Neutral Atomic Gas

§ 29 Draine
Spitzer 3.3b
3.4a

Binney & Merrifield 8.1.4

1) Excitation of HI

Hyperfine $F=1-0$ spin-flip transition @ 21.105 cm
1420.406 MHz

with $g_2 = 3$ $(2s+1)$ and $g_1 = 1$ for stat. weights

$\Delta E = h\nu = 5.9 \times 10^{-6}$ eV $= 0.069$ K

Level pops: determined by detailed balance

$$\gamma_{12} n_1 n_H + J_\nu B_{12} n_1 = \gamma_{21} n_2 n_H + J_\nu B_{21} n_2 + A_{21} n_2$$

$$\Rightarrow \frac{n_2}{n_1} = \frac{\gamma_{12}/\gamma_{21} + J_\nu B_{12}/\gamma_{21} n_H}{1 + (A_{21} + J_\nu B_{21})/\gamma_{21} n_H}$$

Einstein relations $\Rightarrow$ $A_{21} = \frac{2h\nu^3}{c^2} B_{21}$, $B_{21} = \frac{g_1}{g_2} B_{12}$

Boltzmann $\Rightarrow$ $\gamma_{12} = \frac{g_2}{g_1} \gamma_{21} e^{-h\nu/kT_K}$ ← kin. Temp.

$J_\nu \triangleq \frac{2\nu^2 k T_R}{c^2}$ ← rad. Temp. (i.e., BB with $\frac{h\nu}{kT_R} \ll 1$)

$$\Rightarrow \frac{n_2}{n_1} = \frac{g_2}{g_1} \frac{\left[e^{-h\nu/kT_K} + (A_{21}/\gamma_{21} n_H) \frac{kT_R}{h\nu} \right]}{1 + (A_{21}/\gamma_{21} n_H)\left(1 + \frac{kT_R}{h\nu}\right)}$$

Since $kT_R/h\nu \gg 1$ for $T_R \gtrsim 2.73$ K, and $h\nu/kT_K \ll 1 \Rightarrow$

$$\frac{n_2}{n_1} \approx \frac{g_2}{g_1} \approx \frac{3}{1} \Rightarrow \boxed{\frac{n_2}{n_H} \approx \frac{3}{4}}$$

2) Rad. Transfer

$$\frac{dI_\nu}{ds} = \frac{h\nu}{4\pi}\left[\underbrace{n_2 A_{21}}_{j_\nu} - \underbrace{(n_1 B_{12} - n_2 B_{21})}_{K_\nu} I_\nu\right]$$

$$S_\nu = \frac{j_\nu}{K_\nu} = \frac{n_2 A_{21}}{n_1 B_{12} - n_2 B_{21}}$$ source function

$$\Rightarrow S_\nu = \frac{2h\nu^3/c^2 \; B_{21} n_2}{\left(\frac{g_2}{g_1}\frac{n_1}{n_2} - 1\right) B_{21} n_2} = \frac{2h\nu^3/c^2}{\frac{g_2}{g_1}\frac{n_1}{n_2} - 1}$$

Using Einstein relations

$$\Rightarrow S_\nu = \frac{2h\nu^3}{c^2} \cdot \left[\frac{1}{\dfrac{1 + (A_{21}/\gamma_{21} n_H)\left(1 + \frac{kT_R}{h\nu}\right)}{e^{-h\nu/kT_K} + (A_{21}/\gamma_{21} n_H)\left(\frac{kT_R}{h\nu}\right)}} - 1\right]$$

$$= \frac{2h\nu^3}{c^2} \cdot \left[\frac{e^{-h\nu/kT_K} + (A_{21}/\gamma_{21} n_H)\left(\frac{kT_R}{h\nu}\right)}{\underbrace{\frac{h\nu}{kT_K}}_{= 1 - e^{-h\nu/kT_K}} + A_{21}/\gamma_{21} n_H}\right]$$

$$\Rightarrow S_\nu = \frac{2h\nu^3}{c^2}\frac{kT_K}{h\nu}\left[\frac{e^{-h\nu/kT_K} + \frac{A_{21}}{\gamma_{21} n_H} \cdot \frac{kT_R}{h\nu}}{1 + \frac{A_{21}}{\gamma_{21} n_H} \cdot \frac{kT_K}{h\nu}}\right]$$

$[\ ] \rightarrow \chi^{-1}$ of Spitzer 4-15

$[\ ] \sim 1 - \frac{1}{23 n_H}$ for $T_K = 80K$

$A_{21} = 2.87 \times 10^{-15} s^{-1}$, $\gamma_{21} \sim$ few $\times 10^{-11} cm^3 s^{-1}$ Spitzer Table 4.2
(8×10^{-11} for 80K)

$\Rightarrow$ For $\frac{T_K(K)}{n_H(cm^{-3})} \lesssim 10^2$, $\frac{A_{21}}{\gamma_{21} n_H} \frac{kT_K}{h\nu} \ll 1$

if $T_R < T_K \Rightarrow \frac{A_{21}}{\gamma_{21} n_H} \frac{kT_R}{h\nu} \ll 1$ also

$e^{-h\nu/kT_K} \approx 1$ $\Rightarrow$ $\boxed{S_\nu \approx \frac{2\nu^2 kT_K}{c^2}}$

More generally, define $S_\nu \triangleq \frac{2\nu^2 kT_S}{c^2}$, T_S = spin Temperature
$= T_K \cdot [\ ]$

Spin Temp. is generally below T_K if gas is low density since then $[\ ]$ gets smaller.

