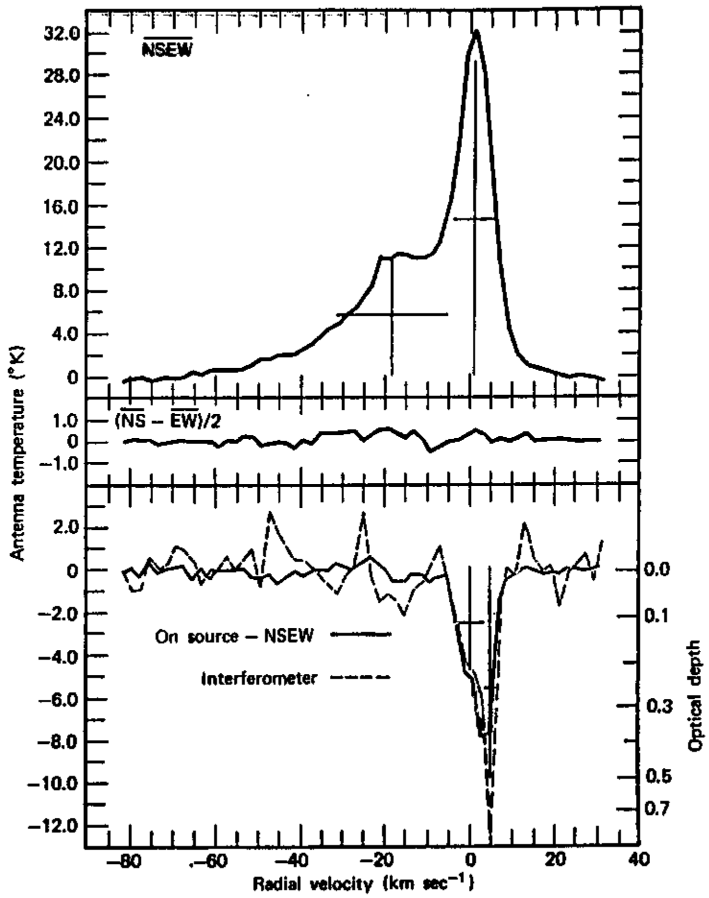



**Figure 3.1 Sample 21-cm emission and absorption line profiles [22].** The lower curve gives the difference of measured antenna temperature (equal to 0.8 $T_b$) between the 21-cm absorption line and the continuous emission in the extragalactic radio source 1610-60, plotted against the radial velocity in the local standard of rest; the dashed curve shows similar data obtained with an interferometer. The right hand vertical scale shows the optical depth computed from the line profiles. The upper plot gives the average antenna temperature of the emission observed one beamwidth (15′) away from the source in the north, south, east, and west directions, while the middle plot gives the difference between the means of the north–south and east–west measures. The line profiles have been fitted by Gaussian components at the indicated velocities; the horizontal lines show for each component the full width at one-half of the maximum $\tau$ or antenna temperature.

Spitzer

for $\tau_0 > 0.2$, observe $\overline{T} \sim 80$ K

T seems to increase as $\tau$ decreases

Strasser & Taylor 2004 - CGPS

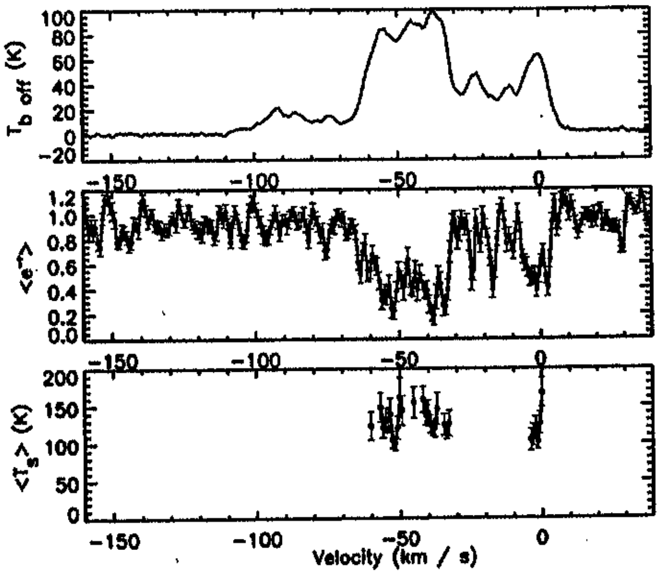



FIG. 2.—Spectra for Maffei 2 ($T_{bg}$ = 32 K); 1 $\sigma$ error bars are shown.

