Lecture 10 - Tracing 21 cm Emission and Absorption

1. Brief History
2. HFS and Spin Temperature
3. Radiative Transfer
4. Evidence for CBM/WNM

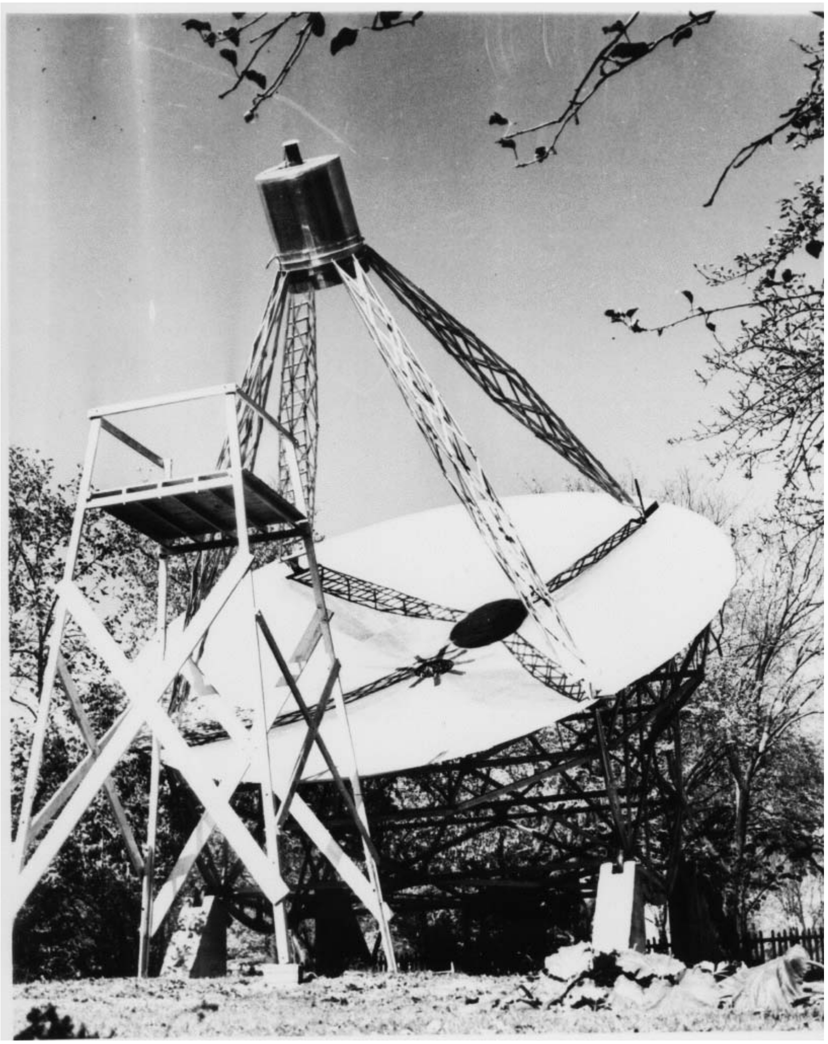
References

Spitzer, Secs, 3.3b, 3.4a, 4.1b
Dopita & Sutherland, Sec, 4.2
Ferriere, RMP 73 1031 2001, Sec. IIIC
Dickey & Lockman, ARAA 28 215 1990
Heiles & Troland, ApJ 586 1067 2003

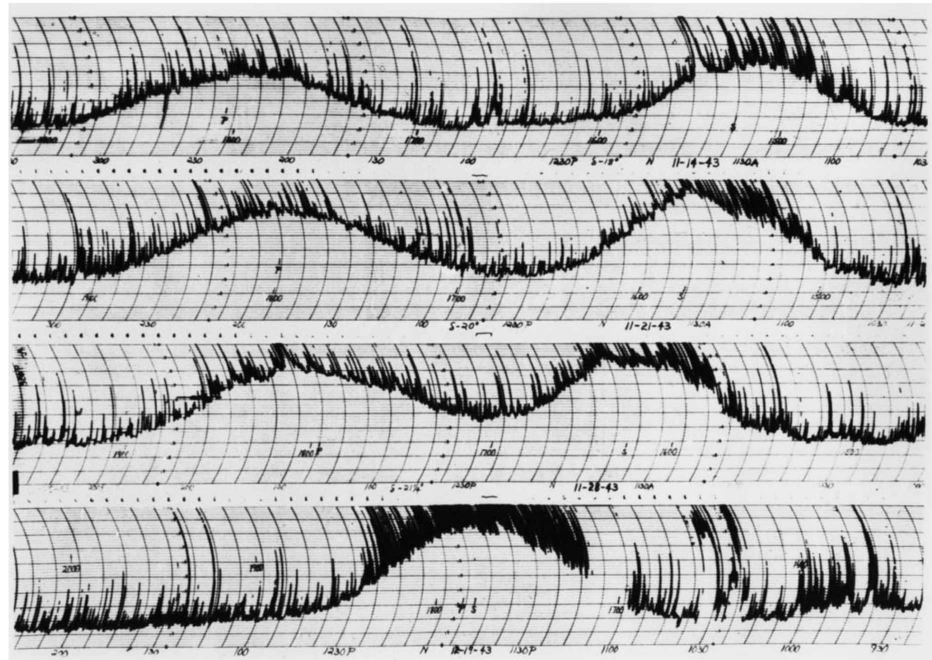
1. The Radio Astronomy Revolution

- Radio astronomy started when Jansky (1932) detected short-wave radiation later identified as coming from the plane of the Milky Way
- Slow progress for a decade
  – Reber mapped the Milky Way (1938-1943)
  – Solar radio emission detected in 1942 (Hey 1946)
  – WW II communications and radar R&D improved receivers
- Early radio studies were of the continuous spectrum
  – Hot HII regions (Mathews & O'Dell AARA 7 67 1969)
  – Microwave background (Thaddeus AARA 10 305 1972)
  – Pulsars (Smith Rep. Prog. Phys. 35 399 1972)

Grote Reber (1911-2002)



Reber's back yard 9-m telescope.
Wheaton, IL, ~1938



Strip charts from Reber's telescope made in 1943. The broad peaks are due to the Milky Way and the Sun. The spikes are interference from automobile ignition.

