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TÜRK ASTRONOMİ DERNEĞİ
TURKISH ASTRONOMICAL SOCIETY

STELLAR ABUNDANCES

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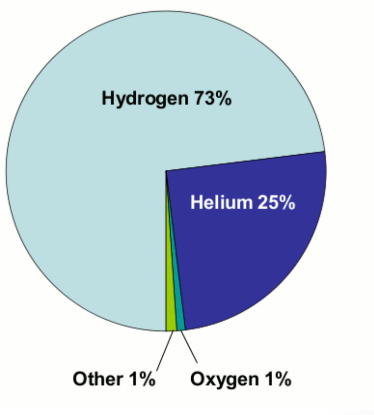
OUTLINE

1. Abundances
2. Characteristics of a star: stellar parameters
3. Spectral Line Formation and Profiles
4. From lines to abundances
5. Model atmospheres

1. ABUNDANCE SCALES



- Mass fractions
- X=H; Y=He, Z=all other elements (=metals) X+Y+Z = 1

  X_{sun}= 0.7381, Y_{sun}= 0.2485, Z_{sun}= 0.0134
- (Asplund et al. 2009)
- $[X/H] = \log (n_X/ n_H)_* - \log (n_X/ n_H)_{sun}$
- EX: [Fe/H] = –2 → star has 1/100 less iron than the Sun
- [Fe/H] = 0.5 → star has 3.16× more iron than the Sun

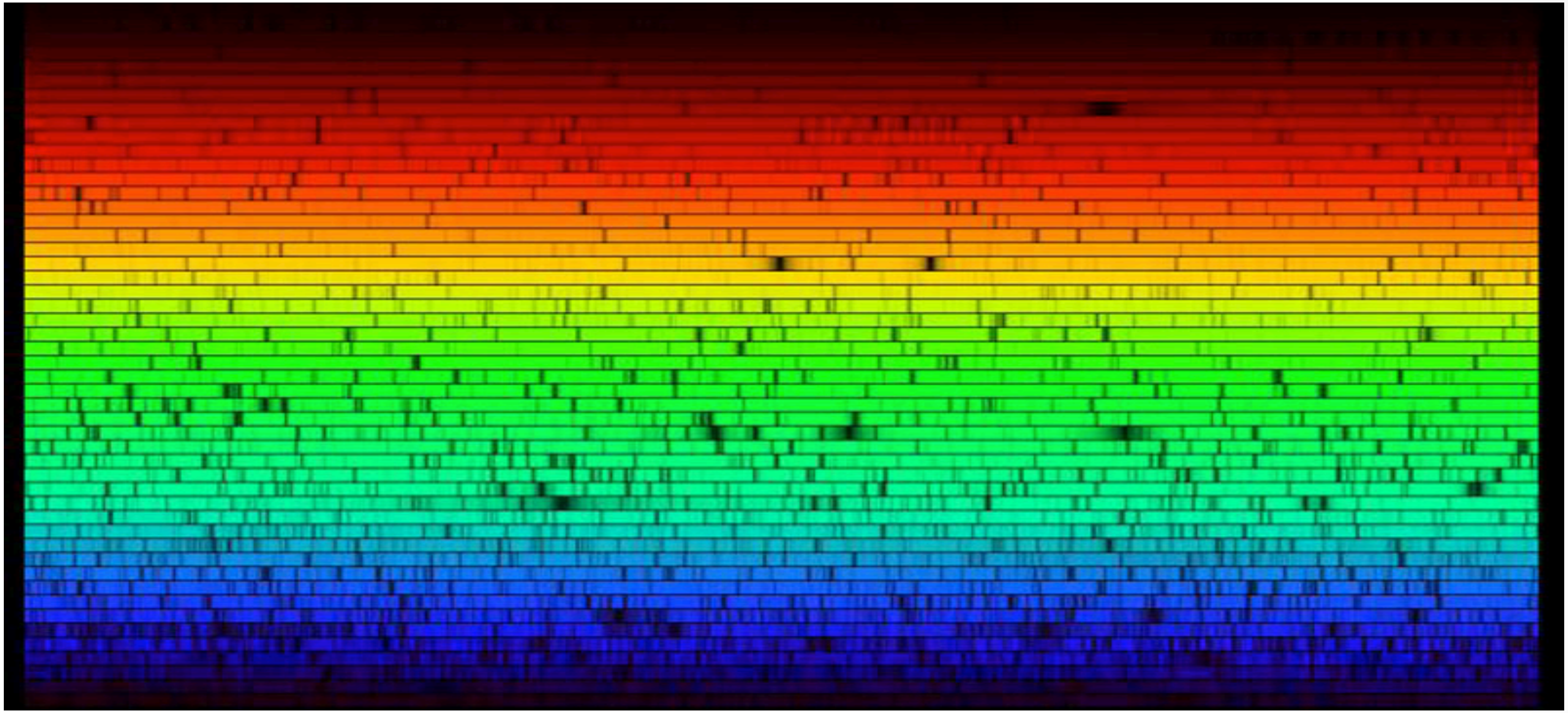
Z	Element	Photosphere	Meteorites	Z	Element	Photosphere	Meteorites
1	H	12.00	8.22 ± 0.04	44	Ru	1.75 ± 0.08	1.76 ± 0.03
2	He	[10.93 ± 0.01]	1.29	45	Rh	0.91 ± 0.10	1.06 ± 0.04
3	Li	1.05 ± 0.10	3.26 ± 0.05	46	Pd	1.57 ± 0.10	1.65 ± 0.02
4	Be	1.38 ± 0.09	1.30 ± 0.03	47	Ag	0.94 ± 0.10	1.20 ± 0.02
5	B	2.70 ± 0.20	2.79 ± 0.04	48	Cd		1.71 ± 0.03
6	C	8.43 ± 0.05	7.39 ± 0.04	49	In	0.80 ± 0.20	0.76 ± 0.03
7	N	7.83 ± 0.05	6.26 ± 0.06	50	Sn	2.04 ± 0.10	2.07 ± 0.06
8	O	8.69 ± 0.05	8.40 ± 0.04	51	Sb		1.01 ± 0.06
9	F	4.56 ± 0.30	4.42 ± 0.06	52	Te		2.18 ± 0.03
10	Ne	[7.93 ± 0.10]	−1.12	53	I		1.55 ± 0.08
11	Na	6.24 ± 0.04	6.27 ± 0.02	54	Xe	[2.24 ± 0.06]	−1.95
12	Mg	7.60 ± 0.04	7.53 ± 0.01	55	Cs		1.08 ± 0.02
13	Al	6.45 ± 0.03	6.43 ± 0.01	56	Ba	2.18 ± 0.09	2.18 ± 0.03
14	Si	7.51 ± 0.03	7.51 ± 0.01	57	La	1.10 ± 0.04	1.17 ± 0.02
15	P	5.41 ± 0.03	5.43 ± 0.04	58	Ce	1.58 ± 0.04	1.58 ± 0.02
16	S	7.12 ± 0.03	7.15 ± 0.02	59	Pr	0.72 ± 0.04	0.76 ± 0.03
17	Cl	5.50 ± 0.30	5.23 ± 0.06	60	Nd	1.42 ± 0.04	1.45 ± 0.02
18	Ar	[6.40 ± 0.13]	−0.50	62	Sm	0.96 ± 0.04	0.94 ± 0.02
19	K	5.03 ± 0.09	5.08 ± 0.02	63	Eu	0.52 ± 0.04	0.51 ± 0.02
20	Ca	6.34 ± 0.04	6.29 ± 0.02	64	Gd	1.07 ± 0.04	1.05 ± 0.02
21	Sc	3.15 ± 0.04	3.05 ± 0.02	65	Tb	0.30 ± 0.10	0.32 ± 0.03
22	Ti	4.95 ± 0.05	4.91 ± 0.03	66	Dy	1.10 ± 0.04	1.13 ± 0.02
23	V	3.93 ± 0.08	3.96 ± 0.02	67	Ho	0.48 ± 0.11	0.47 ± 0.03
24	Cr	5.64 ± 0.04	5.64 ± 0.01	68	Er	0.92 ± 0.05	0.92 ± 0.02
25	Mn	5.43 ± 0.04	5.48 ± 0.01	69	Tm	0.10 ± 0.04	0.12 ± 0.03
26	Fe	7.50 ± 0.04	7.45 ± 0.01	70	Yb	0.84 ± 0.11	0.92 ± 0.02
27	Co	4.99 ± 0.07	4.87 ± 0.01	71	Lu	0.10 ± 0.09	0.09 ± 0.02
28	Ni	6.22 ± 0.04	6.20 ± 0.01	72	Hf	0.85 ± 0.04	0.71 ± 0.02
29	Cu	4.19 ± 0.04	4.25 ± 0.04	73	Ta		−0.12 ± 0.04
30	Zn	4.56 ± 0.05	4.63 ± 0.04	74	W	0.85 ± 0.12	0.65 ± 0.04
31	Ga	3.04 ± 0.09	3.08 ± 0.02	75	Re		0.26 ± 0.04
32	Ge	3.65 ± 0.10	3.58 ± 0.04	76	Os	1.40 ± 0.08	1.35 ± 0.03
33	As		2.30 ± 0.04	77	Ir	1.38 ± 0.07	1.32 ± 0.02
34	Se		3.34 ± 0.03	78	Pt		1.62 ± 0.03
35	Br		2.54 ± 0.06	79	Au	0.92 ± 0.10	0.80 ± 0.04
36	Kr	[3.25 ± 0.06]	−2.27	80	Hg		1.17 ± 0.08
37	Rb	2.52 ± 0.10	2.36 ± 0.03	81	Tl	0.90 ± 0.20	0.77 ± 0.03
38	Sr	2.87 ± 0.07	2.88 ± 0.03	82	Pb	1.75 ± 0.10	2.04 ± 0.03
39	Y	2.21 ± 0.05	2.17 ± 0.04	83	Bi		0.65 ± 0.04
40	Zr	2.58 ± 0.04	2.53 ± 0.04	90	Th	0.02 ± 0.10	0.06 ± 0.03
41	Nb	1.46 ± 0.04	1.41 ± 0.04	92	U		−0.54 ± 0.03
42	Mo	1.88 ± 0.08	1.94 ± 0.04				

SOLAR ABUNDANCES

- Present-day solar photosphere elemental abundances

- Lodders et al. 2009
- Asplund et al 2009

HOW TO EXTRACT ELEMENTAL ABUNDANCES FROM THESE LINES?



OBTAINING INFORMATION FROM SPECTRA

- Chemical analysis usually proceeds using a curve-of-growth technique.
- alternative is to synthesize the whole region.

TO GET AN ABUNDANCE

- Start with :
  - Star ID (spectral type or photometric classification)
  - Atmospheric properties → line formation
    - Effective temperature + Surface gravity + "Metallicity"
- Then follow:
  1. Interpolate published model atmosphere grids (or make own)
  2. Compute theoretical (synthetic) spectrum for assumed abundances
  3. Compare with observations and iterate on abundances

2.STELLAR PARAMETERS

- **Effective temperature T_{eff}:** T of a blackbody with same L and same R as the real star: $L = 4\pi R^2 \sigma T_{eff}^{\ 4}$
- **Surface gravity:** $g = GM / R^2$ (usually expressed in cgs units and as log$g$)
- **Metallicity Z** or iron content [Fe/H], and [alpha/Fe]:

$$Z = \frac{mass\ of\ elements\ heavier\ than\ He}{total\ mass\ in\ a\ unit\ volume} \approx 0.018 \text{ for the Sun}$$

$$\left[\frac{Fe}{H}\right] = \log\left(\frac{N(Fe)}{N(H)}\right)_* - \log\left(\frac{N(Fe)}{N(H)}\right)_{sun}$$

$$\left[\frac{\alpha}{H}\right] = \log\left(\frac{N(\alpha)}{N(H)}\right)_* - \log\left(\frac{N(\alpha)}{N(H)}\right)_{sun}$$, where α is an α -element

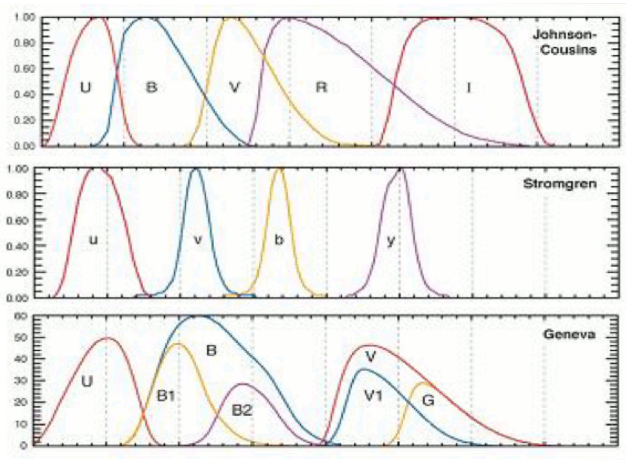
2.1.HOW TO DETERMINE T_{EFF}?

