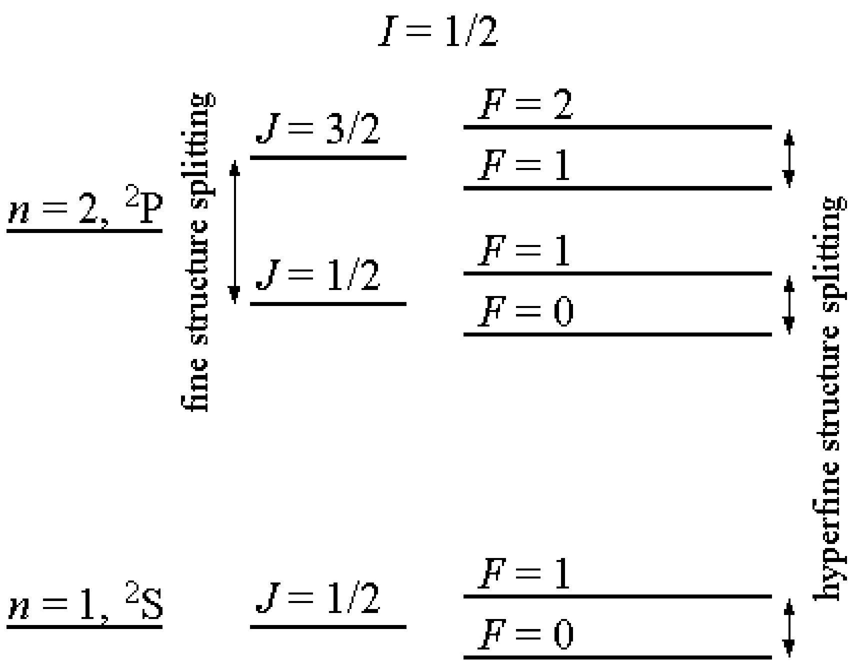
Information in a Spectral Line

Fine Structure and Hyperfine Structure

Fine structure: between e^- spin and e^- orbital angular momentum

Hyperfine structure: between nucleus (or nuclei in molecules) with internal **E** and **B** fields; energy much smaller than that of a fine structure



http://en.wikipedia.org/wiki/File:Fine_hyperfine_levels.png

21 cm Line

Collisional excitation

$$F = 1/2 + 1/2 = 1 \text{ or } F = 1/2 - 1/2 = 0$$

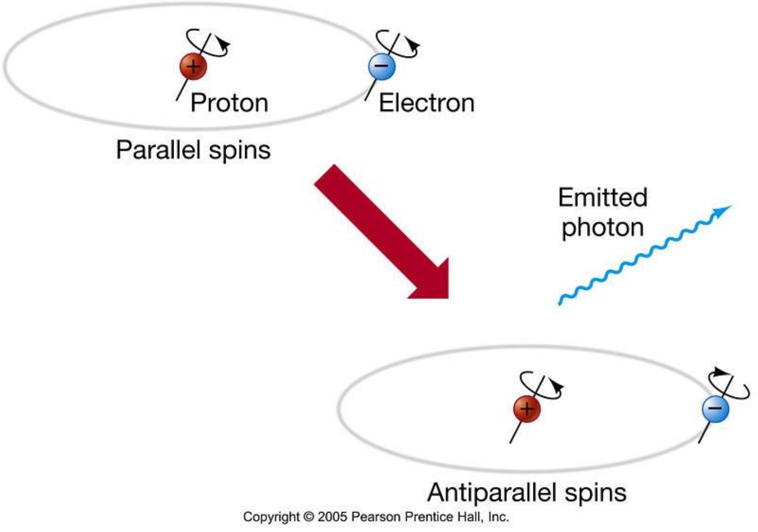
$$F = 1 \text{ to } F = 0$$

$$A_{10} = 2.8843 \times 10^{-15}\mathrm{s}^{-1} = (11\ \mathrm{Myr})^{-1}$$

$$\lambda \approx 21.106\ \mathrm{cm};\ 5.87 \times 10^{-6}\ \mathrm{eV};$$

$$\nu \approx 1420.406\ \mathrm{MHz}$$

$$f = 5.75 \times 10^{-12}$$



Spontaneous de-excitation

Magnetic moment of p^+ ←→ of e^- charge
←→ of e^- orbit

➔ hyperfine structure

i.e., splitting of the ground state of H I

The 21 cm line is

- a magnetic dipole transition
- a forbidden transition

$$\tau_{\mathrm{HI,HI}}\ (\text{collision}) \approx \frac{1}{n\sigma v} \approx (1\times10^{-16}\times10^{5})^{-1} \approx 10^{11}\ \mathrm{s} \ll\ 1/A_{10}$$

So LTE OK, and $n_1/n_0 = (g_1/g_0)\ \exp(-\chi/kT)$,
where $g_0 = 1, g_1 = 3, \chi/k \approx$ 70 mK.

Population ratio determined by

✓ collisions

✓ cosmic background radiation

✓ Ly alpha pumping → Ly alpha radiation could excite 21 cm line via transitions involving the $n = 2$ level as an intermediate state (Field, 1959, ApJ, 129, 551)

$$T_B = T_{bg}\, e^{-\tau} + T_s(1 - e^{-\tau})$$

In reality we measure the spectrum with respect to the continuum (beam-switching)

$$\begin{aligned}
\Delta T_B &= T_B - T_{bg} \\
&= T_{bg}\, e^{-\tau} + T_s - T_s\, e^{-\tau} - T_{bg} \\
&= (T_s - T_{bg})(1 - e^{-\tau})
\end{aligned}$$

One can show that

$$\tau(v) = \frac{N(v)}{C \cdot T_s}$$

v [km s^{-1}]; $C = 1.83 \times 10^{18}$ cm^{-2} K^{-1} (cm s^{-1})$^{-1}$; N: column density [# cm^{-2}]

$$N_H = 1.82 \times 10^{18} \int_0^{\infty} T_s \, \tau_\nu(v) \, dv$$

v in [km s^{-1}]

(Mihalas & Binney)

For $T_{bg} << T_s$

- Optically thin ($\tau << 1$)

  $$T_B = T_s \, \tau = \frac{N(v)}{C \cdot T_s}$$

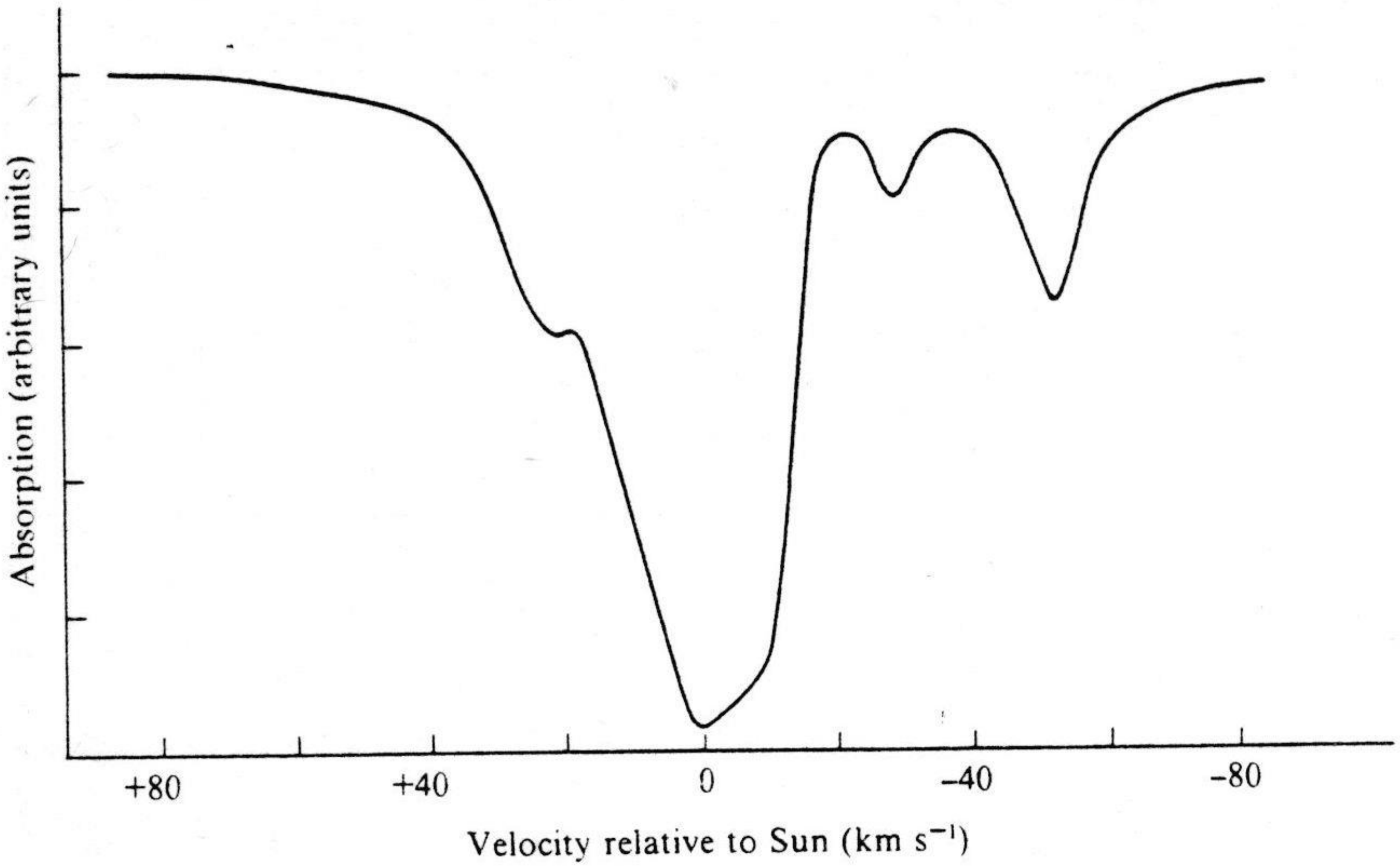
  That is, measured brightness temperature $\propto$ column density per unit velocity

- Optically thick ($\tau >> 1$)

  $$T_B = T_s$$

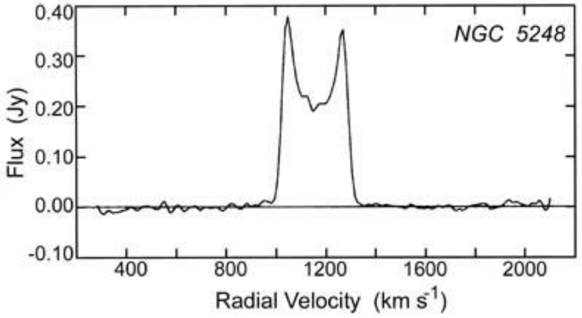
  That is, photons emitted within the cloud get absorbed inside the cloud; only photons emitted within $\tau < 1$ of the front surface manage to escape.

