THE INTERSTELLAR MEDIUM: III
Diffuse Atomic Gas: The HI-21cm line

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OUTLINE

- Background.
- The HI-21cm hyperfine transition.
- Absorption and emission issues.
- The spin temperature.
- HI column densities, spin and kinetic temperatures, HI masses.
- HI-21cm observational studies.

Background

- Kinetic temperature : $f(v) = (m/2\pi kT_K)^{1/2}\, e^{-mv^2/2kT_K}$
- Excitation temperature : $(n_u/n_l) = (g_u/g_l)\, e^{-h\nu/kT_X}$
- Radiation temperature : $B(\nu,T_R) = (2h\nu^3/c^2)\,[e^{h\nu/kT_R} - 1]^{-1}$

  Rayleigh-Jeans limit : $B(\lambda,T) = (2kT/\lambda^2)$
- Einstein A-coefficient : $A_{ul} = (64\pi^4 e^2 \nu^3/3hc^3)(g_u/g_l)\, |D_{ul}|^2$
- Equation of radiative transfer:

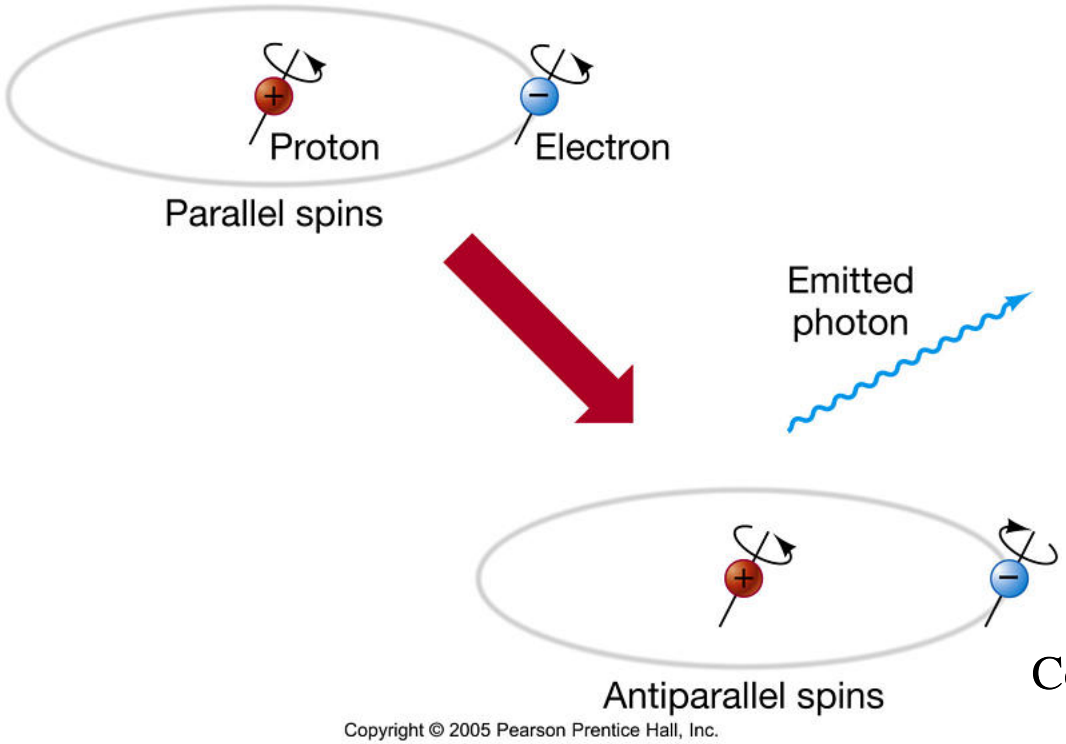
  $I_\nu(\tau_\nu) = I_\nu(0)\, e^{-\tau_\nu} + {}_0\int^{\tau_\nu} e^{-(\tau_\nu - \tau)} S_\nu\, d\tau$, where $S_\nu \equiv (j_\nu/\kappa_\nu)$.