Early Radio Continuum Observations

160 MHz

480 MHz

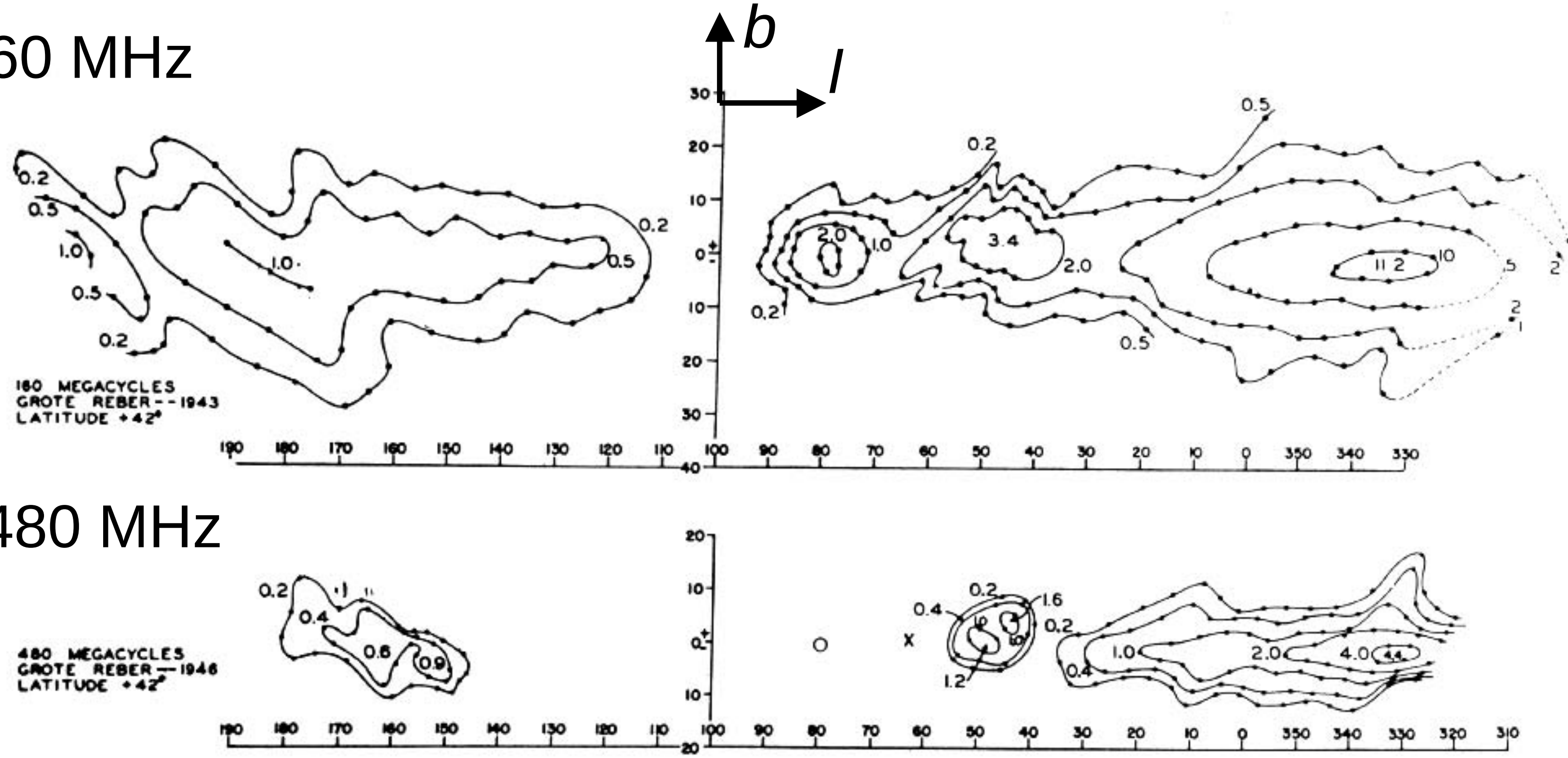


FIG. 7—Contours of constant intensity at 160 MHz and 480 MHz, taken at Wheaton, Illinois.

Between 1938 and 1943, Reber made the first radio surveys of the Milky Way and detected discrete sources in Cygnus & Cassiopeia. Non-thermal emission.

HI 21 cm Emission

- Predicted by van de Hulst in 1945, grad student of Oort
- Discovered by Ewen & Purcell of the Harvard Physics Dept. (Nature 168 356 1951)
  - Soon confirmed by Dutch and Australians
  - Three observations reported together in *Nature*
  - Dutch lost the race after fire destroyed their original receiver
- Generally in emission but also in absorption against continuum radio sources such as HII regions
- Atomic H is a major constituent of the interstellar gas
- 21 cm line measures

  - quantity of interstellar HI

  - excitation temperature

  - radial velocities from Doppler shift
- The 21 cm line was the only astronomical radio line known until the 1963 detection of OH (Weinreb et al.)

Early Results on HI Regions

- n(HI) ~ 1 cm^{-3} in spiral arms and 0.1 cm^{-3} in between

  $$T \sim 125 \text{ K}$$

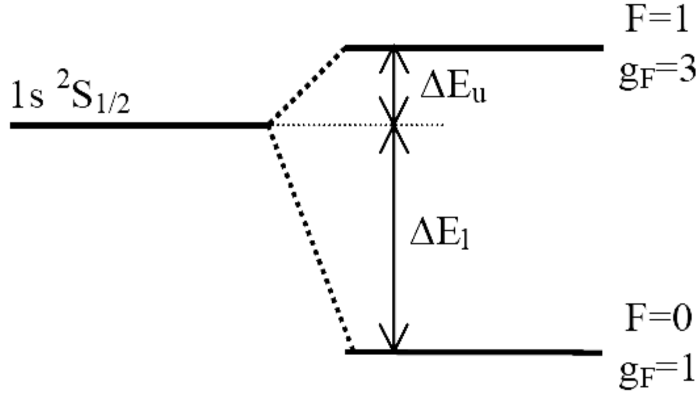
- Increasing sensitivity and angular resolution showed large variations in density and temperature; density and temperature tend to be anticorrelated
- Consistent with heating ~ $\boldsymbol{n}$ and cooling ~ $\boldsymbol{n^2}$,
- Embodied in two-phase model of Field, Goldsmith & Habing 1969): Cool, dense *clouds* in warm, low-density *intercloud* medium in approximate pressure equilibrium:

  $$\boldsymbol{n_{CNM}\, T_{CNM} \approx n_{WNM}\, T_{WNM}}$$

- The intercloud medium was thought to contain about half the neutral atomic hydrogen
  - $\boldsymbol{T_{WNM}} \approx 8000$ K and $\boldsymbol{n_{WNM}} \sim 0.4$ cm^{-3}
  - $\boldsymbol{T_{CNM}} \approx 80$ K and $\boldsymbol{n_{CNM}} \sim 40$ cm^{-3}

2. HI Hyperfine Structure and Spin Temperature

- HI has one electron (spin $\boldsymbol{S} = 1/2$) and one proton (nuclear spin $\boldsymbol{I} = 1/2$), and the $1s^2S_{1/2}$ ground state has zero orbital angular momentum $\boldsymbol{L} = 0$.
- The **total angular momentum** is $\boldsymbol{F = I + S}$, with total quantum number $F = 0,1$