~ 400 lines of site in Galactic Plane

$$e^{-\tau_v} = \left(1 - \frac{T_B^{off} - T_{on}}{T_{bg,cont}}\right)$$

$$T_S(v) = \frac{T_B(v)}{1 - e^{-\tau(v)}}$$

- spin tempeature = kinetic tempeature if we have a single component in equilibrium

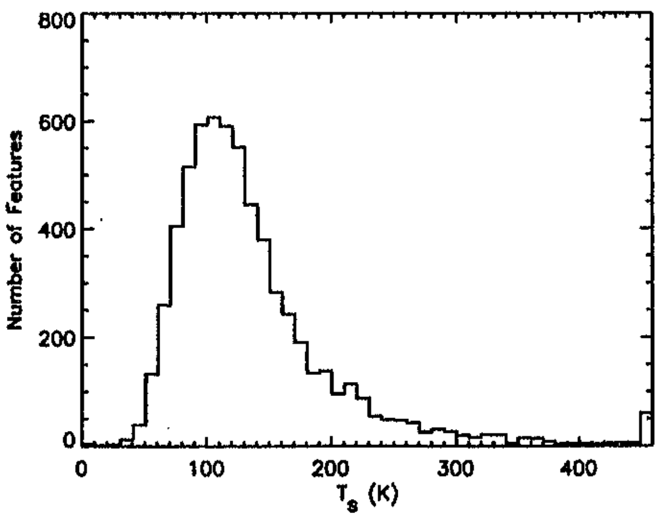



FIG. 4.—Distribution of spin temperatures for all channels where $T_{on-off}$ S/N > 5. The last bin contains all channels with $T_s$ higher than 450 K.

median value 120 K

→ with 2 components, $T_s$ is mean of kinetic tempeature weighted by column density

Two component ISM - if WNM does not absorb CNM and

$\tau_{WNM} << \tau_{CNM}$

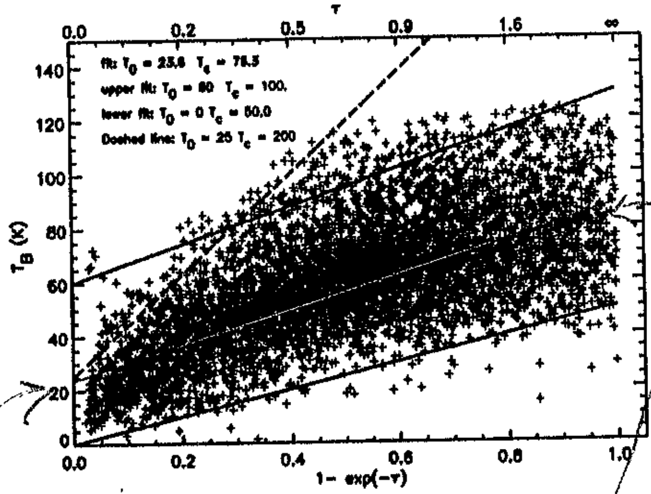



FIG. 5.—$T_B$ vs. $1-e^{-\tau}$ with least-squares fit and envelopes. The optical depth goes to zero on the left, and approaches infinity on the right.

$$T_B = T_0 e^{-\tau_c} + T_\infty (1 - e^{-\tau_c})$$

$$T_0 = T_w \tau_w$$

$$T_\infty = T_w \tau_w q + T_c$$

$q$ = fraction of warm gas in front of cold gas

$T_0 = 24$ K

$T_\infty = 88$ K

$T_c = 64 - 88$ K

$(q = 0 - 1)$

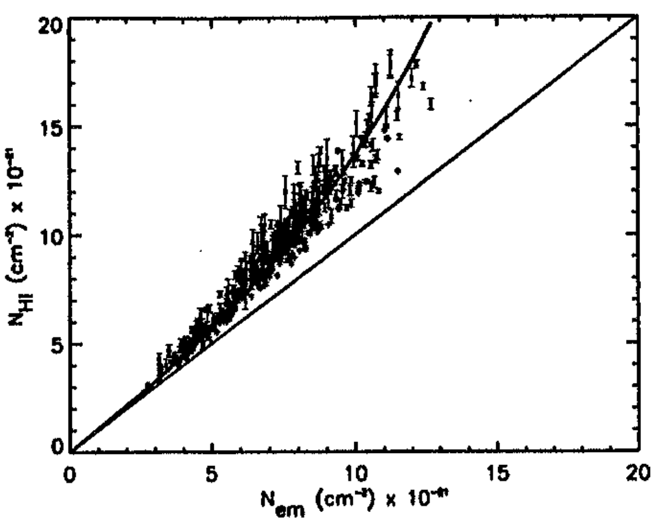



FIG. 10.—Emission column density vs. total column density (assuming a one-phase medium) for all the sources. The lines show a 1 : 1 relationship and an empirical fit to the data (eq. [8]).

