STELLAR SPECTROSCOPY II.

DETERMINATION OF STELLAR PARAMETERS AND ABUNDANCES

Lezione VII- Fisica delle Galassie
Cap 8-9 Carrol & Ostlie

And
For neural network in astronomy:
Leung & Bovy (2018)

Laura Magrini

OUTLINE of the lecture (continuing from the previous lecture):

The aim of this lecture is to learn how we can obtain information about the stellar parameters (temperature, surface gravity, global metallicity and individual element abundances) from a stellar spectrum
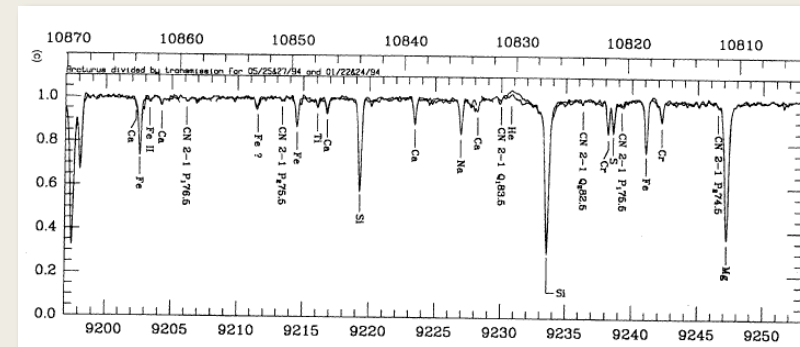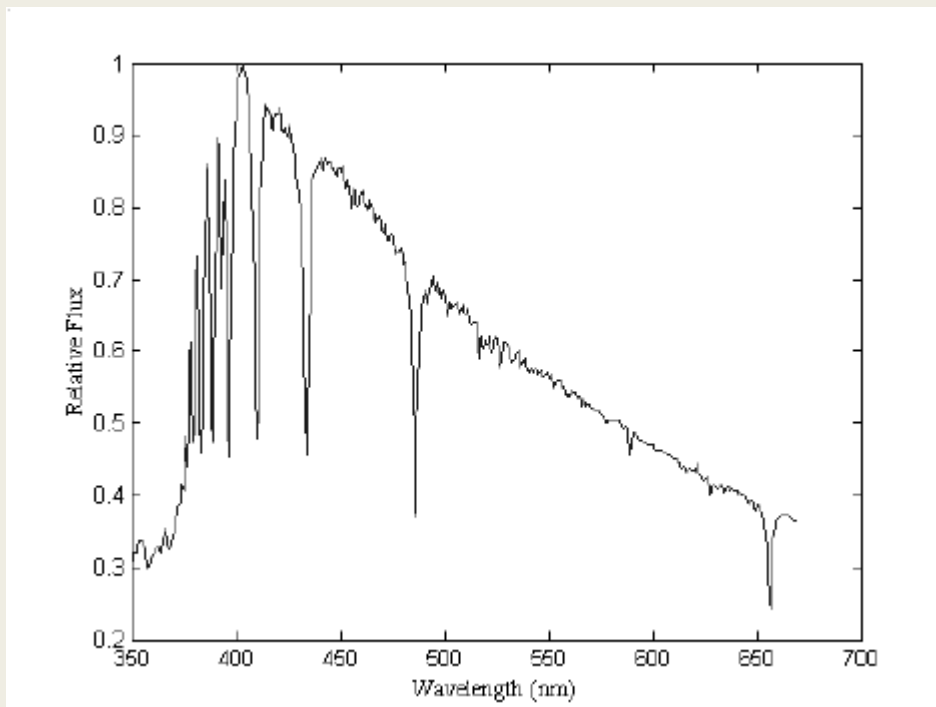

Globally it is a blackbody, but each small portion of the spectrum contains a large quantity of information

