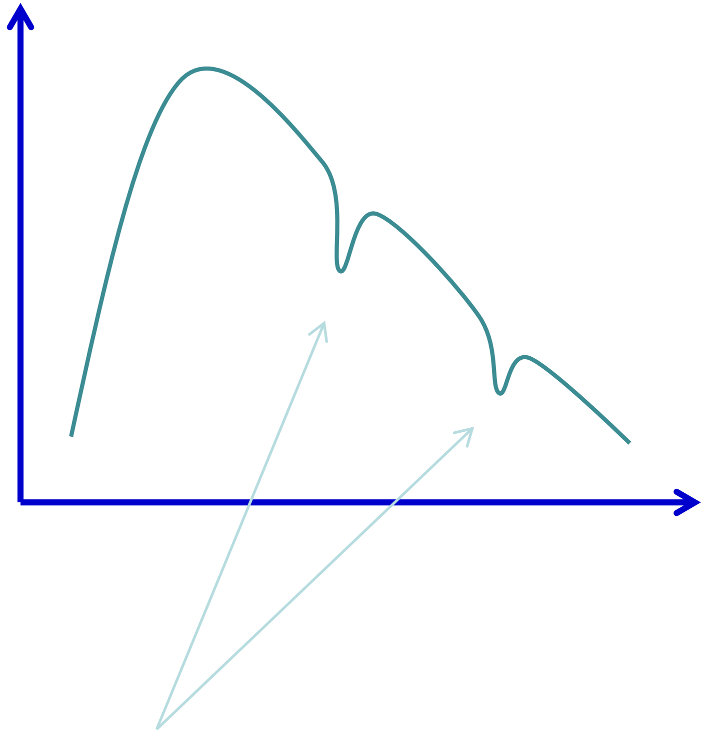
Chemical Abundances

The same total energy? The same number of absorbing atoms?



$\int I_\nu \, d_\nu$ at different λs?

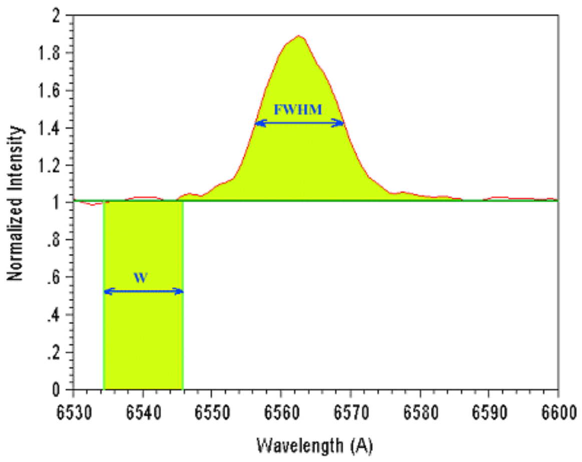
Equivalent Width

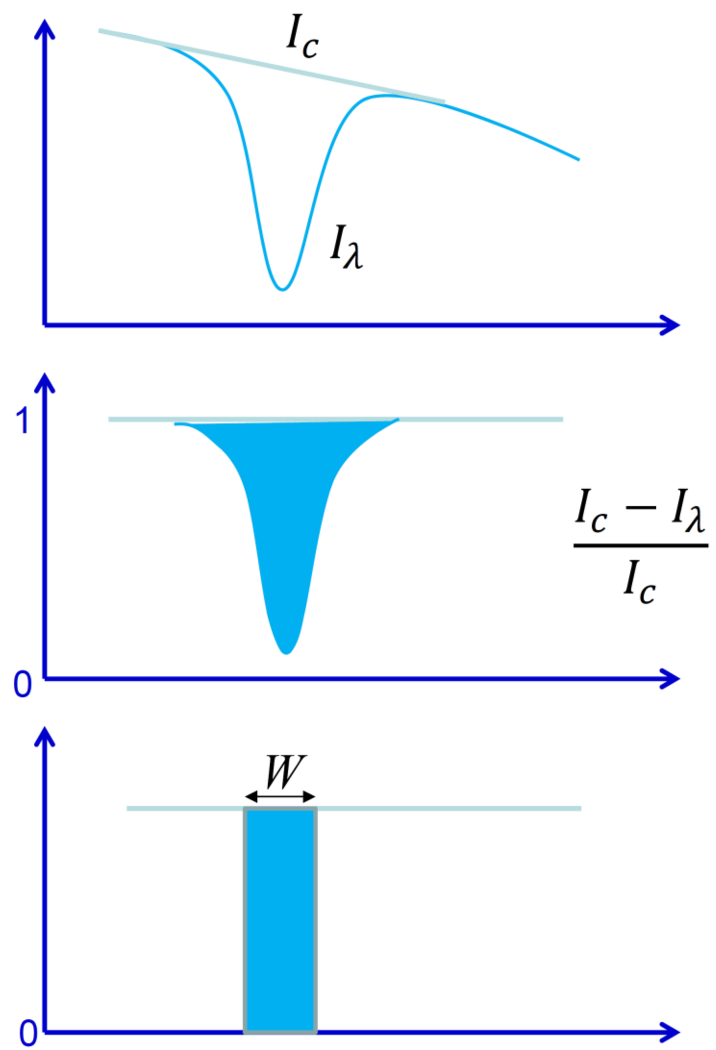
$$W_\lambda = \int_{-\infty}^{\infty} \frac{I_c - I_\lambda}{I_c}\, d\lambda = \int 1 - e^{-\tau_\lambda}\, d\lambda$$

measures the total absorption (strength) in a line, where I_c is the continuum and I_λ is the line profile.

