Diffuse Interstellar Medium

- Basics, velocity widths
- H I 21-cm radiation (emission)
- Interstellar absorption lines
- Radiative transfer
- Resolved Lines, column densities
- Unresolved lines, curve of growth
- Abundances, depletions

Basics

- Electromagnetic radiation and ISM gas are **not** in local thermodynamic equilibrium (LTE)
- Thus, the populations of atomic and molecular energy levels are **not** specified by LTE.
- A good assumption for low density ($n_H < 10^7$ cm^{-3}) gas is that the electrons remain in their lowest energy levels
- However, collisions between electrons, atoms, and molecules will establish a Maxwellian velocity distribution.

$$P(\mathrm{v}_r) = \frac{1}{\sqrt{\pi}b} e^{-(\mathrm{v}_r/b)^2} \quad \text{where } b = \sqrt{\frac{2kT}{m}}$$

b = velocity spread parameter, T = temperature
v_r = velocity in one dimension, m = mass of particle

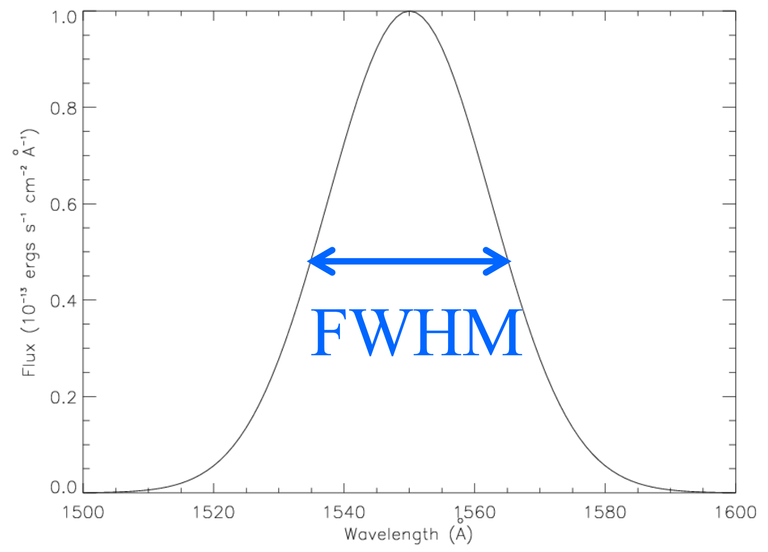
- Note that the previous equation describes a **Gaussian** profile, normally defined as:

$$P(\mathrm{v}_r) = \frac{1}{\sqrt{2\pi}\sigma} e^{-\frac{1}{2}(\mathrm{v}_r/\sigma)^2}$$

where v_r = radial velocity, σ = velocity dispersion

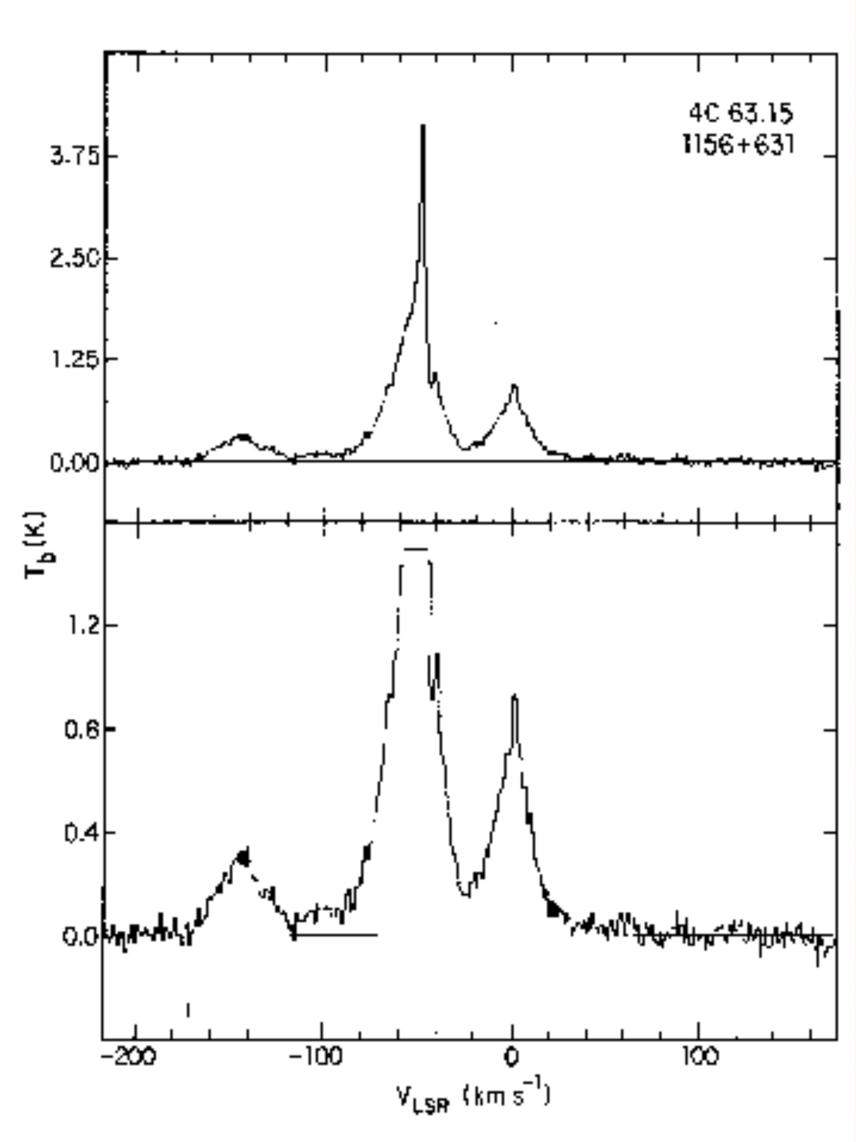
- Thus: $b = \sqrt{2}\sigma$
- Note the full-width at half-maximum for a Gaussian is:

$$\mathrm{FWHM} = 2.355\ \sigma$$



Ex) H I 21-cm emission line (1420 MHz)

- What is the FWHM for H I from a cloud of gas at T = 50 K?
- FWHM ≈ 1 km/sec - But what is observed?



- emission profiles are not Gaussian, much broader than thermal width
  - this indicates turbulence
- there are multiple components
  - multiple clouds in the line of sight

Note: T_b = brightness temperature

$$= \frac{c^2}{2k\nu^2} I_\nu \text{ (in the Raleigh-Jeans limit)}$$

What is the emission process for H I 21-cm?