- **The conditions for local thermodynamic equilibrium (LTE) are satisfied, and so, as already seen, the source function is equal to the Planck function, $S_\lambda = B_\lambda$**
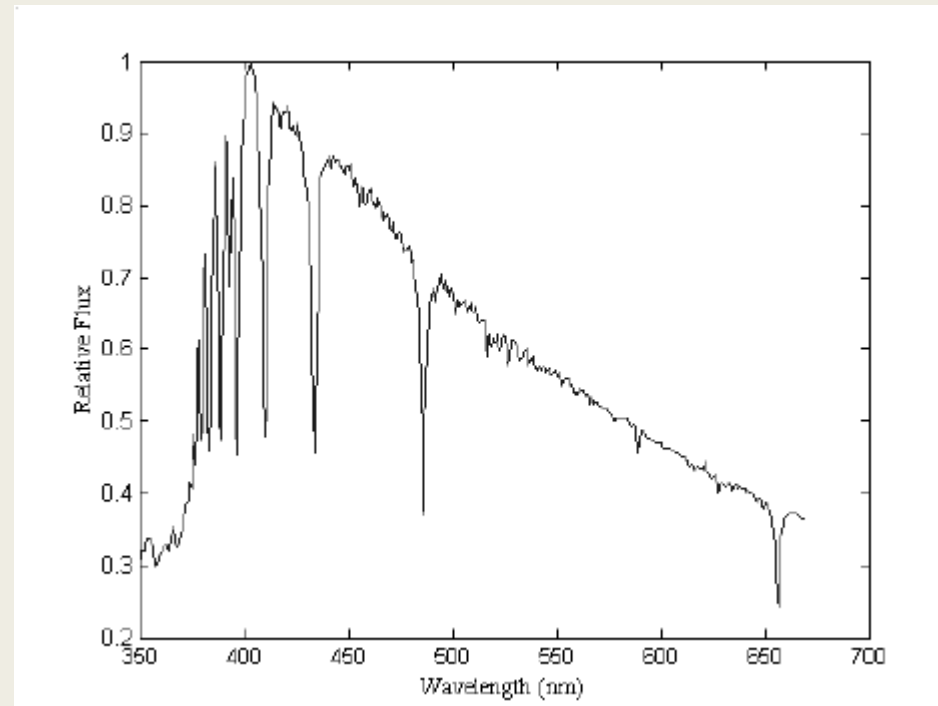
The formation of absorption lines

- Absorption lines are created when an atom absorbs a photon with exactly the same energy necessary to make an upward transition from a lower to a higher orbital
- **The energy of photons depends on the types of stars** (their effective Temperature)

**FIGURE 11**   The dependence of spectral line strengths on temperature.
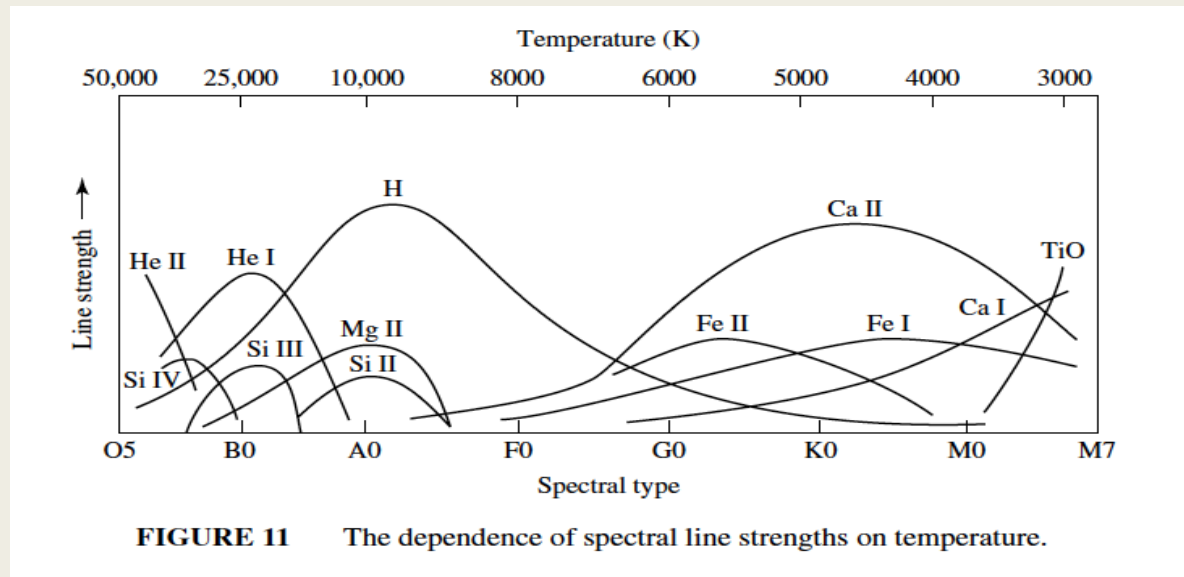
What is an equivalent width?

The equivalent width of a spectral line is a measure of the area of the line on a plot of intensity versus wavelength.

It is found by forming a rectangle with a height equal to that of continuum emission, and finding the width such that the area of the rectangle is equal to the area in the spectral line.

It is a measure of the strength of spectral features.