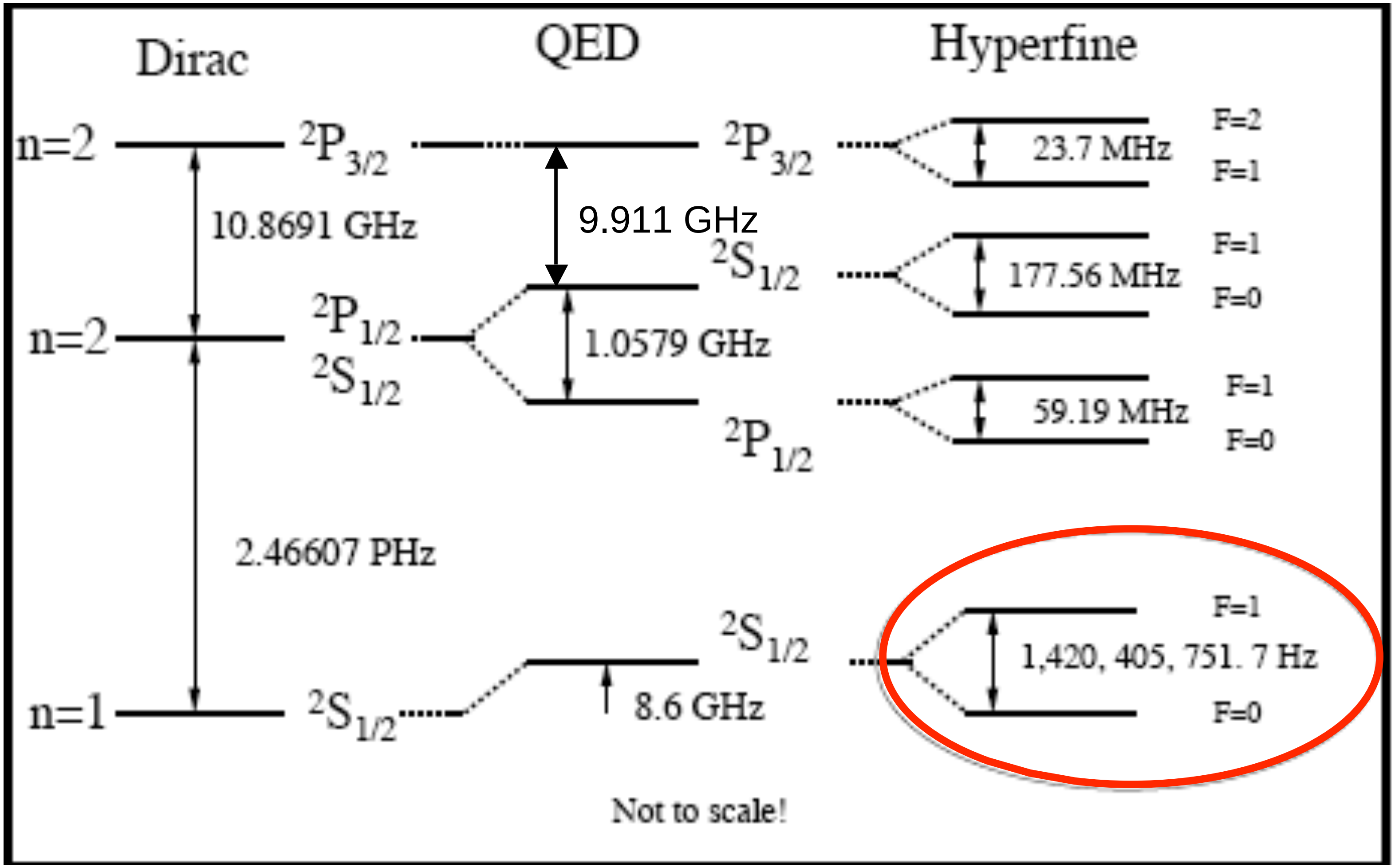
- The lab frequency of the F=1-0 transition is:

$$\nu_{10} = 1420{,}405{,}751.786 \pm 0.01 \text{ Hz}$$

$$h\nu_{10} = 5.879\text{x}10^{-6} \text{ eV} \quad \text{and} \quad T_{10} = h\nu_{10}/k = 0.0682 \text{ K}$$

HI Hyperfine Structure Level Separations

Not to Scale!



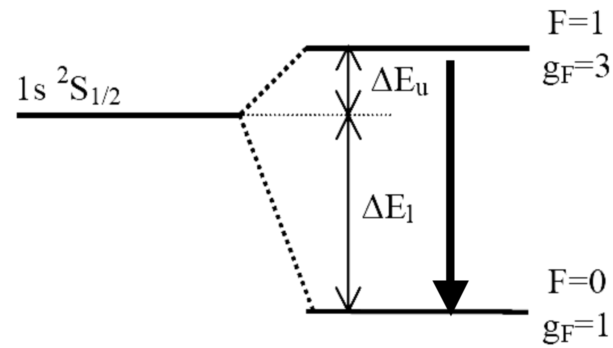
For the frequencies of the allowed hf transitions of the n = 2 level, see Dennison et al. ApJ, 633, 309, 2005.

Properties of the HI HFS Transition

The F = 1-0 transition is magnetic dipole. With its low frequency; the A-value is tiny

$$\mathbf{A_{10} = 2.85 \times 10^{-15}\ s^{-1},}$$

corresponding to a mean lifetime of 11 Myr. The absorption oscillator strength is $\boldsymbol{f_{01} = 5.75 \times 10^{-12}}$



The level populations are affected by ***spin-exchange collisions*** between H atoms, e.g.

$$\uparrow\downarrow \; + \; \downarrow\uparrow \;\rightarrow\; \uparrow\uparrow \; + \; \downarrow\downarrow$$

$$\mathrm{H(1,0) + H(1,0) \rightarrow H(1,+1) + H(1,-1),}$$

discussed first by Purcell & Field (ApJ 124 542 1958).
The collisional de-excitation rate is ~10^{-10} cm^{3}s^{-1} for T > 50 K.
(Zygelman ApJ 622 1356 2005). Thus the critical density is tiny

$$\boldsymbol{n_{cr} = A_{10}/k_{10} \approx 3 \times 10^{-5}\ \mathrm{cm}^{-3}}$$

21-cm Analog Transitions

Deuterium (p,n)

^{2}H: $\boldsymbol{I}$ = 1, S = 1/2 --> F= 1/2, 3/2

$\nu_{3/2,1/2}$ = 327.384 MHz **(92 cm)**

$A_{3/2,1/2}$ = 4.69 x 10^{-17} s^{-1}

Definitive detection: Rogers et al.