- Radiative transitions between hyperfine levels of the electronic ground state (n=1)
- Upper state: electron and proton spins are parallel, $g_k = 3$

  (g_k = statistical weight = 2S+1, S = total spin quantum #)
- Lower state: electron and proton antiparallel, $g_j = 1$
- A_{jk} = transition probability = 2.9×10^{-15} sec^{-1}

  →Lifetime of upper level = 11 million years!
- Thus for $n_H \approx 1$ cm^{-3}, collisions dominate - levels are populated according to the Boltzman equation:

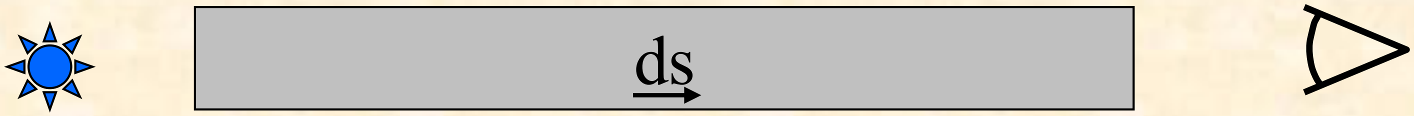
$$\frac{n_k}{n_j} = \frac{g_k}{g_j} e^{-\frac{(E_k - E_j)}{kT}} \approx \frac{g_k}{g_j} \approx 3$$

Since the energy difference between levels is very small

- The populations of the levels are essentially independent of temperature in the ISM.

Interstellar Absorption Lines:

Radiative Transfer



$$dF_\nu = -\kappa_\nu F_\nu ds + j_\nu ds$$

where κ_ν = opacity, j_ν = emissivity

For UV and optical absorption lines: $j_\nu = 0$

So: $dF_\nu = -\kappa_\nu F_\nu ds$

Let: $d\tau_\nu = -\kappa_\nu ds$ $\quad \tau_\nu$ = optical depth (# of mean free paths)

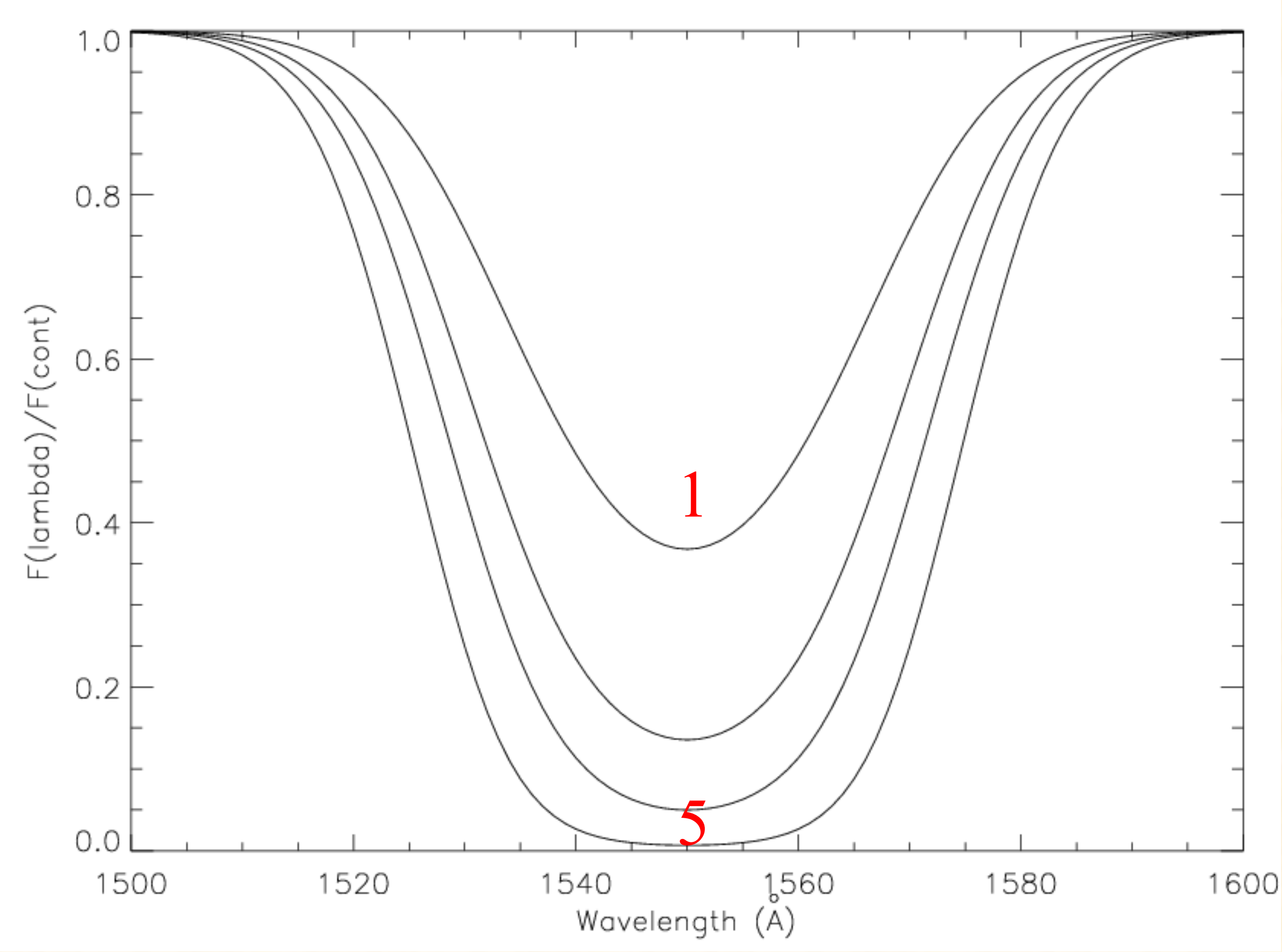
$$\tau_\nu = \int_0^{\tau_\nu} d\tau'_\nu = \int_{F_\nu}^{F_c} \frac{dF'_\nu}{F'_\nu} = \ln\left(\frac{F_c}{F_\nu}\right) \qquad \frac{F_\nu}{F_c} = \exp(-\tau_\nu)$$

(F_c = continuum flux, F_ν = observed flux)

Can do the same for λ: $\tau_{\lambda} = \ln(F_c / F_{\lambda})$

Ex) Assume a Gaussian profile in optical depth.

What is (F_{λ}/F_c) *for* $\tau(\lambda_0) = 1, 2, 3, 5$?



Note: These lines are resolved: FWHM (line) > FWHM (LSF)

LSF – line-spread function (profile of line that is intrinsically infinitely narrow)

How do we get column densities from absorption lines?