It is usually measured in mÅ.
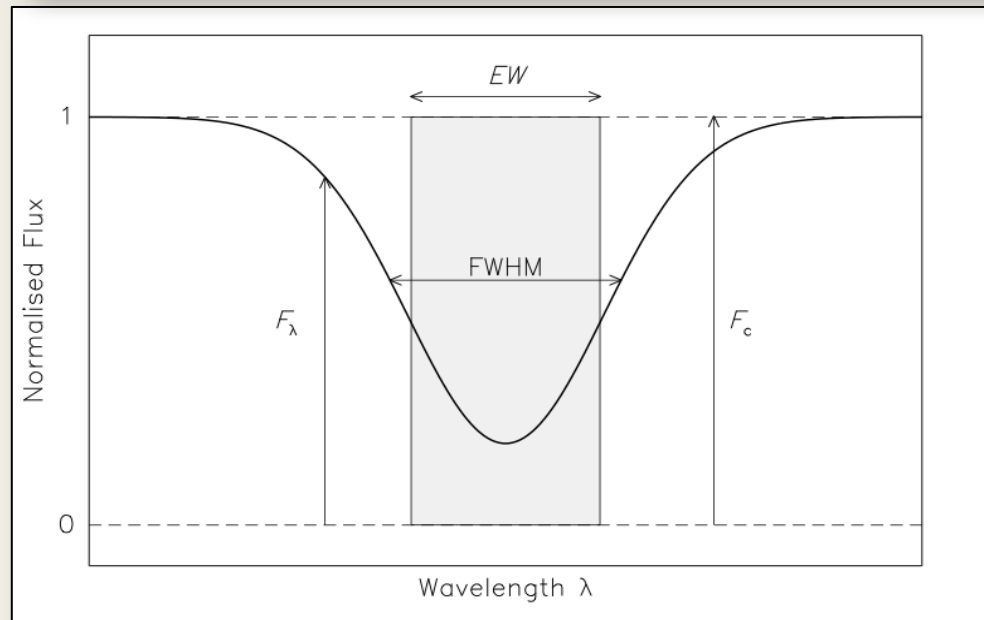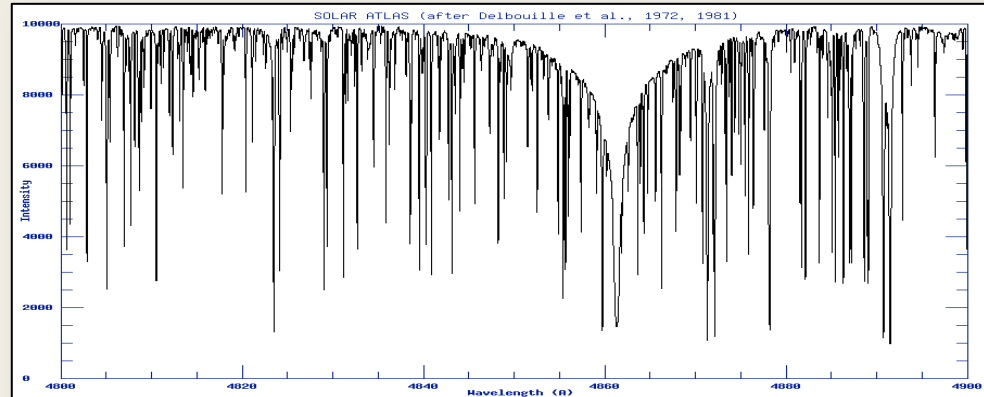
What is an equivalent width?

- The opacity κ_λ of the stellar material is greatest at the wavelength at the center and it decreases moving into the wings.

- The center of the line is formed at lower T, thus in cooler regions of the stellar atmosphere.

- Moving into the wings from , the line formation occurs at higher T

- It merges with the continuum produced at an optical depth of 2/3.
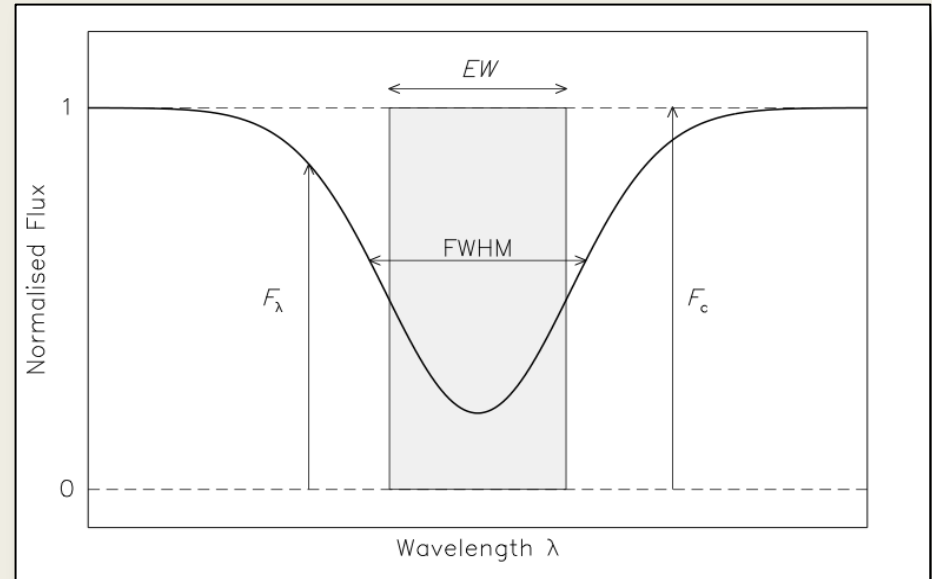
$$W = \int \frac{F_c - F_\lambda}{F_c}\, d\lambda,$$