ApJ 133 1624 2007

Helium-3+ (2p,n)

$^3He^+$ $\boldsymbol{S}$ = 1/2 , $\boldsymbol{I}$ = 1/2 --> $\boldsymbol{F}$ = {0, 1}

$\nu_{\boldsymbol{10}}$ = 8.665,650 GHz **(3.5 cm)**

A_{01} = 1.96 x 10^{-12} s^{-1}

Detected in HII regions: Rood et al.
Space Science Reviews, 84 185 1998

Both transitions are of cosmological significance.

Hyperfine Level Population

The small critical density, $n_{cr} \approx 3 \times 10^{-5}$ cm^{-3}, might suggest that the levels are thermalized at interstellar densities. But under certain conditions, external radiation fields, e.g., the CBR, can affect the population. We use the Boltzmann-like formula to define the excitation or *spin temperature* T_S as

$$\boxed{\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\left(-{h\nu}/{kT_S}\right) = 3\exp\left(-{h\nu}/{kT_S}\right)}$$

To analyze the population, we write down the rate equations in the presence of a radiation field u_ν

$$n_0\left(nk_{01} + B_{01}u_\nu\right) = n_1\left(A_{10} + B_{10}u_\nu + nk_{10}\right)$$

and solve for n_1 / n_0 in the limit $h\nu / kT << 1$ where

$$u_\nu = 8\pi kT_R / c\lambda,^2$$

and use the relations between B_{01}, B_{10} and A_{10} (Lec02).

Spin Temperature

Making us of the fact that $h\nu / kT \ll 1$, this leads to

$$\frac{n_1}{n_0} \approx 3\left[\frac{kT_R / h\nu + n/n_{CR}(1 - h\nu / kT)}{1 + kT_R / h\nu + n / n_{CR}}\right],$$

but from the definition of T_S we also have $n_1 / n_0 \approx 3(1 - h\nu / kT_S)$

Equating these expressions allows the following solution, after some tedious algebra and also assuming again that $h\nu / kT_S \ll 1$

$$\boxed{T_S \approx \frac{T + yT_R}{1 + y},}$$

T_S is the weighted mean of T and T_R

$$y \equiv \frac{kT}{h\nu}\frac{n_{CR}}{n} \approx \frac{T}{0.0682\ \mathrm{K}}\frac{2.85 \times 10^{-5}\mathrm{cm}^{-3}}{n} = T\ \frac{4.18 \times 10^{-4}\ \mathrm{cm}^{-3}}{n}$$

We have assumed that $k_{10} = 10^{-10}$ cm^3 s^{-1}, ignoring the possibility of an increase at high T. From the numbers, we see that y, which measures the deviation of T_S from T, can become significant at low density and high temperature.

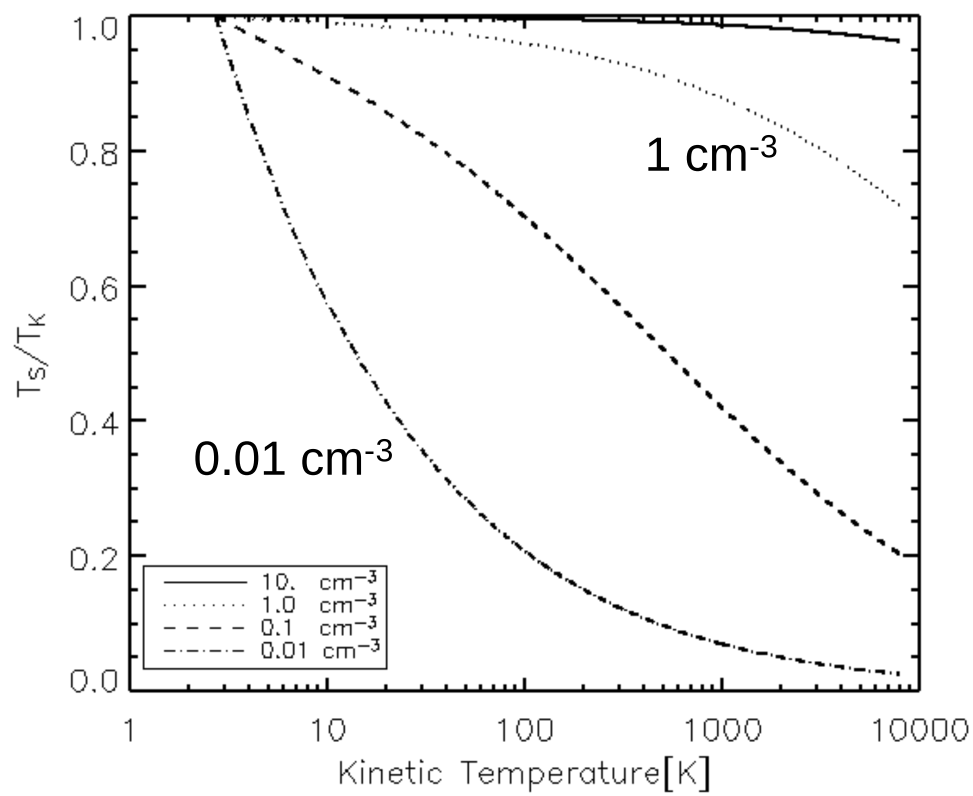
Ratio of Spin and Kinetic Temperatures

- T_S is between T and T_R
- $T_S << T$ for low n and high T

- Estimate for CNM
  - n = 40 cm^{-3}, T= 80 K
  - $y \approx 10^{-3}$, $T_S \approx T$
- Estimate for WNM
  - n = 0.4 cm^{-3}, T= 8000 K
  - $y \approx 1$, $T_S \approx 0.5\ T$

- Modified by scattered Lyα, which tends to equalize T_S and T

- For the outer Milky Way, see Corbelli & Salpeter, ApJ 419 94 1993



$$T_S \approx \frac{T + yT_R}{1+y} \qquad y \equiv \frac{kT}{h\nu}\frac{n_{CR}}{n}$$

$$T_R = 2.7\text{K and low densities}$$

Observing the HI 21-cm Line

- Galactic 21 cm radiation can be detected in virtually all directions, usually in emission.
- In front of a source of continuum radiation, it appears in absorption
- The hf splitting is ≈ 5.9 μeV, or $h\nu/k_B$ =0.068 K.