I. Resolved Lines : FWHM(Line) > FWHM(LSF)

Consider absorption from levels j to k :

$\kappa_\nu = n_j s_\nu$ where $n_j =$ # atoms / cm^3 in state j

$s_\nu =$ cross section per frequency

$\kappa_\nu = n_j s \Phi_\nu$ where $s =$ integrated cross section

$\Phi_\nu =$ line profile ($\int \Phi_\nu d\nu = 1$)

$$\tau_\nu = \int d\tau_\nu = \int \kappa_\nu ds' = s\,\Phi_\nu \int n_j ds'$$

$$\tau_\nu = s\,\Phi_\nu N_j \quad (= sN_\nu)$$

If we integrate over frequency :

$$\int \tau_\nu d\nu = sN_j \int \Phi_\nu d\nu \quad = \quad sN_j \quad (N_j = \text{column density})$$

So : $N_j = \frac{1}{s}\int \tau_\nu d\nu$ where $s = \frac{\pi e^2}{m_e c} f_{jk}$ (Spitzer, Chpt 3)

f_{jk} = oscillator strength from lower level j to higher level k

Now as a function of λ:

$$Note: \quad \nu = \frac{c}{\lambda} \quad , \quad \frac{d\nu}{d\lambda} = -\frac{c}{\lambda^2}$$

$$N_\lambda d\lambda = N_\nu d\nu$$

$$N_\lambda = N_\nu \frac{d\nu}{d\lambda} = N_\nu \frac{c}{\lambda^2}$$

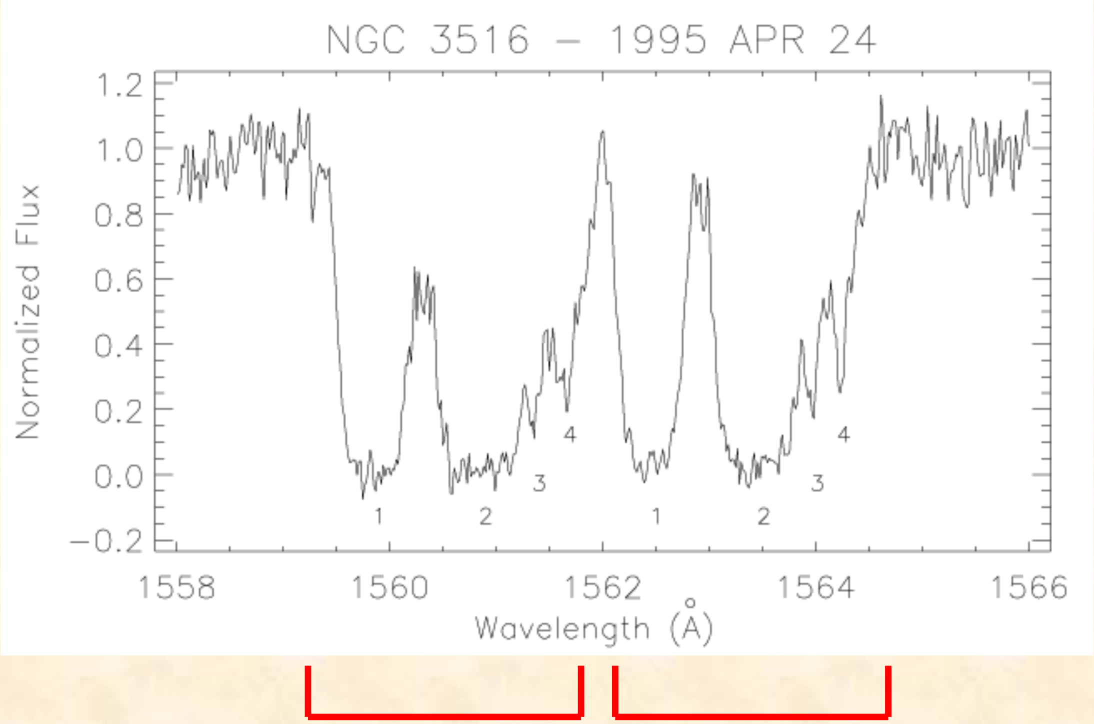
$$N_j = \int N_\lambda d\lambda = \frac{m_e c^2}{\pi e^2} \frac{1}{f_{jk} \lambda_{jk}^2} \int \tau_\lambda \, d\lambda$$

$$\boxed{N_j = 1.1298 \times 10^{20} \; \frac{1}{f_{jk} \lambda_{jk}^2} \int \tau_\lambda \, d\lambda \qquad (\lambda\text{: Å}, \quad \text{N: cm}^{-2})}$$

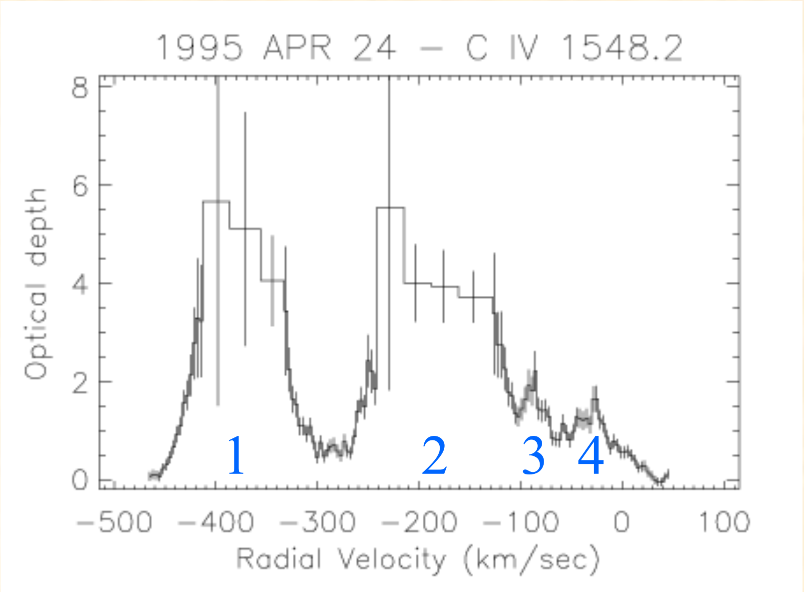
Thus, for a resolved line [FWHM (line) > FWHM (LSF)]:

Determine $\tau_\lambda = \ln\left(F_c / \mathrm{F}_\lambda\right)$ and integrate over λ to get N_j

- Note: for resolved line, don't need W_λ (EW), assumption of Gaussian distribution, or curve of growth!
- Ex) Intrinsic blueshifted C IV absorption in Seyfert galaxy NGC 3516 (Crenshaw et al. 1998, ApJ, 496, 797)



C IV λ1548.2 λ1550.8



-integrate $\tau(v_r)$ to get N(C IV) for each component (1 – 4)

Good general reference: Savage & Sembach, 1991, ApJ, 379, 245

II. Unresolved Lines: FWHM(Line) < FWHM(LSF)

$$W_\lambda = \int \left(1 - F_\lambda / F_c\right) d\lambda = \int \left(1 - e^{-\tau_\lambda}\right) d\lambda = \frac{\lambda_{jk}^2}{c} \int \left(1 - e^{-\tau_\nu}\right) d\nu$$

1) For unsaturated lines (small τ_ν):

$$W_\lambda = \frac{\lambda_{jk}^2}{c} \int \tau_\nu d\nu = \frac{\lambda_{jk}^2}{c} \frac{\pi e^2}{m_e c} f_{jk} N_j$$

(λ - Å, W_λ - Å, N - cm^{-2})

Thus: $\boxed{N_j = 1.1298 \times 10^{20} \dfrac{1}{f_{jk} \lambda_{jk}^2} W_\lambda}$

$$\frac{W_\lambda}{\lambda_{jk}} = \frac{\pi e^2}{m_e c} N_j \lambda_{jk} f_{jk} = 8.85 \times 10^{-13} N_j \lambda_{jk} f_{jk}$$

- This is the linear part of the curve of growth.