Normalized tine profile,

$$\phi_\nu = \frac{I_c - I_\lambda}{I_c}$$





The equivalent width W_λ has the dimension of λ, e.g., Å or mÅ; negative for an emission line.

$$\frac{W_\lambda}{\lambda} = \frac{W_\nu}{\nu} = \frac{W_v}{c}$$

Curve of Growth

… used in estimation of the abundance of a species by the equivalent width of a spectral line

$$\tau_\nu = \kappa_\nu \, ds = n\sigma_\nu \, ds = N \, \sigma_\nu$$

where N is the column density   particles per sky area

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

$$\tau_\lambda = N\left(\frac{\pi e^2}{mc^2}\right) f \, \lambda_0^2 \, \phi_\lambda$$

(i) For weak lines ($\tau_\lambda \ll 1$)

That is, every absorbing atom/ion contributes to *W.*

$$W_\lambda = \int \tau_\lambda \, d\lambda = N \frac{\pi e^2}{mc^2} \, f \, \lambda_0^2 \propto N \, f$$

or

$$\frac{W_\lambda}{\lambda} = N \frac{\pi e^2}{mc^2} f \lambda_0 = 8.85 \times 10^{-13} \, N f \lambda$$

where N is in [cm^{-2}], and λ in [cm].

(ii) For strong lines ($\tau_\lambda \gg 1$)

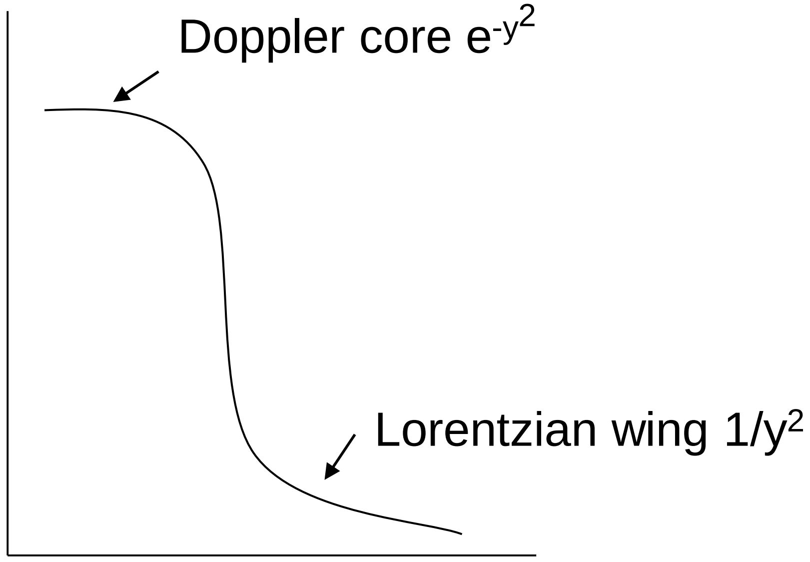
$$W_\lambda \propto \sqrt{N f}$$

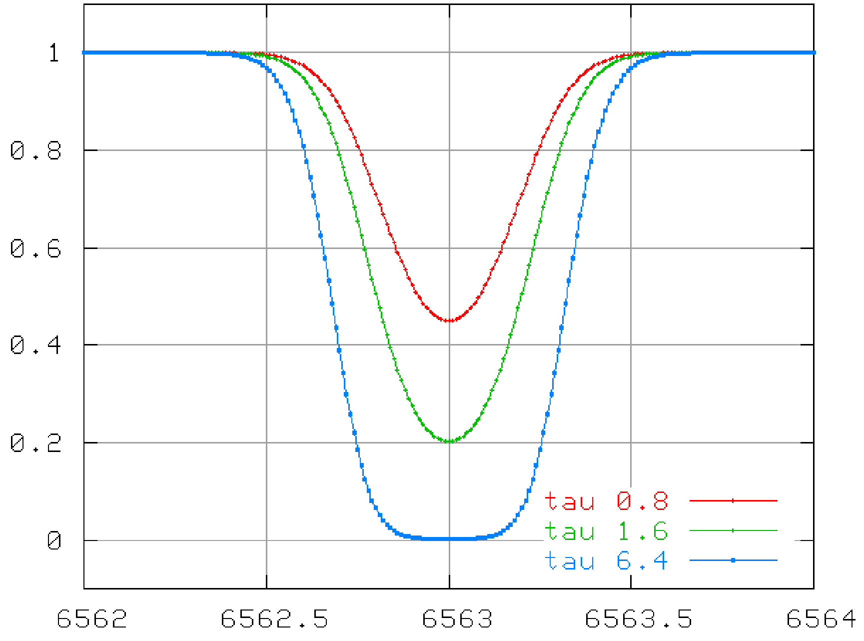
(iii) Intermediate case

$$W_\lambda \propto \sqrt{\ln N f}$$

Line wings

Line starts to “saturate”, *W* is almost independent of the number of absorbing atoms