Formation of an absorption line

Form Lectures of H. Ludwig
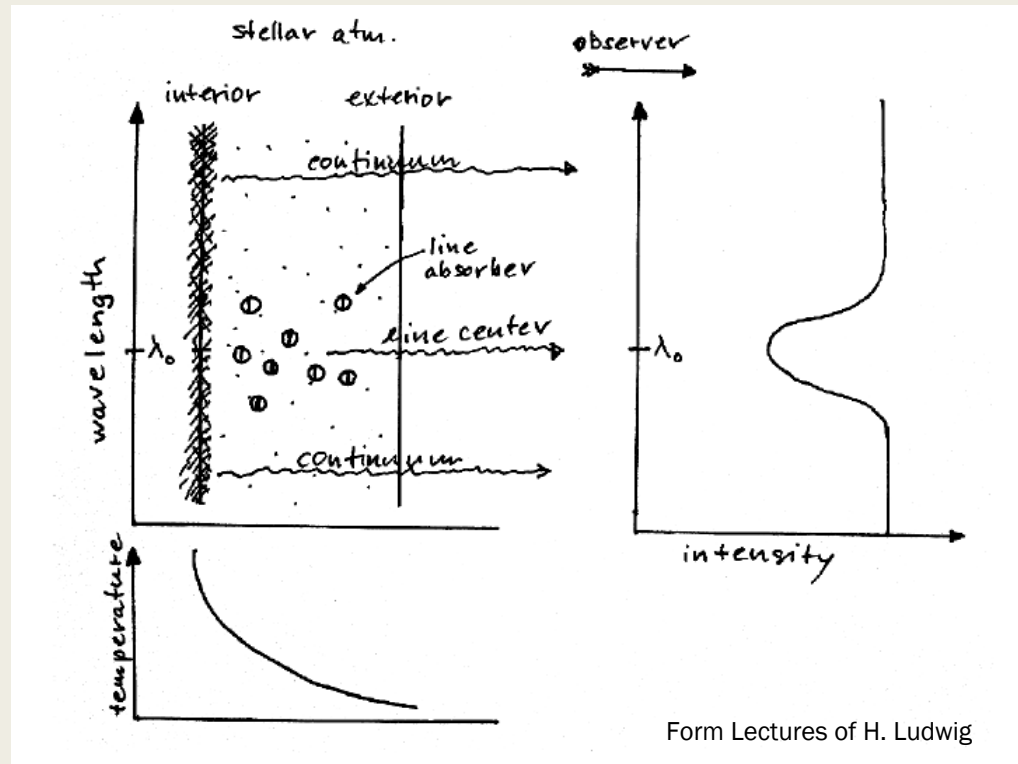
- Hot, i.e. bright, continuous spectrum emitted in the deepest layers of the photosphere

- Part of the emitted light is intercepted by absorbing atoms in the higher atmosphere on the way out, forming the absorption line