Line center → line of sight velocity (radial velocity; RV)



RV → Galactic rotation model → cloud distance

- $T_s > T_{bg} \rightarrow$ 21 cm in emission
- $T_s < T_{bg} \rightarrow$ 21 cm in absorption

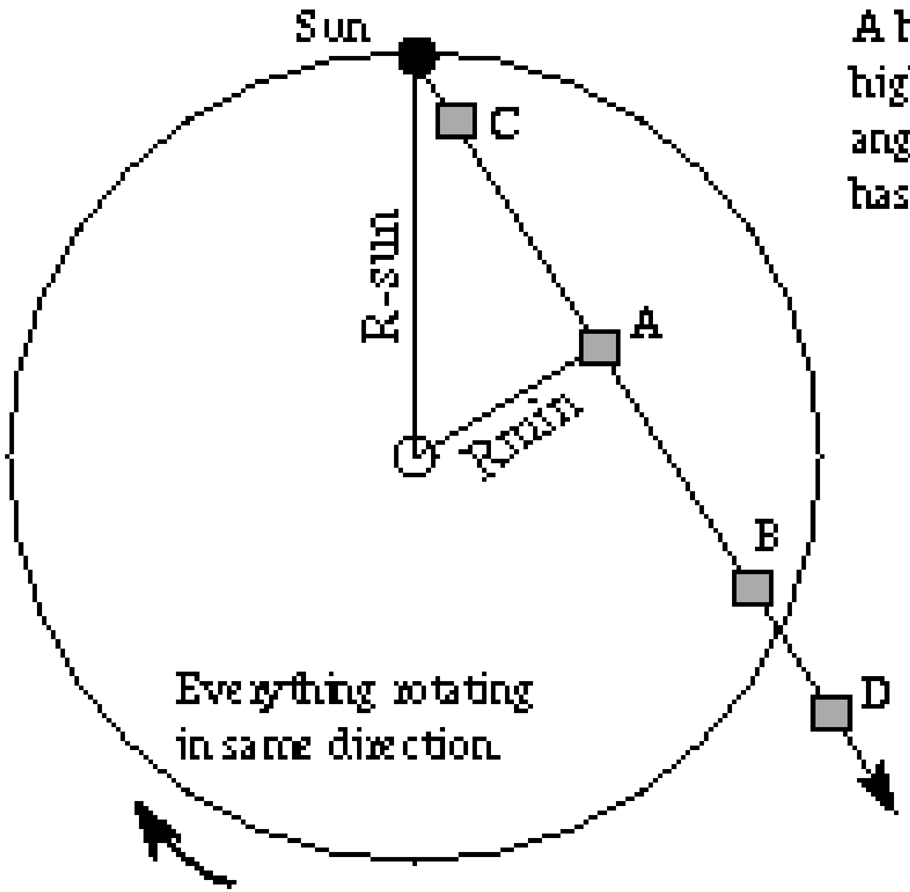


If $T_s = 2.73$ K, the cloud is not detectable. For any Galactic H I cloud, $T_s > 2.73$ K.

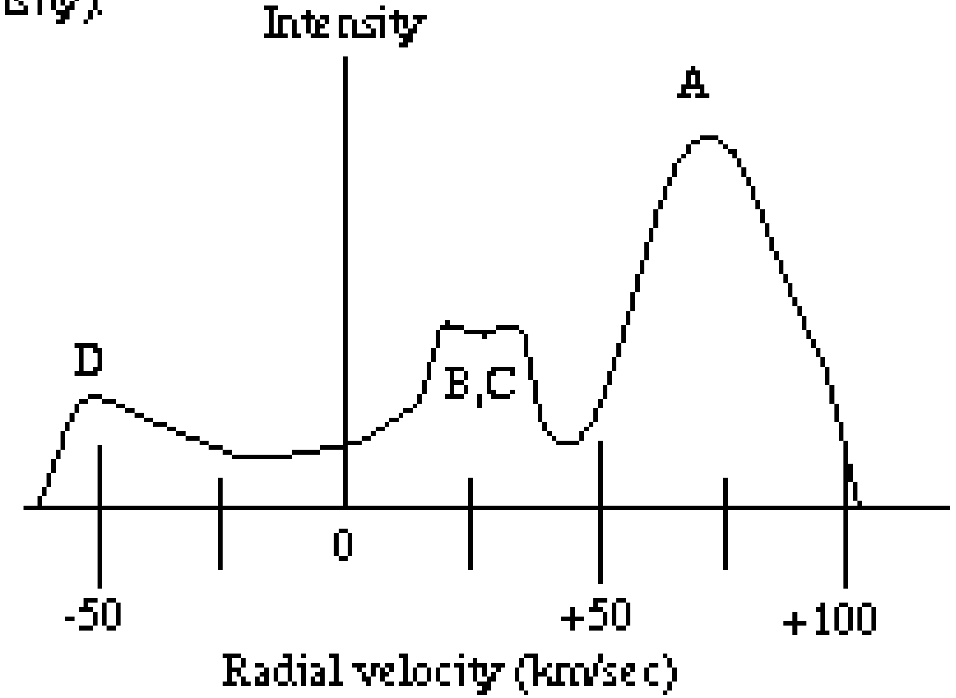
21 cm emission has been used extensively to map out the distribution of H I in the Milky Way galaxy and other galaxies.

Spiral arms are prominent. Two or more arms toward the same direction can be separated by different velocities.

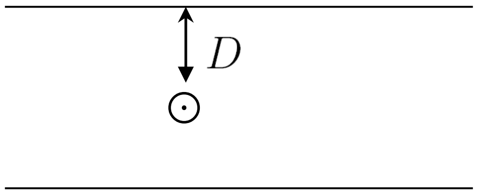
With strong distant radio sources (e.g., QSOs), one can observe H I in absorption thus study of the warm IG component.



A has greatest angular speed and moving fastest away from sun. A has higher density of H. B & C moving at about same angular speed > sun's angular speed. D is outside solar distance–slower angular speed and has less material (density).



$$\boxed{N_H = 1.82 \times 10^{18} \int_0^\infty T_s \, \tau_\nu(v) \, dv}$$



$T_B \sim 10$ K, $\Delta v \sim$1–10 km s^{-1}, so $N_H \sim 10^{20}$ cm^{-2}
$D \sim$ 100–200 pc

Assuming $N_H = \int_0^\infty n_H \, dx \approx n_H \, D$, so $n_H \sim 1$ cm^{-3}

$$\int I \, ds = \int h\nu \, \alpha \, n_e \, n_p \, ds$$

where EM = Emission Measure = $\int_0^L n_e \, n_p \, ds$ along the line of sight

If $n_e \approx n_p$, EM = $\int_0^L n_e^2 \, ds$

Typically EM$\sim 10^2$–10^3 [pc cm^{-6}] for Galactic clouds

If assuming [depth]$\sim$[width] $\rightarrow$ get n_e

THE ASTROPHYSICAL JOURNAL, **224**:132–142, 1978 August 15

A SURVEY OF INTERSTELLAR H I FROM Lα ABSORPTION MEASUREMENTS. II.

R. C. BOHLIN,*† B. D. SAVAGE,*‡ AND J. F. DRAKE§

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ABSTRACT

The *Copernicus* satellite has surveyed the spectral region near Lα to obtain column densities of interstellar H I toward 100 stars. The distance to 10 stars exceeds 2 kpc and 34 stars lie beyond 1 kpc. Stars with color excess $E(B-V)$ up to 0.5 mag are observed. A definitive value is found for the mean ratio of total neutral hydrogen to color excess,

$$\boxed{\langle N(\mathrm{H\,I} + \mathrm{H_2})/E(B-V)\rangle = 5.8 \times 10^{21} \text{ atoms cm}^{-2} \text{ mag}^{-1}}.$$

For stars with accurate $E(B-V)$, the deviations from this mean are generally less than a factor of 1.5. A notable exception is the dark-cloud star ρ Oph, with $N(\mathrm{H\,I} + \mathrm{H_2})/E(B-V) = 15.4 \times 10^{21}$ atoms cm^{-2} mag^{-1}. A reduction in visual reddening efficiency for the grains that are larger than normal in the ρ Oph dark cloud probably explains this result. The conversion of atomic hydrogen into molecular form in dense clouds is observed in the gas to $E(B-V)$ correlation plots. The best estimate for the mean total gas density for clouds and the intercloud medium, as a whole, in the solar neighborhood and in the plane of the Galaxy, is $\langle n(\mathrm{H\,I} + \mathrm{H_2})\rangle = 1.15$ atoms cm^{-3}; and those for the atomic gas and molecular gas alone are $\langle n(\mathrm{H\,I})\rangle = 0.86$ atoms cm^{-3} and $\langle n(\mathrm{H_2})\rangle = 0.143$ molecules cm^{-3}. Where molecular hydrogen is a negligible fraction of the total gas, $\langle n(\mathrm{H\,I})\rangle = 0.16$ atoms cm^{-3} with a Gaussian scale height perpendicular to the plane of about 350 pc, as derived from high-latitude stars. Considerable variation in mean density is present, with $n(\mathrm{H\,I})$ ranging from <0.008 to 12 atoms cm^{-3}. Some correlation exists between neighboring directions, with densities smaller than normal toward the Gum nebula and above average in the Sco-Oph association. The general agreement and a few specific discrepancies between the Lα and 21 cm measurements of the gas are discussed.

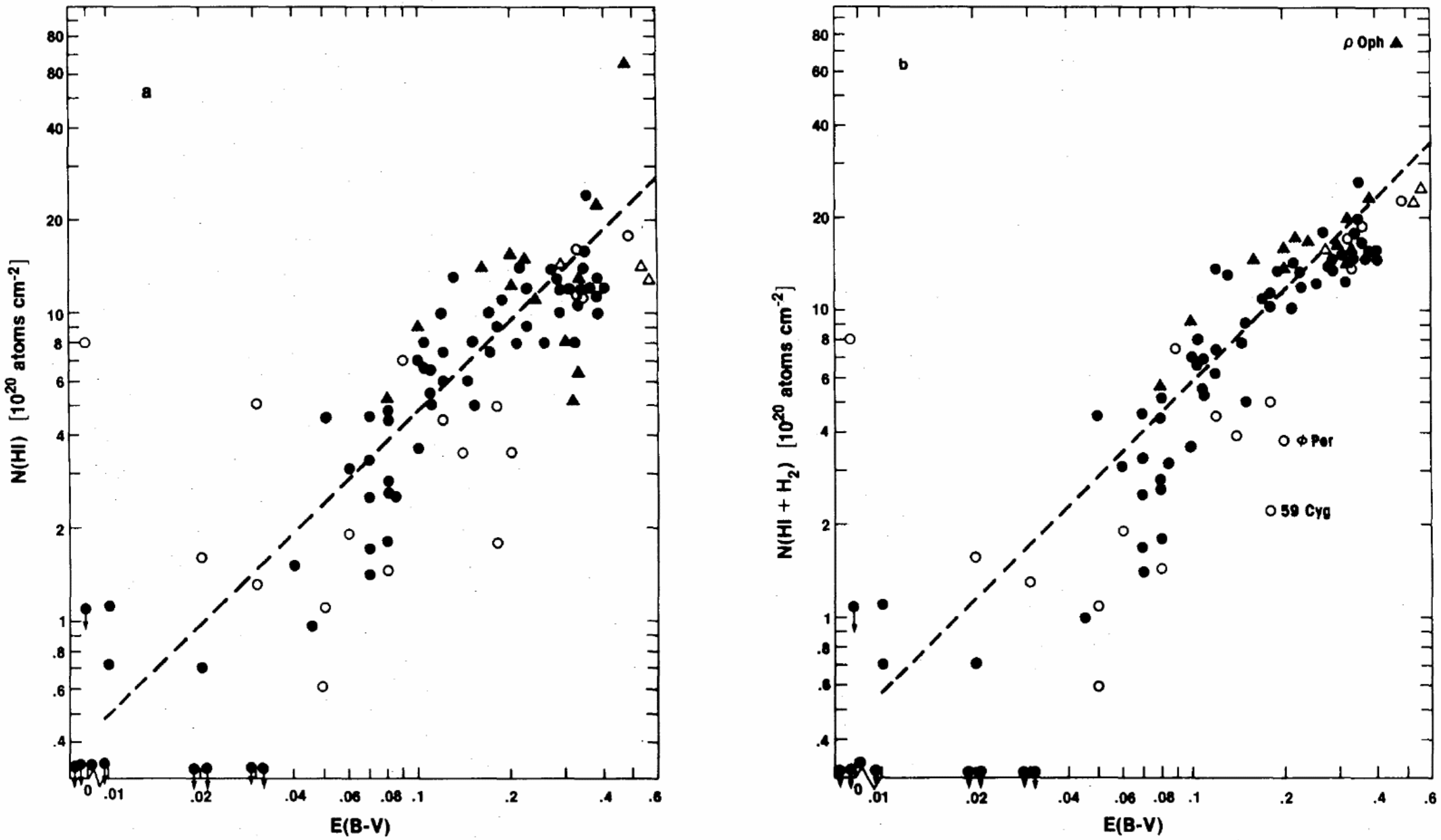


FIG. 2.—(*a*) The correlation between the atomic hydrogen column density $N(\text{H I})$ and $E(B-V)$. (*b*) The correlation between the total hydrogen column density, $N(\text{H I} + \text{H}_2) = N(\text{H I}) + 2N(\text{H}_2)$, and $E(B-V)$. In both (*a*) and (*b*), the dashed lines are the average ratios from Table 2. *Triangles*, stars with high mean densities, $n(\text{H I} + \text{H}_2) > 1$ atom cm^{-3}; *circles*, cases where $n(\text{H I} + \text{H}_2) < 1$ atom cm^{-3}. *Open symbols*, stars with uncertain $E(B-V)$ that were omitted in calculating the mean ratios.