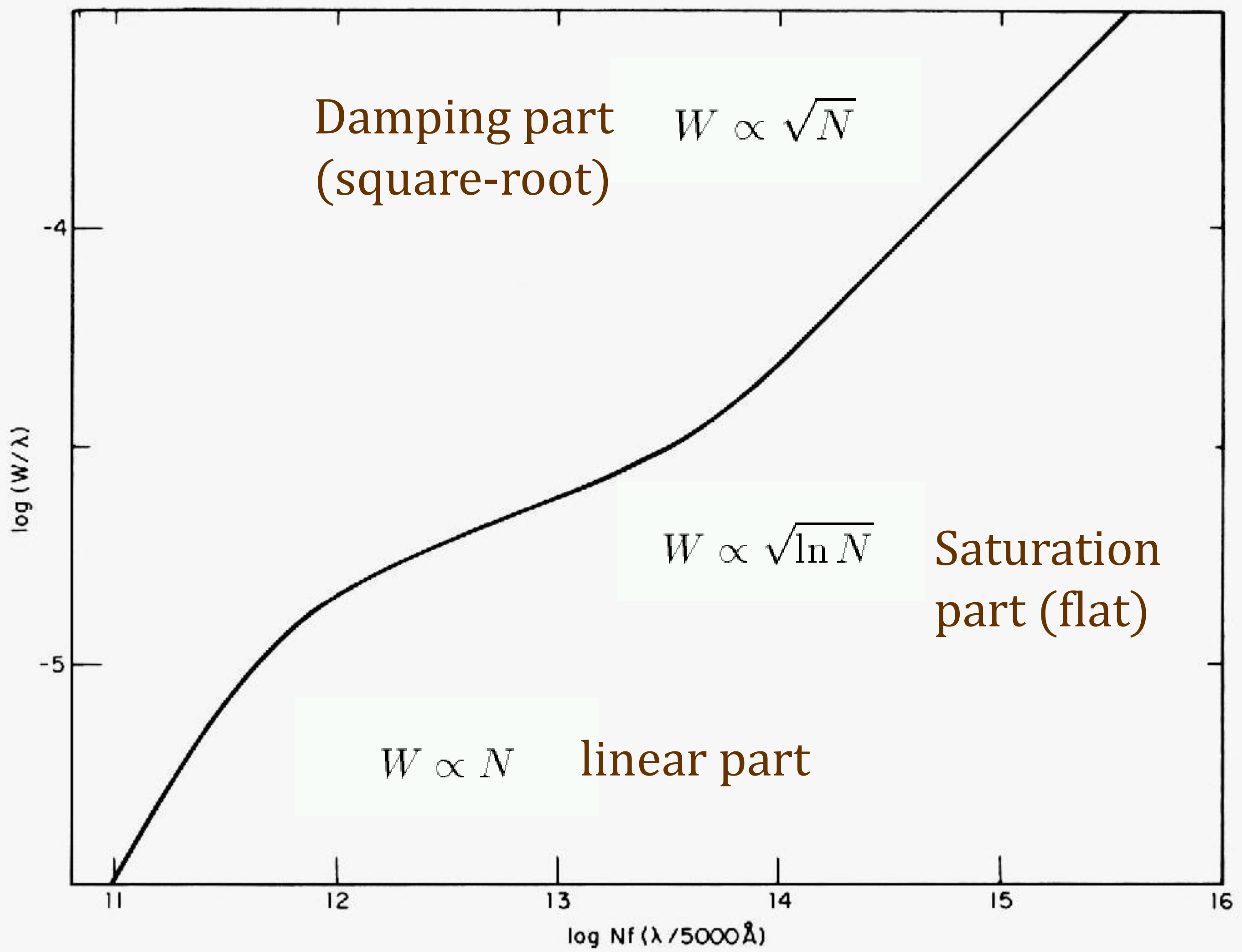
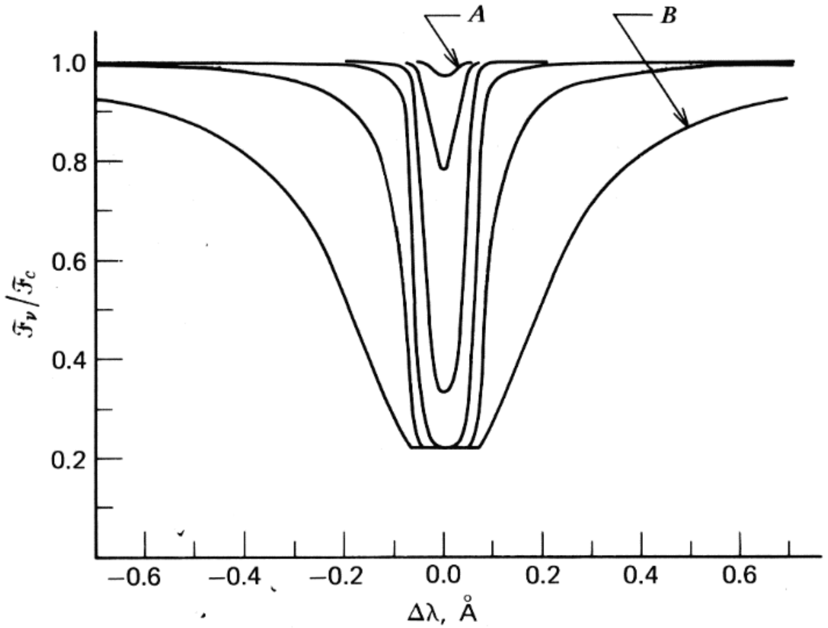
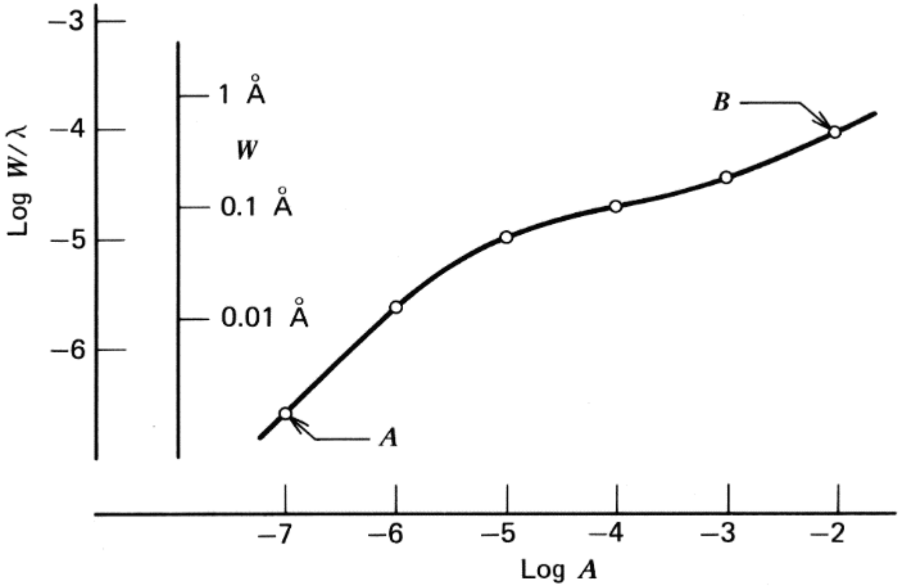


Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)

- 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, stellar atmosphere modeling, etc.
- If it is an excitation transition, use the Boltzmann equation to compute the total number of the species of the same ionization state.
- Then use the Saha equation to compute the total number of the element of all the ionization states.

Amount of absorbers → both the line profile and the equivalent width change





Gray Fig. 13.12

Read D. Morton's paper

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

INTERSTELLAR ABSORPTION LINES IN THE SPECTRUM OF ZETA OPHIUCHI

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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.

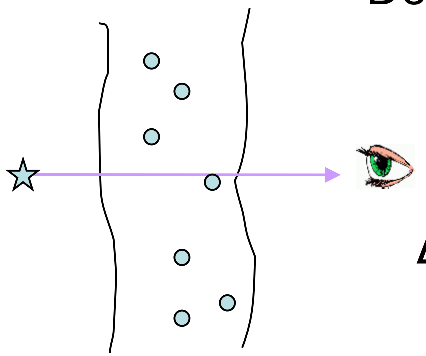
Relative to hydrogen, most of the elements in the H I clouds are depleted by factors of 3 to 4000 compared with the solar system abundances. Only sulfur and zinc are present in the gas with near normal abundances. Several elements, particularly Al, Si, and Fe, appear to be depleted in the H II regions 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_λ measured = 84 mÅ → N (K I) = ?

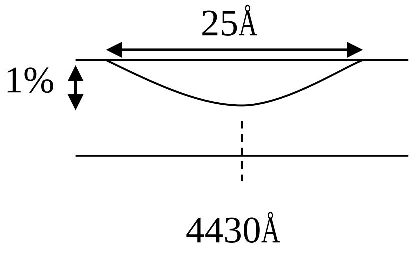
Ex 2: Application to unidentified lines the "diffuse interstellar bands" (DIBs), 100+ such bands most between 440 to 685 nm. Ref: Herbig 1995, ARAA, 33, 359

Do these lines originate from abundances?



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

Observed $I/I_0 = 0.99$



Δλ≈ 25 Å, extremely broad for Doppler broadening

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

Ex 3: The Doublet Ratio Method → 2 lines from the same elements, e.g., close doublets Na I, Ca II ← Saha eq.

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

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

Indeed, this was observed; $T_c \uparrow$ → *condense first* → *depletion* ↑

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

INTERSTELLAR ABUNDANCES: GAS AND DUST

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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.