Optical depth: $d\tau_\nu = \frac{h\nu}{4\pi}(n_1 B_{12} - n_2 B_{21})\, ds$

For uniform medium, the solution of xfer. equation is:

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

Define brightness Temperature such that:

$$I_\nu \triangleq \frac{2\nu^2}{c^2} kT_B$$

$\Rightarrow$ Solution is

$$\boxed{T_B = T_B(0)\, e^{-\tau_\nu} + \left(1-e^{-\tau_\nu}\right) T_S}$$

Optically thin emission:

$$1-e^{-\tau_\nu} = \tau_\nu \quad \Rightarrow \quad \Delta T_B \triangleq T_B - T_B(0) = \left(1-e^{-\tau_\nu}\right)\left(T_S - T_B(0)\right) = \tau_\nu \cdot \left(T_S - T_B(0)\right)$$

$$\Rightarrow T_B \approx T_S \cdot \tau_\nu \quad \text{for small } T_B(0)$$

<u>Absorption</u>: $T_B(0) \gg T_S$

$$T_B(ON) - T_B(0) = \Delta T_B(ON) = T_B(0)\left(e^{-\tau_\nu} - 1\right) + T_S\left(1-e^{-\tau_\nu}\right)$$

$$T_B(OFF) - T_B(0) = \Delta T_B(OFF) = \left(1-e^{-\tau_\nu}\right) T_S$$

$$\Rightarrow \Delta T_B(ON) - \Delta T_B(OFF) = T_B(0)\left(e^{-\tau_\nu} - 1\right)$$

$$\Rightarrow e^{-\tau_\nu} = 1 + \frac{\Delta T_B(ON) - \Delta T_B(OFF)}{T_B(0)}$$

T_B away from line is $T_B(0)$

$\Rightarrow$ T_S, τ_ν are both determined

<u>Optical depth and column</u>:

$$\tau_\nu = \frac{h\nu}{4\pi}\left(n_1 B_{12} - n_2 B_{21}\right) s = \frac{h\nu}{4\pi}\left(\frac{n_1 B_{12} - n_2 B_{21}}{n_2 A_{21}}\right) n_2 A_{21} s$$

$$= \frac{h\nu}{4\pi}\,\frac{1}{S_\nu} \cdot n_2 A_{21} s = \frac{h\nu}{4\pi}\,\frac{c^2}{2\nu^2 k T_S} \cdot n_2 \frac{2h\nu^3}{c^2} B_{21} s$$

$$= \frac{(h\nu)^2}{4\pi}\,\frac{n_2 B_{21}}{k T_S} \cdot s \quad \text{and } n_2 = \frac{g_2}{g_1} n_1, \quad B_{21} = \frac{g_1}{g_2} B_{12} \Rightarrow n_2 B_{21} = n_1 B_{12}$$

$$\Rightarrow \tau_\nu = (h\nu)^2 \cdot \frac{n_1 B_{12}}{4\pi k T_s} s \quad , \quad \text{Binney + Merrifield 8.18}$$

$$\tau_\nu = \frac{h\nu}{4\pi} \frac{c^2}{2\nu^2 k T_s} A_{21} \cdot \frac{3}{4} \underbrace{n_H s}_{N_H} \Rightarrow \boxed{\tau_\nu = \frac{3}{32} \frac{h c^2 A_{21}}{\nu k T_s \pi} \cdot N_H(\nu)}$$

$$N_H(\nu)\, d\nu = N_H(v)\, dv$$

$$\frac{d\nu}{\nu} = \frac{dv}{c} \Rightarrow d\nu = \frac{\nu}{c} dv = \frac{dv}{\lambda}$$

$$N_H(\nu)\, d\nu = N_{H,TOT} \cdot f(\underset{c\cdot(1-\frac{\nu}{\nu_0})}{\underset{\shortparallel}{v}})\, dv = N_{H,TOT} \cdot f(v)\, \lambda\, d\nu$$

$$\Rightarrow N_H(v) = N_{H,TOT} \cdot f(v) \cdot \lambda$$

$$\tau_\nu = \underbrace{\frac{3 h c^2 \lambda A_{21}}{32\pi \nu k}}_{\frac{3 h c \lambda^2 A_{21}}{32\pi k}} \frac{N_{H,TOT}\, f(v)}{T_s}$$

$$\boxed{\tau_\nu = \left(5.489 \times 10^{-14}\ \mathrm{K\ cm^3\ s^{-1}}\right) \cdot \frac{N_{H,TOT}\, f(v)}{T_s}} \quad \text{Spitzer 3-37}$$

$$= 5.489 \times 10^{-19} \left(\frac{N_H}{\mathrm{cm^{-2}}}\right) \cdot \left(\frac{f(v)}{1/\mathrm{km\ s^{-1}}}\right) \left(\frac{1}{T_s/K}\right)$$

Since, for emission $\tau_\nu = \frac{T_B}{T_s}$ ($T_B(0)$ negligible)

$$\Rightarrow N_{H,TOT} = \frac{\int T_B(v)\, dv}{5.49 \times 10^{-14}\ \mathrm{K\ cm^3\ s^{-1}}}$$

$$\Rightarrow \boxed{N_{H,TOT} = 1.82 \times 10^{18}\ \mathrm{cm^{-2}\ K^{-1}\ (km\ s^{-1})^{-1}} \int T_B(v)\, dv} \quad \text{Spitzer 3-38}$$

Absorption-emission experiments can be used to determine both τ and T_B $\Rightarrow$ yield $N_{H,TOT}$ and T_S

Typical lines of sight have a mix of warm and cold

Emission $\propto \int T_B \, dv \Rightarrow$ yields total column assuming $\tau < 1$, since upper level is always 3/4 of pop. no matter what. However, $\tau \propto \frac{N}{T_S} \Rightarrow \tau_{mix} \propto \frac{N_c}{T_c} + \frac{N_w}{T_w}$

$\Rightarrow$ because cold clouds have larger τ in general, T_S tends to be dominated by their temperature.