  Since T > 2.7 K for much of the ISM, $hv << kT$

  and $n_1/n_0 = 3$ is a good approximation
- For the temperature of HI regions, nearly all H is in the ground electronic level

$$n(\mathrm{H}) = n_0 + n_1 = 4n_0$$

- 21-cm emission provides a good measure of total H, provided the optical depth is small
- The absorption strength is very sensitive to T_s

3. 21-cm Line Radiative Transfer

From Lec02, the equation of transfer $\frac{dI_\nu}{d\tau_\nu} = S_\nu - I_\nu$ for a uniform slab has the solution

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

The source function and the absorption coefficient in this case are easily transformed using the population formula for the HI hf levels

$$\frac{n_1}{n_0} = \frac{g_1}{g_0}\exp\left(-{h\nu}/{kT_S}\right) = 3\exp\left(-{h\nu}/{kT_S}\right)$$

On substitution and use of the Einstein *A* and *B* coefficients and the Planck intensity B_ν, the results are simply expressed in terms of the spin temperature:

$$\boxed{\begin{aligned} S_\nu &\equiv \frac{c}{4\pi}\frac{n_1 A_{10}}{n_0 B_{01} - n_1 B_{10}} = B_\nu(T_S) \\ \kappa_\nu &= \frac{h\nu}{c}\left(B_{01}n_0 - n_1 B_{10}\right) = \frac{h\nu}{c}\; n_0 B_{01}(1 - e^{-h\nu/kT_S}) \end{aligned}}$$

HI Radiative Transfer

Recalling the definition of optical depth, $d\tau_\nu = \kappa_\nu ds$, the equation of radiative transfer can now be written as

$$\frac{dI_\nu}{d\tau_\nu} = B_\nu(T_S) - I_\nu .$$

Defining *brightness temperature* by $I_\nu \equiv 2kT_B / \lambda^2$, T_B satisfies the equation

$$\frac{dT_B}{d\tau_\nu} = T_S - T_B$$

Use the integrating factor e^{τ_ν} to rewrite this as

$$\frac{d}{d\tau_\nu}(e^{\tau_\nu} T_B) = e^{\tau_\nu} T_S$$

Integrating between 0 and τ_ν for constant T_S yields: $e^{\tau_\nu} T_B - T_B(0) = (e^{\tau_\nu} - 1) T_S$.

Next define $T_{BG} \equiv T_B(0)$ and $\Delta T_B = T_B - T_{BG}$ to write the solution as

$$\boxed{\Delta T_B = (T_S - T_{BG})(1 - e^{-\tau_\nu})}$$

21-cm Line Optical Depth

We calculate the optical depth form the definition $d\tau_\nu = \kappa_\nu ds$ and the absorption coefficient

$$\kappa_\nu = \frac{h\nu}{c}\, n_0 B_{01}(1 - e^{-h\nu/kT_S})$$

Since this formula involves the frequency integrated Einstein B coefficient, we have to multiply it by the line shape function $\phi(\nu)$ and replace the density in the $F = 0$ level by the column density N_0 required by the integration over s (NB: Later use $V/c = (\nu - \nu_0)/\nu_0$)

The optical depth is

$$\tau_\nu = \frac{h\nu}{c} N_1 B_{01}\left[1 - e^{-h\nu/kT_s}\right]\phi(\nu) \approx \frac{h\nu}{c} N_0 \frac{h\nu}{kT_s} B_{01}\phi(\nu) = \frac{3hc\lambda}{8\pi\, kT_S}\frac{N_H}{4} A_{10}\,\phi(\nu)$$

Assuming only Gaussian broadening, the optical depth at line center is

$$\tau_0 = \frac{3hc\lambda^2}{32\pi^{3/2}\, kT_S}\frac{N_H}{b} A_{10} \approx \frac{N_H}{4.19\times 10^{20}\,\mathrm{cm}^{-2}}\left(\frac{100K}{T_S}\right)^{-3/2}$$

Optical Depth

For a typical column of $N_H = 2 \times 10^{20}\ \mathrm{cm}^{-2}$, this formula gives

$$\text{For CNM}: \quad \tau_0 \approx 0.6 \frac{N_H / 2\times 10^{20}\mathrm{cm}^{-2}}{T_{2S}\, b_5}$$

CNM is optically thick

$$\text{For WNM}: \quad \tau_0 \approx 6\times 10^{-4} \frac{N_H / 2\times 10^{20}\mathrm{cm}^{-2}}{T_{4S}\, b_6}$$

WNM is optically thin

Change from frequency to veloocity in the the line shape function

$$\phi(V)dV = \phi(\nu)d\nu \ \text{ or } \phi(V) = \lambda\,\phi(\nu)$$

$$\text{Optical depth in } \nu: \qquad \tau_\nu = \frac{3hc\lambda}{8\pi k T_S}\frac{N_H}{4} A_{10}\,\phi(\nu)$$

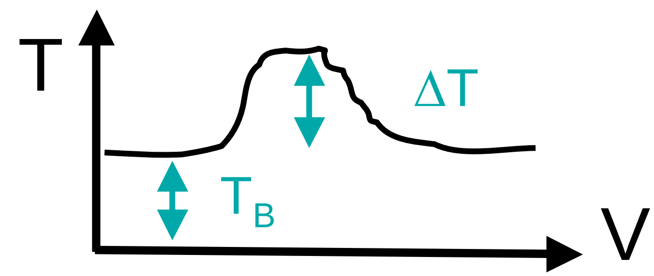
$$\text{Optical depth in velocity}: \quad \tau_V = \frac{3hc\lambda^2}{8\pi k T_S}\frac{N_H}{4} A_{10}\,\phi(V)$$

The integral over the line is then

$$\int_{line} \tau_V\, dV_5 = \frac{N_H / T_S}{1.83\times 10^{18}\, cm^{-2} K^{-1}} \ \text{km/s}$$

Note the 1/T_S dependence

Idealized Observation of the 21 cm Line



- $\Delta T_B = (T_S - T_{BG})(1 - e^{-\tau_\nu})$

- $\Delta T_B = T_B - T_{BG} > 0$ corresponds to an emisison line

  $\Delta T_B = T_B - T_{BG} < 0$ corresponds to an absorption line

T_S >> T_{BG}: Emission Line Formation

- For $T_S >> T_B$

$$\Delta T_B = T_S (1 - e^{-\tau_v})$$

$$d\tau_V = \frac{3hc\lambda^2}{8\pi\, kT_S} \frac{n_{HI}}{4} A_{10}\, \phi(V)\, ds$$

- Eliminate T_S

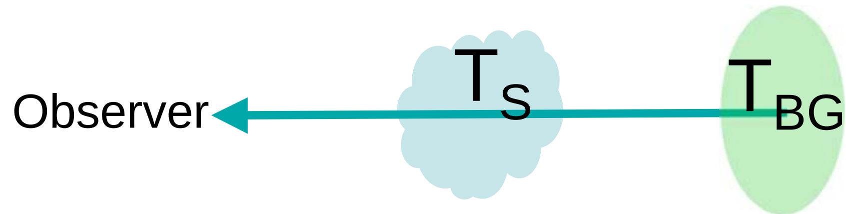
$$\frac{\Delta T_B\, d\tau_V}{1 - e^{-\tau_v}} = \frac{3hc\lambda^2}{8\pi\, k} \frac{n_{HI}}{4} A_{10}\, \phi(V)\, ds$$