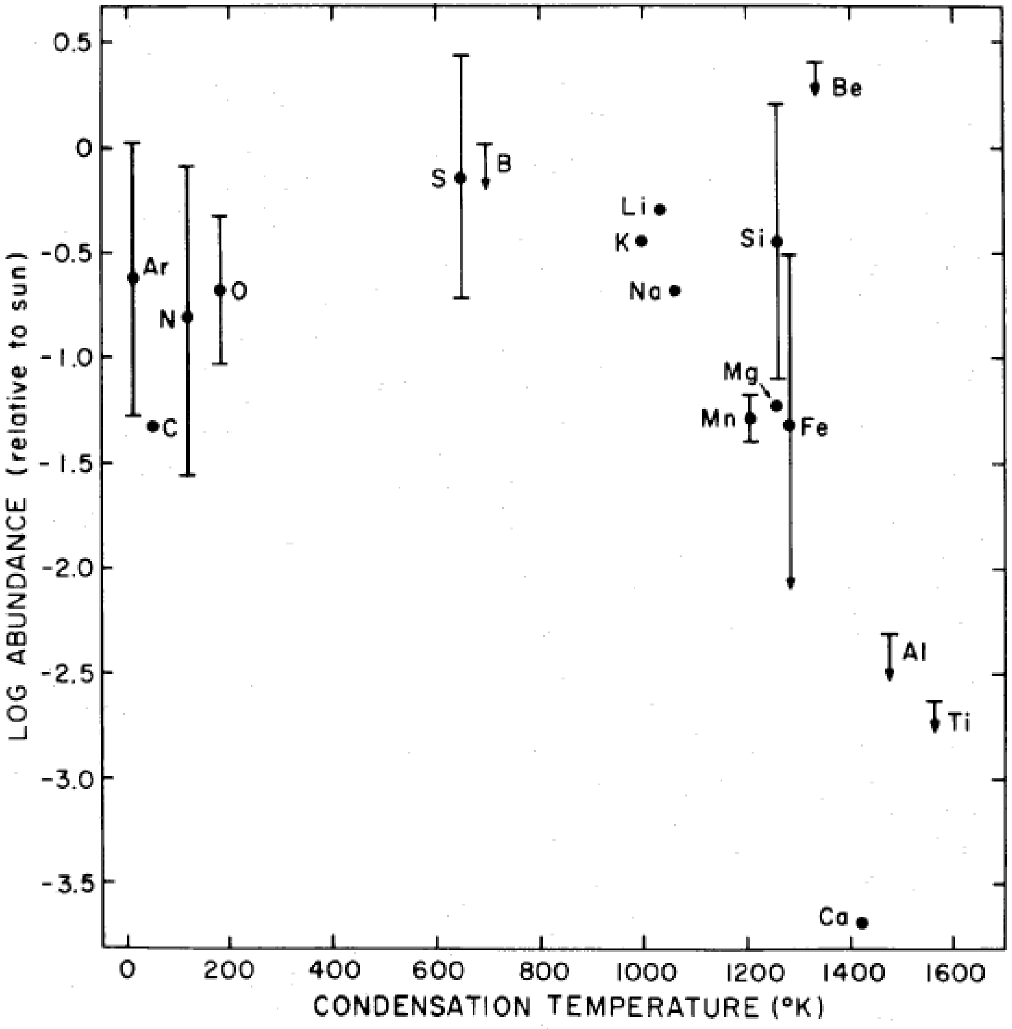

FIG. 1.—Logarithmic abundances of gas-phase elements in ζ Oph, relative to solar-system values, plotted against the condensation temperature calculated for an oxygen-rich atmosphere (table 3). It is suggested that elements above 500° K condensed as cores in stellar nebulae or atmospheres, while those 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

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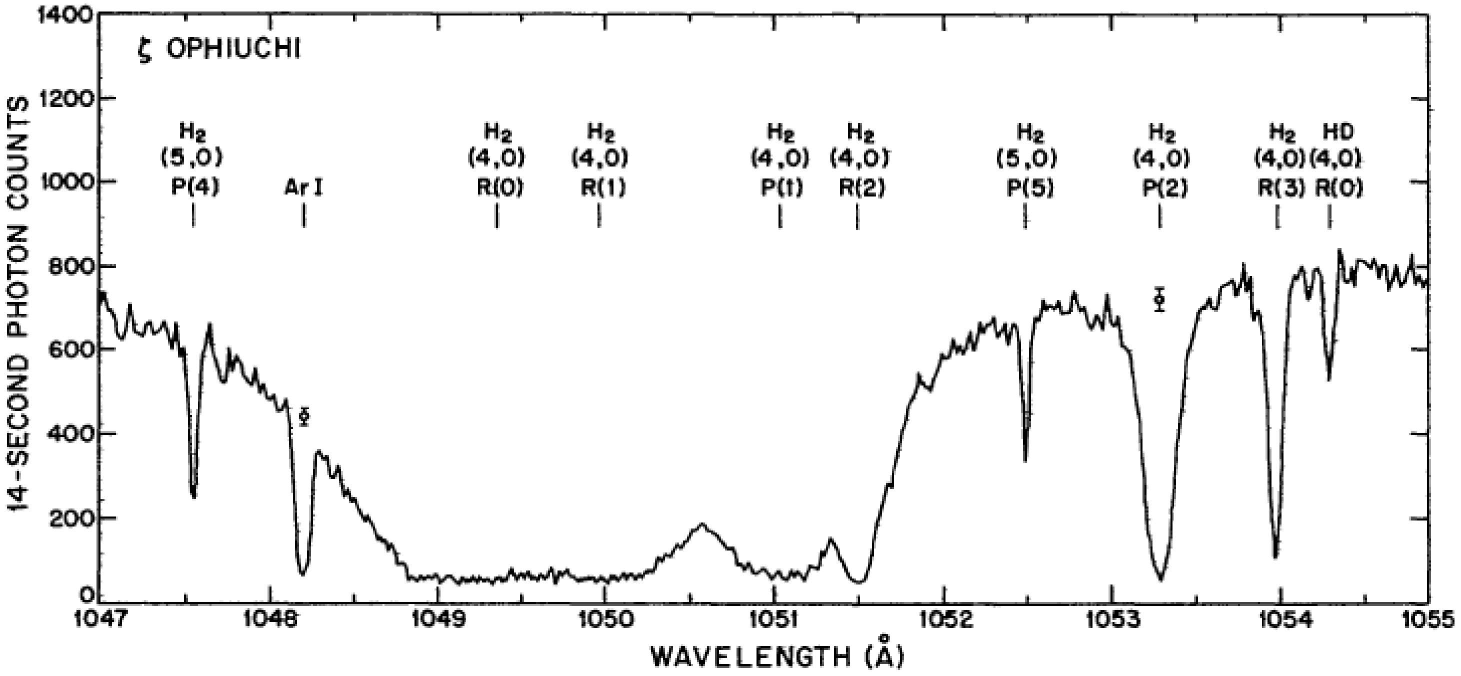

Figure 1 High-resolution scan of the O9.5 V star ζ Oph [$m_V = 2.56$, $E(B-V) = 0.32$] over an 8-Å interval. Error bars show the dispersion in photon counts expected from statistical fluctuations. The wavelengths of an Ar I line and of various rotational features in the (4,0) and (5,0) vibrational Lyman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