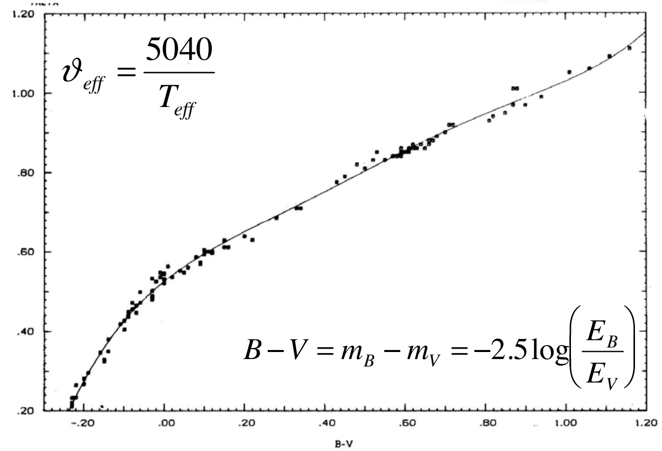
- Multicolour photometry calibrated

with stars having fundamentally determined T_{eff}
  - Johnson's UBV
  - Stromgren's uvby
  - Geneva UBV B1 B2 V1 G
- Low resolution spectroscopy:

ratios of suitable strong lines → T_{eff}

or spectral type + calibration T_{eff} vs spectral type

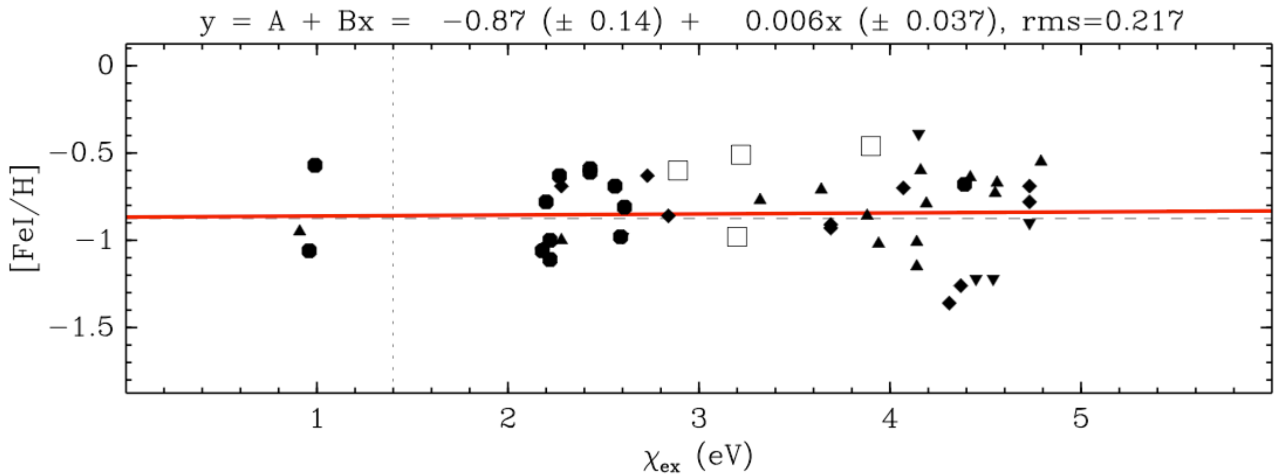




Source: Bessell 2005

2.1.HOW TO DETERMINE T_{EFF}?

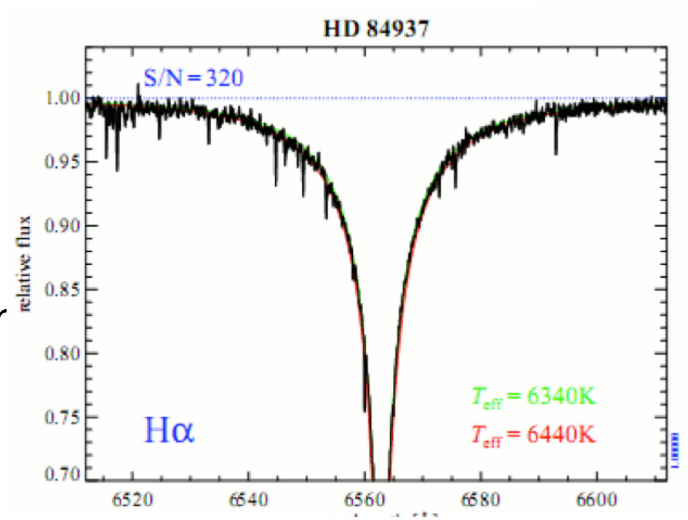
- Spectroscopic T_{eff} indicators: excitation equilibrium
- T_{eff} is determined such that the abundance of an element (usually Fe) is independent of the excitation potential (χ_{exc}) of the individual lines
- One needs many lines of a single element sampling a range of χ_{exc} iron Final precision depends on spectral resolution, choice and number of lines and S/N ratios



Source: Letarte, PhD

- Spectroscopic T_{eff} indicators: H lines
- Wings of Balmer lines (above 5000K)
- Cool stars: OK
  Log *g* and metallicity sensitivity is low,
- some dependence on the mixing-length parameter
- Main challenge: recovering the intrinsic line profiles

from (echelle) observations and proper normalization

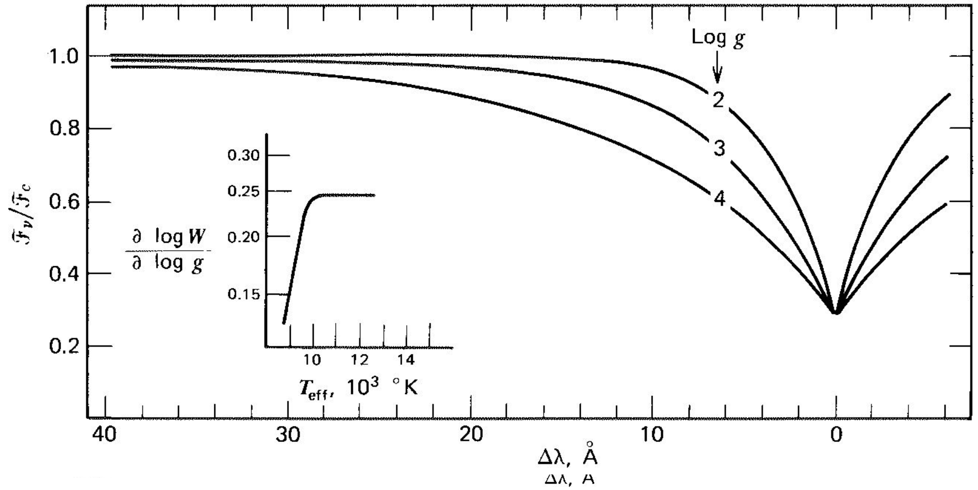


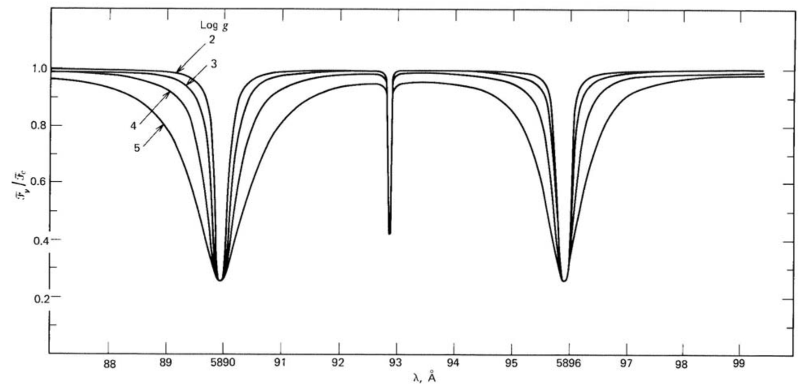
- Hot stars: Balmer lines can constrain the surface gravity

2.2. HOW TO DETERMINE LOGG?

- **Spectroscopy:**
  - Ratio of Fe II to Fe I lines
  - B-type stars: profile of H Balmer lines
  - Later type stars: profile of strong metallic lines

  (e.g. Na I D doublet, Ca II infrared triplet)
- **Calibrated photometry**
- **Parallaxes** $\Rightarrow$ L, R, (M) $\rightarrow$ g





2.2. HOW TO DETERMINE LOGG?

- **Spectroscopic log *g*: ionization balance**
- Measure of elements in two ionization states (e.g., FeI & Fe II):

both should yield same abundance, A.

- Gravity is a free parameter,

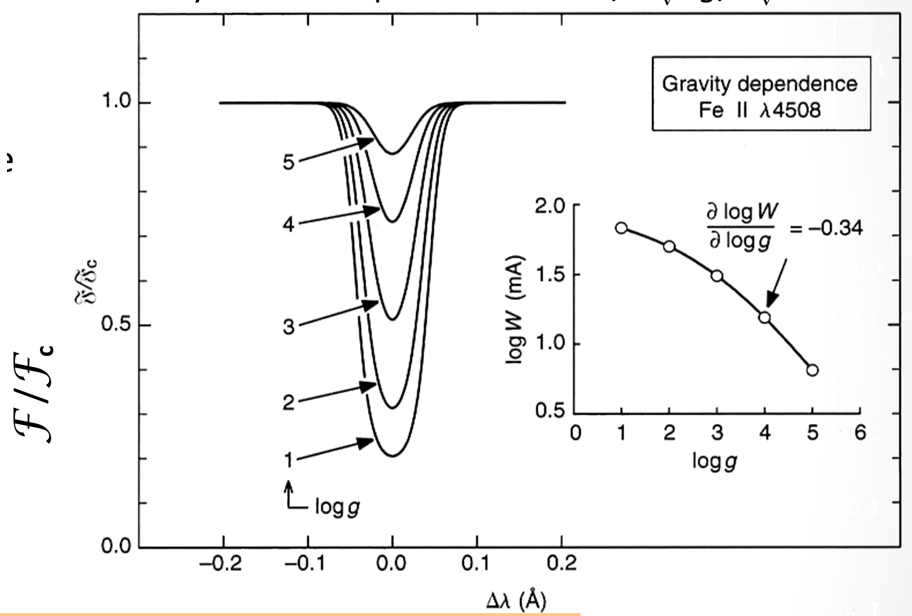
to be varied until equality is reached.