<u>Distribution</u> Kulkarni & Heiles 1987
Wolfire et al 2003, ApJ 587, 278

@ solar neighborhood, looking $\perp$ to the Galactic plane,

$\Sigma \sim 6.5 M_\odot pc^{-2}$ (Radhakrishnan et al 1972)

CNM + WNM (HI emission) $\Sigma \sim 8 M_\odot pc^{-2}$ (Dickey + Lockman 1990)

WIM $\Sigma \sim 2 M_\odot pc^{-2}$ (Reynolds)

Molec. $\Sigma \sim 1-2 M_\odot pc^{-2}$

CNM $\rightarrow$ 40%
WNM $\rightarrow$ 60%
(Heiles & Troland 2003)

$\Rightarrow$ Total $\Sigma \sim 11-12 M_\odot pc^{-2}$

Malhotra (1995), $H = 120$ pc inside $R < 5$ kpc
$H = 260$ pc at solar circle

Possible multiple comps. w/different thickness (Lockman)

Average midplane density $n_{HI} = 0.6 \, cm^{-3}$ for $R = 4-12$ kpc

<u>CNM clouds, temp + colum.</u> (Heiles + Troland 2003, ApJ 586, 1067)

Broad ($\gtrsim 9$ km/s) emission seen on all los at intermediate + high lats. $\rightarrow$ diffuse WNM

Narrow (< 5 km/s) seen in 1/3 $\rightarrow$ CNM

→ emission

ν → only narrow seen in absorption, why? "lower τ"

$\tau \propto \frac{1}{T_s}$ → narrow features are cold clouds
broad features WNM

⇒ Doing emission - absorption studies yield $T_s \sim 50-200$ K

$N_H \sim 0.3 - 2 \times 10^{20}$ cm^{-2}

"Median" cloud has $N_H = 0.8 \times 10^{20}$ cm^{-2} and $T = 115$ K, $\tau_{peak} = 0.11$

Recent Heiles + Troland:

median	cold cloud	2×10^{20}	0.5×10^{20}
	warm cloud	8×10^{20}	1.3×10^{20}
		$\lvert b \rvert < 10$	$\lvert b \rvert > 10$

$N_H = 10^{20}$ cm^{-2} ⟺ Σ 1 $M_\odot$ pc^{-2}

See Heiles & Troland (2003) plots

Temperature of WNM

Requires opt, IR, UV lines (HI obs are biased toward the cold)

Use HI emission to find components w/o absorption counterpart
Their linewidths give upper limits to temperature.

~ 1/2 comps. have $T_K < 5{,}000$ K (Heiles 2000)

Using optical + UV lines toward distant stars comb. with HI
↓ Ca ↓ Si, C, N, Mg, S ← space based

data, Fitzpatrick + Spitzer (1997) comp. temperatures (+ ionis. and density info) → Temp. upper limits of 5,000 - 7,000 K, but also some lower

Temp. ranges $\ll 8{,}000$ K for WNM are unstable if P = fixed (but WNM has long cooling time)

Density

From modeling opt/UV lines (Fitzpatrick + Spitzer)
n_e as small as $0.02\ cm^{-3}$ $\quad n_e \sim$ few $\times 0.01 - 0.1\ cm^{-3}$

If X_e known (or estimated) $\Rightarrow n = \frac{n_e}{X_e}$

X_e? E.g., assume single component, $X_e = \frac{N_{e\perp}}{N_{WNM}}$ from DM / from HI em.

Heiles (2000) local ISM $X_e \equiv \frac{N_{e\perp}}{N_{WNM\perp}} \sim 0.2$

$\Rightarrow n_{WNM} \sim$ a few tenths, but very uncertain.

CNM density? No direct probe.

Can assume pressure to derive: $nkT = P$, $n_{TYP} \sim 100\ cm^{-3}$

If single spherical cloud observed, $\Rightarrow n$ from $\frac{N_{HI}}{L_{size\perp}}$ from HI em.

$\Rightarrow$ but probably clouds are sheets/filaments and this is not a valid assumption

Heating - Cooling

Spitzer 5.1d, Wolfire et al. (1995), Wolfire et al. (2003)

Ionization $\longrightarrow$ 1) Cosmic rays

Primary CRs + secondary e^-

Primary e energy $\sim 35\ eV$

Volume CR ionization rate $\sim 3\times10^{-17}\, n\ cm^{-3} s^{-1}$

including (50%) effect of secondaries

(Solar wind screens low E CRs)

Couples gas to "rad." field

2) Soft X-rays

Directly ionize H and He, primary e can ionize other elements

Rate ~~decay~~ depends on N_H to X-ray source

$\zeta \sim 10^{-15} s^{-1} H^{-1}$ to $10^{-18} s^{-1} H^{-1}$ for $N = 10^{18}$ to $10^{20} cm^{-2}$

Wolfire et al (1995)

Equil. ionization fraction is determined by balancing recombs. $n_e n_p \alpha^{(2)}$ with ionizations.