(1975) ARAA

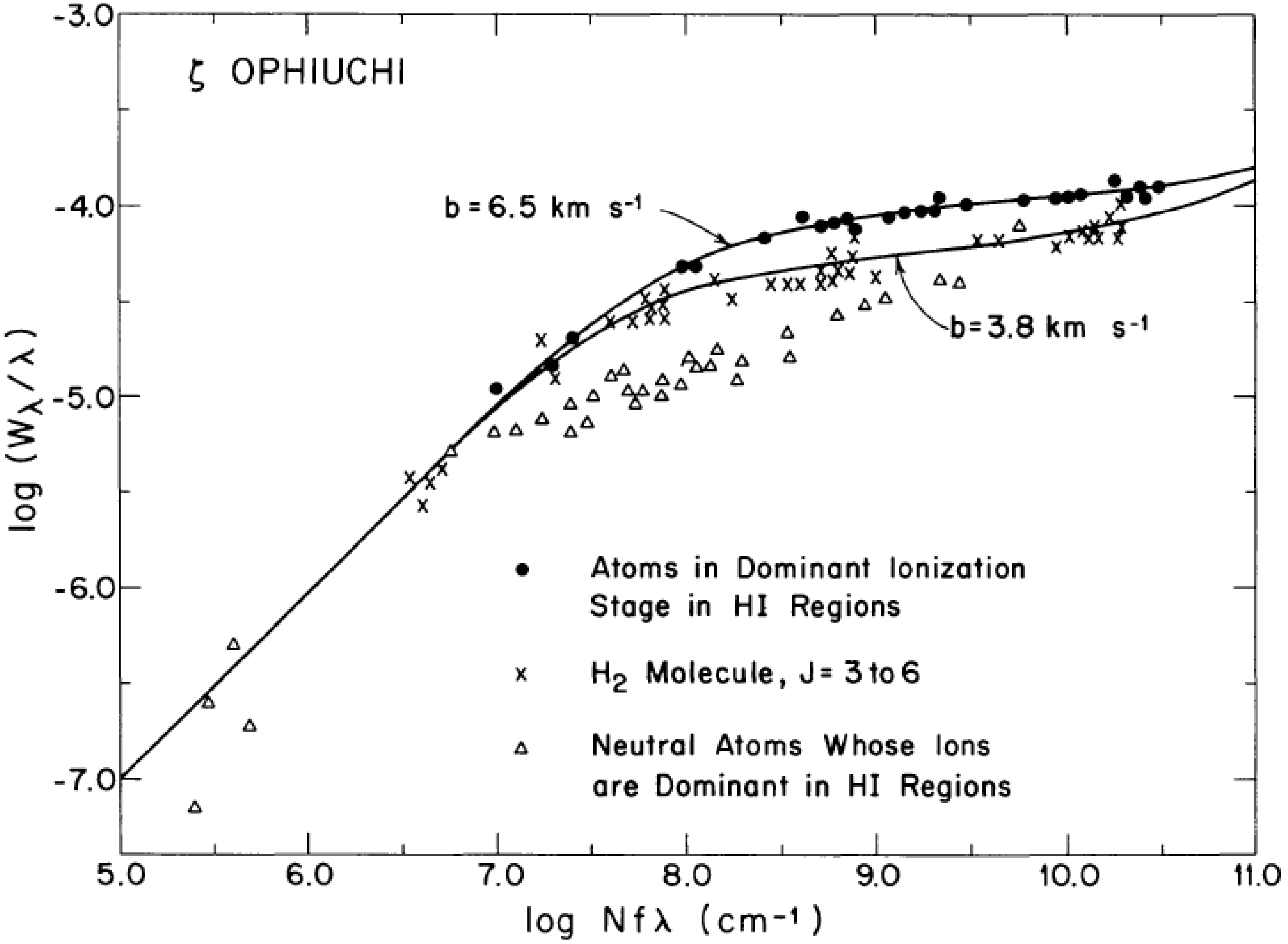

Figure 2 Curves of growth for different groups of interstellar lines in ζ Oph. The filled circles represent lines produced by N I, Ar I, Mg II, Si II, S II, and Fe II; the triangles show C I, Na I, Mg I, S I, K I, and Fe I. The crosses represent H_2 Lyman lines from the rotational levels $J = 3$–6.