Bohlin et al 1978

TABLE 2

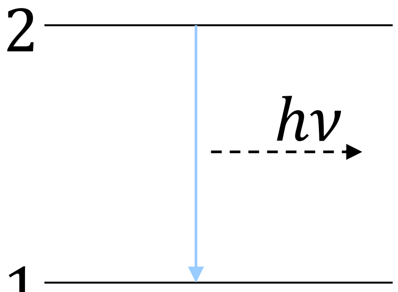
OBSERVATIONAL AVERAGES

	30 "Intercloud" Stars $f < 0.01$	45 "Cloud" Stars $f > 0.01$	All 75 Stars
$\langle n(\mathrm{H\,I})\rangle = \dfrac{\Sigma N(\mathrm{H\,I})}{\Sigma r}$ (atoms cm^{-3})........	0.16	0.44	0.35
$\langle n(\mathrm{H_2})\rangle = \dfrac{\Sigma N(\mathrm{H_2})}{\Sigma r}$ (molecules cm^{-3})........	< 0.001	0.053	0.036
$\langle n(\mathrm{H\,I} + \mathrm{H_2})\rangle = \dfrac{\Sigma[N(\mathrm{H\,I}) + 2N(\mathrm{H_2})]}{\Sigma r}$ (atoms cm^{-3})........	0.16	0.55	0.42
$\langle E(B-V)/r\rangle = \dfrac{\Sigma E(B-V)}{\Sigma r}$ (mag kpc^{-1})........	0.10	0.28	0.22
$\langle r\rangle = \dfrac{\Sigma r}{\text{no. of stars}}$ (pc)........	620	870	770
$\langle N(\mathrm{H\,I})/E(B-V)\rangle = \dfrac{\Sigma N(\mathrm{H\,I})}{\Sigma E(B-V)}$ (atoms cm^{-2} mag^{-1})........	5.0×10^{21}	4.8×10^{21}	4.8×10^{21}
$\langle N(\mathrm{H\,I} + \mathrm{H_2})/E(B-V)\rangle = \dfrac{\Sigma[N(\mathrm{H\,I}) + 2N(\mathrm{H_2})]}{\Sigma E(B-V)}$ (atoms cm^{-2} mag^{-1}).....	5.0×10^{21}	5.9×10^{21}	5.8×10^{21}

Bohlin et al 1978

Einstein Coefficients

Spontaneous emission



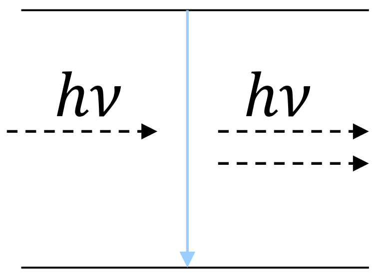
$\boldsymbol{j}$

$\boldsymbol{A_{21}}$

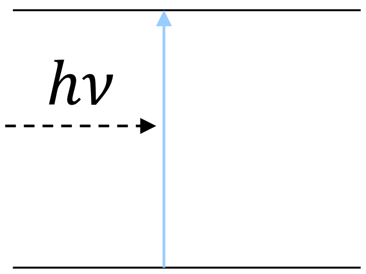
$[\mathrm{s}^{-1}]$

$\boldsymbol{A_{21}}$ --- probability

Stimulated (induced) emission



(Stimulated) absorption



$\boldsymbol{k}$

$\boldsymbol{B_{21}}$ $\boldsymbol{B_{12}}$

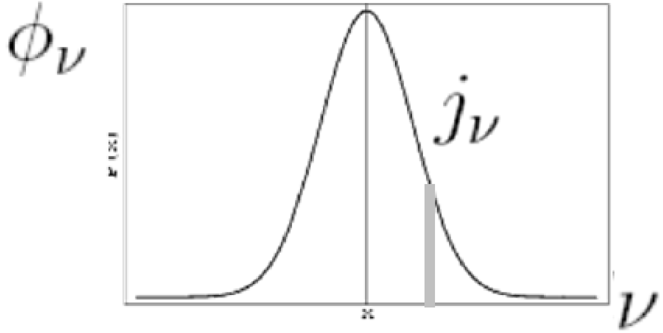
$[\mathrm{cm}^3\ \mathrm{erg}\ \mathrm{s}^{-1}\ \mathrm{Hz}^{-1}]$

$\boldsymbol{B\ u_\nu}$ --- probability

Einstein (1917)

Recall for emission,

$$j_\nu = \frac{h\nu_0}{4\pi} n_2 A_{21} \phi(\nu) \qquad \int_0^\infty \Phi_\nu \, d\nu = 1$$



A_{21} [s^{-1}]: Einstein A coefficient for spontaneous transition
= probability per unit time.

$1/A_{21}$ [s]: lifetime staying at level 2 (remaining excited)

Likewise, for absorption (including stimulated emission --- dependent on the incident intensity)

$$\kappa_\nu = \frac{h\nu_0}{4\pi} \phi(\nu)(n_1 \, B_{12} - n_2 \, B_{21})$$

Lorentz (damping) profile

$$\boxed{\phi(\Delta\nu) = \frac{\gamma}{(2\pi\Delta\nu)^2 + (\gamma/2)^2}}$$

Classical treatment

Atom absorbing a photon → excited → e^- oscillates as a dipole

Equation of motion: $m\ddot{r} = -4\pi r\nu_0^2$

Such a dipole radiates with power $\mathbb{P} = \frac{2}{3}\frac{e^2}{c^3}|\ddot{r}|^2$

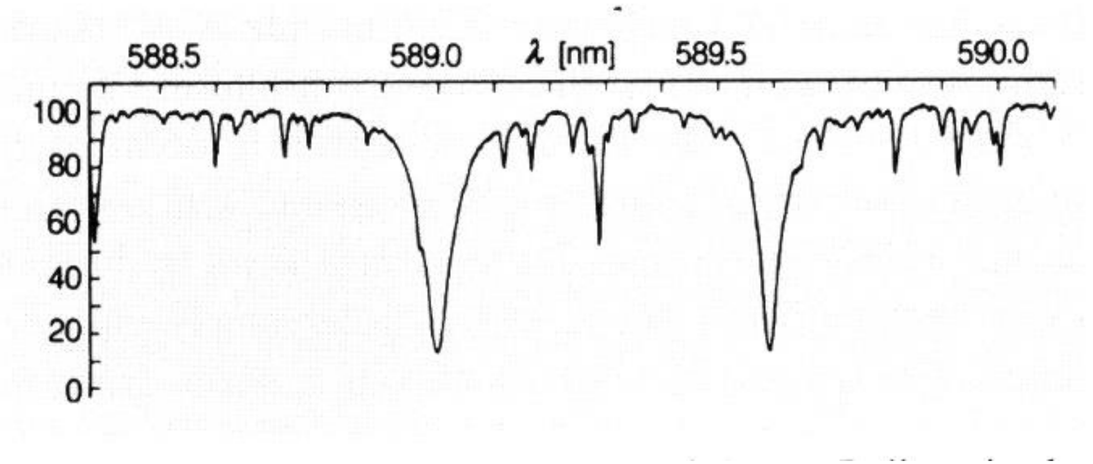
Energy is radiated away → damping force to slow down the e^-

The force is $\mathcal{F} = \frac{2}{3}\frac{e^2}{c^3}|\dddot{r}|^2$, and for a small damping

→ a simple harmonic motion (around ν_0)…

Line Broadening

Natural Broadening



$$I_\nu = \frac{1}{(\nu - \nu_0)^2 + \left(\gamma/_{4\pi}\right)^2}$$

The Lorentzian profile peaks at ν_0, and has a width γ related to the Einstein A coefficient

QM Heisenberg energy-time uncertainty principle $\Delta E \, \Delta t \geq h$

That is, the energy of a give state cannot be specified more accurately than this → $\Delta\nu \approx 1/\,\Delta t$.

Typically $\Delta t \approx 10^{-8}$ s (recall Einstein's A coefficients), so the natural width of a line $\gamma \approx 5 \times 10^{-5}$ nm.

Doppler Broadening

Particle thermal random (kinetic, turbulent) motion along line of sight → Doppler shift $\langle mv^2/2\rangle = 3\,kT/2$

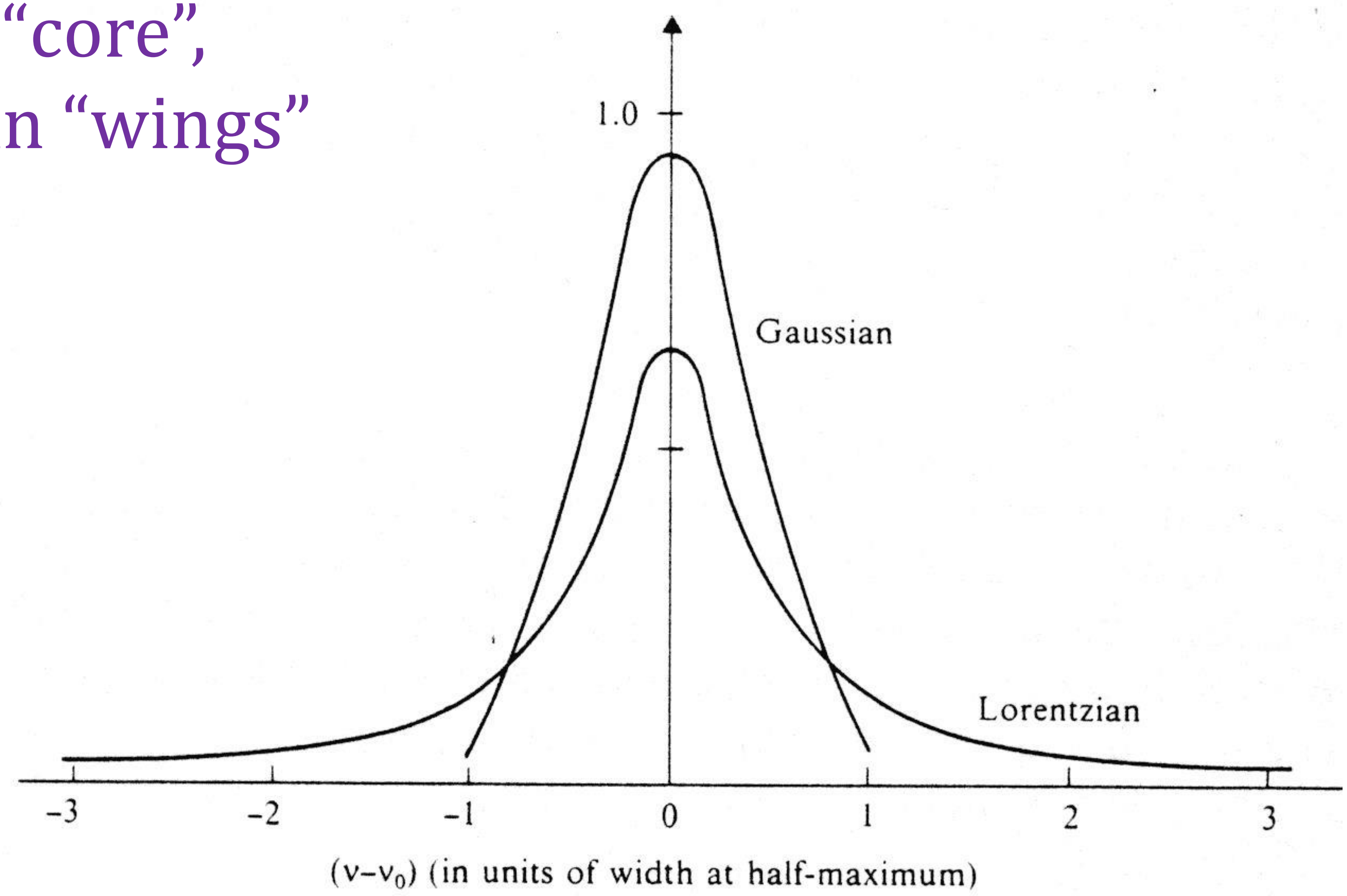
$$\frac{\nu - \nu_0}{\nu_0} = \frac{v_Z}{c}$$