Formation of an absorption line

Form Lectures of H. Ludwig
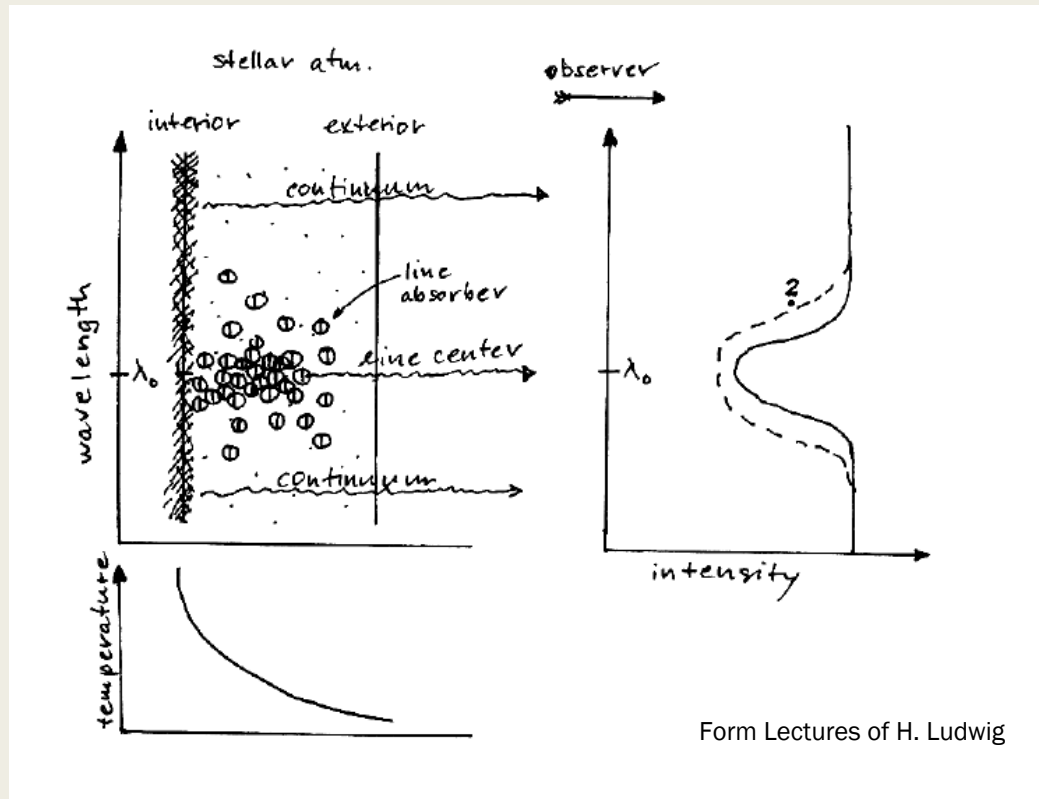
- If the number of the absorbers increases, the line becomes deeper, and then it saturates

Line broadening

Natural broadening:

Due to the uncertainty principle of Heisenberg, an electron in an excited states occupies its orbital for a short time, thus the energy cannot be precise

$$\Delta E \simeq \hbar / \Delta t \text{ (uncertainty in the energy)}$$

Considering that the energy of a photon can be expressed as $E = hc/\lambda$, the associate uncertainty is

$$\Delta \lambda \simeq \frac{\lambda^2}{c} /(1/\Delta t_{in} + 1/\Delta t_{fin})$$

where Δt_{in} and Δt_{fin} are the lifetimes of the electron in the initial and final states

- The lifetime of an electron in the first and second excited states of hydrogen is about $\Delta t = 10^{-8}$ s.
- The natural broadening of the Hα line of hydrogen, $\lambda = 656.3$ nm, is then $\Delta \lambda \approx 4.57 \ 10^{-5}$ nm~ $5 \ 10^{-4}$ A~0.5 mA

Line broadening

Doppler broadening:

In thermal equilibrium, the velocities of atoms (with mass m) follow the Maxwell-Boltzmann distribution with the **most probable velocity**

$$V = \sqrt{\frac{2kT}{m}}$$

Since the atoms are moving, the wavelengths of the light absorbed or emitted by the atoms in the gas are Doppler-shifted according to $\Delta\lambda/\lambda = \pm|vr|/c$.

$$\Delta\lambda \simeq \frac{2\lambda^2}{c} \sqrt{\frac{2kT}{m}}$$

The Doppler broadening of the Hα line of hydrogen, $\lambda = 656.3$ nm in the Solar photosphere (T~5777 k), is then $\Delta\lambda \approx 4.3 \cdot 10^{-2}$ nm.

→ **The Doppler broadening is ~1000 greater than the natural broadening**

Line broadening

Pressure broadening:

The orbitals of an atom can be perturbed in a collision with a neutral atom or an ion. The results is called collisional or *pressure broadening.*

The general shape of the line is like that found for natural broadening ➔ *damping profile or Lorentz profile*

An approximate calculation of the broadening can be done estimating **the time between collision**:

$$\Delta t = \frac{l}{v} = \frac{1}{n\sigma\sqrt{2kT/m}}$$

with *l* **mean free path**, that can be expressed with $n\sigma$, in which n number density and σ collision cross section

The corresponding broadening is: $\Delta\lambda \simeq \frac{\lambda^2}{\pi c} 1/\Delta t$

$$\Delta\lambda \simeq \frac{\lambda^2}{\pi c} n\sigma\sqrt{\frac{2kT}{m}}$$

The pressure broadening of the Hα line of hydrogen, $\lambda = 656.3$ nm in the Solar photosphere (T~5777 k), is then $\Delta\lambda \approx 2.6 \ 10^{-5}$ nm, similar to the natural broadening (but it depends in the condition of the star, it can be much higher)

Line broadening

Pressure broadening:

The broadening is proportional to the number density: narrower lines observed for the more luminous giant and supergiant stars are due extended low density atmospheres. The typical pressure broadening is similar to natural broadening.
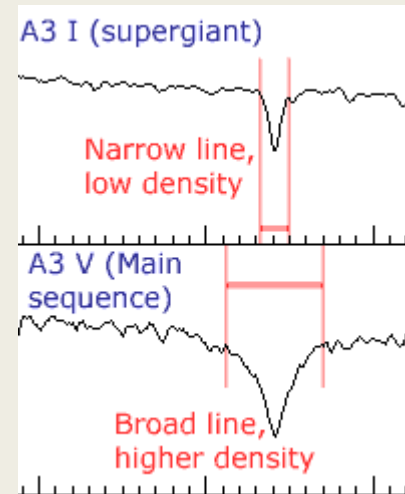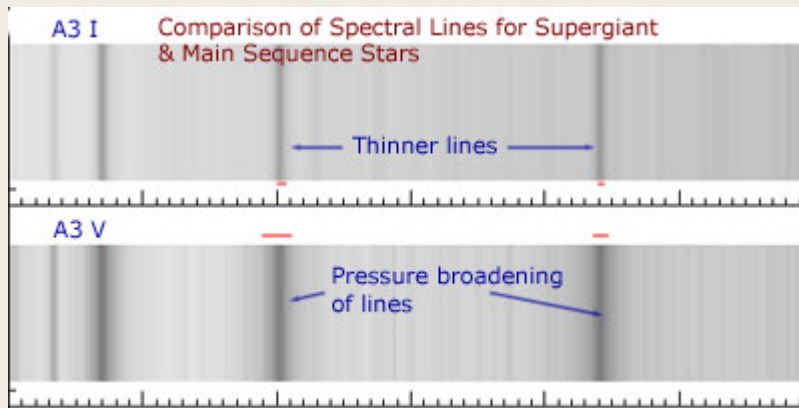
Comparison of spectral line widths for A3 I and A3 V class stars. The broader lines for the V luminosity class star arises due to the denser outer layers in the atmosphere of the main sequence star.
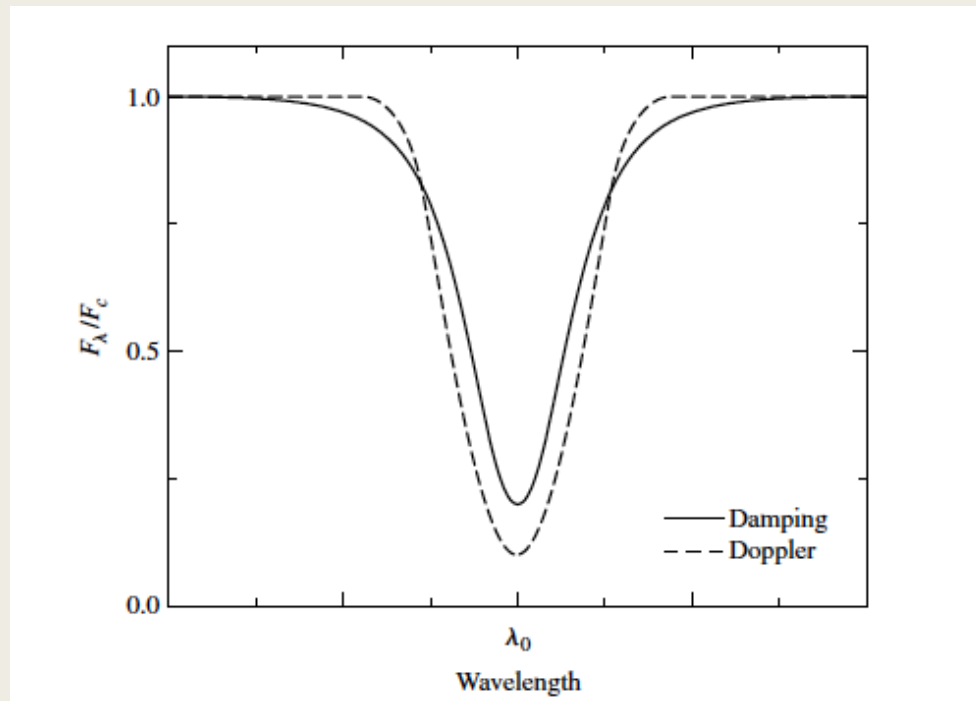
From http://outreach.atnf.csiro.au/education/senior/astrophysics/spectra_astro_types.html.

Line broadening

Voigt profile:

The combination of Damping and Doppler profiles give a total profile called → **Voigt profile**

- Doppler broadening dominates near the center

- Damping dominates on the wings of the line

Calculation of spectral lines

- The shape and intensity of a spectral line is related to the **abundance of the element N_a**, but not only….

- We need to know, how photons interacts with atoms:

  ➢ Temperature and density to solve the Boltzmann and Saha equations (and to determine the broadening of the lines)

  ➢ The probability of a given transition within the orbitals

    - The relative probabilities of an electron making a transition from the same initial orbital are given by the f –values or **<u>oscillator strengths</u>** for that orbital.