- By definition, gravity is related to

$$P_g \propto g^{2/3} \text{ and } P_e \propto g^{1/3}$$

- In cool stars :
  - Fe I, the dominant species,
  will depend on 1/Pe
  - Fe II, the minority species,
  - with majority of atoms in state i – 1 = 1,
  will depend on 1/Pe

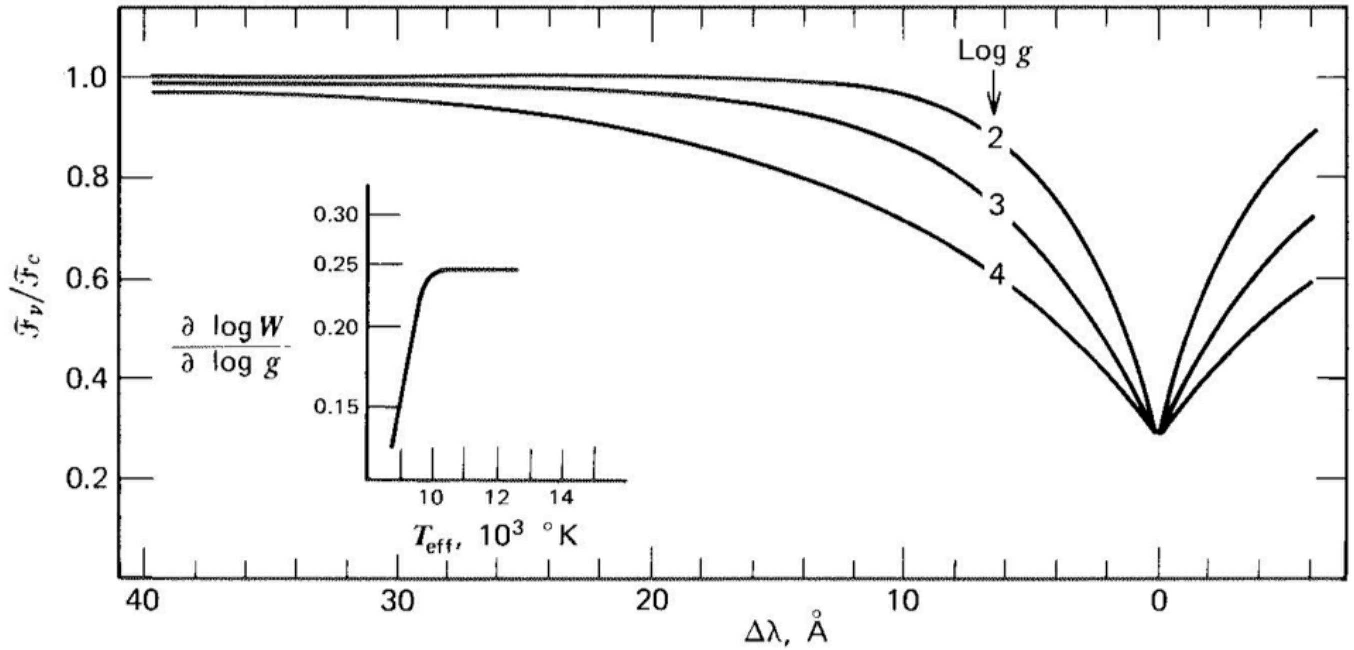
Hydrostatic equilibrium $dP/d\tau_\nu = g/\kappa_\nu$



$\Delta\log\varepsilon = 0.1\text{dex} \rightarrow \Delta\log g = 0.3\text{dex}$ (0.1dex ≈ line-to-line scatter)

2.2. HOW TO DETERMINE LOGG?

- **Spectroscopic log *g*:** **Balmer Lines**
  Hγ: pressure indicator for $T_{eff} > 7500K$



2.2. HOW TO DETERMINE LOGG?

- **Spectroscopic log *g*: the strong line method**

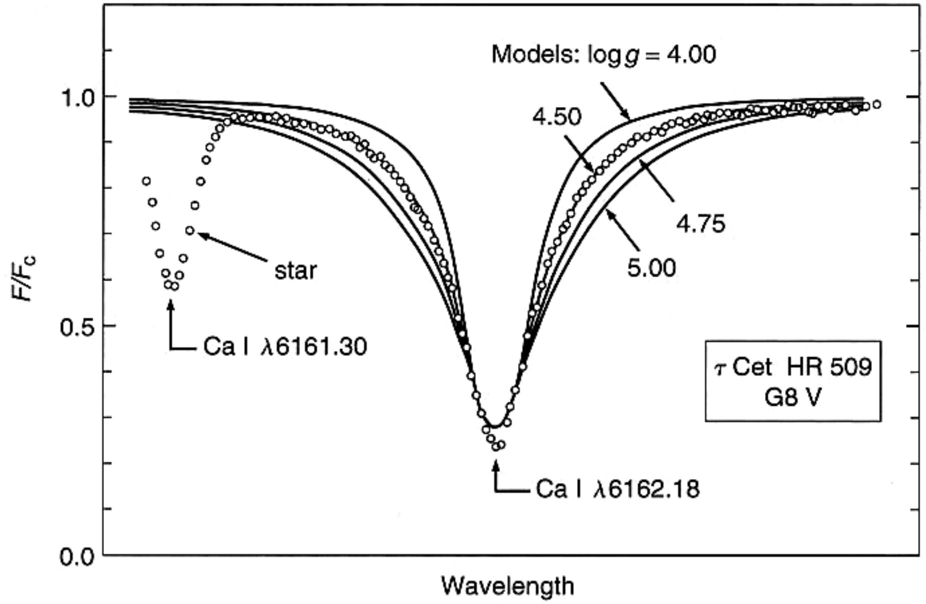
Damped (neutral) lines show a strong gravity sensitivity, because $L_\nu \; \alpha \; \gamma_6 \; \alpha \; P_g / \, g^{2/3}$

- Like with ionization equilibria,

log ε needs to be known

- best if obtained from weak lines

of the same ionization stage, preferably originating from the same lower state: CaI 6162, FeI 4383, MgI 5183, CaI 4226

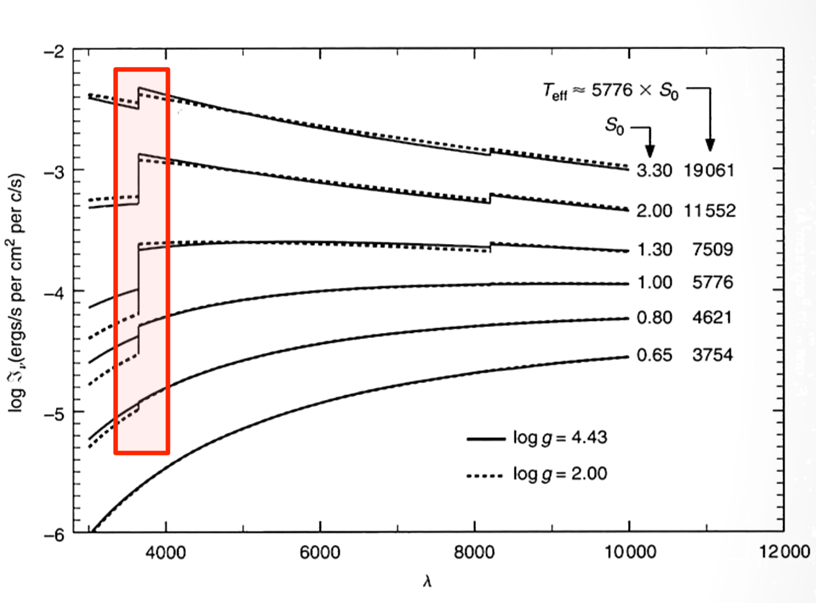


Below [Fe/H] ≈ −2, there are no optical lines strong enough to serve as a surface-gravity indicator

Source: Gray, Fig. 15.4

2.2. HOW TO DETERMINE LOGG?

- **Photometric log *g***
  Largest gravity sensitivity: Balmer jump at 3647Å
- Colour indices like (*U* –*B*) or (*u* –*y*) measure the Balmer discontinuity
- Disadvantages:
  high line density in spectral region (missing opacity problem)
- difficulties with ground-based observations in th near-UV
- The c1 index [(*u* –*b*)–(*b* –*y*)] works well for metal-poor giants (Önehag *et al*. 2008)



2.3. HOW TO DETERMINE (A FIRST GUESS OF) [FE/H]?

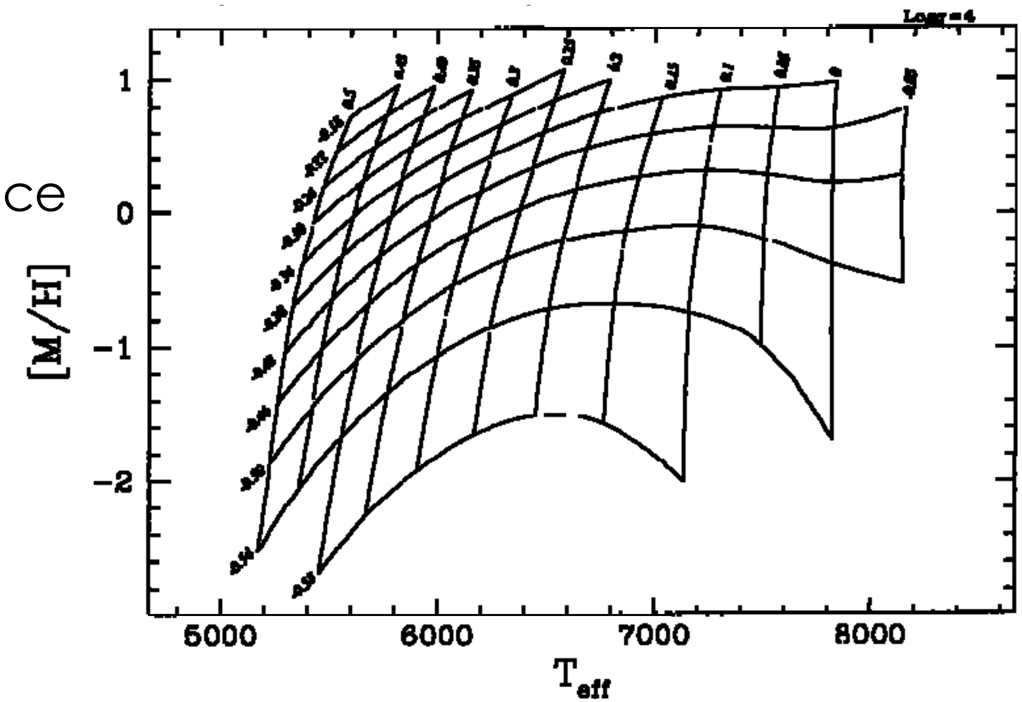
- **Calibrated photometry**
- After T_{eff} (and maybe reddening)

the *global* metallicity has largest influence on stellar flux

- Difficult for stars with [Fe/H] < –2

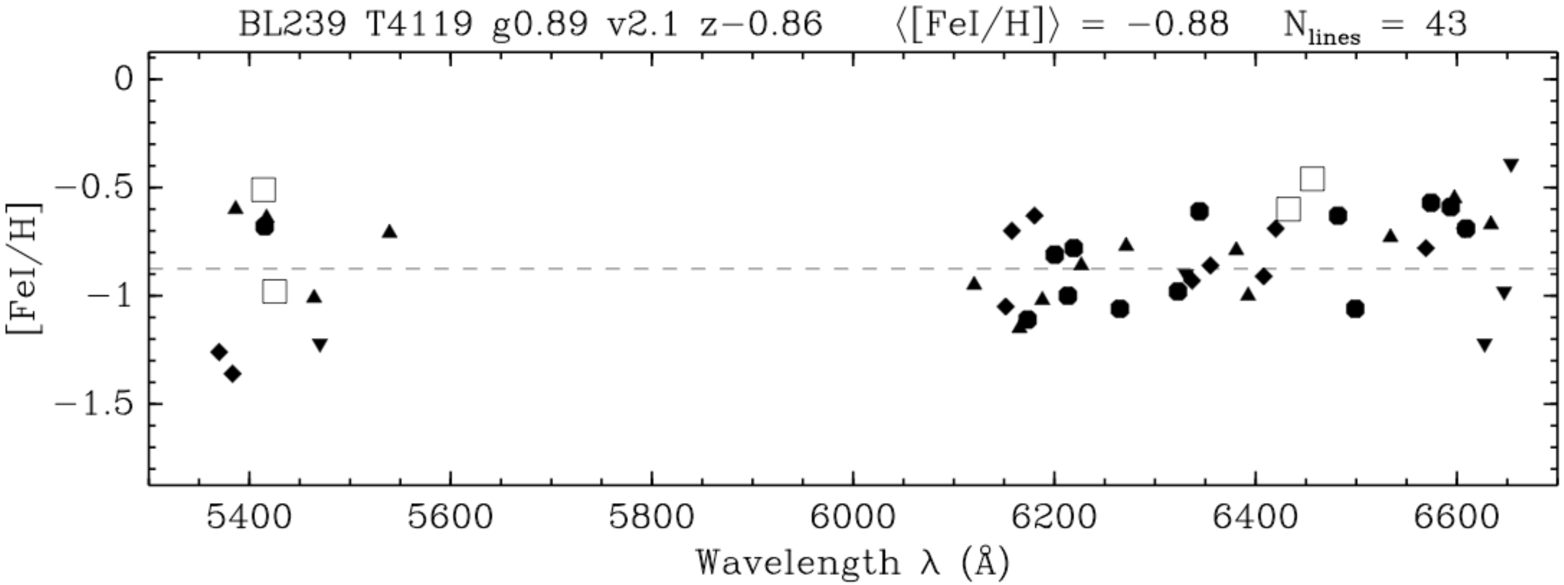
(e.g. $\delta(U-B)$ loose sensitivity)