If Maxwellian (Gaussian) → a profile spread

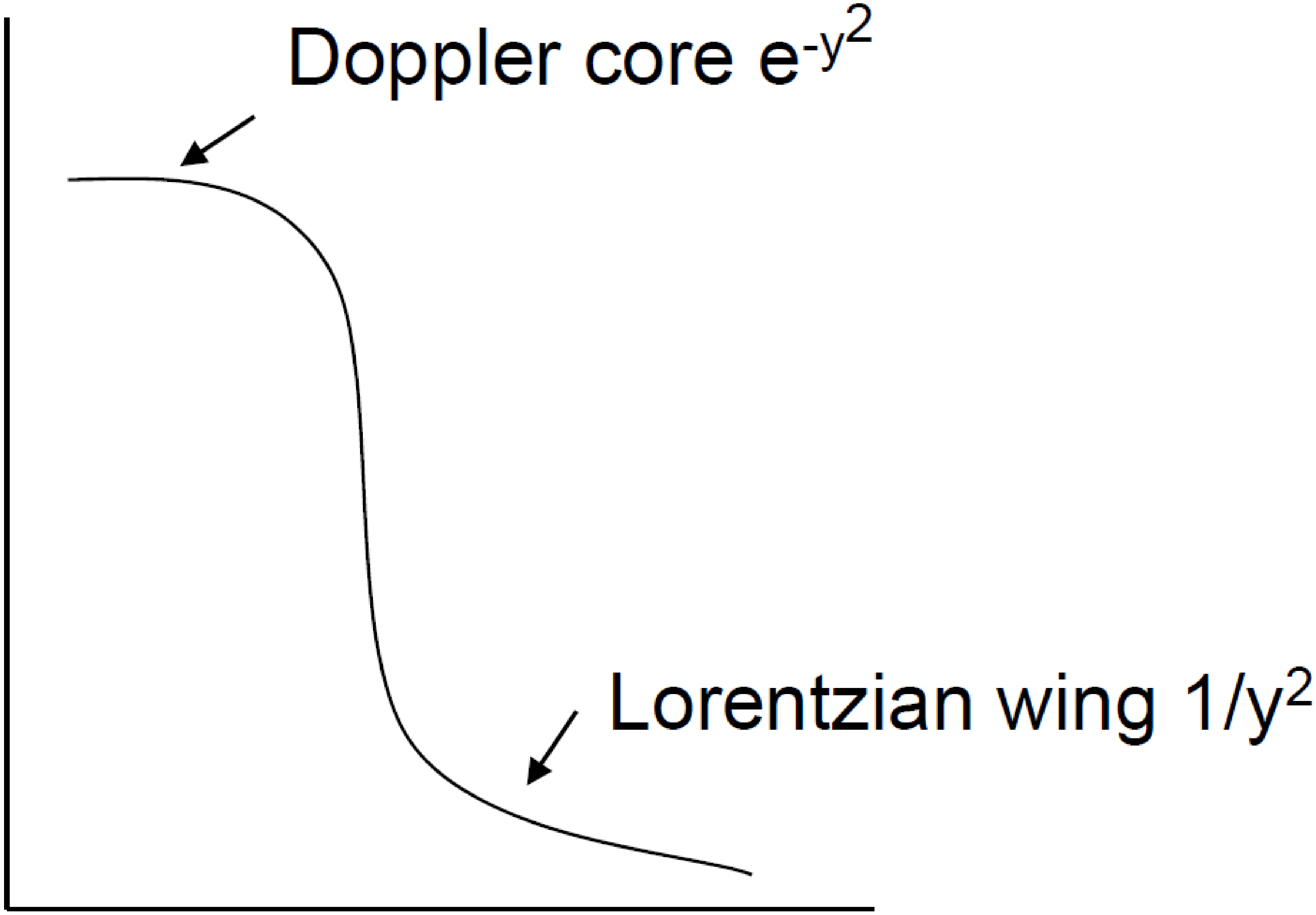
$$I_\nu = e^{-\left.(\nu-\nu_0)^2\right/2\delta^2}$$

where $\delta^2 = \nu_0^2\, kT/mc^2$

Gaussian “core”, Lorentzian “wings”



When areas are normalized, the Doppler profile is more peaked, and the Lorentzian profile is higher away from ν_0.


Doppler core e^{-y^2}
Lorentzian wing $1/y^2$

Collisional Broadening

Collision → radiation train interrupted

Energy levels shifted by nearby particles, especially ions and electrons ("**Stark Effect**" due to E field); also called pressure broadening, and is density dependent.

Profile similar to Lorentzian, but the width $\approx 1/\tau_0$,
where τ_0 is the mean free path. Given τ_0 is thousands of years, collision broadening is usually not important in ISM.

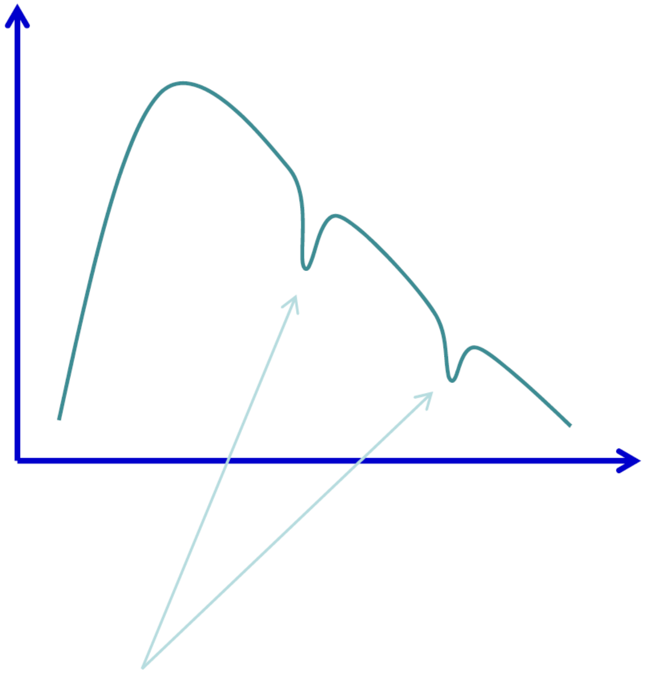
Zeeman Broadening

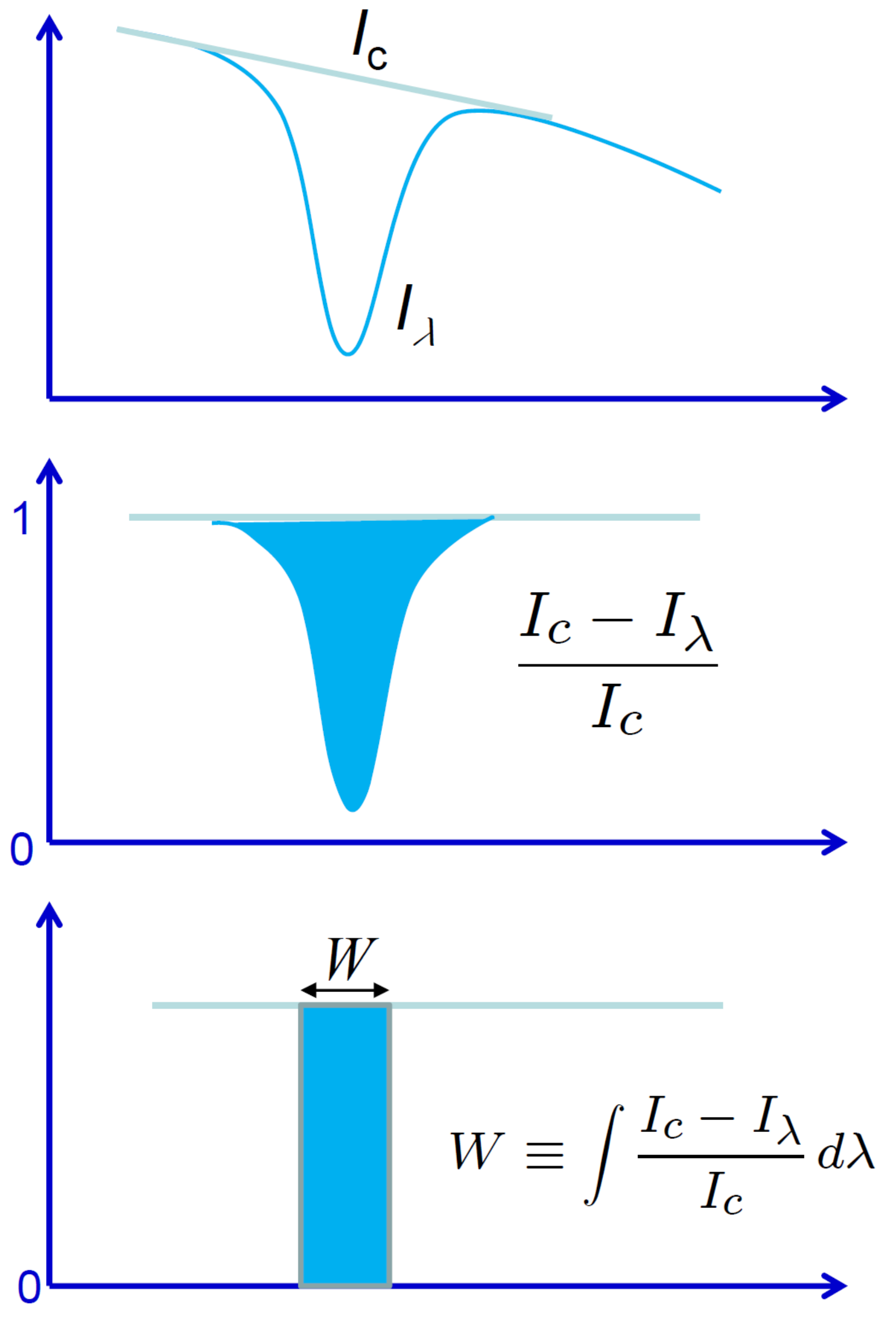
Energy levels spilt to 3 or more sublevels in a magnetic field
→ **Zeeman effect** (Pieter Zeeman)

Spectral lines closed spaced ($\propto$ **B** strength), may not be resolved
→ line broadened

Additional broadening mechanisms: rotation, expanding, turbulence, ...