Heating

CI: diffuse UV ionizes low-ion pot. atoms, particularly Carbon

CI ion. is 11.3 eV
H ion is 13.6 eV → so plenty of photons available

$\frac{n_e}{n_H} \geq \frac{n_C}{n_H} = 4\times10^{-4} \times d_C$ → abundant

↑ gas phase depletion

FUV rad. field: Habing field (1968)

↑ sufficient to fully ionize CI

$G_0 = 1.6\times10^{-3}$ erg $cm^{-2} s^{-1}$

More recent revisions (Draine, etc)

$\chi = 1.7 G_0$

Heating rate is ioniz. rate × excess energy/ioniz. ~ 2 eV

ion rate ≡ recomb rate $= \alpha^{(2)} n_e^2$

⇒ Heating rate is $\bar{E}_2 \alpha^{(2)} n_e^2 = \Gamma_c n$

CR: $\Gamma \zeta_{CR} n \bar{E}$ $\bar{E} \sim 35$ eV ⇒ $\Gamma_{CR} \sim 10^{-28} - 10^{-27} s^{-1} H^{-1}$

X-ray: Attenuation-dependent, $\Gamma_{xray} \sim$ 1-few $\times 10^{-27}$ erg $s^{-1} H^{-1}$

Photoelectric Heating

Grains are small, $a = 3-100\,\text{Å}$

Heating rate: $n\Gamma = n_d \sigma_d \int \frac{4\pi J_\nu}{h\nu} \cdot Q \cdot y \cdot (E - \text{ion. pot.})$

- n_d: # density of grains
- σ_d: x section (area)
- $\frac{4\pi J_\nu}{h\nu}$: # of photons
- Q: γ abs. efficiency ~1
- y: photoejection efficiency "quantum yield" ~0.1 for small grains + UV rad.

$$n\Gamma = 10^{-24}\, n\, \epsilon\, G_0 \ \text{erg cm}^{-3}\,\text{s}^{-1}$$

G_0: rad field in units of "Habings" (1.6×10^{-3} erg cm^{-2} s^{-1})

ϵ: fraction of UV abs by grains converted to gas heating

$$\epsilon = \frac{4.9\times10^{-2}}{1+\left[\left(\frac{G T^{1/2}}{n_e}\right)/1925\right]^{0.73}} + \frac{3.7\times10^{-2}\,(T/10^4)^{0.7}}{1+\left[\left(G T^{1/2}/n_e\right)/5000\right]}$$

Low T dominant

larger recomb. rate at high T lowers grain charge, ⇒ e more easily ejected.

Low $\frac{G T^{1/2}}{n_e}$ → grains are neutral or negative, $\epsilon \sim 0.05-0.09$

high $\frac{G T^{1/2}}{n_e}$ → pos. charge, ϵ lower

This is the dominant heating except @ very large density (CI heating ↑)

Cooling (Spitzer 6.2a)

Lyα: @ high T e collisions excite H to n=2, radiating Lyα which is absorbed by dust and radiated in IR

$$\Lambda = 7.3\times10^{-19}\, n_e\, n(\text{HI})\, e^{-1.2\times10^5/T} \ \text{erg cm}^{-3}\,\text{s}^{-1}$$ 6-12 Spitzer

<u>CII</u> : CII fine structure line ($E = 0.0079$ eV) @ 157.7 μm is collisionally excited and radiatively de-excited

Biggest cooling line in galaxies

$$\Lambda = 7.9 \times 10^{-27} n_H^2 d_c e^{-92/T} \text{ erg cm}^{-3}\text{s}^{-1}$$

↑ depletion

Spitzer 6-13

<u>Other fine structure</u> : OI (63 μm), CI (609 μm, 370 μm) may be important depending on situation

<u>Recomb onto small grains</u> : @ $T > 10^4$ K (low densities)

Thermal energy $\sim kT$ is lost by recomb. onto grains

$$n^2 \Lambda = 4.65 \times 10^{-30} T^{0.94} (G T^{1/2}/n_e)^{\beta} n_e n \text{ erg s}^{-1}\text{ cm}^{-3}$$ Wolfire eq. 9