  $j_\nu \equiv$ Emissivity; Attenuation coefficient, $\kappa_\nu = n_l\sigma_{lu}(\nu) - n_u\sigma_{ul}(\nu)$.
- For a uniform medium, with level populations given by T_X:

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

The HI-21cm Line

- "Spin-flip" transition: e^{-}-p^{+} spins go parallel to anti-parallel.



$\nu_{21cm} = 1420.40575...$ MHz

Courtesy: NRAO

- "Forbidden" magnetic dipole transition: $A_{21cm} = 2.87 \times 10^{-15}$ s^{-1}.
- Large mean lifetime $\sim 1/A_{21cm} \approx 10^{7}$ years!
- Narrow natural broadening, $\Delta\nu_{21cm} \sim A_{21cm}/2\pi \approx 5 \times 10^{-16}$ Hz!

The HI-21cm Line: Absorption Issues

- Level populations: $(n_1/n_0) = (g_1/g_0)\, e^{-h\nu/kT_S}$.

  $T_S \equiv$ "Spin temperature"; $g = (2S + 1)$; $g_1 = 3$, $g_0 = 1$.

- $h\nu/k \approx 0.07$ K, $\ll T_S$ ⇨ $(n_1/n_0) \approx 3\,(1 - h\nu/kT_S)$ ⇨ $n \approx 4n_0$.

- The absorption cross-section is given by

$$\sigma_{10}(\nu) = (g_1/g_0)\,(c^2/8\pi\nu^2)\, A_{21cm}\, \phi(\nu).$$

- The attenuation coefficient, $\kappa_\nu = n_0\sigma_{01}(\nu) - n_1\sigma_{10}(\nu)$.

$$\Rightarrow \kappa_\nu = (c^2/8\pi\nu^2).\, 3.\, A_{21cm}\,.\,(n/4).\,\phi(\nu)\,[1 - e^{-h\nu/kT_S}]$$

$$= (3c^2/32\pi\nu^2)\,.\,A_{21cm}.\, n.\,\phi(\nu)\,(h\nu/kT_S)$$

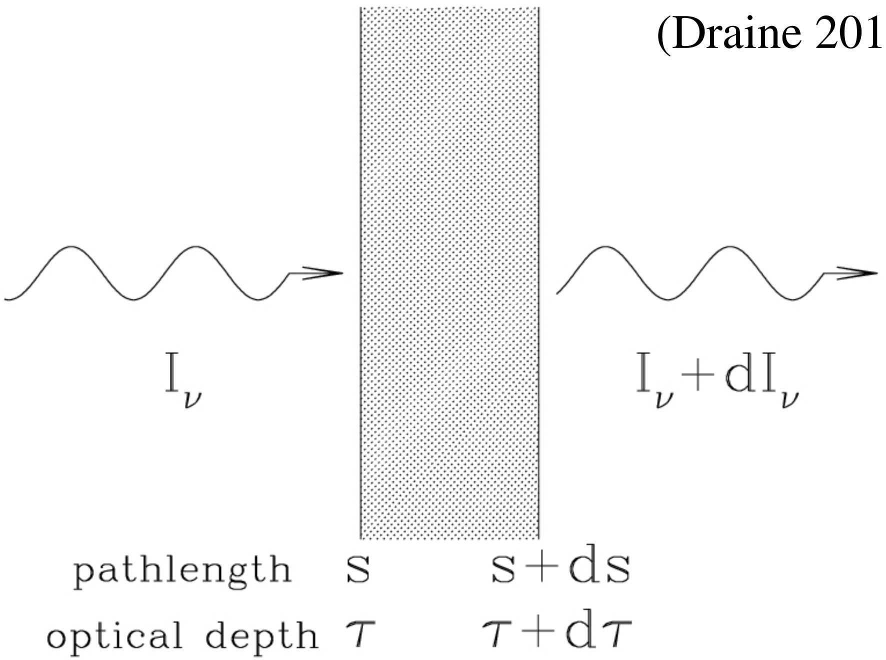
- Optical depth, $\tau_\nu = \int \kappa_\nu\, ds = (3c^2/32\pi\nu^2)\; A_{21cm}\,\phi(\nu)\,.\,(h\nu/kT_S)\, N_{HI}$

  ⇨ Total HI column density, $N_{HI} = 1.82 \times 10^{18} \int T_S\, \tau_\nu\, dV$.