Line Strength
and
Chemical Abundances



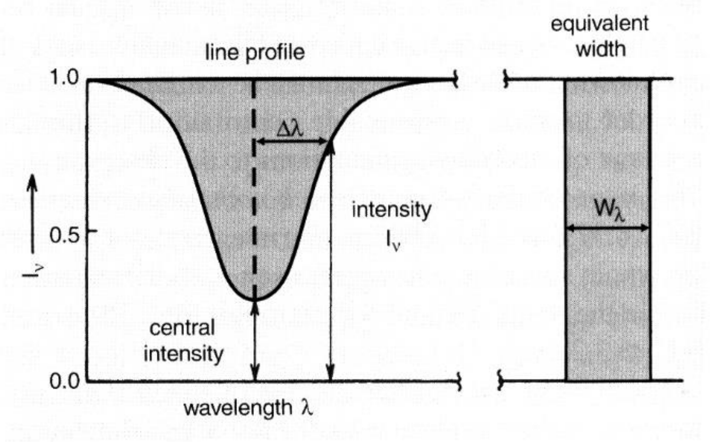


Photons of different wavelengths have different energies. Which line is "stronger" (= energy missing in the spectrum? Number of absorbing atoms?)

Equivalent Width

Compared with local "continuum", i.e., where there is no absorption, how much energy is absorbed.

$$\phi_\nu = \frac{I_c - I_\lambda}{I_c} \qquad \frac{W_\lambda}{\lambda} = \frac{W_\nu}{\nu} = \frac{W_\mathrm{v}}{c}$$



$$W_\lambda = \int_{-\infty}^{\infty} \frac{I_c - I_\lambda}{I_c}\, d\lambda = \int 1 - e^{-\tau_\lambda}\, d\lambda$$

is the **equivalent width** (W), which measures the absorption (strength) of a spectral line, where I_λ is the line profile, and I_c is the continuum (at the same λ).

W in unit of [Å] or [mÅ]; traditionally negative for emission lines.

$$\sigma_\nu = \left(\frac{\pi e^2}{mc}\right) f \phi_\nu \qquad\qquad \sigma_\nu d\nu = \sigma_\lambda d\lambda$$

$\tau_\nu = \kappa_\nu ds = n\,\sigma_\nu ds = N\,\sigma_\nu$, where N is the column density

$\tau_\lambda = N\left(\frac{\pi e^2}{mc^2}\right) f\,\lambda_0^2\,\phi_\nu$, where f is the oscillator strength

(1) For a weak line ($\tau_\lambda \ll 1$) Every absorbing atom contributes.

$$W_\lambda = \int \tau_\lambda\, d\lambda = N\left(\frac{\pi e^2}{mc^2}\right) f \lambda_0^2 \propto\; Nf$$

or

$$\frac{W_\lambda}{\lambda\,[\mathrm{cm}]} = N\left(\frac{\pi e^2}{mc^2}\right) f \lambda_0 = 8.85 \times 10^{-13}\, N\,[\mathrm{cm}^{-2}]\, f_{12}$$

Spitzer

(2) For a strong line ($\tau_\lambda \gg 1$), damping wings important

$$W_\lambda \propto \sqrt{Nf}$$

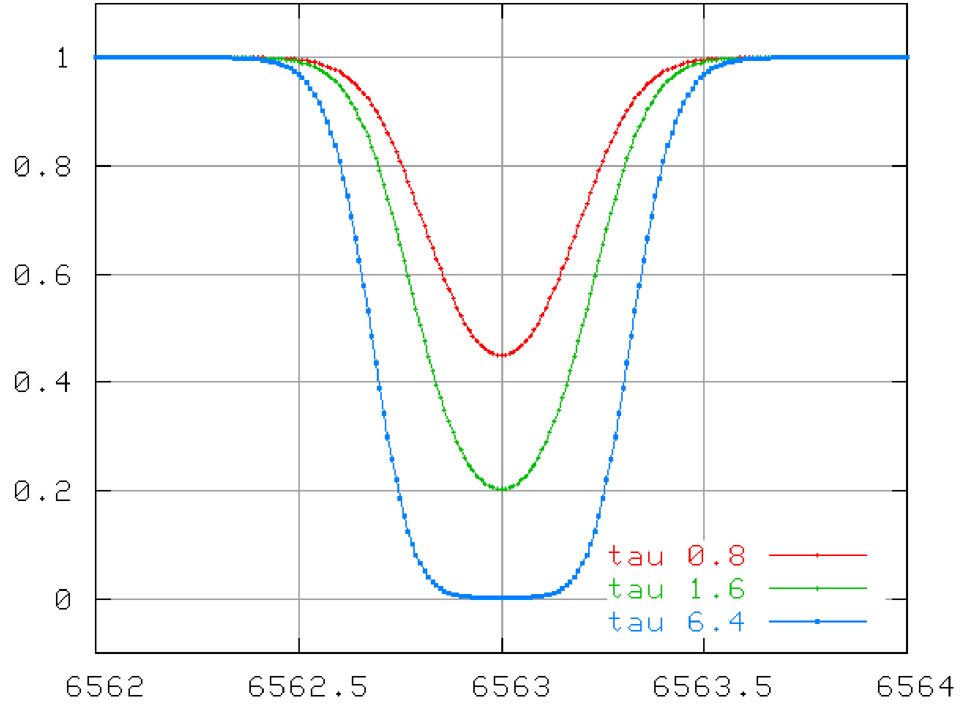
Line starts to "saturate", W almost independent of # of absorbing atoms

(3) For an intermediate case

$$W_\lambda \propto \sqrt{\ln Nf}$$

Line strength (equivalent width)
→ abundance

Curve of growth



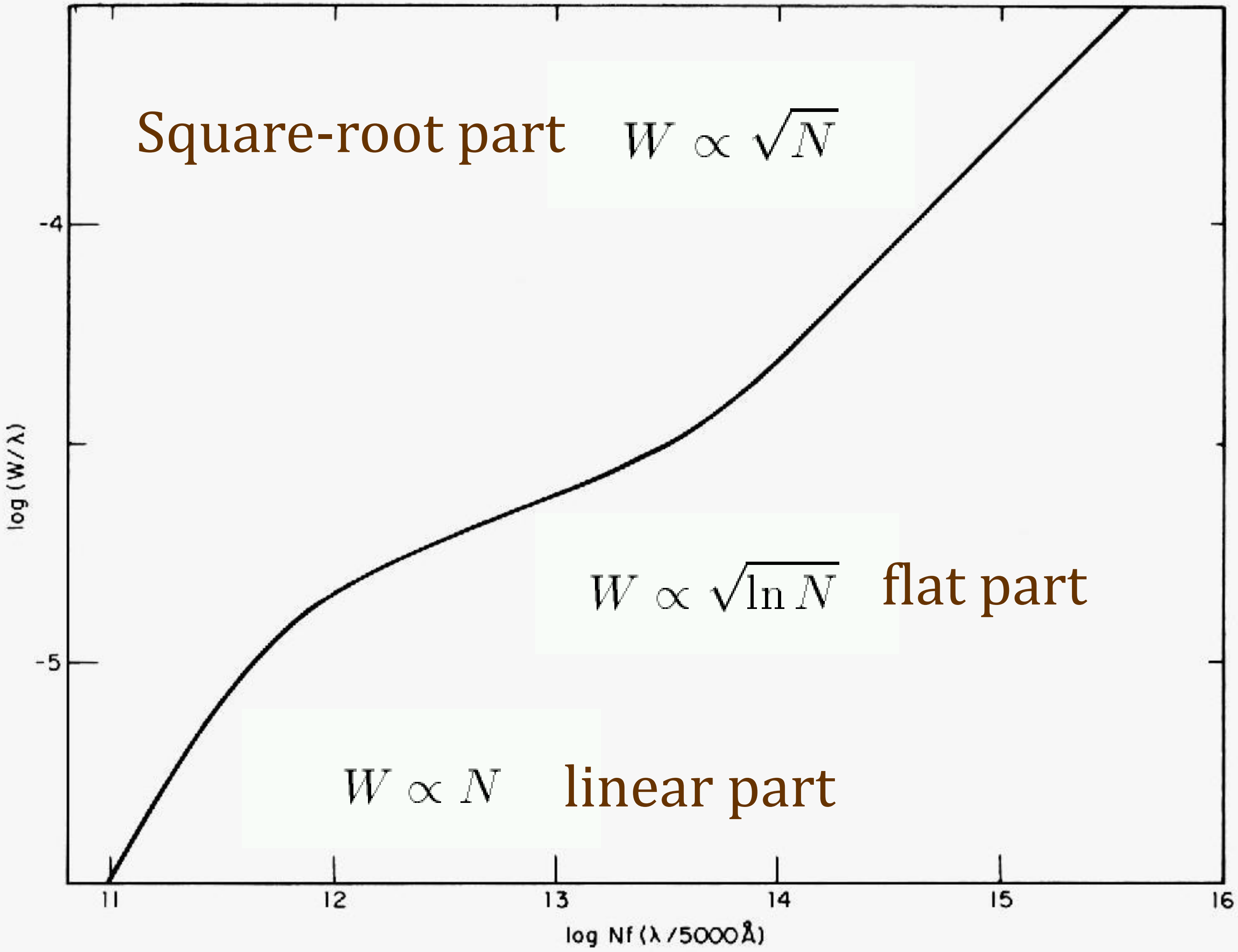


Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

- W_λ gives the abundance of the absorbing atom/ion.
- It is a coarse estimate (~5%), with many uncertainties. A more accurate measurement requires high-dispersion spectroscopy, atmosphere/ISM modeling, etc.
- If it is an excitation transition, use the Boltzmann equation to compute the total number of the species.
- Then use the Saha equation to compute the total number of the element.

Read D. Morton's paper

THE ASTROPHYSICAL JOURNAL, 197:85–115, 1975 April 1

INTERSTELLAR ABSORPTION LINES IN THE SPECTRUM OF ZETA OPHIUCHI

DONALD C. MORTON
Princeton University Observatory
Received 1974 August 12

ABSTRACT

Extensive high-resolution scans with the ultraviolet spectrometer on the *Copernicus* satellite have been combined with the available ground-based data on interstellar lines to obtain temperatures, densities, and abundances in H I clouds and H II regions in the direction of ζ Oph. Column densities have been obtained for 21 elements in various stages of ionization. A new determination for CO and the results for H_2, HD, CH, CH^+, and CN for other authors also have been included. In addition, upper limits have been reported for five elements and 11 molecules. In the ultraviolet scans, 45 lines remain unidentified. Radial velocities and curves of growth were used to locate the species seen in the ultraviolet into one or more of the six clouds already known from the visible spectra. The H_2, HD, and most of the neutral atoms are concentrated in one cloud at a heliocentric velocity of -14.4 km s^{-1}, while N I, O I, Ar I, and most of the first ions are distributed over at least two of these clouds. The velocities of the higher ion states implied there are H II regions in addition to the Strömgren sphere.