2) What is W_λ for unresolved, saturated lines? ($\tau > 1$)

- Assume a Maxwellian velocity distribution and Doppler broadening
- The redistribution of absorbed photons in frequency is:

$$\Phi_\nu = \lambda_{jk} P(\mathrm{v}_r) = \frac{\lambda_{jk}}{\sqrt{\pi} b} e^{-(\mathrm{v}_r/b)^2}$$

$$\frac{W_\lambda}{\lambda_{jk}} = \frac{\lambda_{jk}}{c} \int (1 - e^{-\tau_\nu})\, d\nu \quad \text{where: } \tau_\nu = s\, \Phi_\nu N_j$$

It can be shown that:

$$\boxed{\frac{W_\lambda}{\lambda_{jk}} = \frac{2bF(\tau_0)}{c}}, \quad \text{where } F(\tau_0) = \int_0^\infty [1 - \exp(-\tau_0 e^{-x^2})]dx$$

$$\text{where: } \tau_0 = \frac{N_j s \lambda_{jk}}{\sqrt{\pi} b} = \frac{1.497 \text{ x } 10^{-2}}{b} N_j \lambda_{jk} f_{jk}$$

(τ_0 is optical depth at line center, parameters in cgs units)

- So W_λ = fct (N,b) for a given line (λ,f)
- F(τ_0) is tabulated in Spitzer, Ch. 3, page 53
- For large τ_0: $F(\tau_0) = (\ln \tau_0)^{1/2}$
- This is the flat part of the curve of growth.

3) For very large τ_0, damping wings are important:

$$\boxed{\frac{W_\lambda}{\lambda_{jk}} = \frac{2}{c}(\lambda_{jk}^2 N s \delta_k)^{1/2}}$$

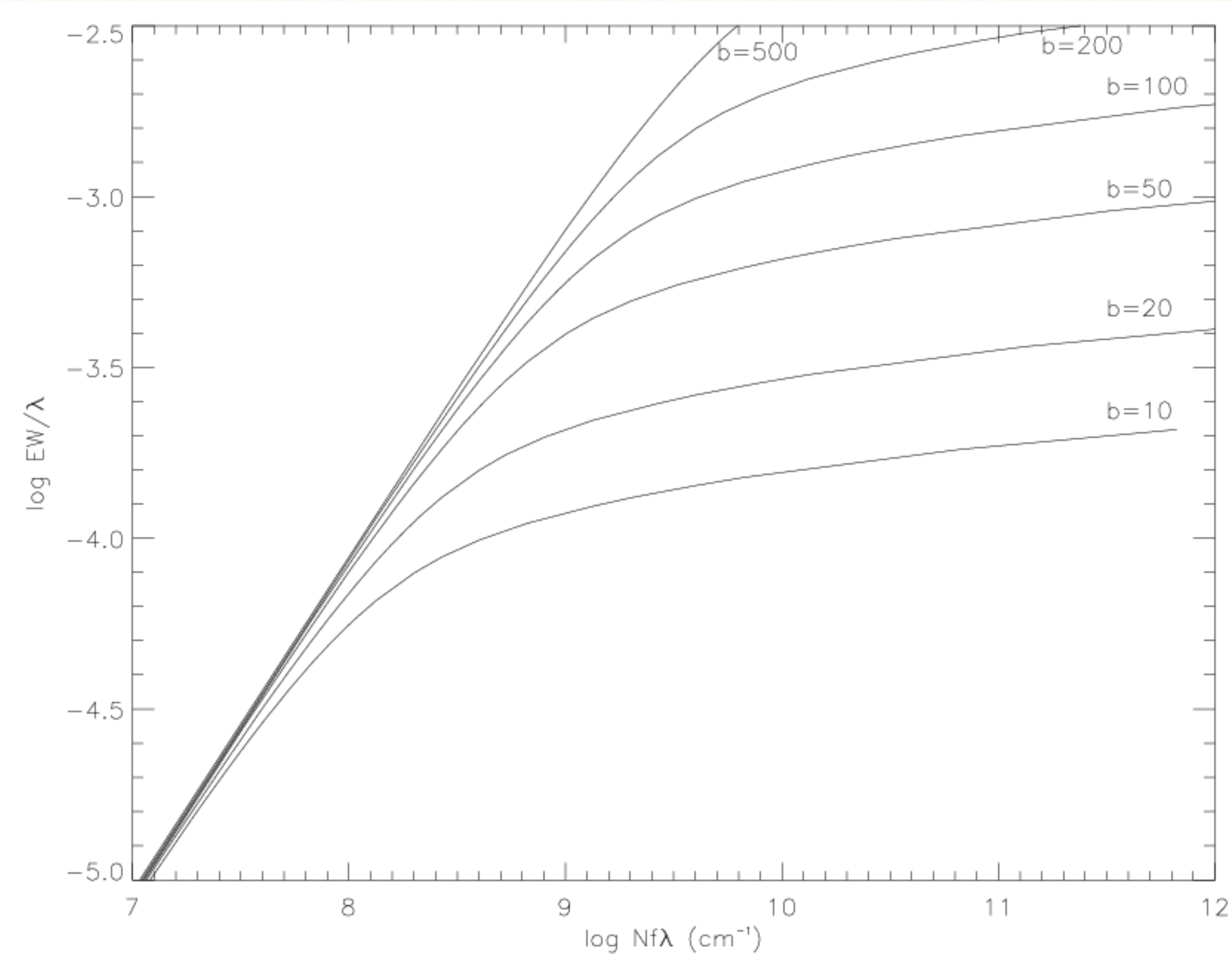
(Lorentzian profile)

$$where\ \delta_k = radiation\ damping\ constant$$

- This is the square root part of the COG, which is only important for very high columns (e.g., Lyα in the ISM).
- The most general COG (2 + 3) uses a Voigt intrinsic profile (Gaussian + Lorentzian)