- Limited precision: ≈0.3 dex



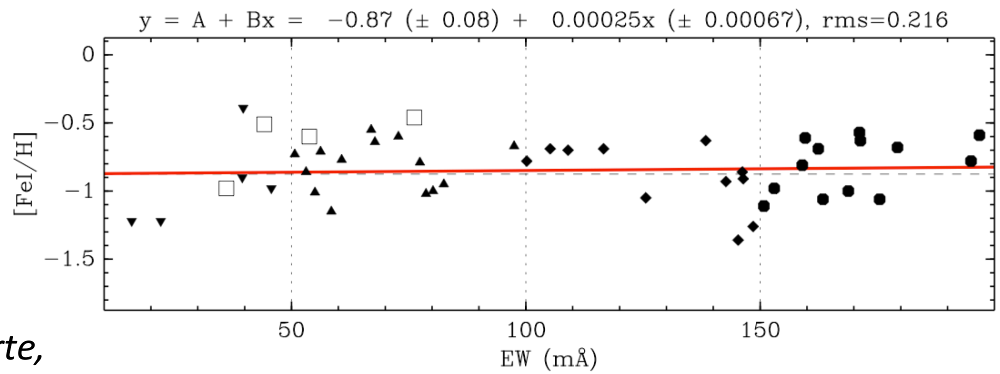
2.3. HOW TO DETERMINE (A FIRST GUESS OF) [FE/H]?

- **Spectroscopy:**
- e.g. equivalent width of some strong lines



2.4.HOW TO DETERMINE THE MICROTURBULENCE VELOCITY?

- Observed EW of saturated lines > predicted values using thermal and natural broadening alone → extra broadening introduced, the micro-turbulent velocity ξ (fudge factor)
- Caused by small cells of motion in the photosphere (treated like an additional thermal velocity in the line absorption coefficient)
- No effect on weak lines: these are gaussian, broadening them also makes them shallower → EW is preserved
- Can be important in strong lines, by broadening and hence de-saturating them.
- It is usually determined by ensuring that for individual elements EW is independen of line. Typical values are 1-2 km/s.



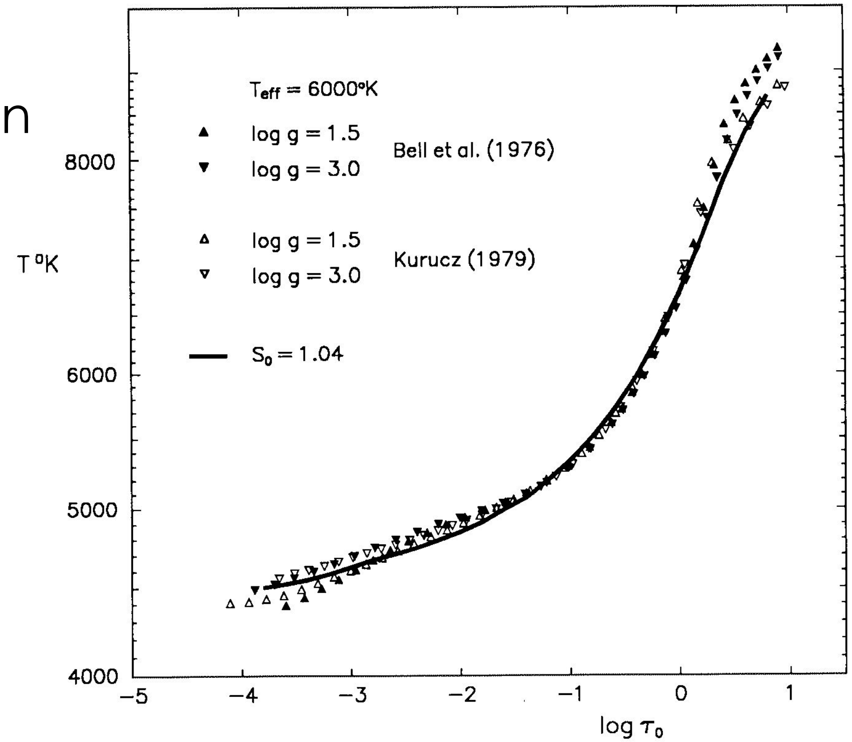
Source: Letarte,

3. SPECTRAL LINE FORMATION & PROFILE

- 3.1. Why are « photospheric » lines in absorption?
- The formation of absorption lines can be understood by studying how the source function S_ν changes with depth.

$W_\lambda \propto d(\ln S_\nu)/d\tau_\nu$

I. atmospheric structure



3.1.SPECTRAL LINE FORMATION

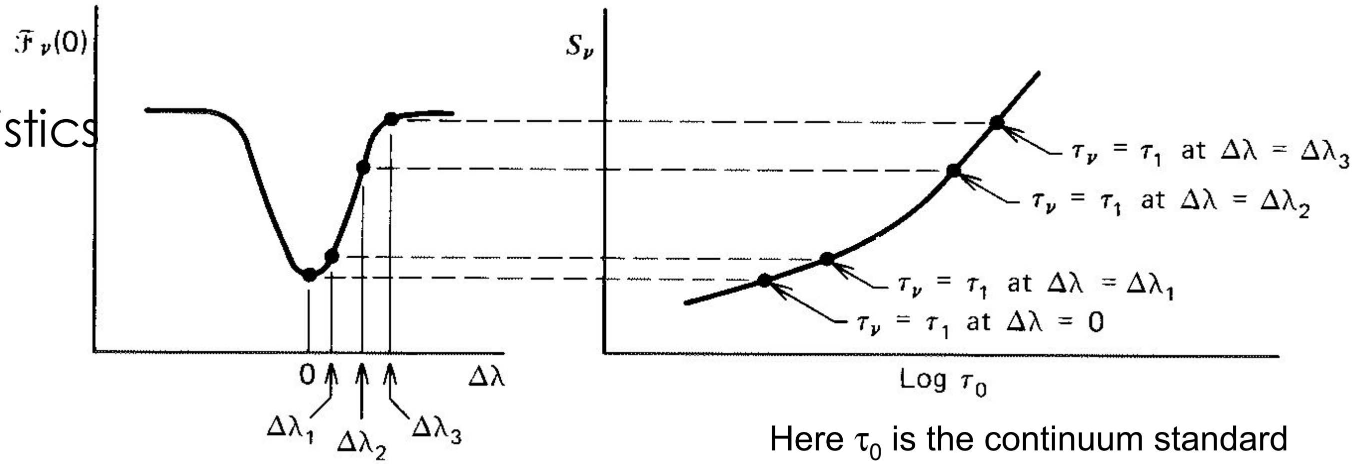
II. Absorption lines : Negative T gradient → source function ↘ outwards ⇒photospheric lines in absorption (similar argument than for limb darkening)

S_ν^l = line source function:

It reduces to the Planck

function for Boltzman's statistics

$$S_\nu^l = \frac{j_\nu}{\kappa_\nu} = \frac{2h\nu^3}{c^2}\frac{1}{\frac{g_2N_1}{g_1N_2}-1}$$



Here τ_0 is the continuum standard optical depth linked with geometric depth (e.g. τ_{5000})

- *Source: Gray*

3.1.SPECTRAL LINE FORMATION

III. Transfer equation: solution provides detailed line profile

$$\frac{dI_\nu}{d\tau_\nu} = -I_\nu + S_\nu$$

Where $S_\nu = \dfrac{j_\nu^l + j_\nu^c}{\kappa_\nu^l + \kappa_\nu^c}$ is the source function,

and $d\tau_\nu = \left(\kappa_\nu^l + \kappa_\nu^c\right)\rho dx$ is the infinitesimal optical depth.

- I_ν: specific intensity (erg s^{-1} cm^{-2} sterad^{-1} Hz^{-1})
- j_ν: emissivity (erg s^{-1} g^{-1} sterad^{-1} Hz^{-1})
- K_ν: absorption coefficient (cm^2 g^{-1})

3.2.IONIZATION STATE & ENERGY LEVEL

- What we want:

1. Enough atoms in the right ionization state(LTE assumption)

- Saha's equation

$$\frac{N_{i+1}N_e}{N_i} = 2\frac{U_{i+1}}{U_i}\left(\frac{2\pi m_e kT}{h^2}\right)^{3/2} e^{-I_i/kT}$$

$$U_i = \sum_n g_{i,n} \exp\left(-\chi_{i,n}/kT\right)$$

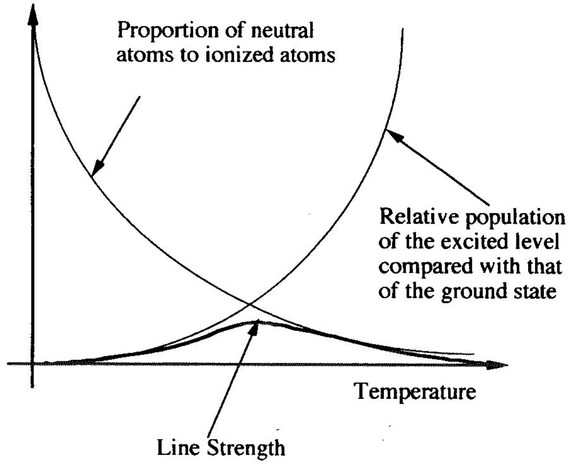
$$\chi_n = E_n - E_1$$

2. Enough atoms or ions excited in the right energy level (LTE assumption)

- Boltzmann's statistics

$$\frac{N_2}{N_1} = \frac{g_2}{g_1} e^{-(E_2-E_1)/kT}$$

- Combination of both →



3.3. LINE WIDTH: BROADENINGS

- **Natural width:** (Lorentzian profile, very narrow) ΔE Δτ=h/2π
  - γ: damping constant
  - f: oscillator strength
  - ν_0: line center
  - N: number density of absorbing atoms/ions
  - Typical FWHM: Δλ≈ 5 x10^{-4} Å

$$\kappa_\nu \rho = N \frac{\pi e^2}{m_e c} f \frac{\gamma / 4\pi^2}{(\nu - \nu_0)^2 + (\gamma / 4\pi)^2}$$

- **Thermal (or Doppler) width:** gaussian profile → center
  - thermal motions of the atoms, randomly distributed shifts
  - Mean abs. coefficient per atom: $\alpha_\nu d\nu = \frac{\sqrt{\pi} e^2}{mc} f \frac{1}{\Delta\nu_D} \exp\left[-\left(\frac{\Delta\nu}{\Delta\nu_D}\right)^2\right] d\nu$

$$\Delta\nu = \nu - \nu_0 \quad \Delta\nu_D = \frac{\upsilon_0}{c}\nu_0 = \frac{\nu_0}{c}\left(\frac{2kT}{m}\right)^{\frac{1}{2}}$$