Calculations of the ionization equilibrium for C, Mg, S, and Ca have shown that the electron density $n_e \sim 0.7$ cm^{-3} in the -14.4 km s^{-1} cloud. Since the ionization of carbon is the primary source of the electrons, the ratio C II/H requires that $n_H \sim 10^4$ cm^{-3} for the total hydrogen nuclei, with a fractional ionization $n_e/n_H \sim 7 \times 10^{-5}$. Both densities could be up to 20 times larger if the cloud is close to the star. The cloud must be no more than 0.05 pc thick. The populations of the fine-structure levels in the C I ground state require $T = 19°$ K. The HD and the excited rotational levels of H_2 need temperatures between 56° and 115°, though the lines appear to have the same velocity as the C I, probably indicating that the dense cloud must have some associated hotter regions.

Relative to hydrogen, most of the elements in the H I clouds are depleted by factors of 3 to 4000 compared with the solar system abundances. Only sulfur and zinc are present in the gas with near normal abundances. Several elements, particularly Al, Si, and Fe, appear to be depleted in the H II regions as well, but nitrogen is normal.

Zeta Ophiuchi = HD 149757, O9.5V (*so few stellar lines*), a rapid rotator $v \sin i \approx 250$ km/s (*so broad stellar lines* → *easy separation from the narrow interstellar lines*)

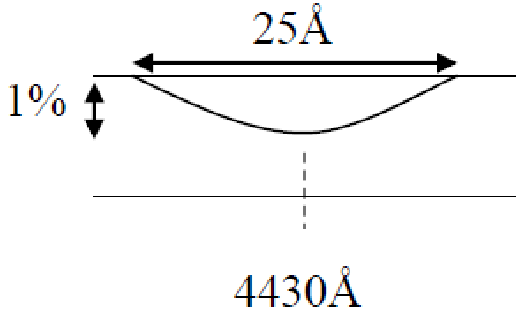
Ex 1: K I line λ7699, $f = 0.339$, $W_\lambda = 84$ mÅ ➔ N (K I) = ?

Ex 2: The Doublet Ratio Method → 2 lines from the same elements, e.g., close doublets Na I, Ca II ← Saha eq.

Ex 3: Application to unidentified lines

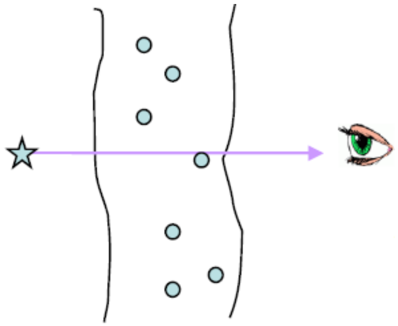
The "diffuse interstellar bands" (DIBs), 500+ such bands between UV and IR.

Do these lines originate from abundances?



$$I = I_0 e^{-\tau} = I_0 e^{-N\sigma}$$

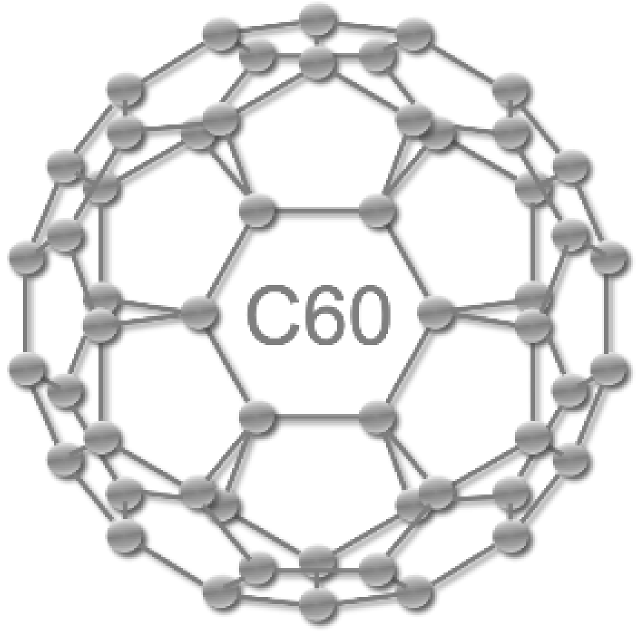
Observed $I/I_0 = 0.99$



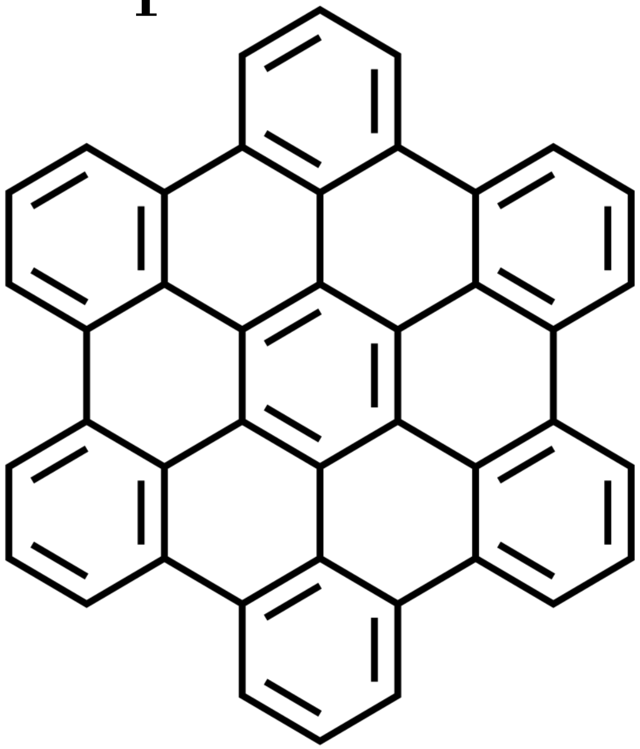
$\Delta\lambda \approx 25$ Å, extremely broad for Doppler broadening

→ estimate N_x, by assuming extreme values of f and compare with N_H

- ✓ Often attributed to polycyclic aromatic hydrocarbons (PAHs) or other large carbon-bearing molecules …
- ✓ But lacking firm lab results or model computation …



fullerene C_{60}^{+}?



Abundances of Elements

In HI regions, $N(x)/N(H)$ more or less depleted with respect to atmospheres of Pop I stars

(1) into molecular forms? If so, depletion should occurs primarily in regions of high densities

Results: Indeed, depletion seen where $E_{B-V} > 0.3$
For $E_{B-V} < 0.05$, abundances normal

(2) into solid forms? If so, depletion should increase for elements of higher condensation temperatures

Results: Indeed, this was observed
$T_c \uparrow \rightarrow$ condense first $\rightarrow$ more depletion

THE ASTROPHYSICAL JOURNAL, **187**:453–459, 1974 February 1

INTERSTELLAR ABUNDANCES: GAS AND DUST

GEORGE B. FIELD
Center for Astrophysics, Harvard College Observatory and Smithsonian Astrophysical Observatory
Received 1973 August 8

ABSTRACT

Data on abundances of interstellar atoms, ions, and molecules in front of ζ Oph are assembled and analyzed. The gas-phase abundances of at least 11 heavy elements are significantly lower, relative to hydrogen, than in the solar system. The abundance deficiencies of certain elements correlate with the temperatures derived theoretically for particle condensation in stellar atmospheres or nebulae, suggesting that these elements have condensed into dust grains near stars. There is evidence that other elements have accreted onto such grains after their arrival in interstellar space. The extinction spectrum of ζ Oph can be explained qualitatively and, to a degree, quantitatively by dust grains composed of silicates, graphite, silicon carbide, and iron, with mantles composed of complex molecules of H, C, N, and O. This composition is consistent with the observed gas-phase deficiencies.

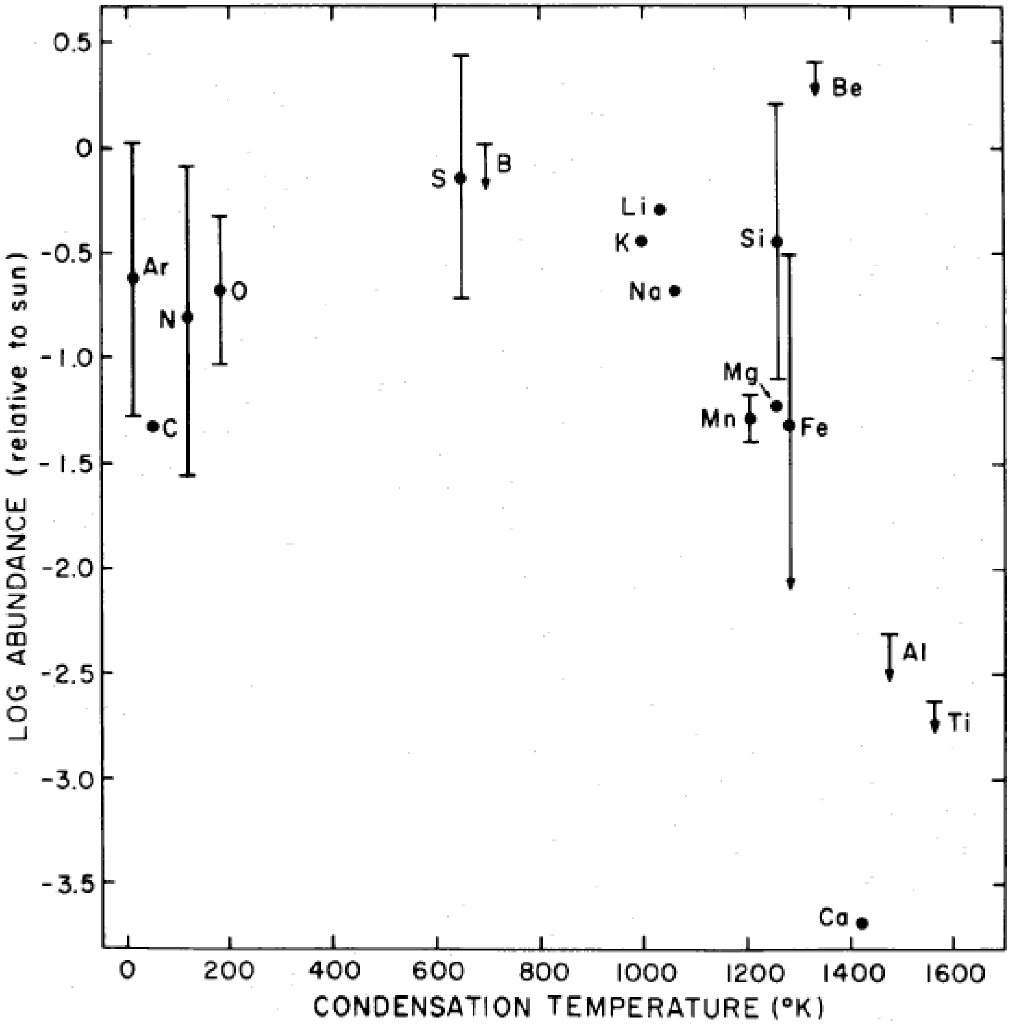


FIG. 1.—Logarithmic abundances of gas-phase elements in ζ Oph, relative to solar-system values, plotted against the condensation temperature calculated for an oxygen-rich atmosphere (table 3). It is suggested that elements above 500° K condensed as cores in stellar nebulae or atmospheres, while those below 500° K condensed as mantles in interstellar space. The large deficiencies of C and Ca are consistent with the latter process.