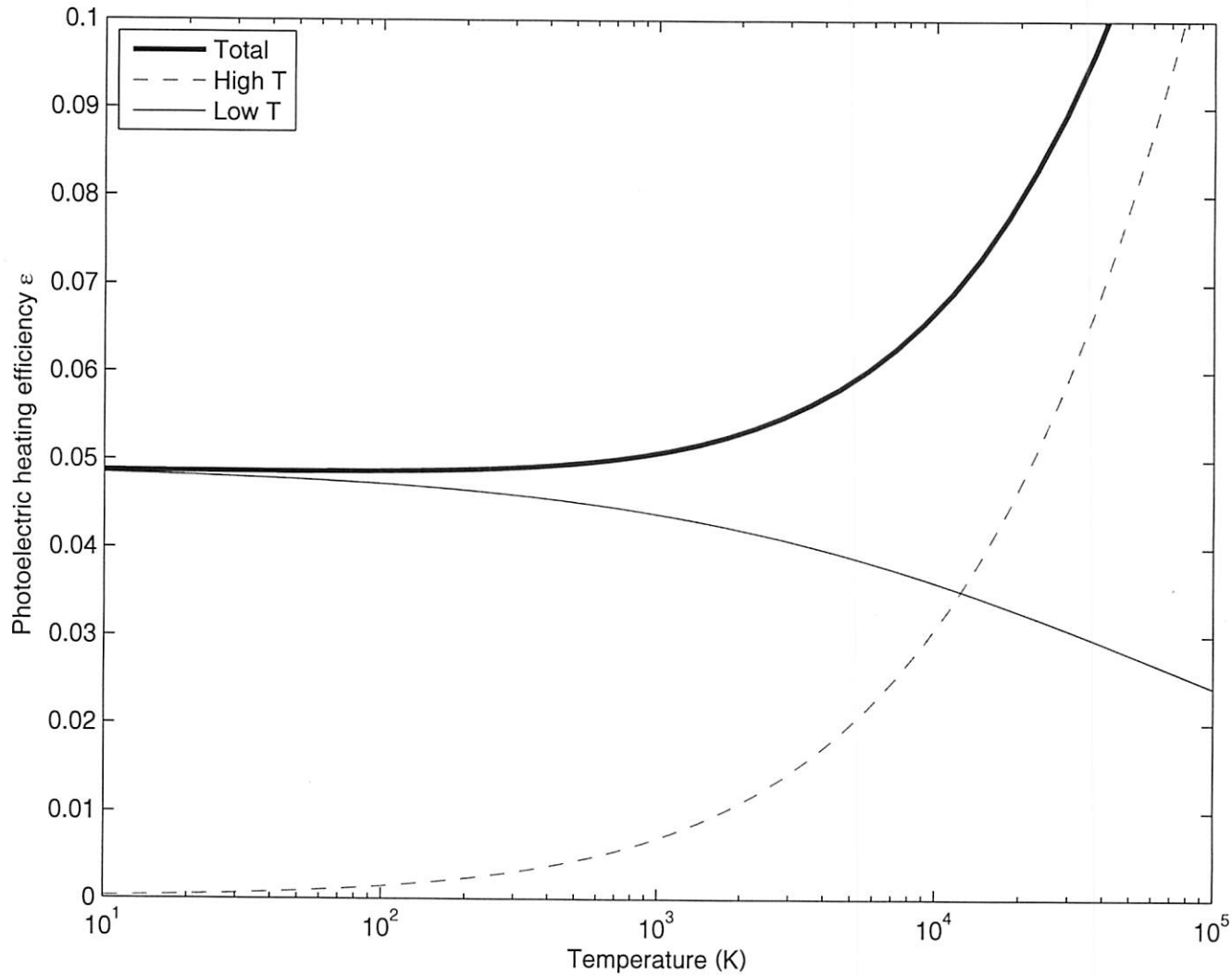
$$\beta = 0.74/T^{0.68}$$

High density : PE heating and CII cooling dominate

Low dens : PE heating + Lyα + PE cooling

⇒ For fixed P, this indicates the stable equilibrium of two phases. We'll see this later

Assuming $n_e = 0.1\ cm^{-3}$
$G = 1$



experiments. Both may be the result of the passage of a shock front through a much larger cloud. The recently discovered structure in the ionized medium on scales of ~10 AU (92c, 281a) might be related to the small-scale structure in the cool neutral medium if, for example, both are caused by instabilities behind supernova shocks, but this connection is only speculative.

2.1.4 OBSERVING SELF-ABSORPTION Just as interstellar Lα absorption can be detected against the broad Lα emission lines from late-type stars, so too can a cold H I cloud appear in absorption against H I emission from warmer gas behind it. Two circumstances are illustrated in Figure 1, along with the 21-cm profiles that result: The telescope on the left measures the sum of the two profiles because the hot cloud is optically thin, and the telescope on the right sees a self-absorbed profile.

Self-absorption was first detected against the low-latitude, bright H I toward the galactic center and anticenter (109, 205). Its occurrence is direct evidence that the kinetic temperature of galactic H I has a large range.

The phenomenon can be difficult to recognize in a complex spectrum, and Knapp (144) has proposed that self-absorbed features be identified by