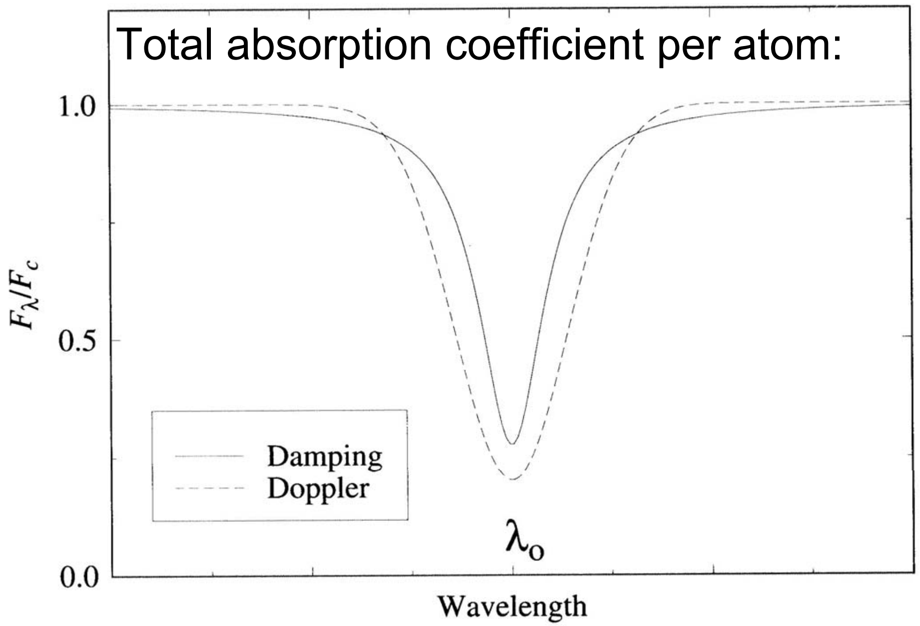
  - In practice, one has to introduce a microturbulent velocity: $\Delta\nu_D = \frac{\nu_0}{c}\left(\frac{2kT}{m} + \upsilon_{turb}{}^2\right)^{\frac{1}{2}}$
  - Typical FWHM: Δλ≈ 0.4 Å

3.3. LINE WIDTH: BROADENINGS

- **Pressure (collisional) width: (van der Waals)** (Lorentzian profile) collisions between particles (energy levels change) → wings , damping profile, γ_6 (cool stars)
- **Zeeman:** In strong magnetic fields atoms can align in quantum ways causing slight separations in the energies of atoms in the same excitation levels. This "splits" the lines into multiple components. The stronger the field, the greater the spliting.
- **Hyperfine:** Interaction between the nuclear magnetic dipole with the magnetic field of the electron can perturb the energy levels of an atom
- Energy level dependent: different for each line
- **Stark:** Perturbation by electric fields: damping profile γ_4 (hot stars, esp. H lines)

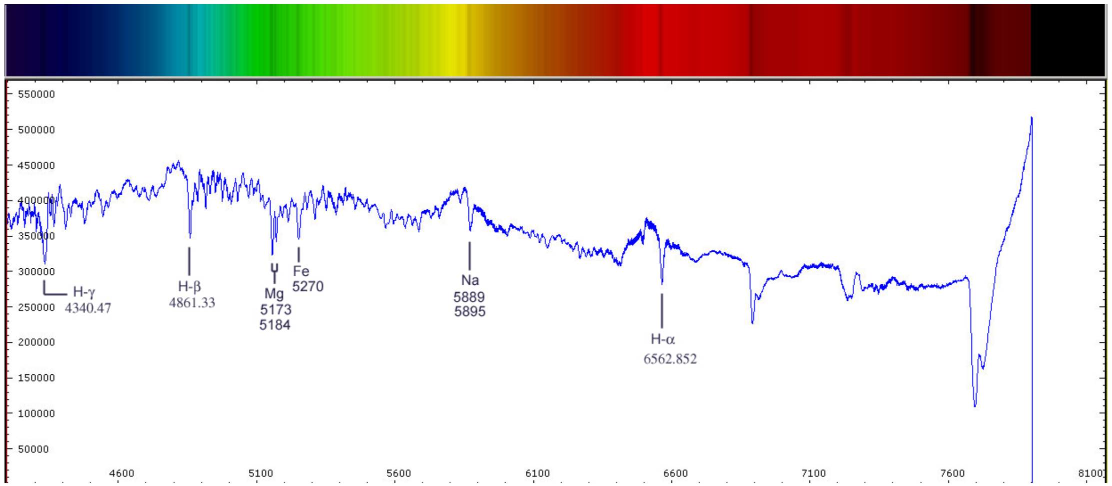
3.3. LINE WIDTH: BROADENINGS

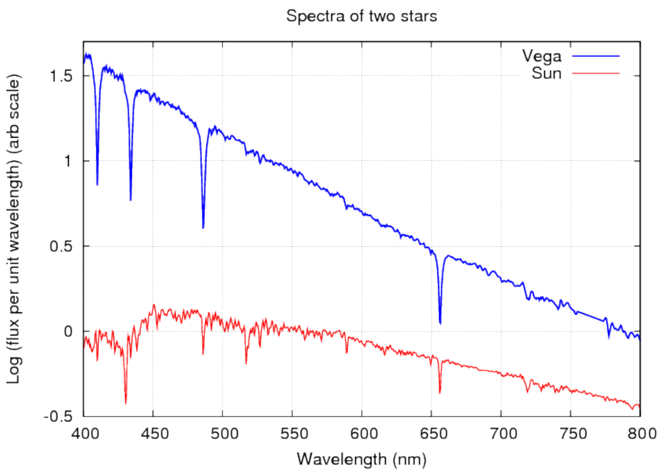
- Total absorption coefficient per atom:
- α(total)= α(nat.)x α(v.d.waals)x α(stark)x α(thermal)
- Where $\gamma = \gamma_{nat} + \gamma_4 + \gamma_6$
- Convolution of
- damping and thermal profiles:
  - **Voigt function**

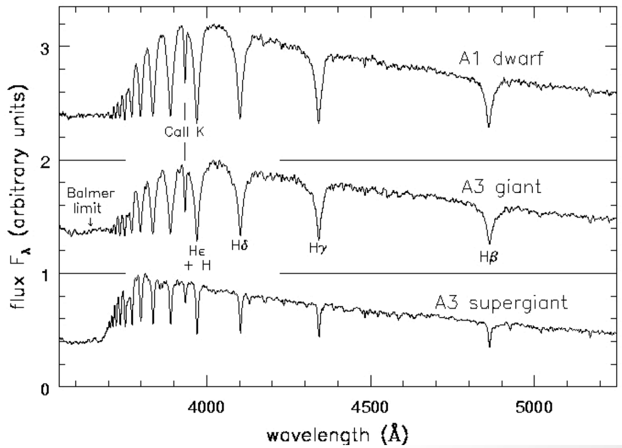


HYDROGEN LINES

- Balmer transitions:
- (from the n=2 excited level)
- strongest in A stars because that is where N (HI, n=2) is highest

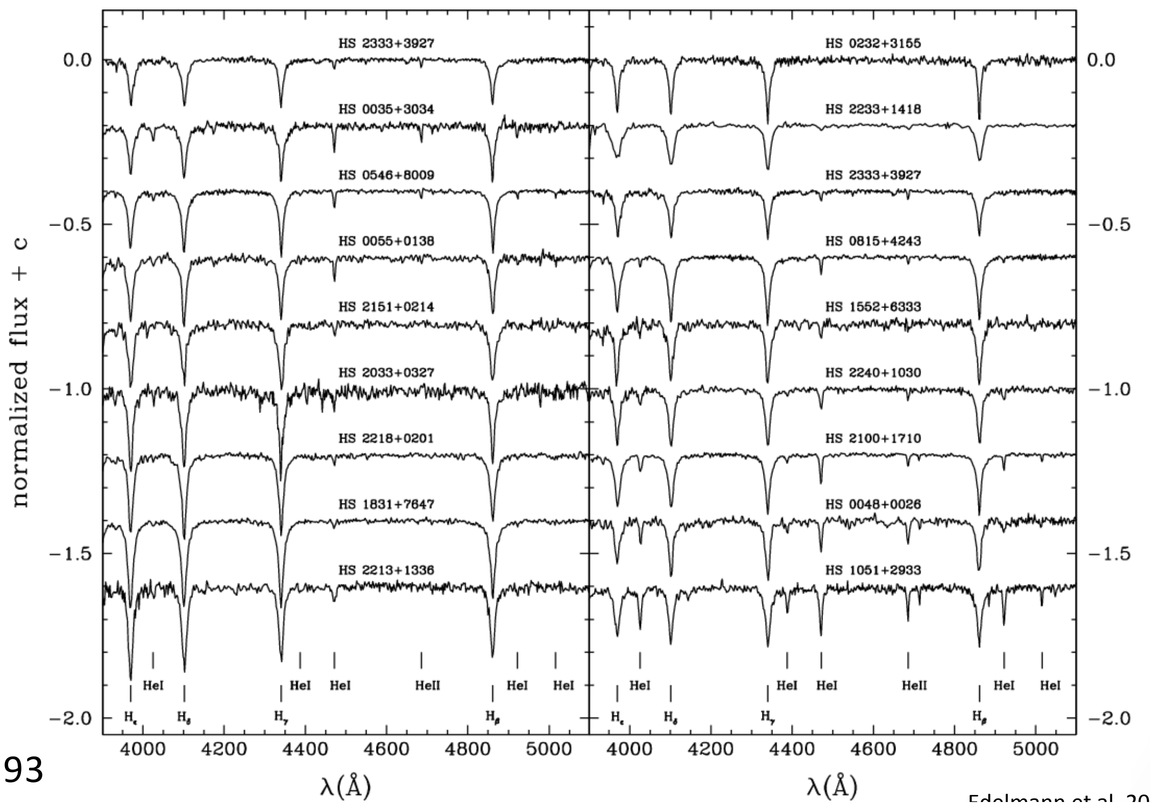






HELIUM LINES

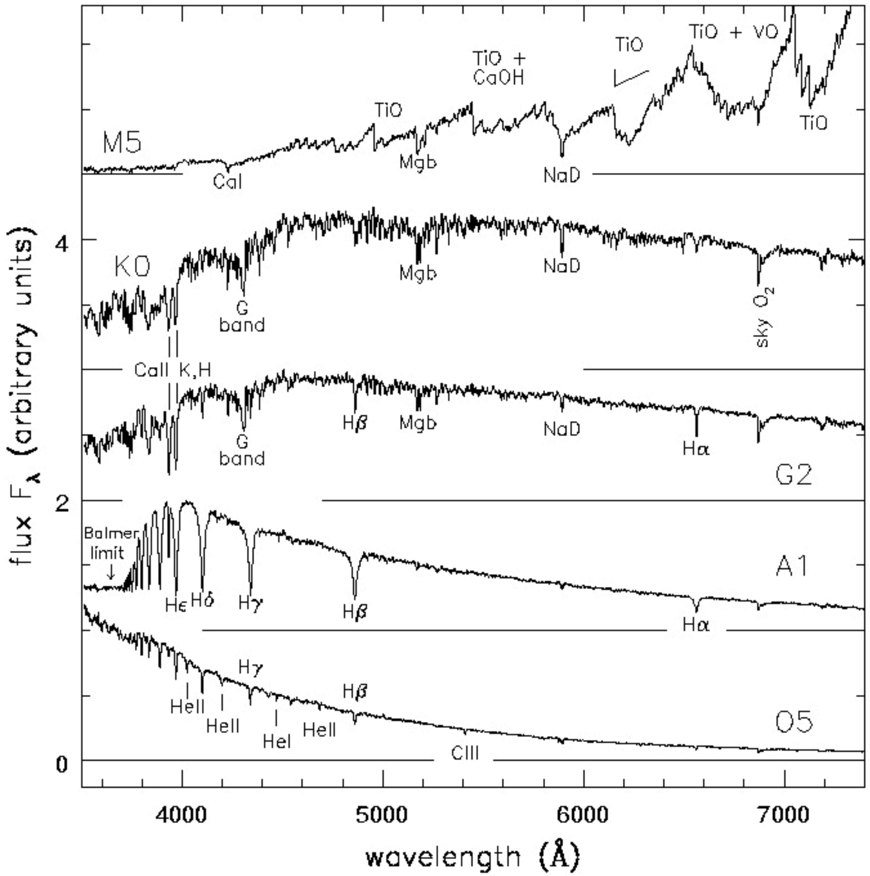
- Second most abundant element
- Detectable only in very hot stars, O- and B-types