ULTRAVIOLET STUDIES OF THE INTERSTELLAR GAS

Lyman Spitzer, Jr. and Edward B. Jenkins
Princeton University Observatory, Princeton, New Jersey 08540

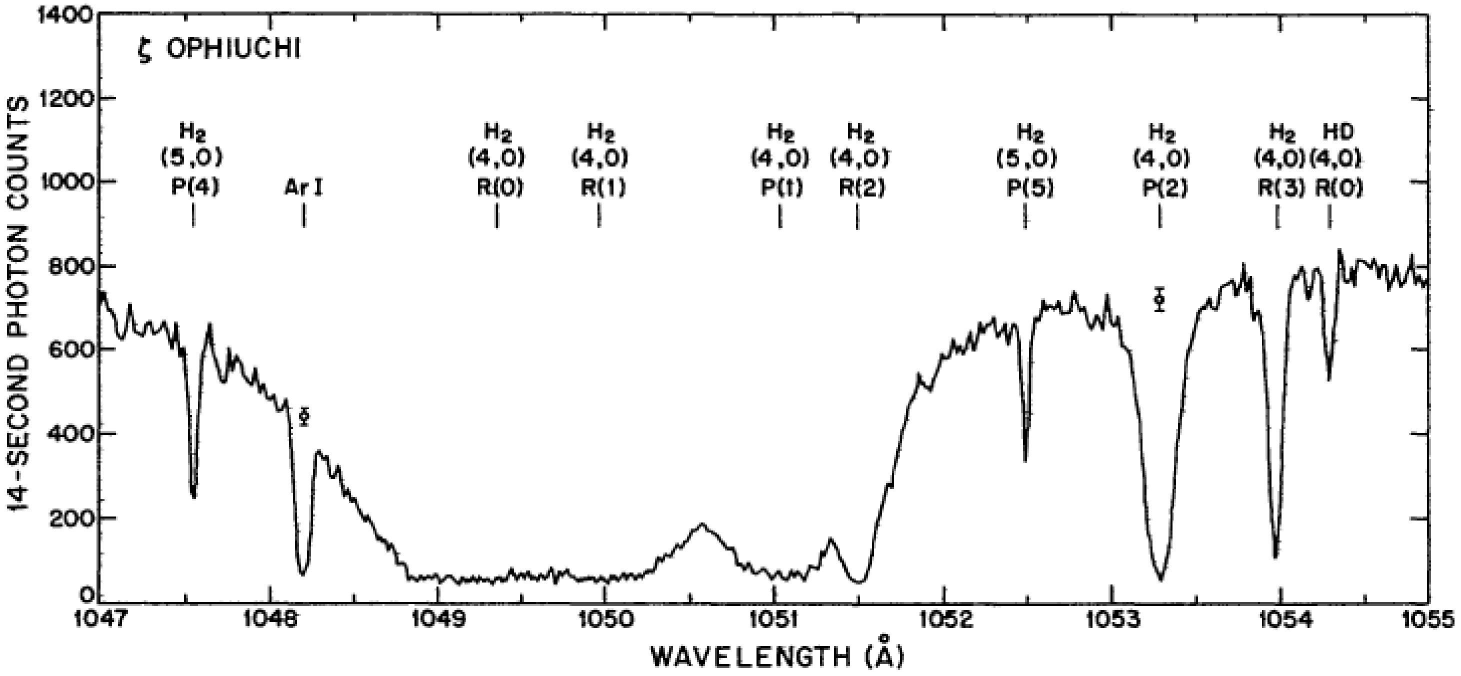


Figure 1 High-resolution scan of the O9.5 V star ζ Oph [$m_V = 2.56$, $E(B-V) = 0.32$] over an 8-Å interval. Error bars show the dispersion in photon counts expected from statistical fluctuations. The wavelengths of an Ar I line and of various rotational features in the (4,0) and (5,0) vibrational Lyman bands of H_2 and HD are shown by vertical lines.

(1975) ARAA

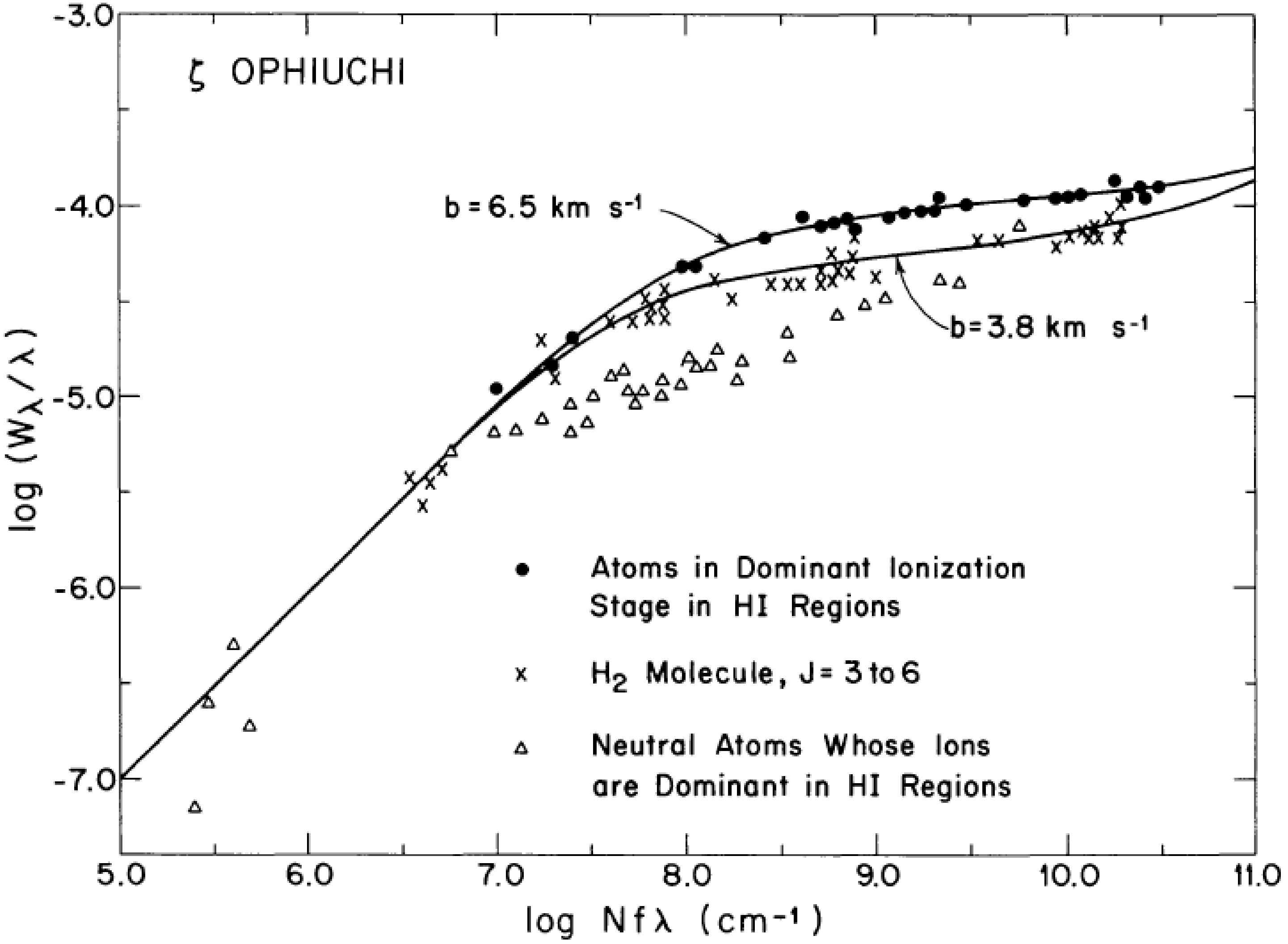


Figure 2 Curves of growth for different groups of interstellar lines in ζ Oph. The filled circles represent lines produced by N I, Ar I, Mg II, Si II, S II, and Fe II; the triangles show C I, Na I, Mg I, S I, K I, and Fe I. The crosses represent H_2 Lyman lines from the rotational levels $J = 3$–6.

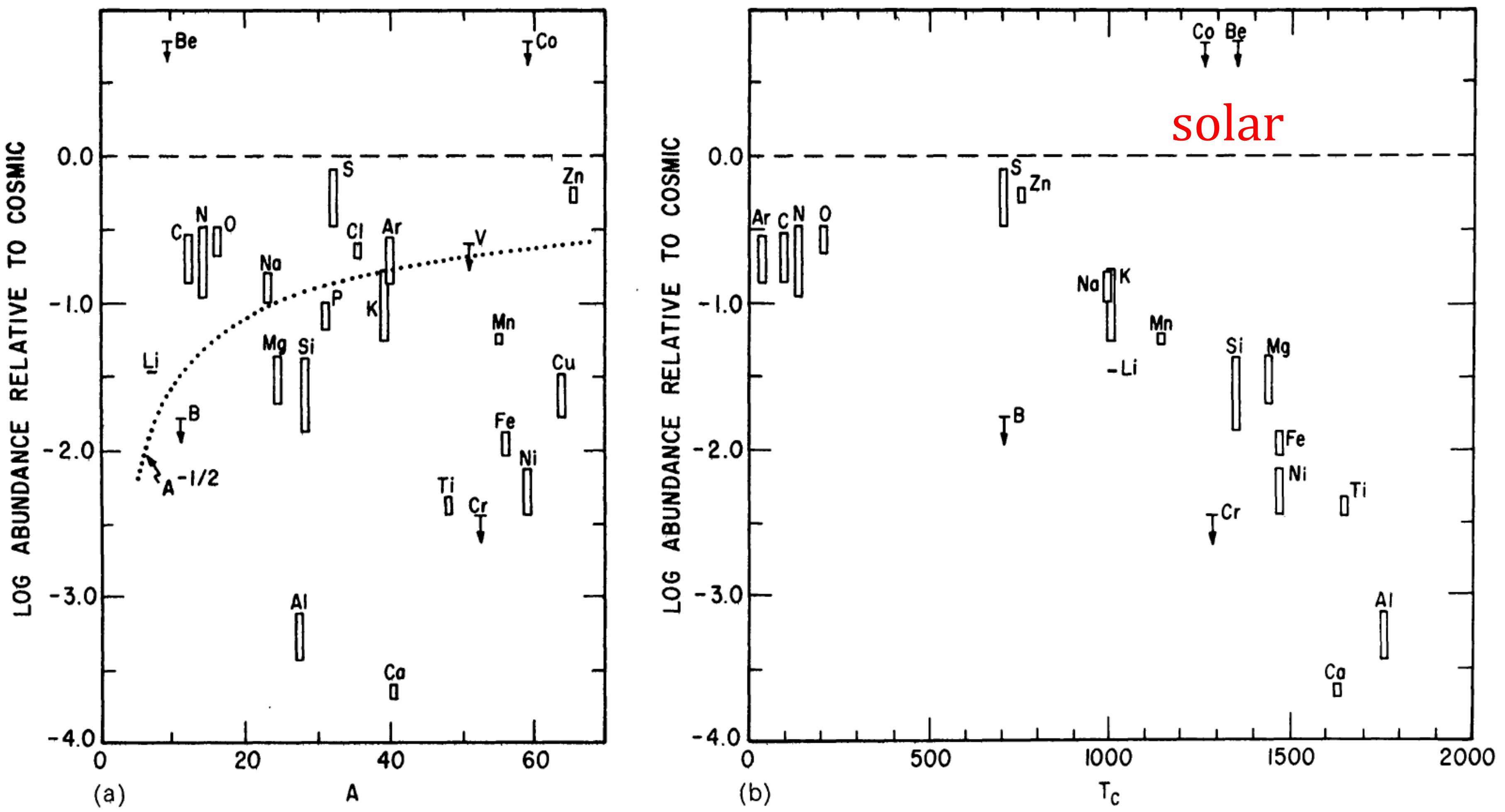


Figure 5 Depletion below solar abundances for elements in their atomic form in the H I gas toward ζ Oph, plotted against atomic mass A in (*a*) and condensation temperature T_c in (*b*). The vertical width of each bar represents the experimental error arising from uncertainties in the respective element's curve of growth. For grains and atoms of a given charge, the nonequilibrium accretion rate in cool interstellar clouds should be proportional to $A^{-1/2}$, illustrated by the dotted line in (*a*). All elements shown here except N, O, and Ar should be predominantly ionized in H I regions.