The inferred column is

$$N_{HI} = 1.83 \times 10^{18} \int_{line} \frac{\Delta T_B \tau_V}{1 - e^{-\tau_v}} dV_5$$

- In the optically thin limit

$$N_{HI} = 1.83 \times 10^{18}\, \mathrm{cm}^{-2} \int_{line} \Delta T_B\, dV_5$$



- *N(HI)* depends only on the integrated brightness temperature
- In the optically thin limit both cool & warm atoms count

$T_S < T_{BG}$: Absorption Line Formation

- Towards a bright source

$$\Delta T_B(\text{on}) = (T_S - T_{BG})(1 - e^{-\tau_\nu}) < 0$$

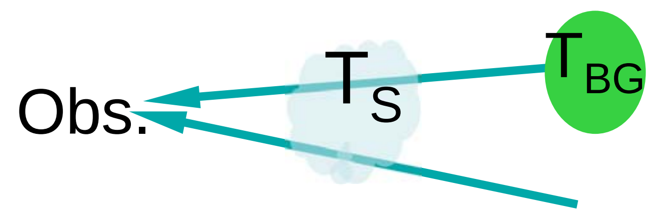
- Off source

$$\Delta T_B(\text{off}) = T_S(1 - e^{-\tau_\nu}) > 0$$

assuming uniformity of T_S and τ_ν

- Two unknowns, two equations; solve for T_S and τ_ν
- Recall that

$$\int_{line} \tau_V \, dV_5 = \frac{N_H / T_S}{1.83 \times 10^{18} cm^{-2} K^{-1}} \text{ km/s}$$