THE HI-21CM LINE: EMISSION ISSUES

- Level populations: $(n_1/n_0) = (g_1/g_0)\, e^{-h\nu/kT_S}$.
- $h\nu/k \approx 0.07$ K $(\ll T_S)$ ⇨ $(n_1/n_0) \approx 3\,(1 - h\nu/kT_S)$ ⇨ $n \approx 4n_0$.
- Equation of radiative transfer:

$$dI_\nu = -I_\nu \kappa_\nu ds + j_\nu ds$$



- $I_\nu = I_\nu(0)\, e^{-\tau_\nu} + {}_0\int^{\tau_\nu} e^{-(\tau_\nu - \tau)} (j_\nu/\kappa_\nu)\, d\tau$.
- Kirchhoff's law: $(j_\nu/\kappa_\nu) \equiv B_\nu(T_S)$

  ⇨ $I_\nu = I_\nu(0)\, e^{-\tau_\nu} + B_\nu(T_S)\,(1 - e^{-\tau_\nu})$.

- For HI-21cm, $(h\nu/kT_S) \ll 1$ ⇨ $T_B = T_B(0)\, e^{-\tau_\nu} + T_S\,(1 - e^{-\tau_\nu})$.
- If there's no background source ⇨ $T_B = T_S\,(1 - e^{-\tau_\nu})$.

HI-21cm Studies

- The HI column density, $N_{HI} = 1.8 \times 10^{18} \int T_S \tau_v \, dV$.

- Isothermal cloud: The brightness temperature, $T_B = T_S (1 - e^{-\tau_v})$.

- For optically-thin absorption, $\tau_v \ll 1 \Rightarrow T_B = T_S . \tau_v$

  $\Rightarrow N_{HI} = 1.8 \times 10^{18} \int T_B \, dV$

  $\Rightarrow$ Can measure N_{HI} directly from HI-21cm emission studies!

- In the general case, $N_{HI} = 1.8 \times 10^{18} \int T_B \tau_v [1 - e^{-\tau_v}]^{-1} \, dV$.

- HI-21cm optical depth depends on *both* N_{HI} & T_S; $\tau_v \propto (1/T_S)$

  $\Rightarrow$ More difficult to detect absorption from warm HI.

- Absorption by an isothermal cloud: $N_{HI} = 1.8 \times 10^{18} \, T_S \int \tau_v \, dV$.

  For multiple clouds on the sightline: $N_{HI} = 1.8 \times 10^{18} \langle T_S \rangle \int \tau_v dV$;

  Column-density-weighted harmonic mean $\langle T_S \rangle = [\Sigma_i (n_i/T_i)]^{-1}$

THE SPIN TEMPERATURE

- Level populations determined by the kinetic temperature, the HI-21cm radiation field and the Lyman-α colour temperature.

- For collisional excitation or de-excitation (i.e. ignoring radiation):

$$(dn_1/dt) = n_c\, n_0\, k_{01} - n_c\, n_1\, k_{10} - n_1\, A_{10}$$

  k_{01} & k_{10} are collisional rate coefficients: $k_{01} = (g_1/g_0)\, k_{10}\, e^{-h\nu/kT_K}$

  $n_c \equiv$ density of the colliding partner.