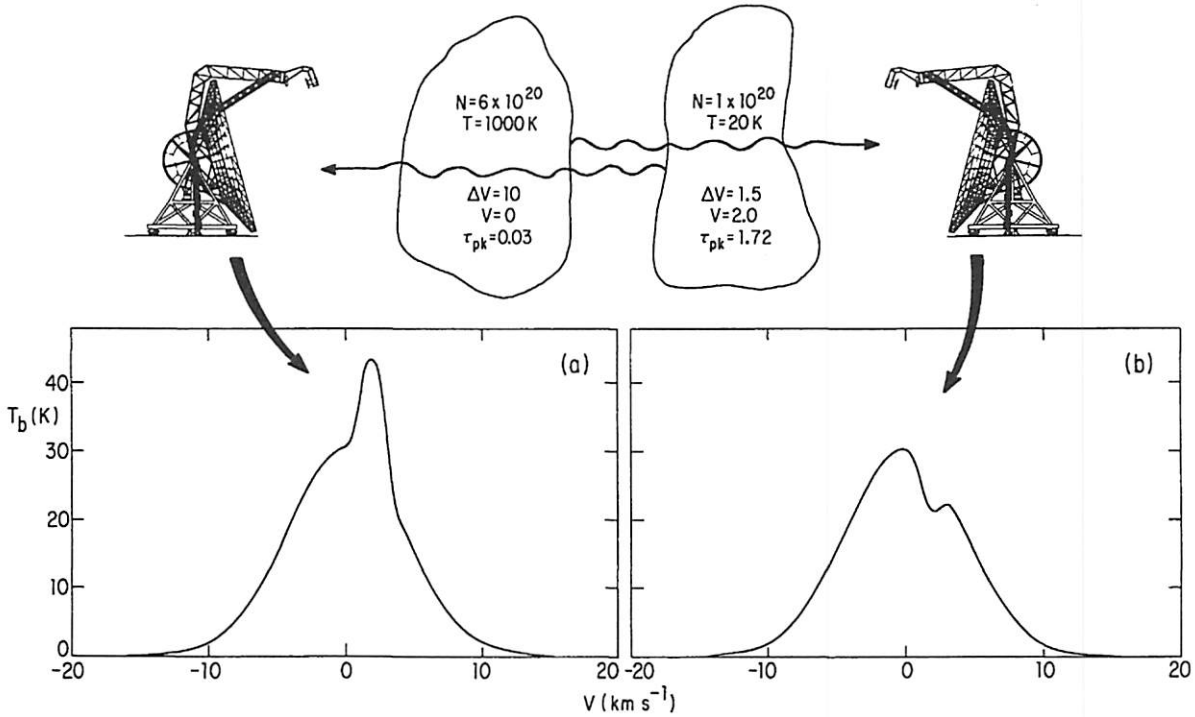
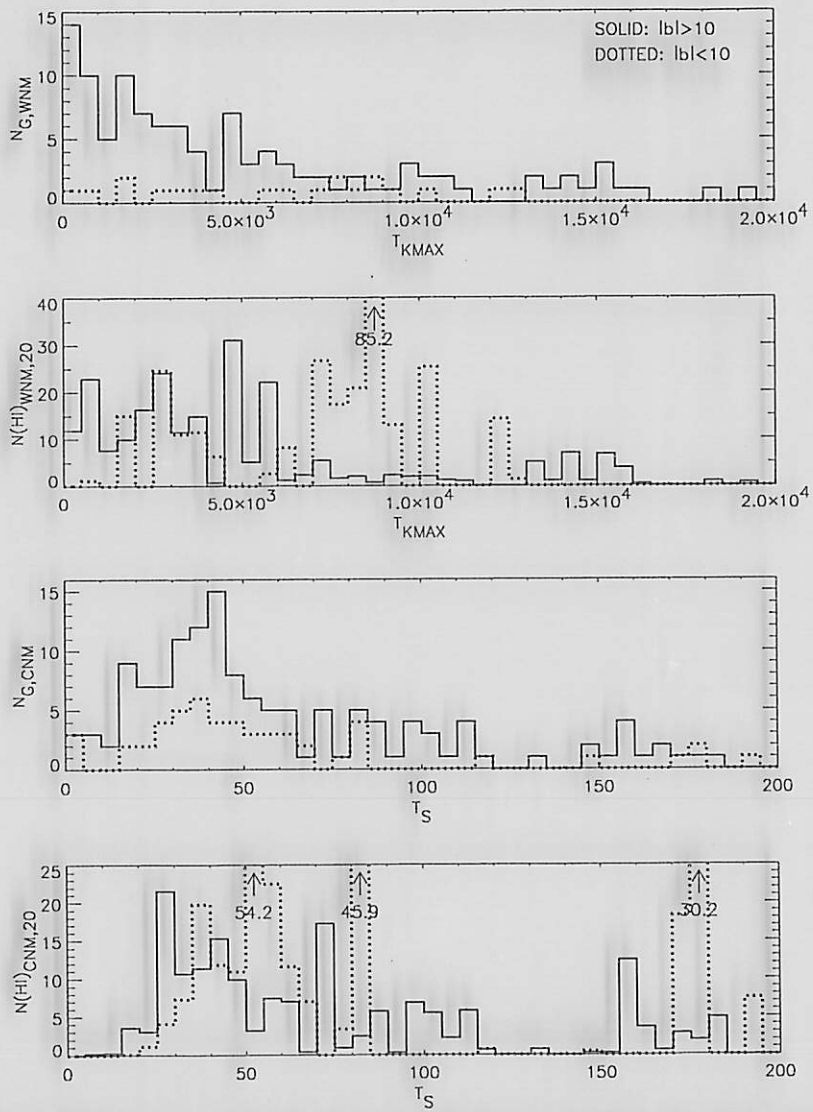


Figure 1 Schematic of the geometry of 21-cm self-absorption. The structure of an emission profile depends on the relative location of hot and cold clouds as viewed by the observer. Superpositions like this are very common at low and intermediate latitudes. The profile on the right (*b*) is self-absorbed.



Heiles & Troland 2003

FIG. 2.—Histograms of $T_{k,\max}$ for the WNM (*top two panels*) and of T_s for the CNM (*bottom two panels*). The solid lines are for $|b| > 10°$ and the dotted ones for $|b| < 10°$. N_G is the number of Gaussian components; $N(\mathrm{H\ I})_{20}$ is column density in units of $10^{20}\ \mathrm{cm}^{-2}$.