Early evidence for CNM/WNM

Clark ApJ 142 1298 1965

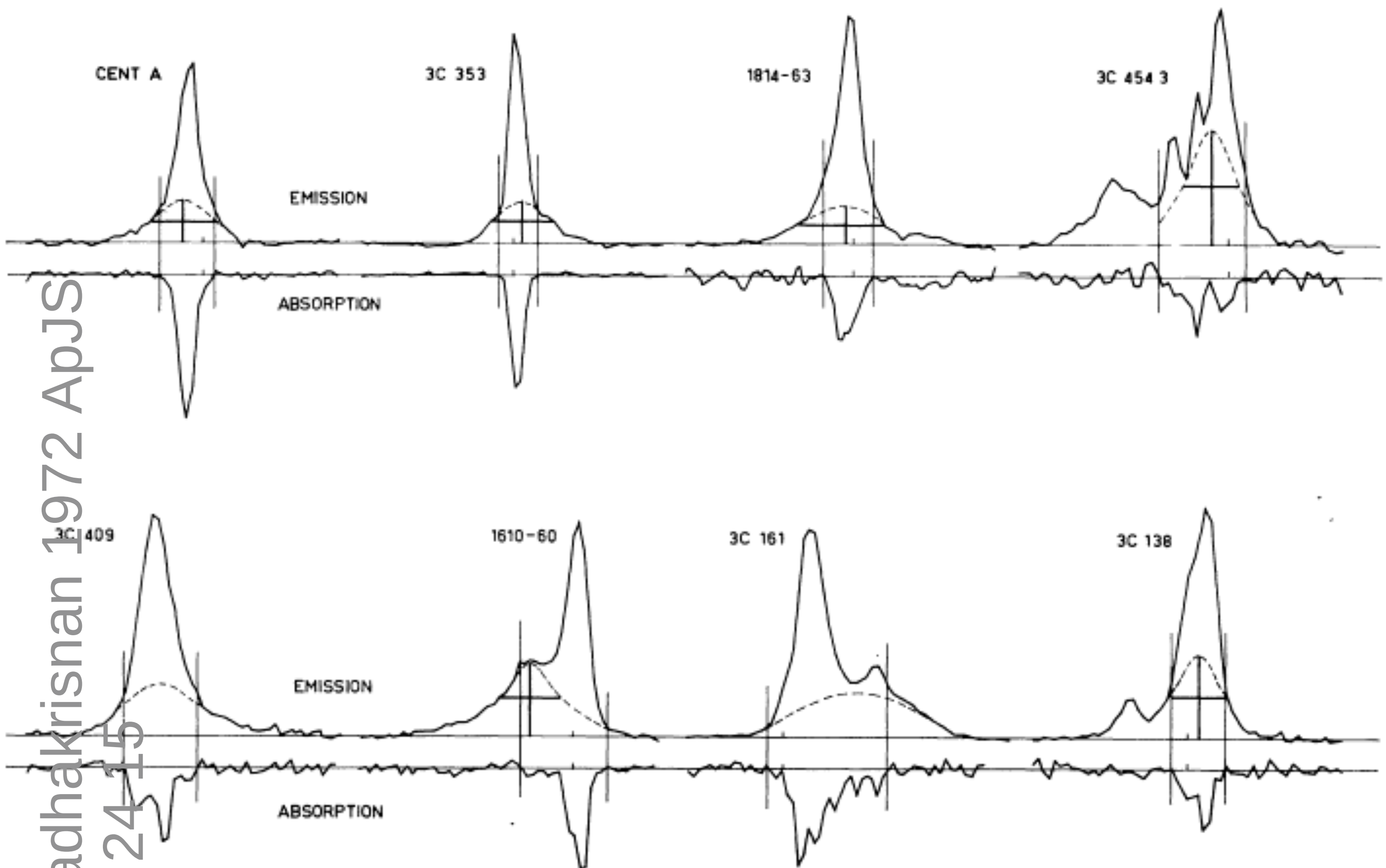
Radhakrishnan ApJS 24 15 1972

Dickey ApJ 228 465 1979

Payne ApJ 272 540 1983

follows on the next slides

4. Evidence for CNM/WNM

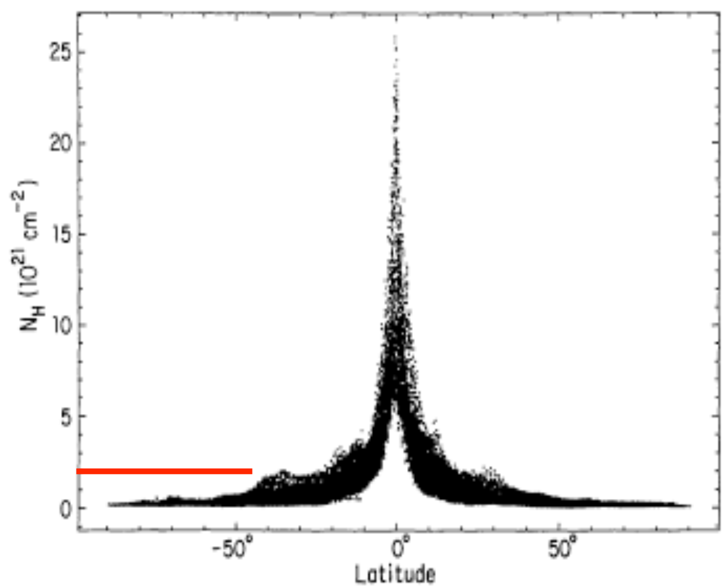


Radhakrisnan 1972 ApJS 24 15

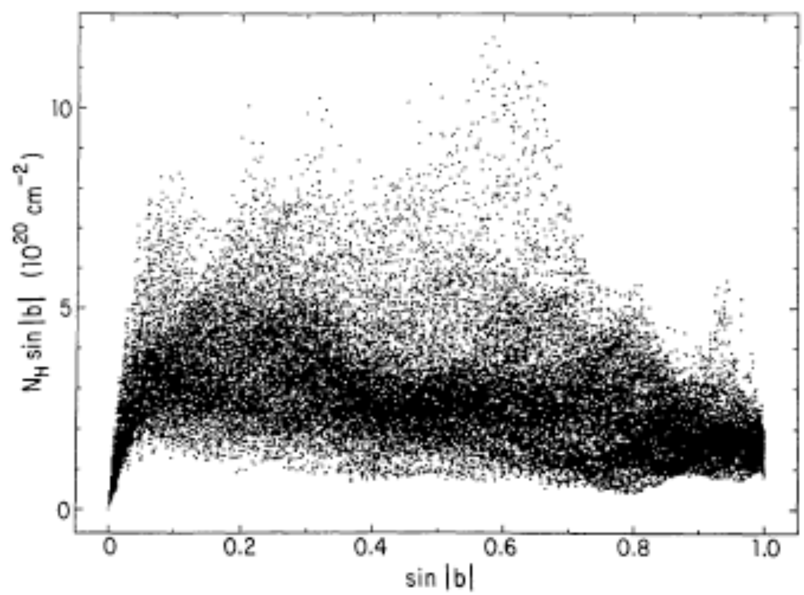
FIG. 32.—Comparison of eight emission and absorption spectra obtained at intermediate latitudes and selected on the basis of high signal-to-noise ratio. The velocity limits of the absorption spectra are demarcated, showing clearly the presence of an optically thin component in every emission spectrum. These components are shown by dashed lines. In six cases (*crosses*) the parameters of the low, wide component were determined by a computer analysis into Gaussians. See text for discussion.

vertical lines: boundaries for $\tau > 0.1$

Dickey & Lockman, ARAA 28 215 1990

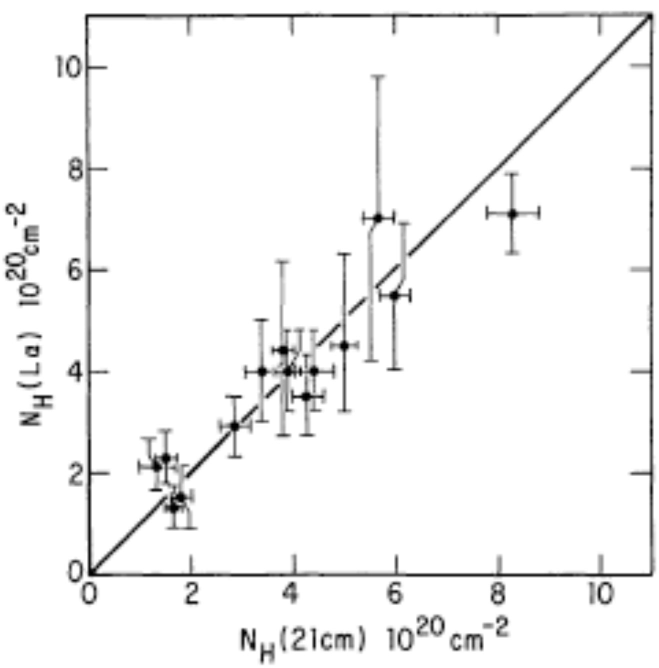


HI column vs *b*
red line: 2×10^{20} cm^{-2}

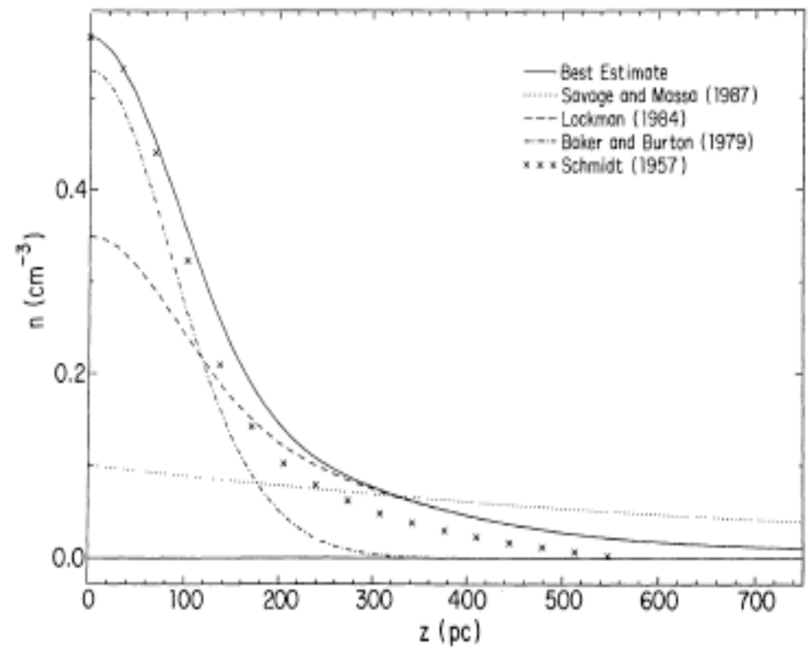


HI vertical column vs. sin *b*
red line: 3×10^{20} cm^{-2}

Dickey & Lockman, ARAA 28 215 1990



Lyα vs. 21 cm column densities



Models of the vertical variation of the HI density. Middle curves are 21 cm. Scale height is ~100 pc

Tentative Summary
Early Evidence for CNM/WNM

- Emission is ubiquitous - absorption is not
  - N(HI) in emission is typically > 5 x 10^{19} cm^{-2}
  - Emission is broader than absorption
- Cool gas is in clouds with a small filling factor (CNM)
- Warm gas is the intercloud medium (WNM)
  - Payne et al. observed ~50 sources with Arecibo
  - For lines of sight with no detectable absorption
    - $\langle 1/T_S \rangle^{-1}$ = 5300 K, i.e., T_{WNM} > 5300 K
  - Local ISM UV absorption studies of local ISM (Linsky et al. ApJ 451 335 1995
    - T = 7000 ± 300 K

Troland & Heiles: Arecibo Millennium Survey II

Ap J 586 1067 2003

Definitive observations and analysis towards 79 extragalactic radio sources with 202 WNM and 172 CNM components mainly for $b > 10^{o}$.