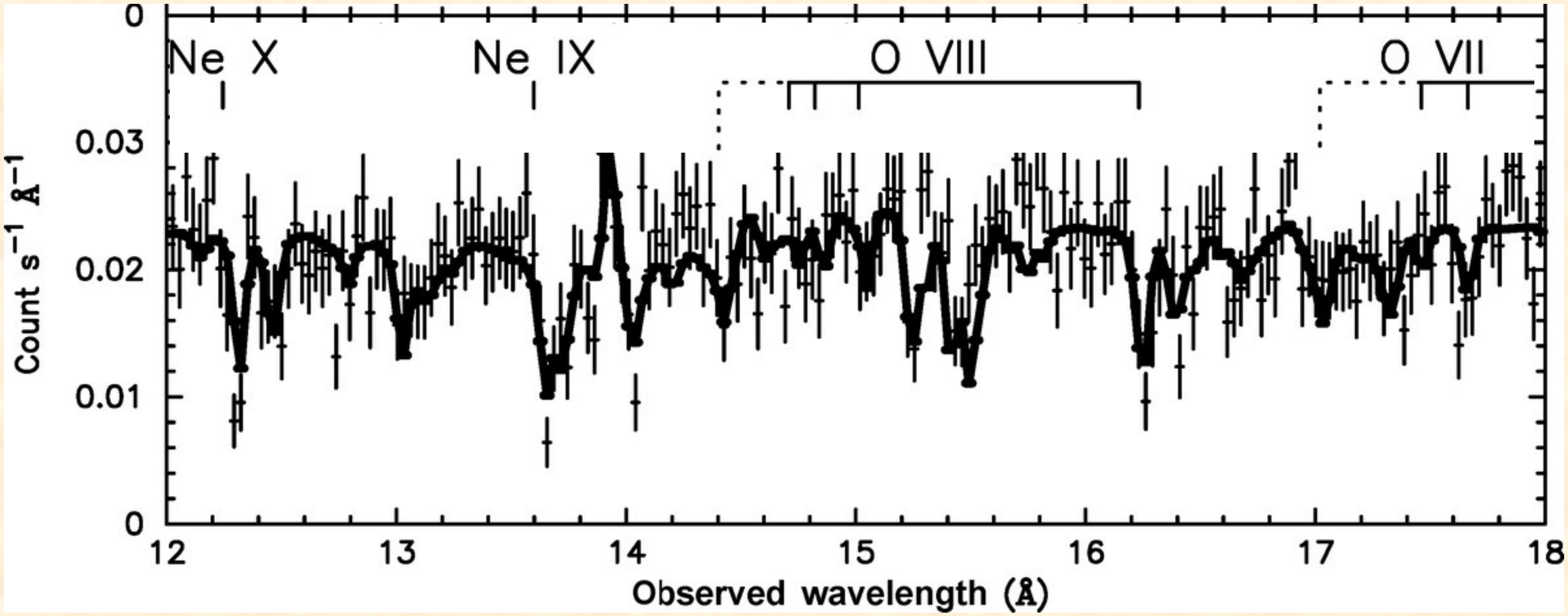
To generate curves of growth (Case 2):

- For a given b and Nλf, determine τ_0 ,F(τ_0), and then W_λ/λ
- Do this for different b values (km/sec) to get a family of curves:



Ex) O VII Absorption in Chandra Spectrum of NGC 5548

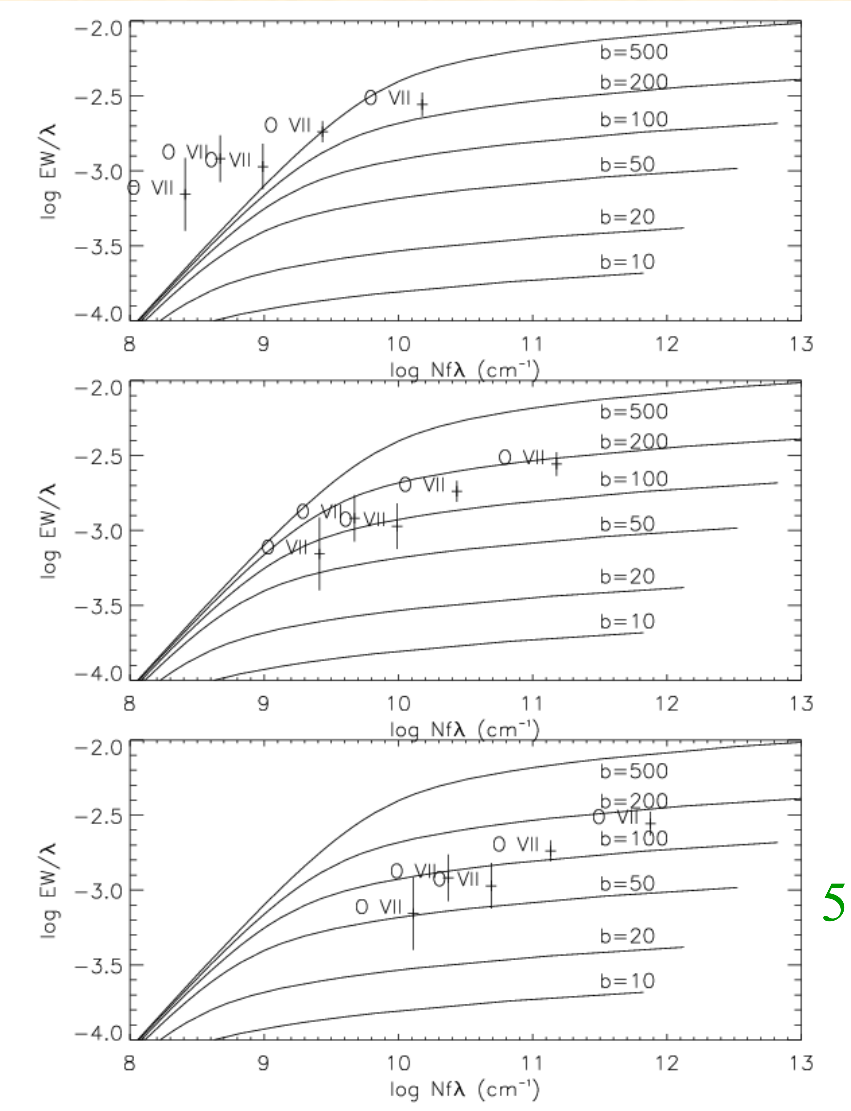
(Crenshaw, Kraemer, & George, 2003, ARAA, 41, 117)



- FWHM (LSF) ≈ 300 km/sec, observed FWHM only slightly larger
- Plot the standard curve of growth (COG) for different b values
- Assume N(O VII) and overplot log(EW/λ) vs. log(Nfλ)
- Try different N (O VII) until you get a match to a particular b.