Source:Edelmann et al. 2003, A&A, 400, 393

METAL LINES

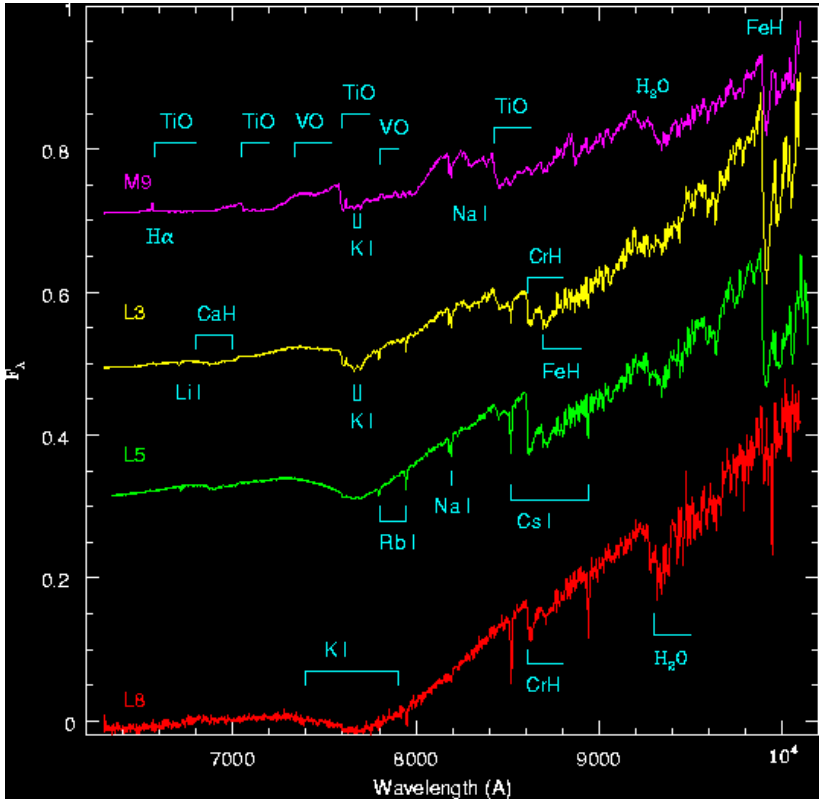
- Line strength depends on level population of the atoms.
- Strongest when temperature is low (lower ionization stages are populated)
- Lines become stronger as T decreases
- Dominate in F, G, K stars



Source: Tolstoy

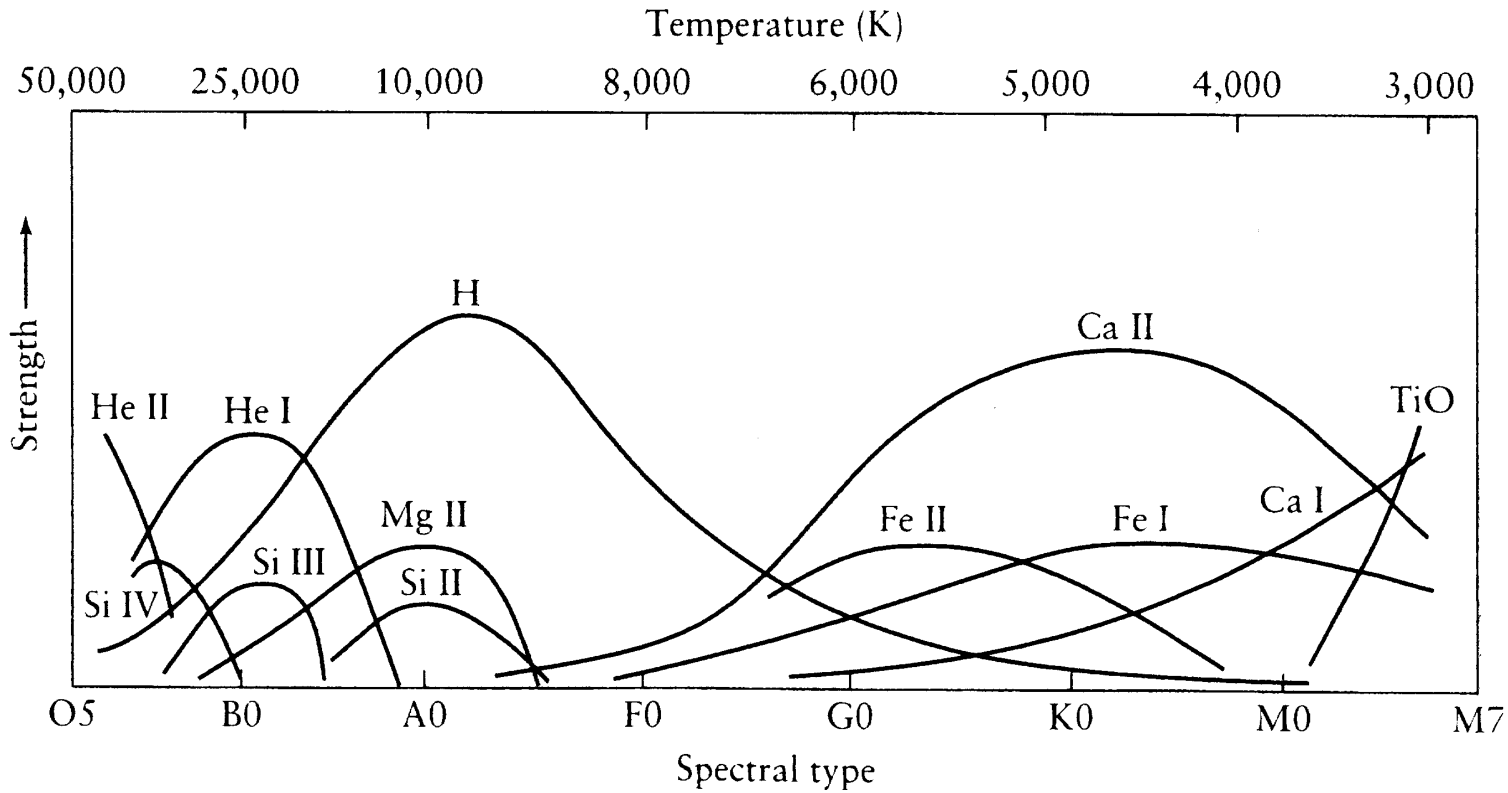
MOLECULAR BANDS

- Form in very cool stars (M-, L-, T-types)
- Can vibrate and rotate,
- Flux significantly reduced in bands
- Electron transitions: Visible+UV lines
- Vibrational transitions: Infrared lines
- Rotational transitions: Radio-wave lines
- M-stars: TiO
  L- / T-stars: CO, H2O and CH4



Source: Kirckpatrick et al, 1999, 2000

DOMINANT FEATURES



4. FROM LINES TO ABUNDANCES

- Need to relate intensity/strength of an observed line to amount of corresponding element in original stellar gas,
- i.e. need to find the number of absorbing atoms per unit area (Na) that have electrons in the proper orbital to absorb a photon at the wavelength of the spectral line
- Boltzmann and Saha equations are applied and combined with the pressure and temperature of the gas to derive an abundance of the element (i.e. to calculate excitation and ionization)

4. FROM LINES TO ABUNDANCES

- However, not all transitions between atomic states are equally likely. Each transition has a relative probability, or ***f*-value** (also called **oscillator strength**).
- Can be calculated theoretically

or measured in a lab

- to find the number of atoms

lying above each cm^2 of photosphere:

- **N_a × *f*-value**

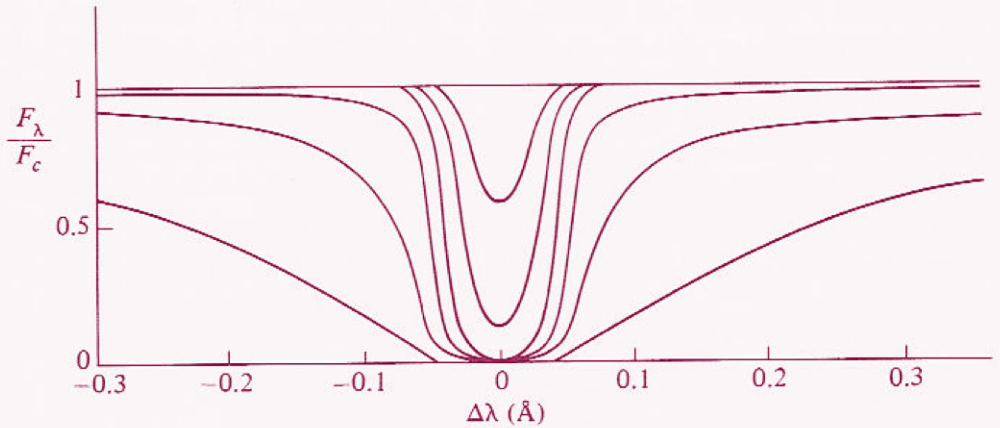


Figure 9.20 Voigt profiles of the K line of Ca II. The shallowest line is produced by $N_a = 3.4 \times 10^{11}$ ions cm^{-2}, and the ions are ten times more abundant for each successively broader line. (Adapted from Novotny, *Introduction to Stellar Atmospheres and Interiors*, Oxford University Press, New York, 1973.)

4.1. EQUIVALENT WIDTH:

- Geometric interpretation: $W_\lambda = \int_0^\infty \frac{I_c - I_\lambda}{I_c} d\lambda$

W_λ =width of a rectangular, completely opaque line

- For a 2-component atmosphere

(continuum source+cool layer of depth h),

let the rectified line profile is: $r(\lambda) = \frac{I_\lambda(0) e^{-[\kappa_l(\lambda)+\kappa_c(\lambda)]h}}{I_\lambda(0) e^{-\kappa_c(\lambda)h}} = e^{-\kappa_l(\lambda)h}$

- Then $W_\lambda = \int_0^\infty [1 - r(\lambda)] d\lambda$

- For faint lines : $W_\lambda \approx \int_0^\infty \kappa_l(\lambda) h \cdot d\lambda = Nh \int_0^\infty \alpha_\lambda d\lambda = Nhf \frac{\pi e^2}{m_e c} \frac{\lambda^2}{c} \propto Nhf\lambda^2$

- where N is the number density of atoms able to absorb the incident radiation

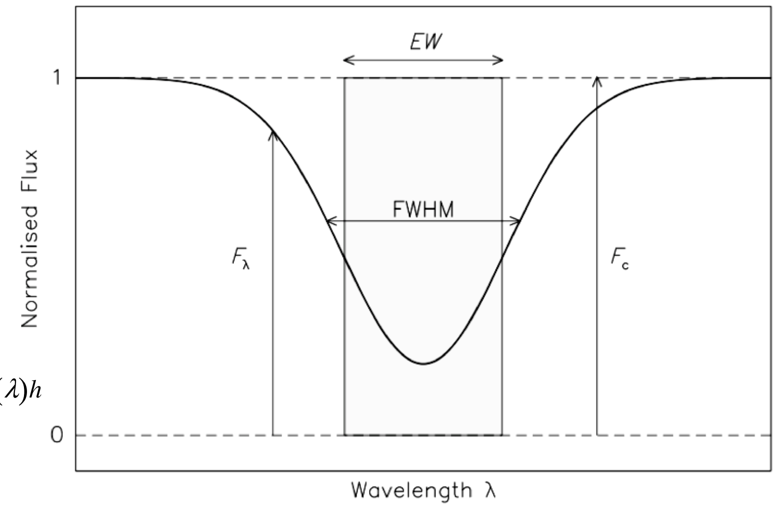


Figure 3.7: The equivalent width of an absorption line is defined as the width of a rectangle that has an area equal to the line, as illustrated in grey. Adapted from Figure 9.18 of Carroll & Ostlie (1996)

4.2. CURVE OF GROWTH

- important tool to determine N_a, the number of absorbing atoms, and thus the abundances of elements in stellar atmospheres, because EW varies with N_a.
- **Weak lines:** *linear part* $\boldsymbol{W \propto A}$
- Doppler core dominates and the width is

set by the thermal broadening $\Delta\lambda_D$.