    - For instance: for hydrogen, f= 0. 637 for the Hα transition and f =0. 119 for Hβ.

Our goal is to determine the value of N_a by comparing the calculated and observed line profiles.

Digression: how abundances are defined in astrophysics

- **Abundances by mass, Z**

The proportion of the matter made up of elements heavier than helium (Y) and hydrogen (X).

It is denoted by Z, which represents the sum of all elements heavier than helium, in mass fraction.

$$X+Y+Z=1$$

Solar Z is 0.0134 (Asplund et al. 2009, ARAA 47, 481)

- **Abundances by number (gas abundances)**

The metallicity of gas is usually expressed by the number ratio of oxygen atoms (or other elements) to hydrogen atoms per unit volume.

Usually a factor 12 is summed to the final value:

$$O/H=\log_{10}(N_O/N_H)+12$$

where N_O and N_H are the numbers of oxygen and hydrogen atoms per unit volume.

- **Abundances by number, referred to Solar values (stellar abundances)**

The metallicity of stars is usually expressed by the number ratio of iron atoms to hydrogen atoms per unit volume, with respect to the solar values:

$$[Fe/H] = \log_{10}(N_{Fe}/N_H)_{star} - \log_{10}(N_{Fe}/N_H)_{Sun},$$

where N_{Fe} and N_H are the numbers of iron and hydrogen atoms per unit volume.

Digression: how abundances are defined in astrophysics

- From Z to [Fe/H]

$$\frac{N_{Fe}}{N_H} = f_{Fe}(\alpha) \times \frac{Z/m_Z(\alpha)}{(1 - Y - Z)/m_H},$$

$f_{Fe}(\alpha)$ is the number fraction of iron with respect to all the elements heavier than helium; m_H is the mass of the hydrogen atom; and $m_Z(\alpha)$ is the average atomic mass of heavy elements weighted by the number of atoms.

It is important to note that $f_{Fe}(\alpha)$ and $m_Z(\alpha)$ depend on the fraction of α-elements ([α/Fe]).

- Here a tool online to convert Y and Z in to [Fe/H]:

http://www2.astro.puc.cl/pgpuc/FeHcalculator2.php

Y~25% by mass, 8% by number of atoms

The curve of growth

The curve of growth is a curve that shows how the equivalent width of an absorption line increases with the number of atoms producing the line.

<u>The EWs of line depends on the number of absorber atoms [three regimes]</u>

- When the density of those atoms is small, the EWs grows linearly with their density (N)

- When the density become higher the EWs tends to saturate, and thus it cannot be used as an indication of the abundances of the atoms

- Finally the EWs is again proportional to the abundance (√N)
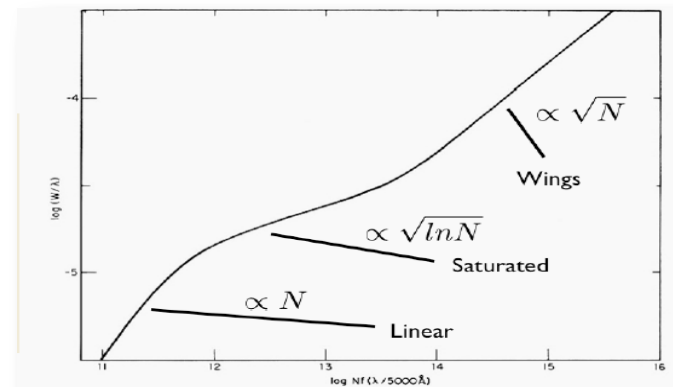
Figure 9.22 A general curve of growth for the Sun. (Figure from Aller, *Atoms, Stars, and Nebulae*, Revised Edition, Harvard University Press, Cambridge, MA, 1971.)
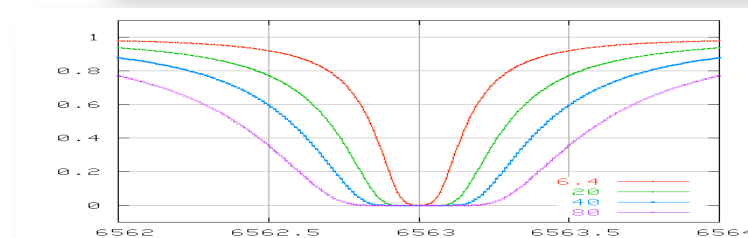
The curve of growth