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ABUNDANCES OF INTERSTELLAR ATOMS FROM ULTRAVIOLET ABSORPTION LINES

EDWARD B. JENKINS
Princeton University Observatory

BLAIR D. SAVAGE
Washburn Observatory, University of Wisconsin

AND

LYMAN SPITZER, JR.
Princeton University Observatory

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ABSTRACT

The equivalent widths of interstellar absorption lines of Mg II, P II, Cl I and II, Mn II, Fe II, Cu II, and Ni II, obtained in a *Copernicus* survey (Bohlin *et al.*), have been analyzed to yield column densities along the lines of sight. The measured depletions are clearly correlated with $\langle n_H \rangle$, the mean hydrogen column density along the line of sight. Depletions also seem to be weakly correlated with various ratios of hydrogen to extinction by dust grains and also variations of extinction with wavelength, although part of these effects are a secondary result of the correlation with $\langle n_H \rangle$. We interpret the apparent coupling of depletion to the mean density in terms of an idealized model (Spitzer) where each element has one value of depletion in the low-density, warm, neutral gas and an enhanced, different value in cold clouds. The difference of apparent depletions for Mg, P, Cl, Mn, and Fe between warm and cold clouds averages 0.44 ± 0.12 (rms) dex, and after we allow for observational errors, the scatter of individual depletions from the overall trend predicted by the model is only ~ 0.10 dex. The identification of the observed apparent depletions with actual ones, while very likely, is not entirely secure because of the possible presence of highly saturated components with very narrow profiles and the possible contamination of the results by H II regions.

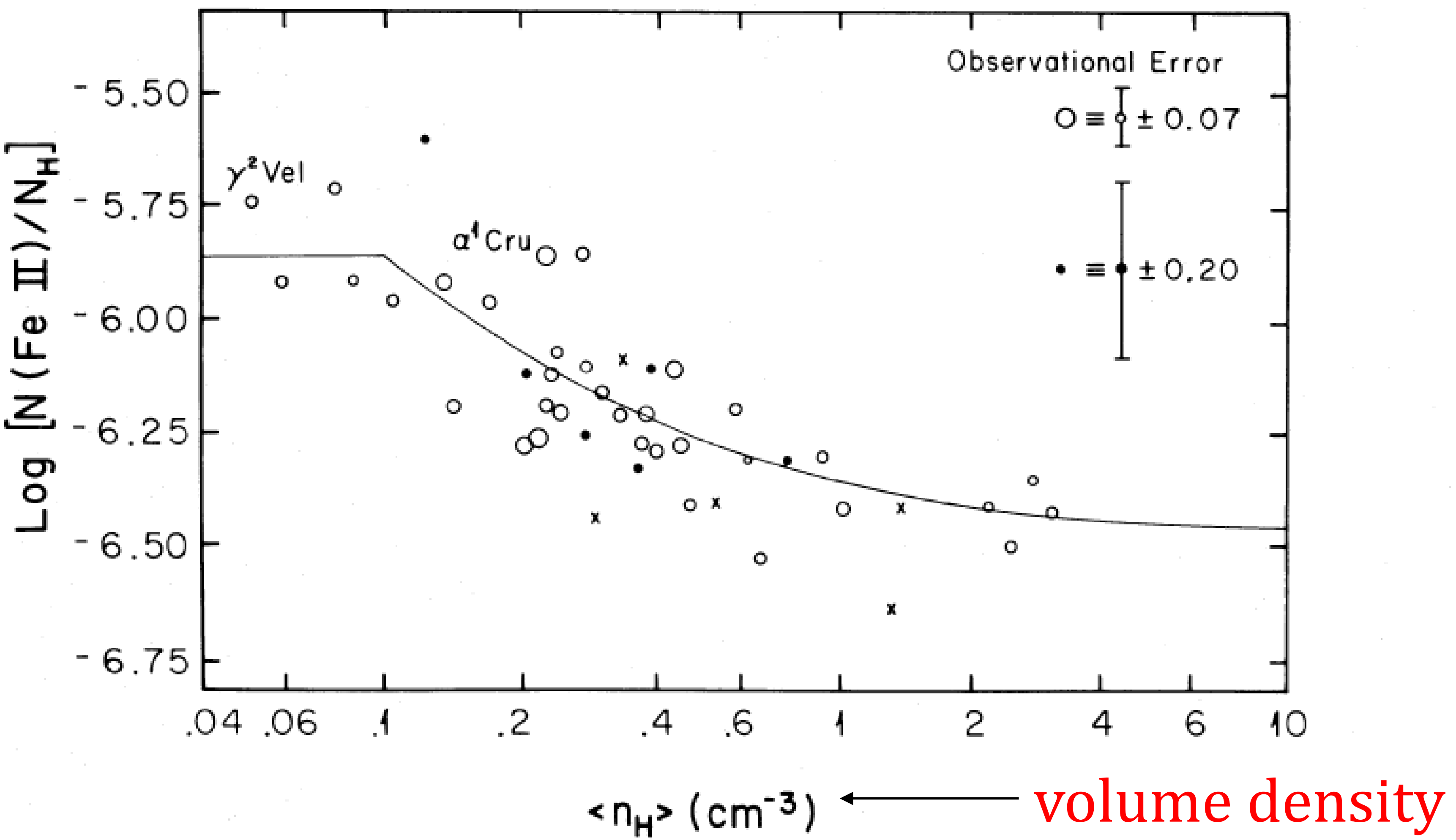
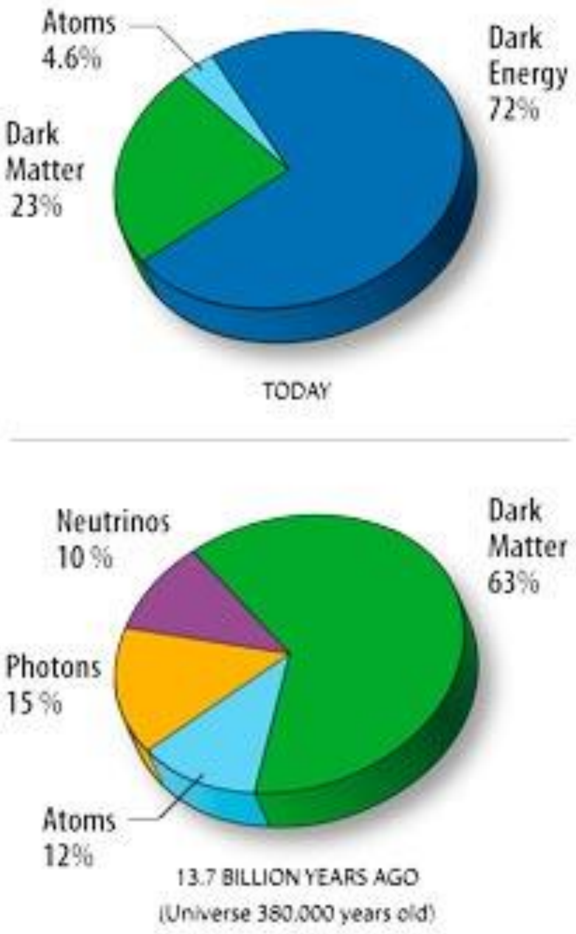
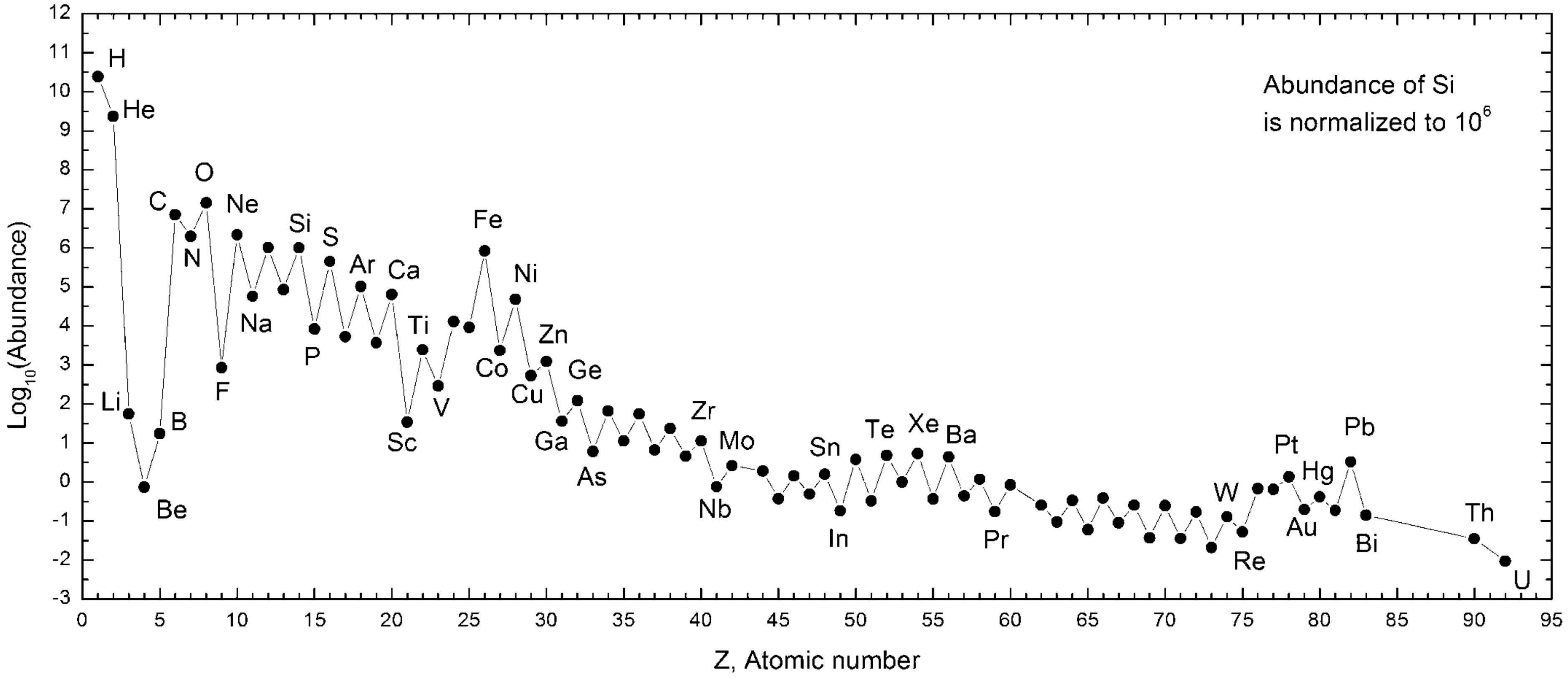


FIG. 5.—Abundance of Fe vs. average density. Logarithm of the abundance ratios, $N(\text{Fe II})/N_H$, is plotted against the value of $\langle n_H \rangle \equiv N_H/R$, the average particle density of hydrogen, $[n(\text{H I}) + 2n(\text{H}_2)]$, along the line of sight of length R. The diameter of each circle is inversely proportional to the expected 1 σ observational error in the logarithmic abundance ratio, as shown by the error bars in the legend. Solid curve represents a two-parameter fit to the theoretical result expected if the abundance ratio has one value in warm neutral gas and another in cold clouds. Note that log $[N(\text{Fe})/N_H]_{\text{cosmic}} = -4.5$.



Estimated proportions of matter, dark matter and dark energy in the universe. Only the fraction of the mass and energy in the universe labeled "atoms" is composed of chemical elements. (*WMAP*)

http://map.gsfc.nasa.gov/media/080998/index.html



- ☐ What are the 5 most abundant cosmic elements?
- ☐ What happens to iron?
- ☐ What about the zigzagging?