Depth of the line grows proportionally

to abundance A

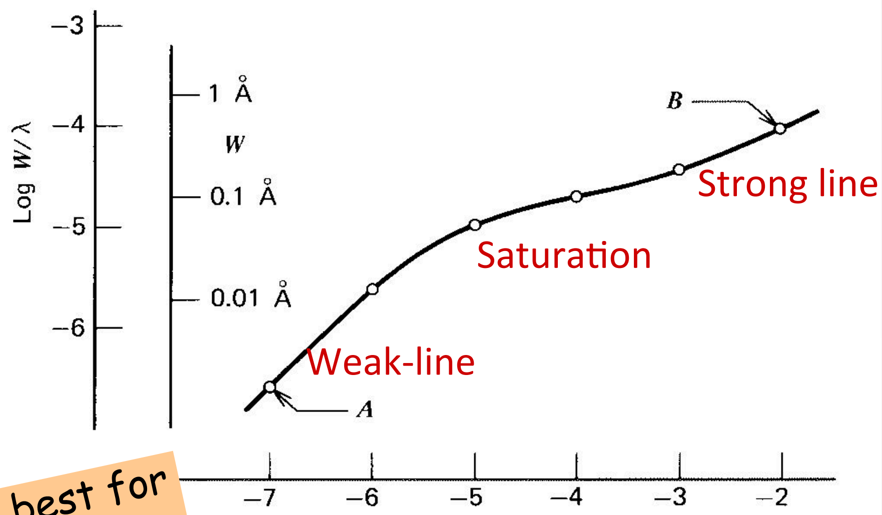
- **Saturation:** *plateau* $\boldsymbol{W \propto \sqrt{\log A}}$
- Doppler core approches max. value and line

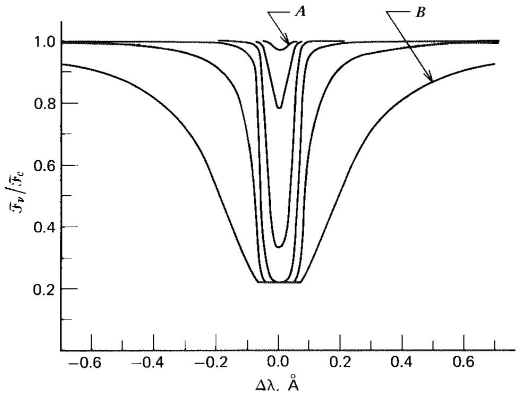
saturates towards a constant value

- **Strong lines:** $\boldsymbol{W \propto \sqrt{A}}$
- damping wings dominate
- optical depth in wings becomes significant compared to κ_ν.
- Strength depends on g, but for constant g

the EW is proportional to $A^{1/2}$

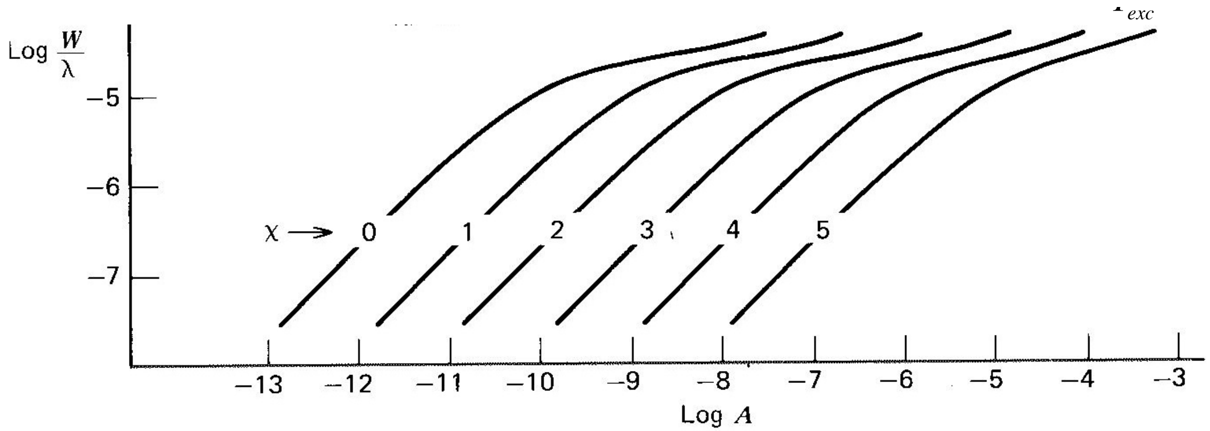
Small/weak lines are best for abundance determination





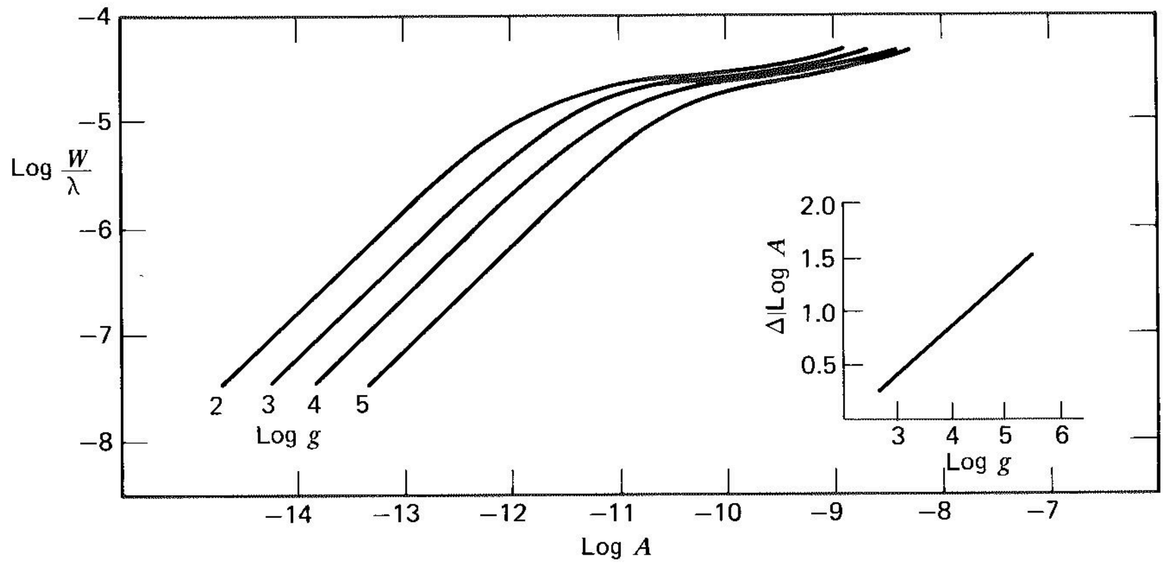
4.2. CURVE OF GROWTH

- CoG dependencies: temperature
- Temperature can affect line strength
- CoG shape looks the same, only shifted for different values of the excitation potential



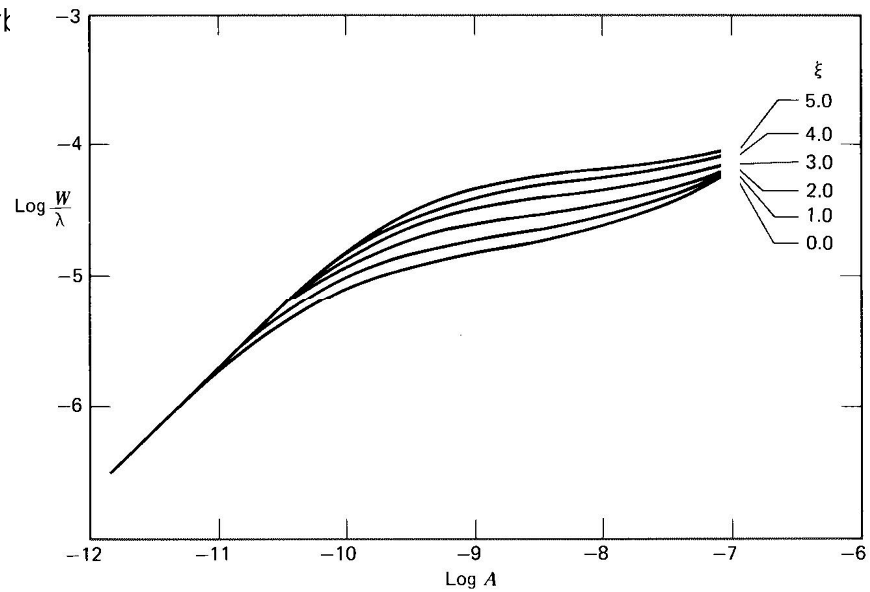
4.2. CURVE OF GROWTH

- CoG dependencies: gravity
- Gravity can affect line strength through:
  - $N_r/N_E \uparrow$, $A\downarrow$ at given W/λ
  - effect important only for ionized species



4.2. CURVE OF GROWTH

- CoG dependencies: microturbulence
- Effect of microturbulence: increase of Doppler width desaturates the lines
- ⇒ strong lines useful to get V_{turb}



4.3. COG ANALYSIS FOR ABUNDANCES

- **Advantages:**
  Simple, you measure the equivalent width of a line and read the abundance off the log W *vs* log A plot
- **Disadvantages:**

  Lots of calculations
  Difficulty in dealing with microturbulence and saturation effects:
- Make an initial guess of ξ
  Theoretical cogs are calculated for all measured EWs of some element with lots of lines
  From each line one derives an abundance A and plots it *vs* W
  If A is found to be a function of W → ξ must be wrong
- One happily choose a new ξ and start all over
- This must continue until one finds convergence !

4.4. SPECTRUM SYNTHESIS

- In real life, one no longer does a curve-of-growth analysis, but rather a full spectral synthesis.