  In the steady state, $(dn_1/dt) = 0 \Rightarrow (n_1/n_0) = n_c k_{01} / [n_c\, k_{10} + A_{10}]$

- Including a radiation field, of specific energy density u_ν

  $\Rightarrow (dn_1/dt) = n_0[n_c k_{01} + n_\gamma\, (g_1/g_0) A_{10}] - n_1[n_c k_{10} + (1 + n_\gamma) A_{10}]$

  where n_γ is the photon occupancy number $= (c^3/8\pi h\nu^3) u_\nu$

- For black-body radiation, $n_\gamma = [e^{h\nu/kT_R} - 1]^{-1}$.

- Steady state: $(n_1/n_0) = [n_c k_{01} + n_\gamma\, (g_1/g_0) A_{10}] / [n_c\, k_{10} + (1 + n_\gamma) A_{10}]$

THE SPIN TEMPERATURE

- $(n_1/n_0) = [n_c k_{01} + n_\gamma (g_1/g_0) A_{10}] / [n_c k_{10} + (1 + n_\gamma) A_{10}]$

- Critical density: Collisional de-excitation = Radiative de-excitation

$$n_{crit,u} = [\Sigma_{l<u} (1 + n_\gamma) A_{ul}] / [\Sigma_{l<u} k_{ul}]$$

If $n_c \gg n_{crit,u}$ ⇨ $T_X = T_K$; if $n_c \ll n_{crit,u}$ ⇨ $T_X = T_R$.

- *Note:* Black-body radiation & $T_R = T_K$ ⇨ $T_X = T_K$ for *all* densities!

- For the HI-21cm line, $n_{crit} = (1 + n_\gamma) A_{10} / k_{10}$.

  Main collision partners: HI atoms. (e.g. Allison & Dalgarno 1969)

  Radiation field temperature ~ (2.73 + 1.04) K = 3.77 K

  ⇨ Photon occupancy number ~ (3.77 / 0.07) ~ 55

  ⇨ $n_{crit} = 1.7 \times 10^{-3} (T_K/100\ \mathrm{K})^{-0.66}\ \mathrm{cm}^{-3}$ $(50\ \mathrm{K} \leqslant T \leqslant 200\ \mathrm{K})$