Curves of Growth

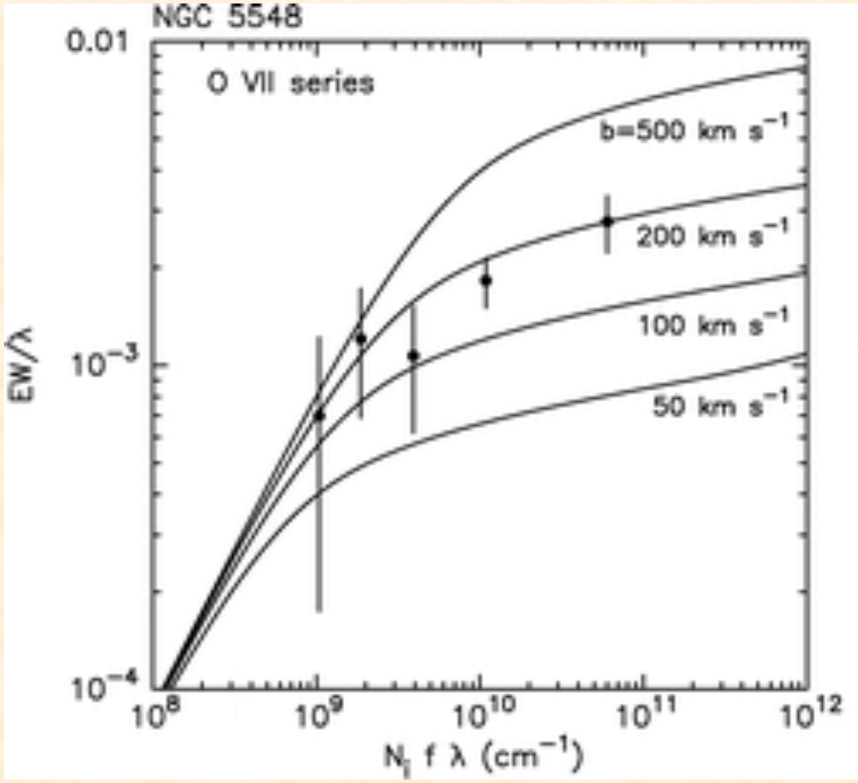
N (O VII)



10^{17}

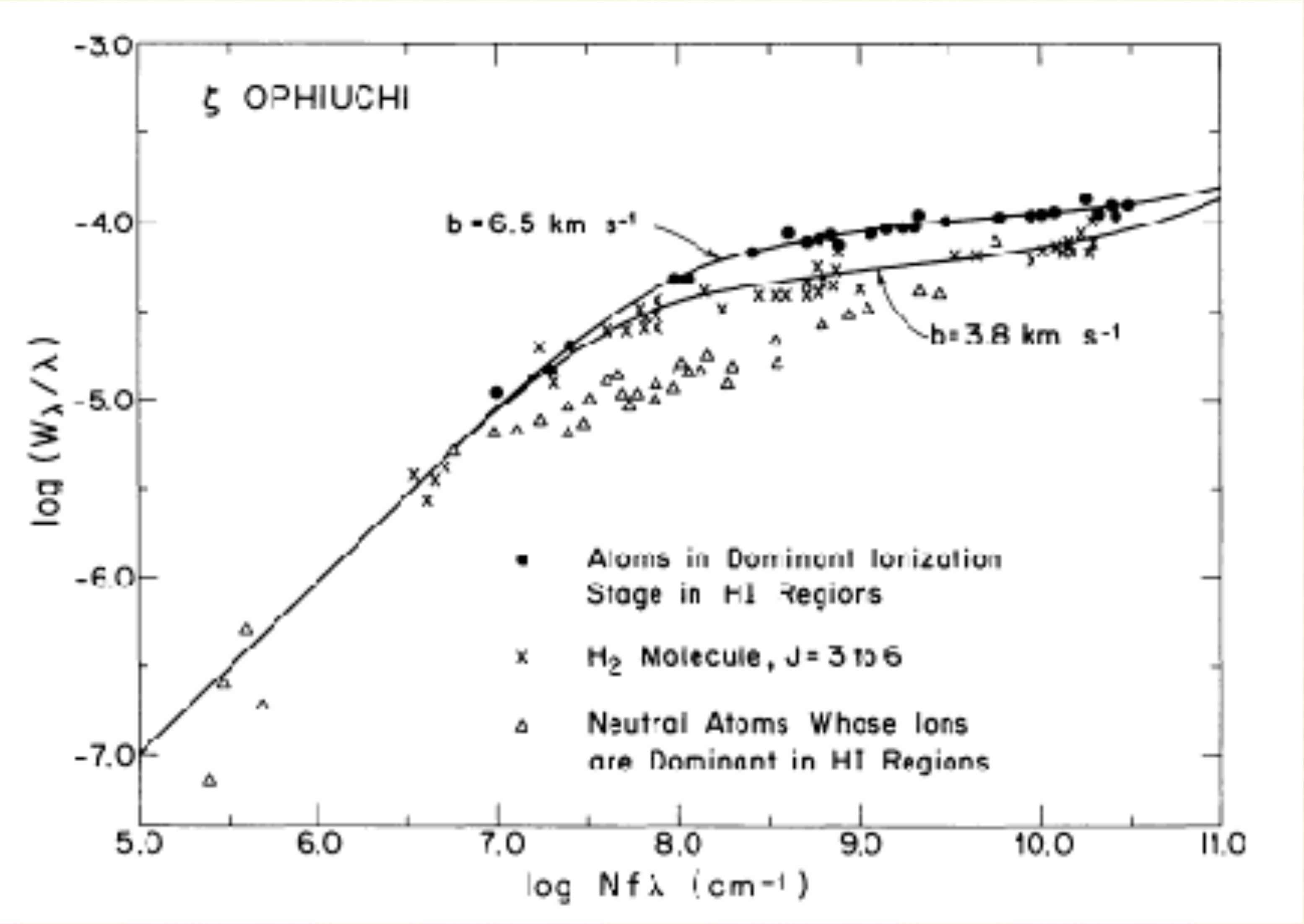
10^{18}

5×10^{18}



b = 200 (±50) km/sec, N(O VII) = 4 (±2) x 10^{17} cm^{-2}

Ex) Depletion in ISM clouds (see Spitzer, page 55)



- Lines from ions expected to appear in the same clouds are shifted horizontally until a "b" value is obtained → N(ion)

Application: Abundances

$$\text{Cosmic Abundance of element x: } A(x) = 12.0 + \log\left(\frac{N_X}{N_H}\right)_{\text{cosmic}}$$