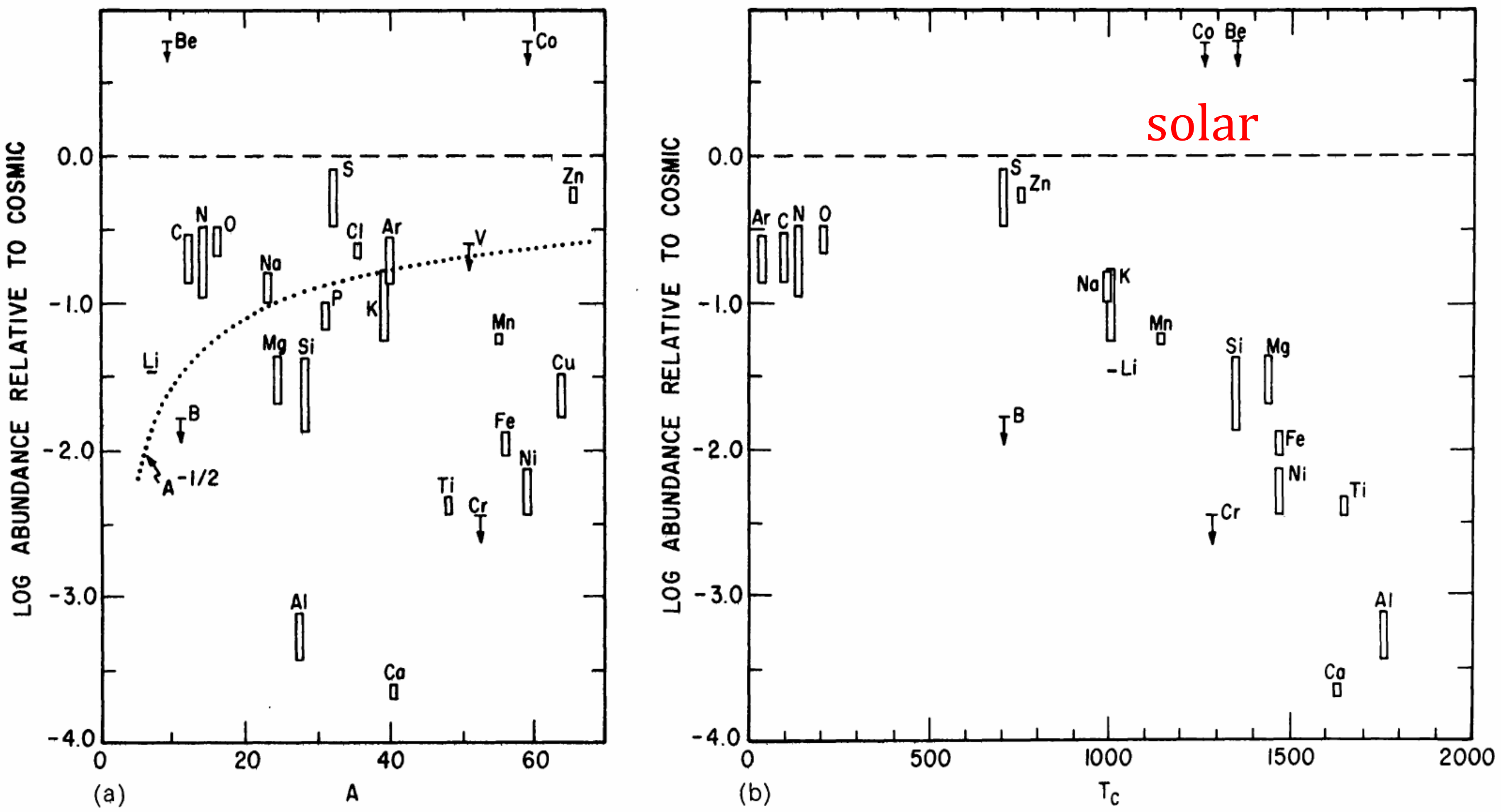

Figure 5 Depletion below solar abundances for elements in their atomic form in the H I gas toward ζ Oph, plotted against atomic mass A in (*a*) and condensation temperature T_c in (*b*). The vertical width of each bar represents the experimental error arising from uncertainties in the respective element's 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.

THE ASTROPHYSICAL JOURNAL, **301**:355–379, 1986 February 1

ABUNDANCES OF INTERSTELLAR ATOMS FROM ULTRAVIOLET ABSORPTION LINES

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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.