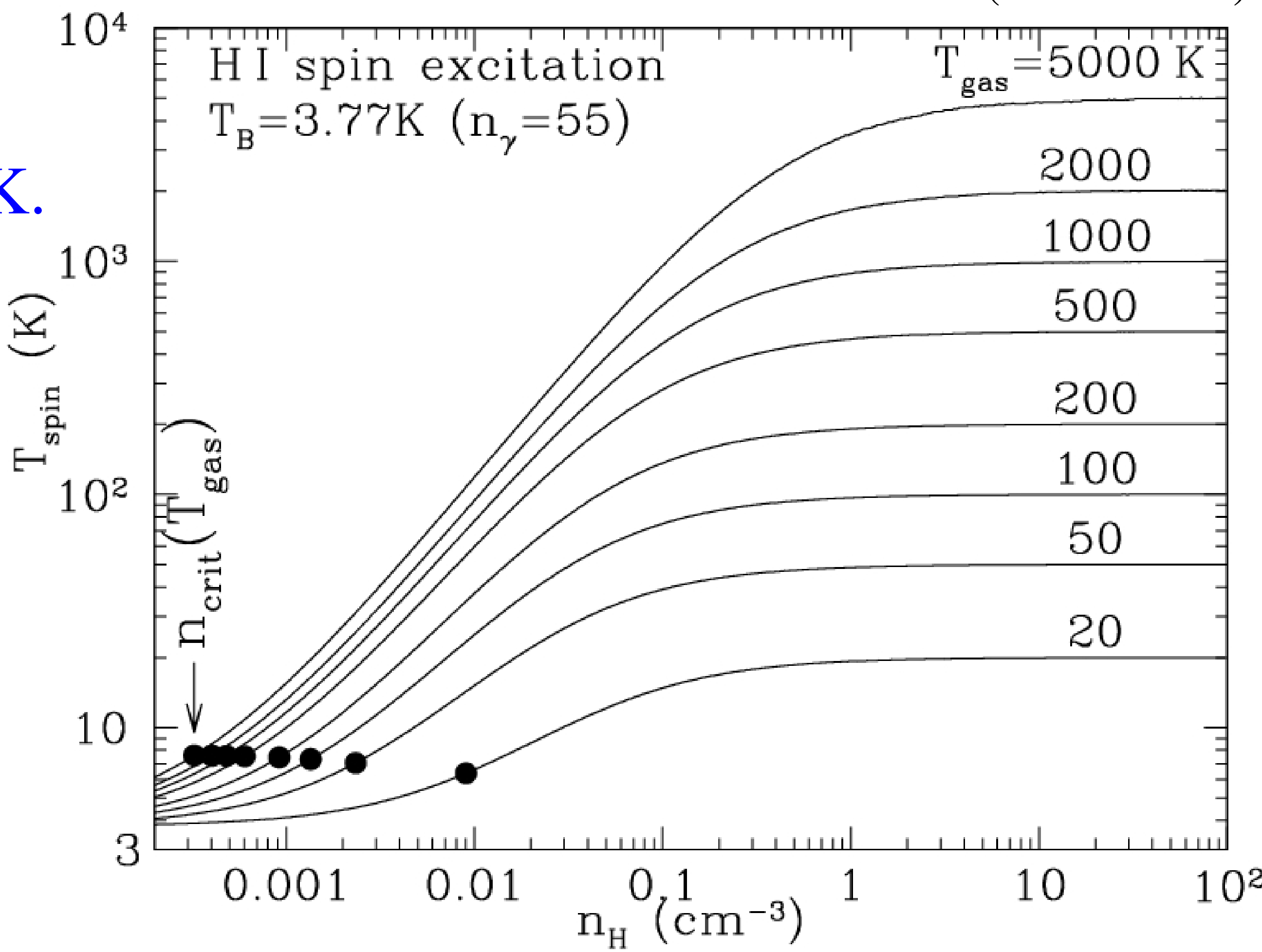
- Solve $T_S = 0.07 / \ln(n_0 g_1 / n_1 g_0)$ for different n_c and T_K values.

The Spin Temperature

- $(n_1/n_0) = [n_c k_{01} + n_\gamma (g_1/g_0) A_{10}] / [n_c k_{10} + (1 + n_\gamma) A_{10}]$

(Draine 2011)

- If $n_c \gg n_{crit}$ ⇨ $T_S = T_K$.
  If $n_c \ll n_{crit}$ ⇨ $T_S = 3.77$ K.



- $n_c > 1\ cm^{-3}$ ⇨ $T_S \approx T_K$.
  $n_c < 1\ cm^{-3}$ ⇨ $T_S < T_K$!

- Collisions insufficient to thermalize HI-21cm levels at low densities.

- Wouthysen-Field mechanism: Lyman-α radiation field ?
  Also insufficient for typical Lyman-α intensities. (Liszt 2001)

HI-21CM STUDIES: OBSERVABLES

- Emission studies: If $\tau_v \ll 1$ ⇨ $N_{HI} = 1.8 \times 10^{18} \int T_B \, dV$
  ⇨ Can measure N_{HI} directly from HI-21cm emission studies!

- Absorption studies : $N_{HI} = 1.8 \times 10^{18} \, T_S \int \tau_v \, dV$.
  ⇨ Can infer T_S if N_{HI} known (HI-21cm emission or Ly-α).

- If $\tau_v \ll 1$, Gaussian line profile in local thermal equilibrium.
  ⇨ Can fit multi-Gaussian profile to infer kinetic temperature.

- Zeeman splitting: Shift of 2.8 Hz /μG between 2 polarizations.
  ⇨ Infer parallel magnetic field via polarization studies.

- External galaxies: HI mass, $M_{HI} = 2.35 \times 10^5 \, D^2 \int S \, dV \quad (M_\odot)$
  Mapping studies: Gas mass, distribution, velocity field.