## Effect of $\tau$ on $N_H$

- straight line is what we expect if
  $$N_H = C \int T dv$$
- data points and curve are what we get if include $\tau \neq 0$

→ simple assumption underestimates total HI column density by about 30% on average

# Heating and Cooling of Diffuse ISM

Spitzer, Ch. 6

In steady state,

kinetic E gained per cm$^3$ per sec = E lost per cm$^3$ per s

$$\Gamma = \Lambda$$

→ steady state occurs at some equilibrium kinetic temperature $T = T_E$

General Energy equation

$$\underbrace{\boxed{n\frac{d}{dt}\left(\frac{3}{2}kT\right) - kT\frac{dn}{dt}} = \Gamma - \Lambda}_{nT\frac{dS}{dt}}$$

$nT\frac{dS}{dt}$ where $S$ = entropy per gram for monatomic gas

$$\Gamma = \Gamma(n,T)$$

$$\Lambda = \Lambda(n,T)$$

Note: if $\mathcal{E}$ is internal energy per unit mass

$$d\mathcal{E} = Tds - pdV$$

$$\rho\frac{d\mathcal{E}}{dt} - \frac{p}{\rho}\frac{d\rho}{dt} = \rho T\frac{dS}{dt}$$

$\rho T \frac{dS}{dt}$ = net thermal input of energy per $cm^3$ per sec

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→ Define a "cooling time" $t_T$ by

$$\frac{d}{dt}\left(\frac{3}{2}kT\right) = -\frac{3k(T-T_E)}{2t_T}$$

So for constant $n$

$$t_T = \frac{-\frac{3}{2}k(T-T_E)}{\underbrace{(\Gamma-\Lambda)/n}_{\text{net cooling rate per atom}}}$$

and $T-T_E \propto \exp(-t/t_T)$

(under some conditions $t_T$ can be $<0$ near $T_E$ → equilibrium T unstable

→ gas cools or heats towards another equilibrium)

# Heating in general

primary mechanism: photo-electric ionization of neutral atoms

- let $E_2$ = K.E. of ejected electron
- in steady state, each ionization offset by capture of an electron, with K.E. = $E_1$
- let $n_i$ = ionized atom density

Net gain with electron-ion recombinations

$$\boxed{\Gamma_{ei} = n_e n_i \sum_j \left( \langle v\sigma_{cj} \rangle \overline{E_2} - \langle v\sigma_{cj} E_1 \rangle \right)}$$

$\langle\ \rangle \equiv$ average over Maxwellian

captures to level $j$

cross-section for an electron capture in state $j$

average over all ionizing photons

Under ISM conditions, almost all photoionizations take place from ground state $\Rightarrow \overline{E_2}$ independent of $j$

$$\boxed{\Gamma_{ei} = n_e n_i \left\{ \alpha \overline{E_2} - \frac{1}{2} m_e \sum_j \langle v^3 \sigma_{ij} \rangle \right\}}$$

where $\alpha \equiv \sum_{m=1}^{\infty} \alpha_m$ is the total recombination coefficient

## Cooling in general

In ISM, primarily by inelastic collisions
Between electrons and ions:

$$\underset{j \to k \text{ per cm}^3 \text{ per sec}}{\#\text{ of excitations}} = n_e \underbrace{n_{ij}}_{\#\text{ ions in level } j} \gamma_{jk}$$

$\gamma_{jk}$ ← rate coefficient $= \langle v \sigma_{jk} \rangle$

$E_{jk} = E_k - E_j$ = K.E. lost by colliding electron

de-excitation → offsetting energy gain

$$\boxed{\Lambda_{ei} = n_e \sum_{j<k} E_{jk} \left( n_{ij} \gamma_{jk} - n_{ik} \gamma_{kj} \right)}$$

Note: assumes all photons escape!
(not valid for dense molecular clouds)

Under typical ISM conditions, ions are in ground state → sum over j omitted, $n_{ij}$ for $j=1$ replaced by $n_i$

## Heating and cooling in HI Regions

- no electron-proton recombinations (H neutral)
- energy gain from photoionization from impurity atoms only