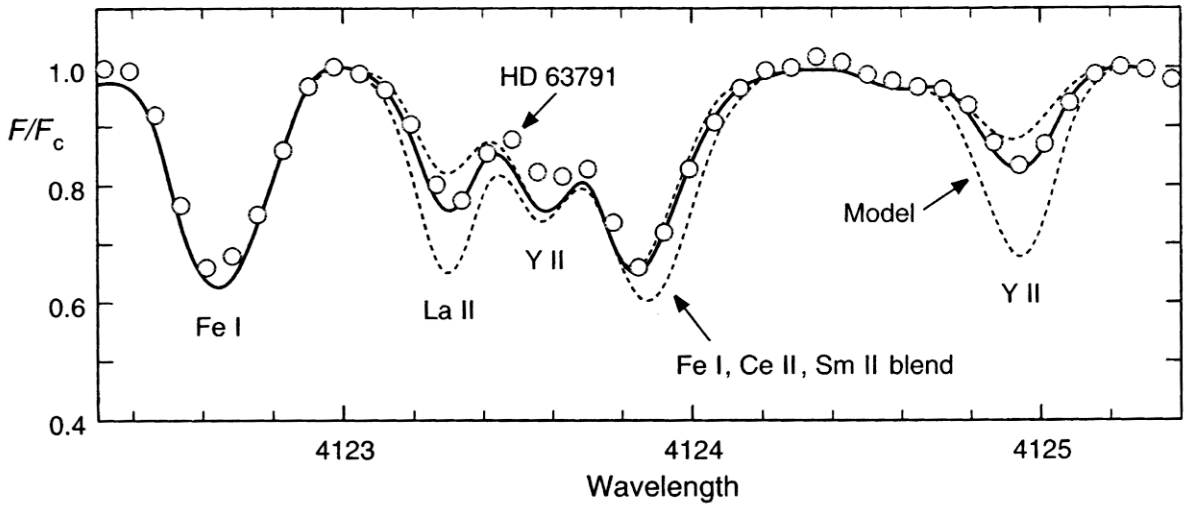
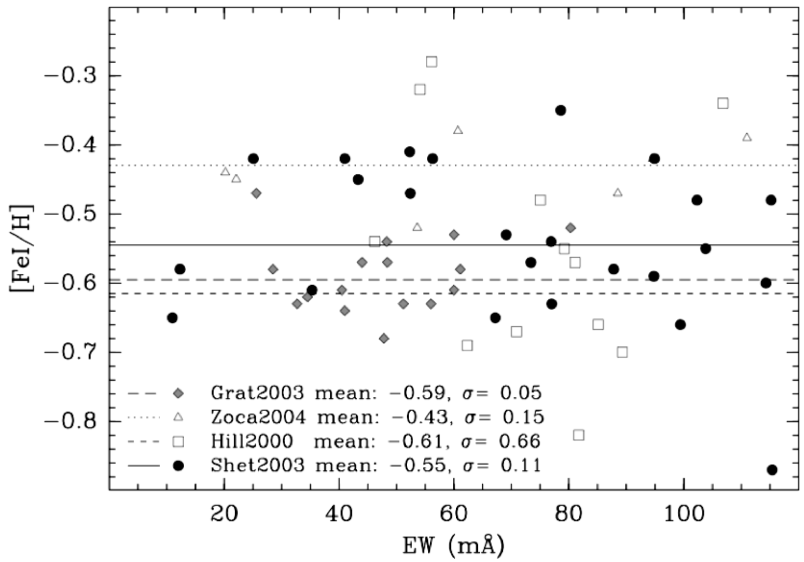


Fig. 16.9. The circles show the observed spectrum, while the lines are for models ($T_{eff} = 4725$ K, $\log g = 1.70$, and $\xi = 1.60$ km/s) with different chemical abundances. The solid line is deemed to fit best. Based on data in Fig. 2 of Burris *et al.* (2000). The resolving power is ~20 000 and the signal-to-noise ratio ~100.

4.5. LINE LISTS

- A proper line list is a critical part of the analysis. Lines need to be chosen carefully, making sure they have **reliable gf-values** and are sufficiently isolated from their neighbours at the resolution of the observations and of course to lie within the wavelength coverage of the instrument.



5. STELLAR ABUNDANCES IN PRACTICE

- **Data needed:**

1- Observed spectrum normalized to the continuum, and equivalent widths

2- Model atmospheres (esp. T-τ relation) for various T_{eff}, logg and chemical compositions

- Kurucz models (ETL, plane parallel): very extended grid,
  - http://kurucz.harvard.edu/grids.html
- MARCS models (ETL, plane parallel): for cool stars (4000 to 8000 K)
  - http://marcs.astro.uu.se/
- TLUSTY models (NLTE, plane parallel): for hot stars (27500 to 55000 K)
  - http://nova.astro.umd.edu/Tlusty2002/tlusty-grids.html

5. STELLAR ABUNDANCES IN PRACTICE

3- Line data: wavelengths, excitation potentials, oscillator strengths, broadening parameters

- Need to know: λ, E_{low}, J_{low}, f, γ_1, γ_2
- **NIST** Atomic Spectra Database
  - http://physics.nist.gov/PhysRefData/ASD/lines_form.html
- **VALD** Vienna Atomic Line Database
  - http://www.astro.uu.se/~vald/php/vald.php
- **HITRAN** HIgh-resoluDon TRANsmission molecular absorptior
  - http://www.cfa.harvard.edu/HITRAN/

Fe I, Fe II	• Fuhr, J. R., and Wiese, W. L. 2006, J. Phys. Chem. Ref. Data, 35, 1669.
Zr II	• Ljung, G., Nilsson, H., Asplund, M., and Johansson, S. 2006, Astronomy and Astrophysics, 456, 1181.
BaI, Ba II	• Klose, J. Z., Fuhr, J. R., and Wiese, W. L. 2002, J. Phys. Chem. Ref. Data, 31, 217.
La II	Lawler, J. E., Bonvallet, G., and Sneden, C. 2001, The Astrophysical Journal, 556, 452.
Ce II	Palmeri, P., Quinet, P., Wyart, J-F., and Biémont, E. 2000, Physica Scripta, 61, 323.
Pr II	Biémont, E., Lefébvre, P.H., Quinet, P., Svanberg, S., and Xu, H.L. 2003, The European Physical Journal D, 27, 33.
(PrII-hyper)	Ivarsson, S., Litzén, U., and Wahlgren, G. M. 2001, Physica Scripta, 64, 455.
Nd II	Den Hartog, E. A., Lawler, J. E., Sneden, C., and Cowan, J. J. 2003, The Astrophysical Journal Supplement Series, 148, 543.
Sm II	Lawler, J. E., Den Hartog, E. A., Sneden, C., and Cowan, J. J. 2006, The Astrophysical Journal Supplement Series, 162, 227.
Eu II	Lawler, J. E., Wickliffe, M. E., Den Hartog, E. A., and Sneden, C. 2001, The Astrophysical Journal, 563, 1075.
Dy I, Dy II	Wickliffe, M.E., Lawler, J.E., and Nave, G. 2000, Journal of Quantitative Spectroscopy & Radiative Transfer, 66, 363.
Tm I, Tm II	Lawler, J. E., and Wickliffe, M. E. 1997, Journal of Optical Society of America B, 14, 737.

5. STELLAR ABUNDANCES IN PRACTICE

- **Tools needed:**

1- Data reduction software:

- Iraf, MIDAS, IDL and/or instrument-specific pipelines

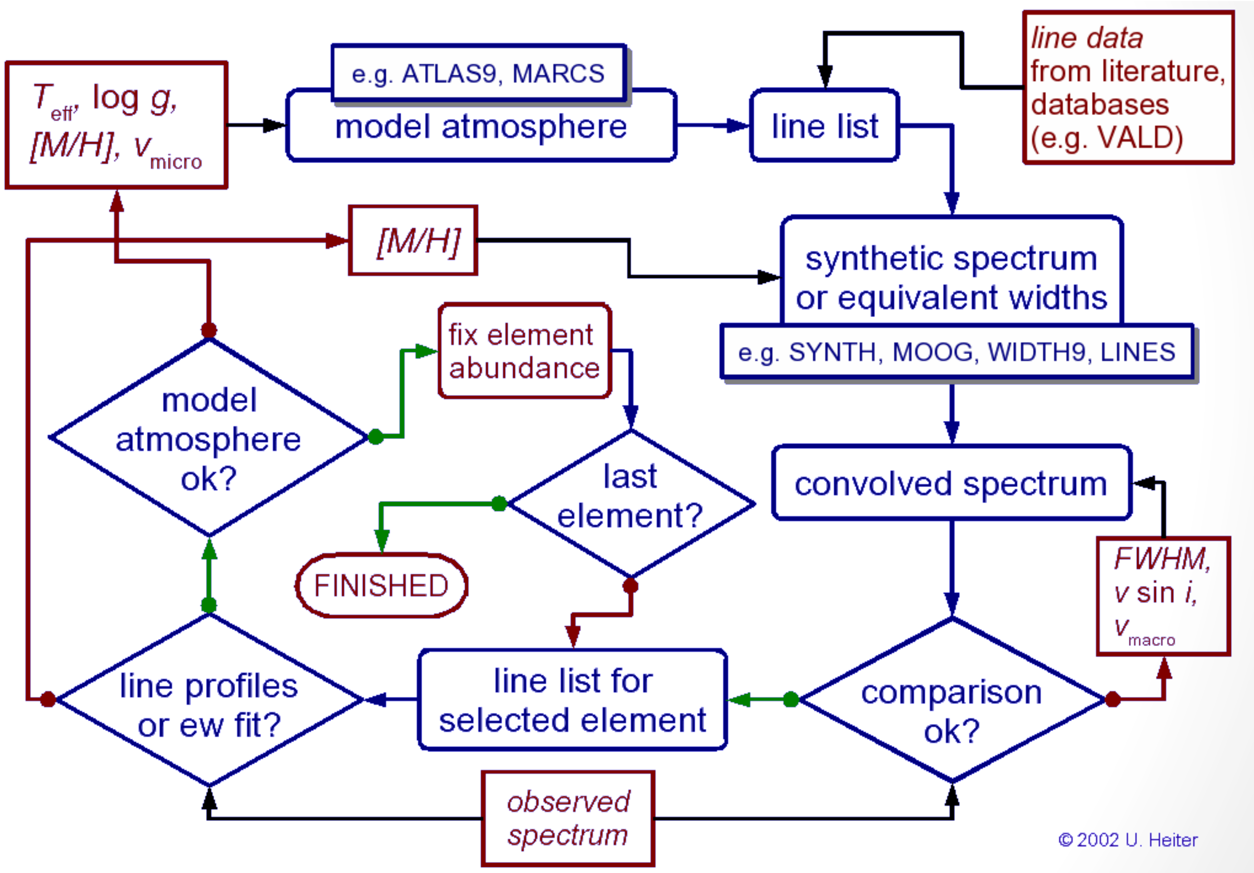
2- Good procedure for continuum normalization:

- REDUCE, VLINE, .. (not so easy!)

3- Code of spectral synthesis, abundance & microturbulance calculations e.g.:

- ATLAS, SYNTHE, WIDTH (Kurucz)
  - http://kurucz.harvard.edu
- Synspec (Hubeny & Lanz) for hot stars
  - http://nova.astro.umd.edu/Synspec43/synspec.html
- Moog (Sneden) for average and cool stars
  - http://verdi.as.utexas.edu/moog.html

5.2. ABUNDANCE ANALYSIS



5. STELLAR ABUNDANCES IN PRACTICE

- **Expected precision:**
- It is difficult to determine :
  - the temperature of a star to better than 50–100 K
  - the gravity of a star to better than 0.1-0.2 dex
  - the microturbulent velocity of a star to better than 0.2km/s
- Differential abundances (rel. to the sun): ≈ 0.04-0.05 dex
- Absolute abundances: > 0.1-0.2 dex!
- Problems:
  - NLTE effects
  - Uncertain or wrong log(gf) values
  - 3D hydrodynamic models → $Z_{sun}=0.012$ instead of 0.018!

WHAT DO WE LEARN FROM ABUNDANCES?

- We seeks to account for the production of the chemical elements that we see in the Universe, its time dependence and for many of the features of galaxies that we observe. Understanding stellar evolution, the birth and death of stars and how they interact with their environments is central to understanding the evolution of galaxies.

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BIBLIOGRAPHY:

- D. F. Gray, 2005, « The observation and analysis of stellar photospheres », Cambridge University Press, 3rd ed.
- • D. Mihalas, 1978, « Stellar atmospheres », 2nd ed., W. H. Freeman & Co.
- • D. Mihalas & B. Weibel-Mihalas, 2000, « Foundations of radiation hydrodynamics »
- • C. R. Cowley, 1995, « An introduction to cosmochemistry », Cambridge University Press
- • R. P. Kudritzki, H. W. Yorke & H. Frisch, 1988 Saas-Fee course, « Radiation in moving gaseous media », eds. Y. Chmielewski & T. Lanz
- • S. J. Adelman & T. Lanz (eds.), 1988, « Elemental abundance analyses », proceedings of the IAU working group on Ap stars Workshop held at the Institut d'Astronomie de l'Université de Lausanne September 7-11, 1987