Fitting of Gaussians yields T_S and N(H) plus information about line widths.

For the CNM: $T_S \approx T$

For the WNM: $T_S \leq T$

For the CNM : T_S = 100-200 K

For the WNM: T_S = 500 - 20,000 K

NB 40-50% (by column) of the WNM is in the thermally unstable regime from 500-5,000 K (Lec11).

Summary Tables from Heiles & Troland II

TABLE 2

MEDIANS AND MEANS OF CNM T_s

b Range	Median T_s (K)	Mean T_s (K)
CNM, $\|b\| > 10°$, by N_G	48	88
CNM, $\|b\| > 10°$, by N(H I)	70	108
CNM, $\|b\| < 10°$, by N_G	47	71
CNM, $\|b\| < 10°$, by N(H I)	63	99

NOTE.—"By N_G" means that the median and mean are taken over Gaussian components with no weighting by N(H I). "By N(H I)" means that half the column density lies above, and half below, the median, and the mean is weighted by N(H I). Fig. 2 presents the histograms, which have long tails at high T_s so that neither the median nor the mean represents the typical values.

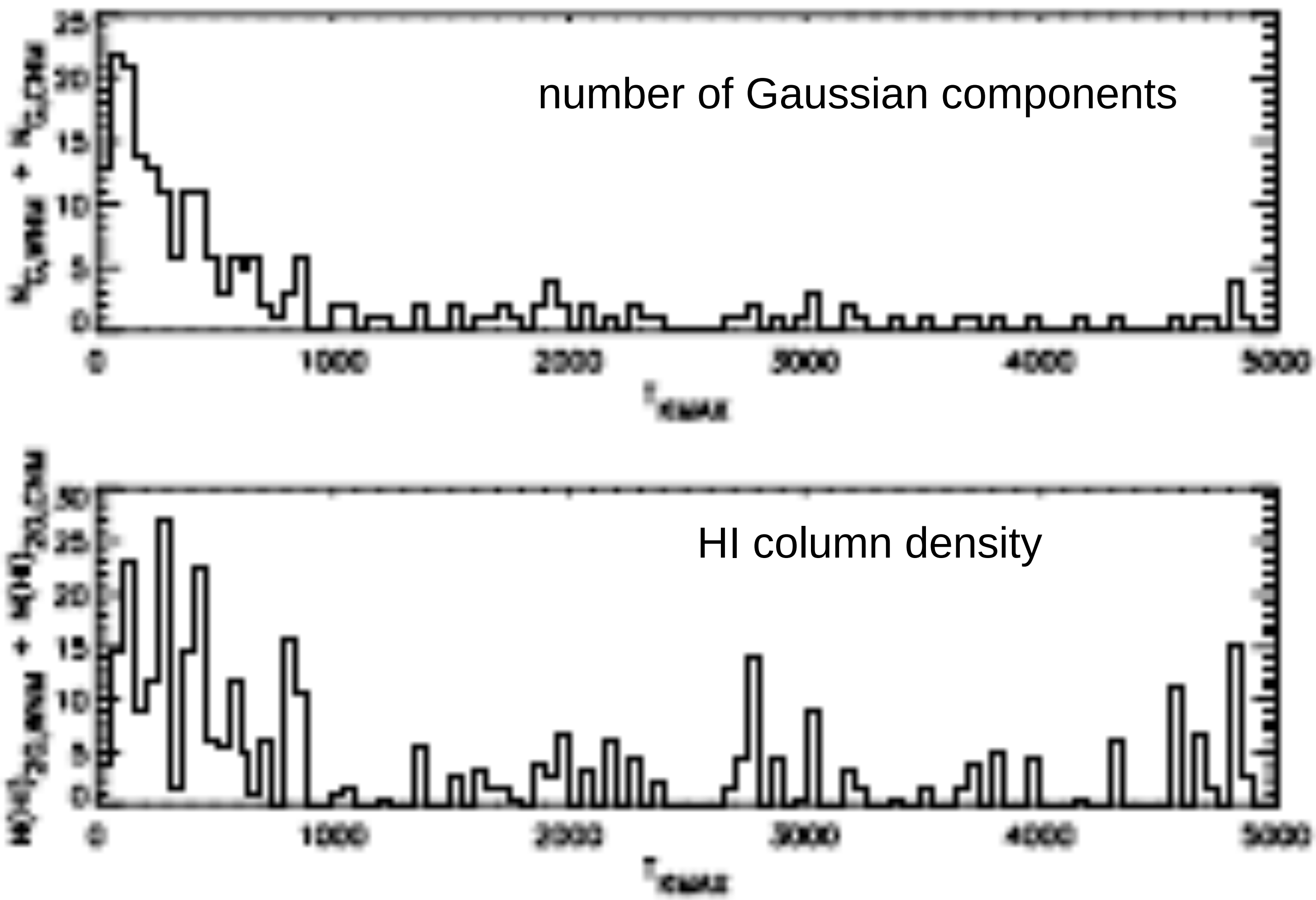
TABLE 3

MEDIANS AND MEANS OF N(H I)

b Range	Median $N(\text{H I})_{20}$ ($\times 10^{20}$ cm^{-2})	Mean $N(\text{H I})_{20}$ ($\times 10^{20}$ cm^{-2})
CNM, $\|b\| > 10°$	0.52	1.27
CNM, $\|b\| < 10°$	1.97	5.00
WNM, $\|b\| > 10°$	1.30	2.04
WNM, $\|b\| < 10°$	8.13	12.03

NOTE.—Fig. 4 presents the histograms.

Heiles & Troland II Temperature Distribution



Clear evidence for two distributions (CNM and WNM)

Heiles & Troland II: Summary Conclusions

1. WNM is 60% of total HI; ~ 50% thermally unstable.

2. Assuming pressure equilibrium with diffuse clouds (p/k = 2250 cm^{-3} K) and approximate temperatures

phase	T (K)	n(HI) (cm^{-3})
CNM	~ 40	~ 56
WNM	~ 4000	~ 0.56

3. The estimated density and measured column density imply line of sight lengths ~ pc. Assuming that the perpendicular dimension is the same is *not* borne out by observations (detailed maps & measurements of closely spaced radio sources). ***CNM clouds are sheet like*****.**