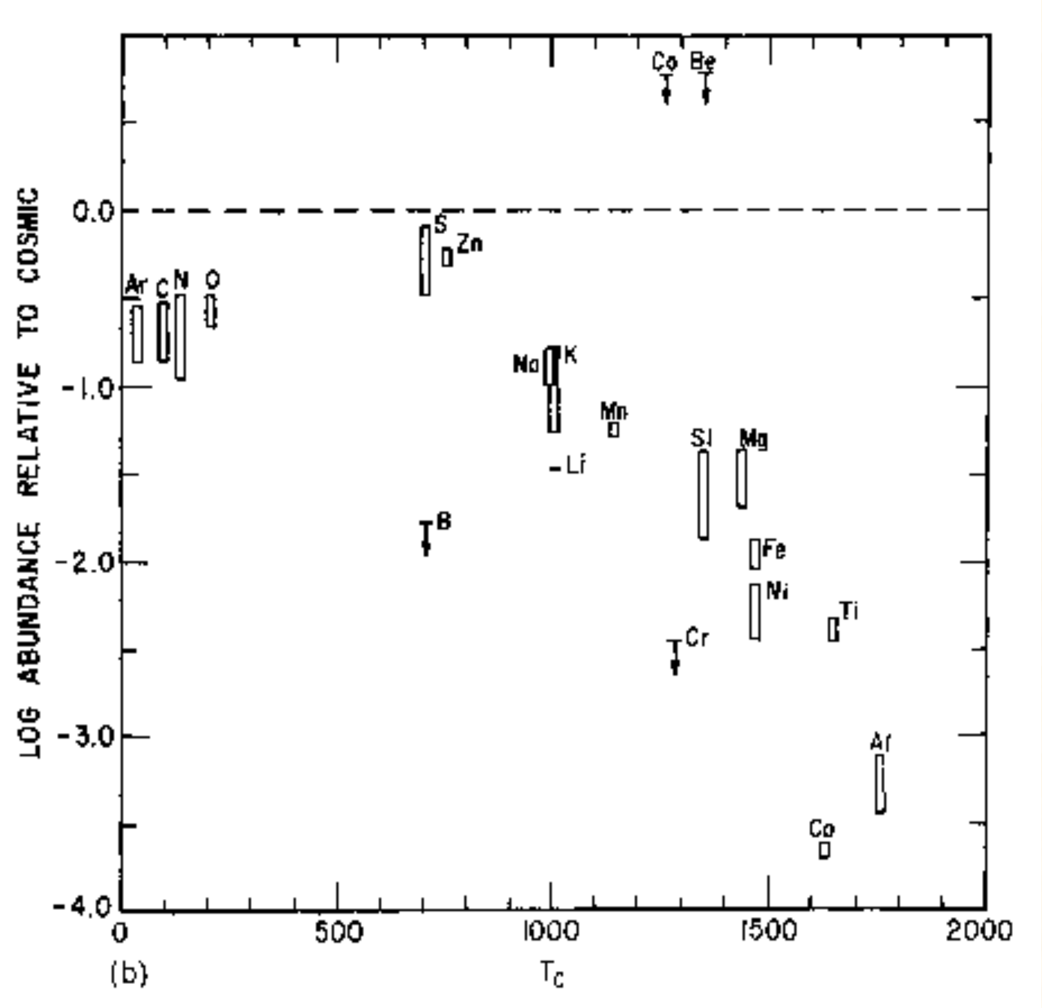
$$\text{Depletion of element x: } D(x) = \log\left(\frac{N_X}{N_H}\right)_{\text{cloud}} - \log\left(\frac{N_X}{N_H}\right)_{\text{cosmic}}$$

(Note: cosmic abundances usually means *solar* abundances)

Cosmic Abundances and Depletions Toward ζ Oph

(from Spitzer, page 4)

Element	He	Li	C	N	O	Ne	Na	Mg	Al	Si	P	S	Ca	Fe
A(x)	11.0	3.2	8.6	8.0	8.8	7.6	6.3	7.5	6.4	7.5	5.4	7.2	6.4	7.4
D(X)		-1.5	-0.7	-0.7	-0.6		-0.9	-1.5	-3.3	-1.6	-1.1	-0.3	-3.7	-2.0



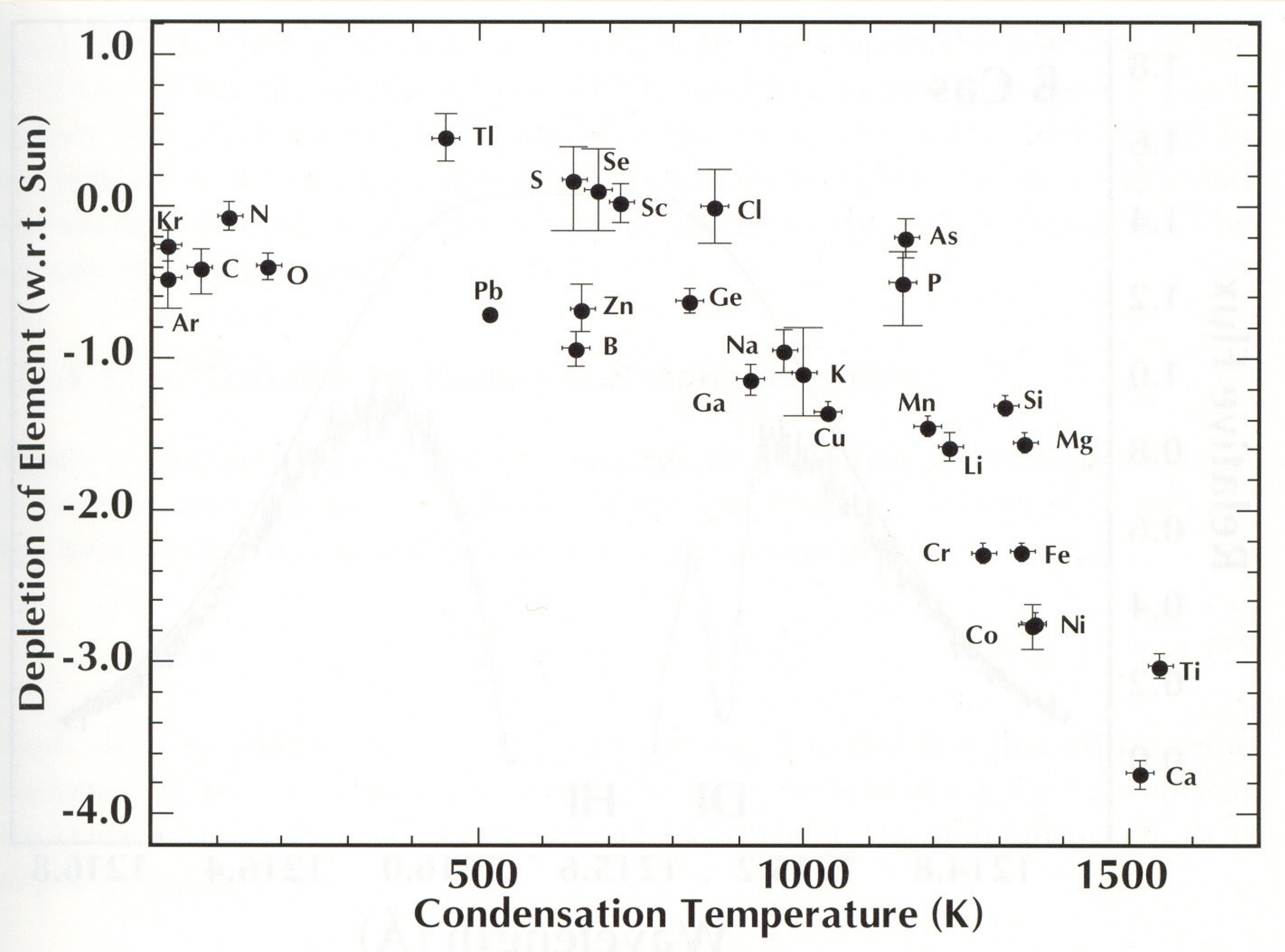
(Condensation Temperature - ° K)