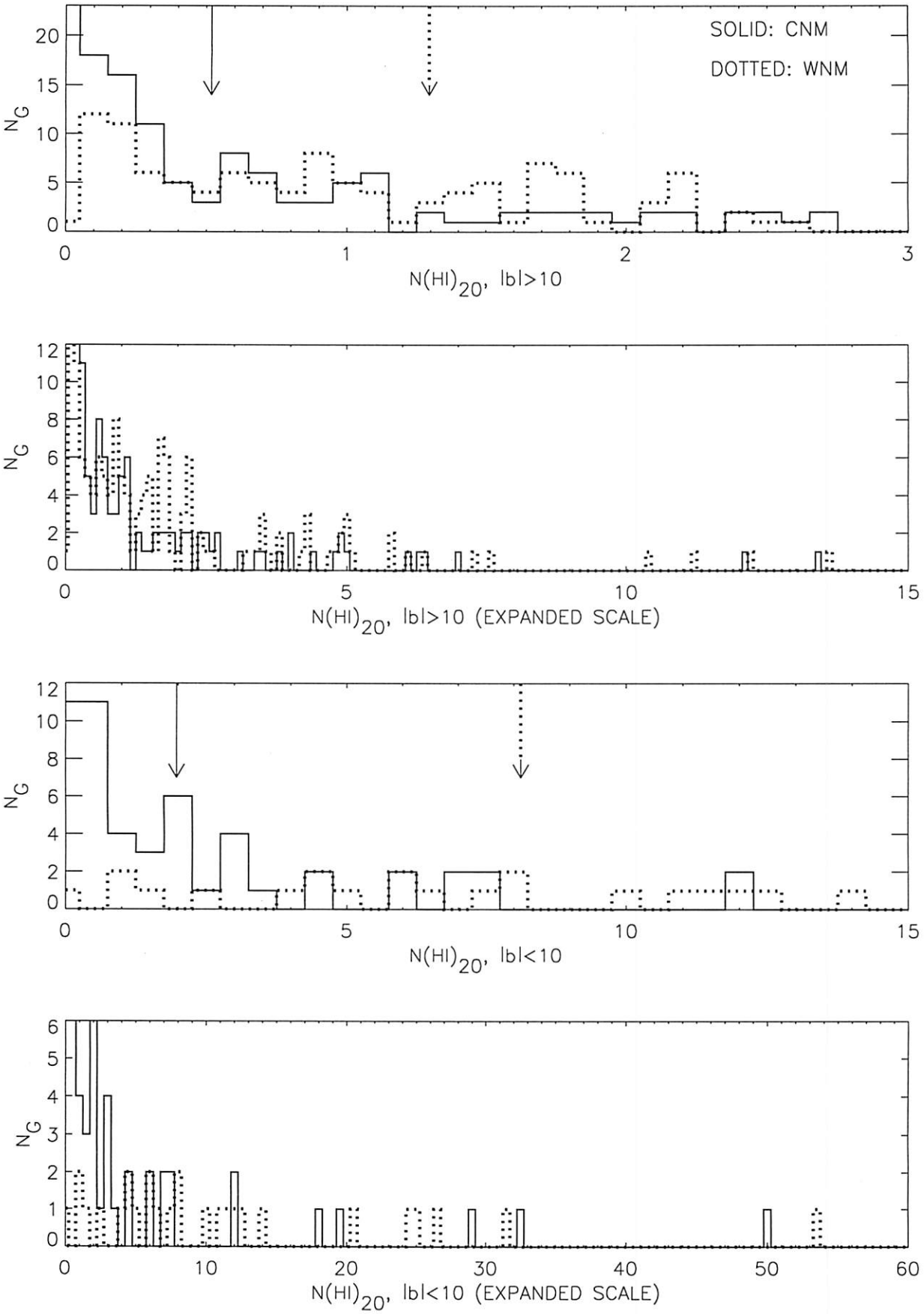


FIG. 4.—Histograms of number of Gaussians N_G and column densities $N(\mathrm{H\ I})_{20}$ for all Gaussian components, both CNM (*solid histogram*) and WNM (*dotted histogram*). The top two panels show $|b| > 10°$ with different scales on both axes to facilitate interpretation; the bottom two panels are for $|b| < 10°$. The arrows show the medians, which are for the (CNM, WNM) of (0.60, 1.30) at $|b| > 10°$ and (2.0, 5.0) at $|b| < 10°$. $N(\mathrm{H\ I})_{20}$ is in units of 10^{20} cm^{-2}.

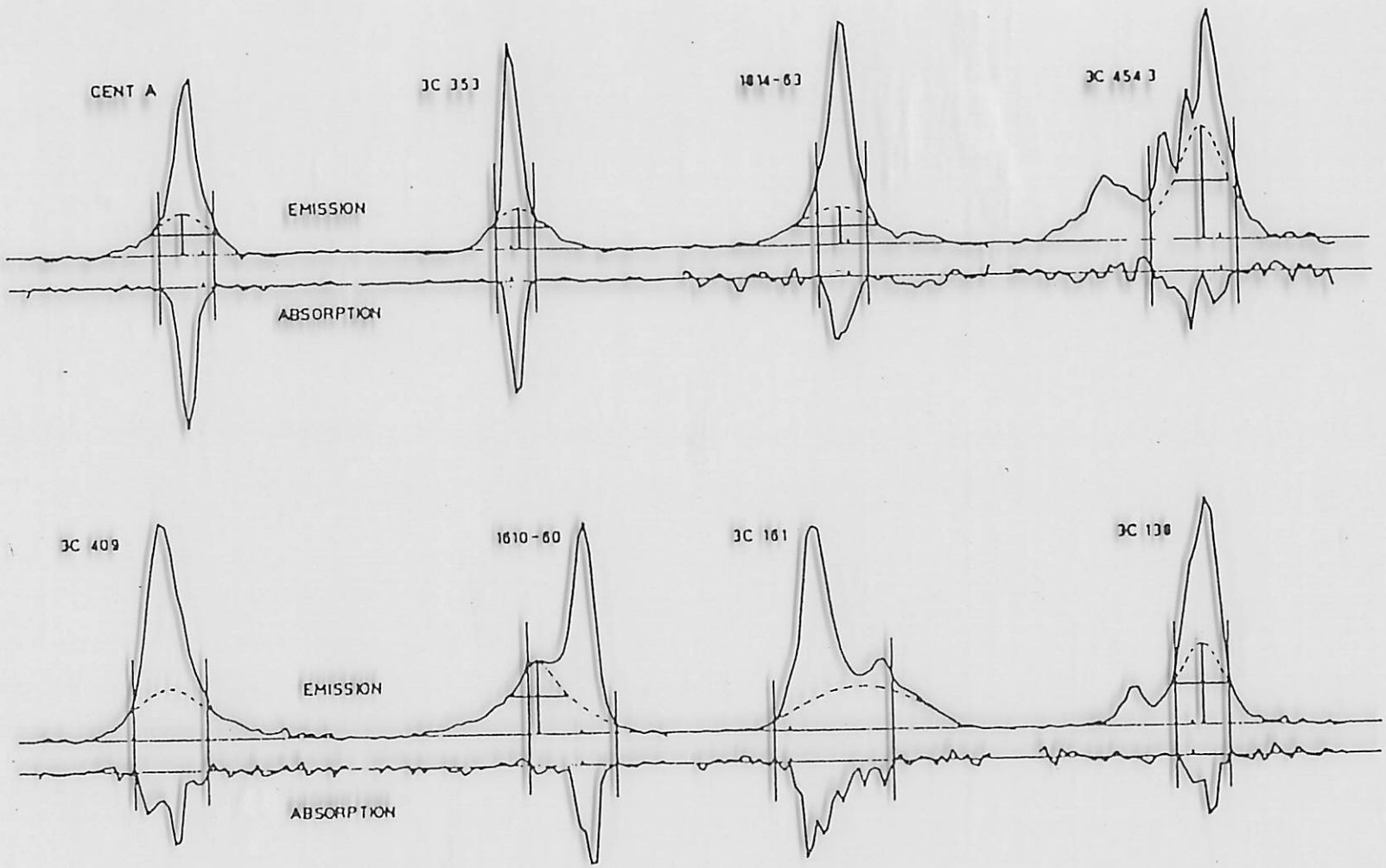


Figure 4-1. A set of high latitude emission and absorption spectra from the Parkes survey (Radhakrishnan *et al.* 1972).