→ $\frac{\Gamma_{ei}}{n_e} \propto n_i \lesssim \frac{1}{2000} \times$ value in HII regions

→ $\frac{\Lambda_{ei}}{n_e}$ is less different from HII regions

→ easier to evaluate cooling than heating

## Cooling Function $\Lambda$

- radiation from neutral atoms, ions, molecules
  → chief excitation by electrons and H atoms

At several $10^3$ K, $e^-$ excitation of neutral H can be an important energy loss

→ $n=2$ level is mainly responsible for radiation

so $\Lambda_{eH} \propto \exp(-E_{12}/kT)$

for 4000 - 12000°K

$$\boxed{\Lambda_{eH} = 7.3\times10^{-19}\, n_e\, n(HI)\, e^{-118,400/T} \quad (\text{erg/cm}^3/\text{s})}$$

Collisional excitation of ions (by neutral H atoms) is frequently a dominant cooling process → CII most abundant ion in HI regions

For CII and T < 100°K

$$\boxed{\Lambda_{HCII} = 7.9\times10^{-27}\, n_H^2\, d_c\, e^{-92/T} \quad \text{erg/cm}^3/\text{s}}$$

$d_c$ = depletion of carbon

$$= \frac{n_c/n_H}{\text{cosmic value } (4\times10^{-4})}$$

$\zeta$ Oph, $d_c = 0.2$

(consider $0.1 \le d_c \le 1$)

→ also consider cooling by $FeII$, $CI$, $OI$, $SII$

Hydrogen molecules can be a source of heat loss → excited by collisions with H → $J = 0 \to 2$ or $J = 1 \to 3$

<u>BUT</u> reverse de-excitation mechanisms can produce energy <u>gain</u>

→ optical pumping can populate upper rotational levels above Boltzmann values

For diffuse clouds with saturated $H_2$ lines and $2n(H_2) > 0.1\, n_H$

$\Rightarrow$ upper J levels overpopulated

$\Rightarrow$ heat source

For reddened stars ($E_{B-V} \geq 0.10$) with strong $H_2$ lines, $J = 3-1$ transitions are chief contributor to heating

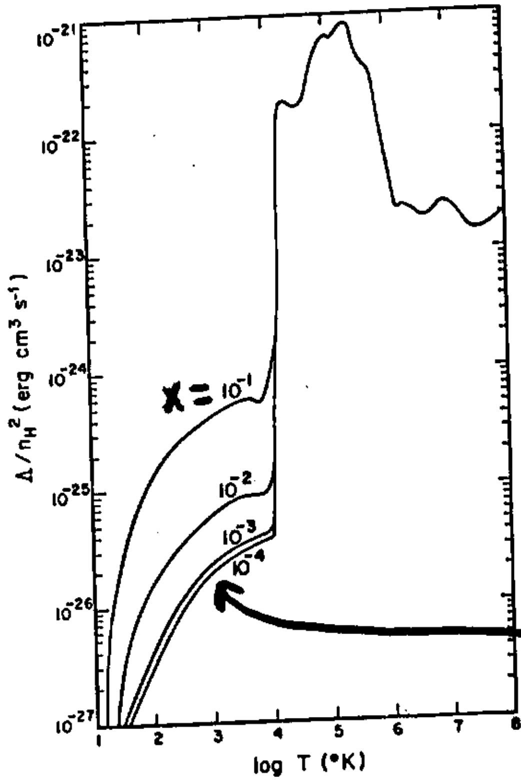
but gain is always $< \Lambda_{HCII}/25$

if $\delta_c \geq 0.2$

# Total Cooling



$x = \frac{n_e}{n_H}$

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collisional excitation by neutral H (not e⁻) dominates

**Figure 6.2 Cooling function for interstellar gas [6].** Values of $\Lambda(T)/n_H^2$ are shown as functions of the temperature $T$. For $T < 10{,}000°$K, the different curves represent different values of $x \equiv n_e/n_H$, while for $T > 10{,}000°$K, collisional ionization is assumed for all elements. Depletion and the possible presence of dust grains [7] or of $H_2$ are ignored.

Features: steep rise at $10^4$ K → due to collisional excitation of H + increase in $n_e$ as hydrogen becomes ionized

Find $t_T \approx \frac{2.4 \times 10^5 \text{ yr}}{n_H}$ (for $\Lambda \gg \Gamma$)

(for $x \sim 5 \times 10^{-4}$ (full ionization of C, Fe, Si) and $H_2$ cooling ignored and no depletion)

valid for $n_H = 1 - 300$ cm$^{-3}$ $T = 50 - 600$ K