-Depletions indicate condensation of elements out of gas phase onto dust grains

-The most refractory elements (highest condensation temperatures) are the most depleted (due to formation in cool star atmospheres)

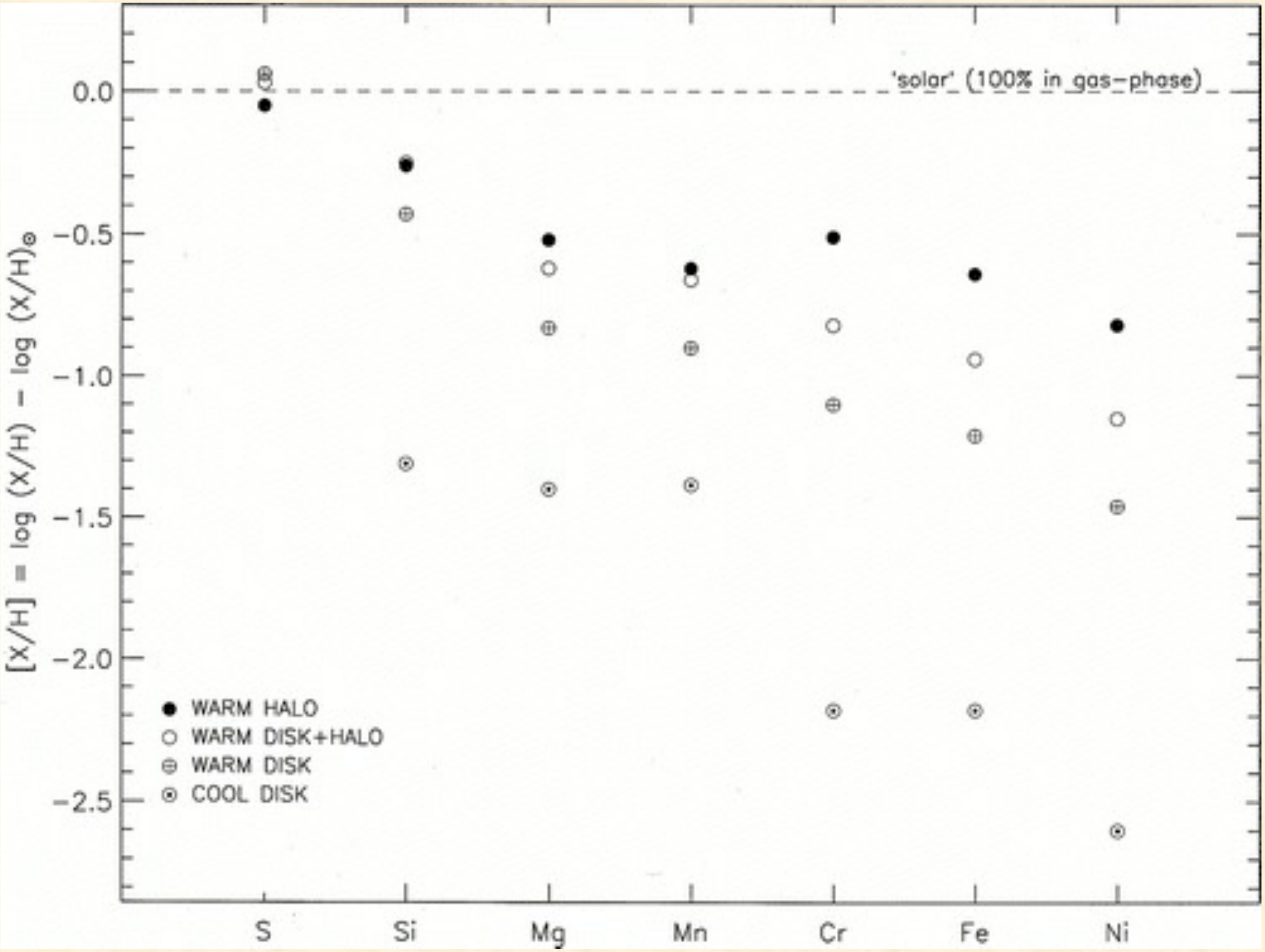
More Recent Depletions

(ζ Oph – Dopita, p. 65)



Gas-Phase Depletions

(Savage & Sembach, 1996, ARAA, 34, 279)



- Dust grains in halo clouds are destroyed by shock fronts from supernova remnants

The Multiphase *Diffuse* Interstellar Medium

(Dopita, Chapter 14)

- Observations by Copernicus and IUE indicate highly-ionized gas (C IV, N V, O VI) in the ISM.
- Two phase model (cold, warm) suggested by Field et al. (1969, ApJ, 155, L49) (in addition to molecular clouds).
- McKee & Ostriker (1977, ApJ, 218, 148) proposed a five-phase model, which is the currently accepted one.
- Each phase is in rough pressure equilibrium ($n_H T \approx 2000 - 6000$ cm^{-3} K)

1) The molecular medium (MM)
2) The cold neutral medium (CNM)
3) The warm neutral medium (WNM)
4) The warm ionized medium (WIM) (i.e., H is mostly ionized)
5) The hot ionized medium (HIM)

Phase	$n_H(cm^{-3})$	T (° K)	h (kpc)	Observations
MM	$\geq 10^3$	20	0.05	CO, HCN, H_2O emission, H_2 abs.
CNM	20	100	0.1	H I 21-cm emission H_2, C II, Si II, Mg II, etc. absorp.
WNM	1.0	6000	0.4	H I 21-cm emission C II, Si II, Mg II absorp. (no H_2)
WIM	0.3	10,000	1	Hα emission Al III, Si IV, C IV absorp.
HIM	10^{-3}	10^6	10	Soft X-ray emission, C IV, N V, O VI absorp.

- Scale height given by: $n_H = n_0 e^{-z/h}$, z = height above Galactic plane (Savage, 1995, ASP Conf. Series, 80, 233)
- Ionization increases with increasing z
- Depletion decreases with increasing z
- Hot phase driven by supernova remnants (shocks destroy dust grains)

What are these phases?

1) MM: self-gravitating molecular clouds <1% of the volume (but ~50% of ISM mass)

2) CNM: only 5% of the volume, sheets or filaments in the ISM

3) WNM: Photodissociation regions (PDRs), hot dust

4) WIM: ~25% of the volume together with WNM, ionized by O stars, SNRs (shocks and cosmic rays)

5) HIM: ~70% of the volume, driven into halo by SNRs

   - heated by shocks, cosmic rays
   - coalesce to form superbubbles, fountains, "chimneys"
   - hot (10^6 K) gas in Galactic halo (O VI absorption)

- McKee and Ostriker model: MM and CNM are dense clouds that are surrounded by WNM and WIM halos, embedded in the HIM
- O VI absorption in halo can also be from infalling gas from IGM (cosmic web) (Sembach et al. 2003, ApJS, 146, 155).