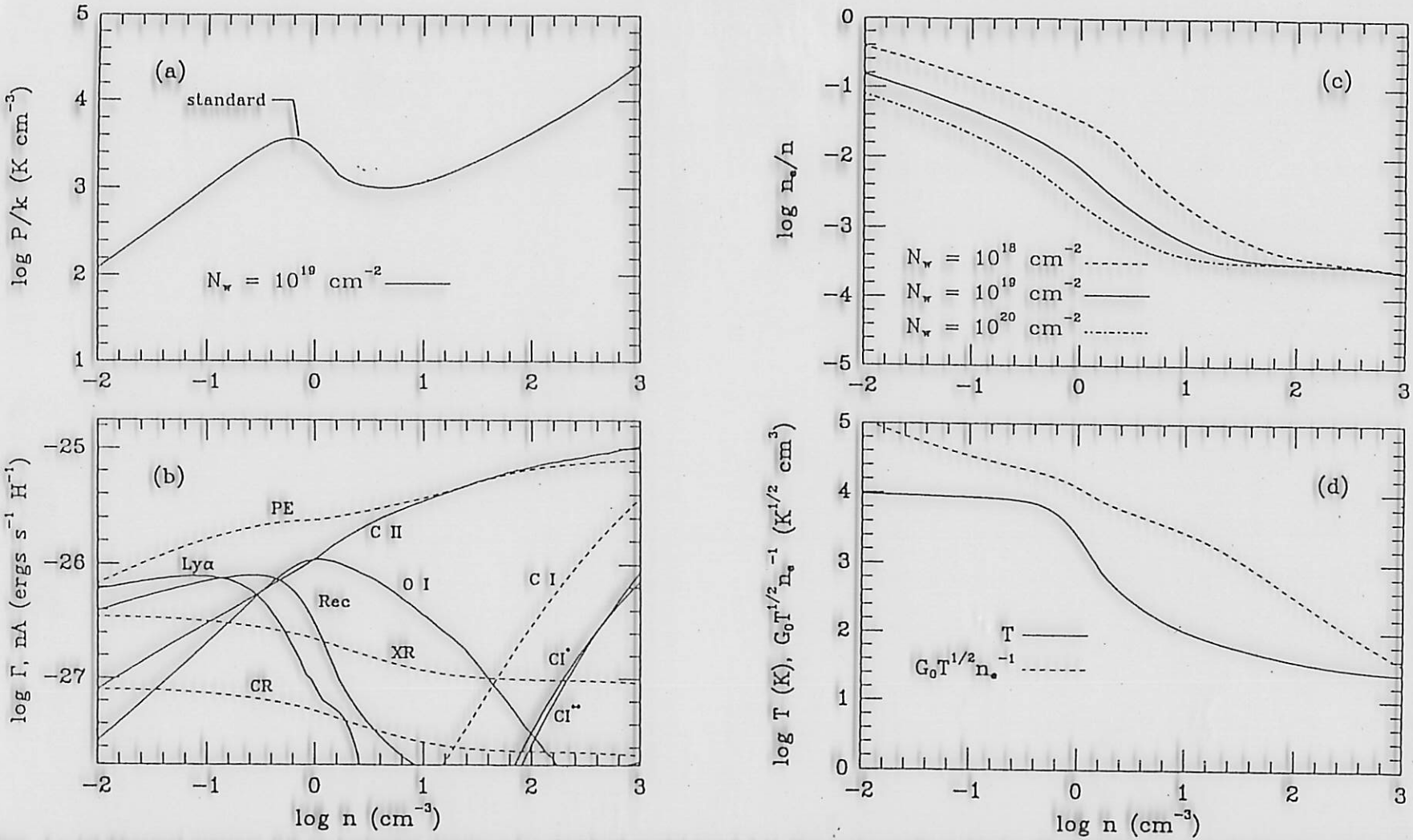


FIG. 3.—(*a*) Thermal pressure P/k vs. hydrogen density n for standard model (see § 3.1). Gas is thermally stable for $d(\log P)/d(\log n) > 0$. (*b*) Heating and cooling rates per hydrogen nucleus vs. density n for pressure curve of panel *a*. Heating rates (*dash*); Photoelectric heating from small grains and PAHs (PE); X-ray (XR); Cosmic ray (CR); photoionization of C (C I). Cooling rates (*solid*); C II fine-structure (C II); O I fine-structure (O I); Recombination onto small grains and PAHs (Rec); Lyα plus metastable transitions (Lyα); C I fine-structure 609 μm (C I*); C I fine-structure 370 μm (C I**). (*c*) Electron fraction n_e/n as a function of hydrogen density n for the pressure curve of panel *a* (*solid*). Also shown are curves for $N_w = 10^{18}$ cm^{-2} (*dash*), and $N_w = 10^{20}$ cm^{-2} (*dash-dot*). (*d*) Gas temperature T (*solid*) and ionization parameter $G_0\,T^{1/2}/n_e$ (*dash*) as a function of hydrogen density n for the pressure curve of panel *a*.