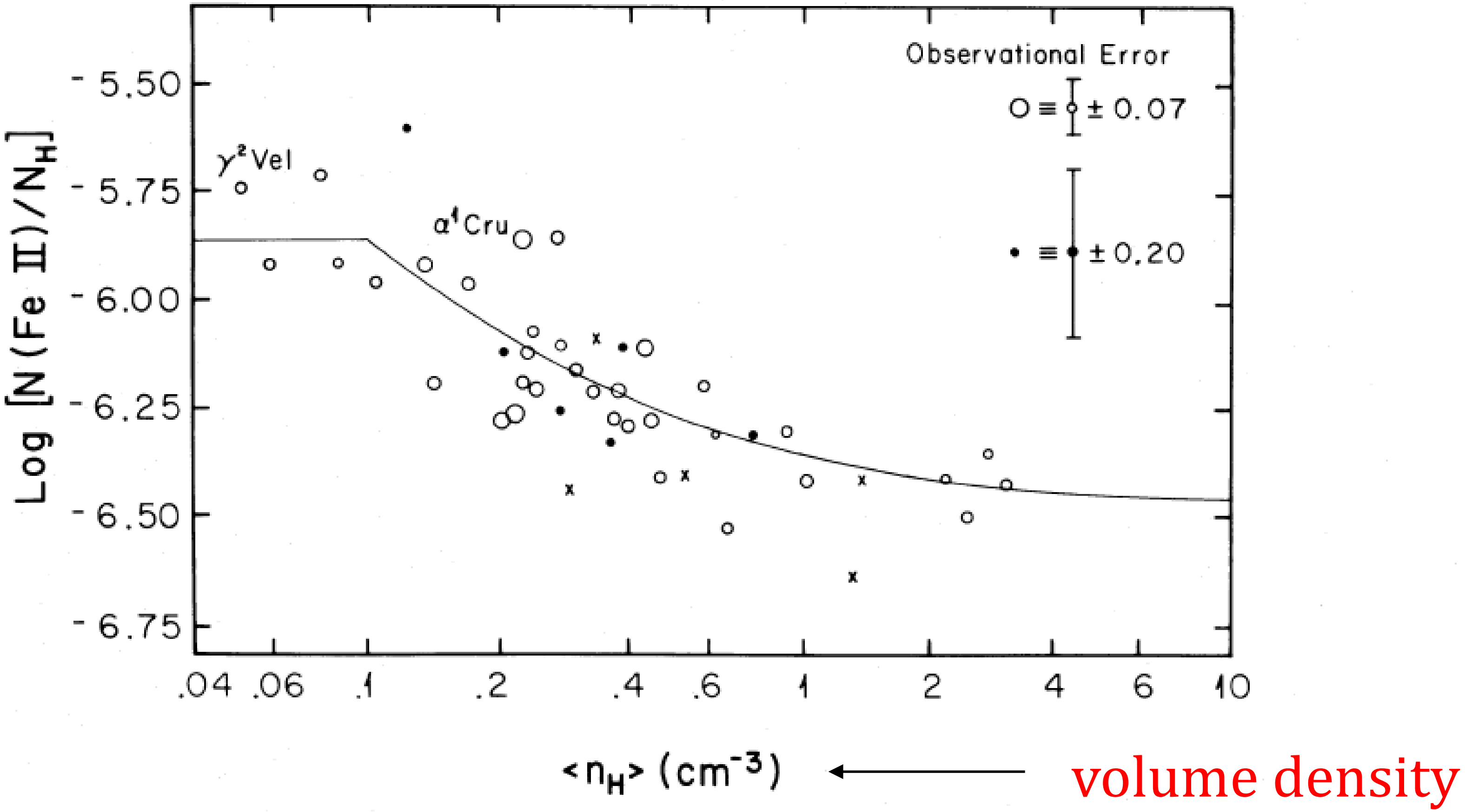
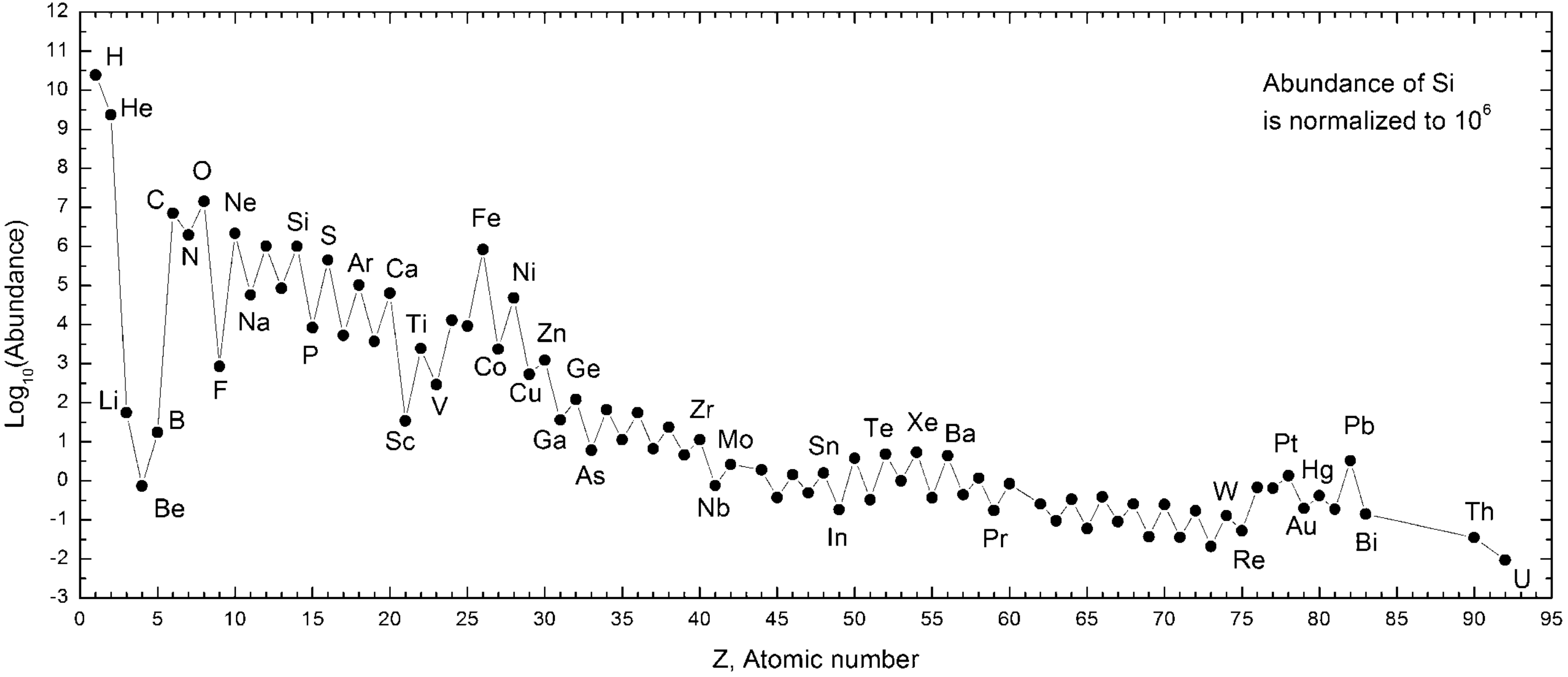


FIG. 5.—Abundance of Fe vs. average density. Logarithm of the abundance ratios, $N(\text{Fe II})/N_H$, is plotted against the value of $\langle n_H \rangle \equiv N_H/R$, the average particle density of hydrogen, $[n(\text{H I}) + 2n(\text{H}_2)]$, along the line of sight of length R. The diameter of 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 $\log [N(\text{Fe})/N_H]_{\text{cosmic}} = -4.5$.



- ☐ What is the 1st, 2nd, 3rd, and 4th most abundant elements?
- ☐ What happens to iron?