- The number of absorbing atoms (abundance) can be determined by comparing the equivalent widths from **different absorption lines** produced by the same atom/ion in the same state (and so having the same column density in the stellar atmosphere) with a theoretical curve of growth.
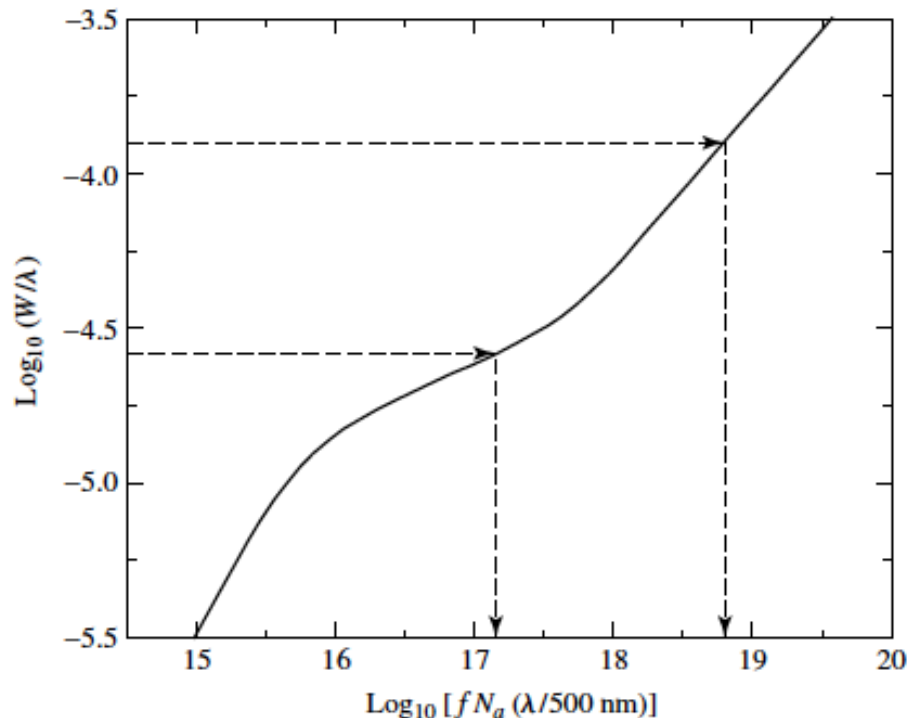
- On a common wavelength scale

- Considering the oscillator strength of each line

The curve of growth

- A curve-of-growth analysis can also be applied to lines originating from atoms or ions in different initial states

  1. applying the **Boltzmann equation** to the relative numbers of atoms in different states of excitation allows us to calculate the **excitation temperature → in LTE approximation it is the effective temperature**

  2. It is possible to use the Saha equation to find either the **electron pressure** or the ionization temperature (if the other is known) in the atmosphere from the relative numbers of atoms at various stages of ionization.

Determination of stellar parameters from spectral analysis

1. Deriving the EFFECTIVE TEMPERATURE (from Boltzmann equation):

To compute the T_{eff} of a star from its spectrum, we require that the abundance of an element is independent of the excitation potential of the <u>individual lines</u>.

This is so because, all the lines of a given element should give the same abundance for the same star.

In practice, there is a (small) scatter around an average value.

A T_{eff} which is incorrect will affect the weak excitation potentials more than the strong potentials or vice versa.
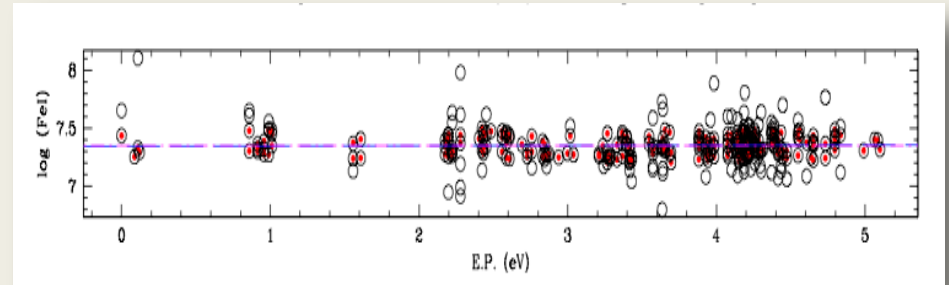
To use this method, we need many lines of a single element sampling a range of EP, as for example FeI lines in cool stars (F-G-K stars).

Determination of stellar parameters from spectral analysis

1. Deriving the EFFECTIVE TEMPERATURE (from Boltzmann equation):

Star: sun.iron T_{eff}: 5277 LGg: 4.44 [Fe/H]: 0.00 xi: 1.10

-500 K

Lower EP → need more energy to be excited

Star: sun.iron T_{eff}: 5777 LGg: 4.44 [Fe/H]: 0.00 xi: 1.10

correct temperature

If Teff is the correct one, all lines give the same abundance

Star: sun.iron T_{eff}: 6277 LGg: 4.44 [Fe/H]: 0.00 xi: 1.10

+500 K

Higher EP → need less energy to be excited
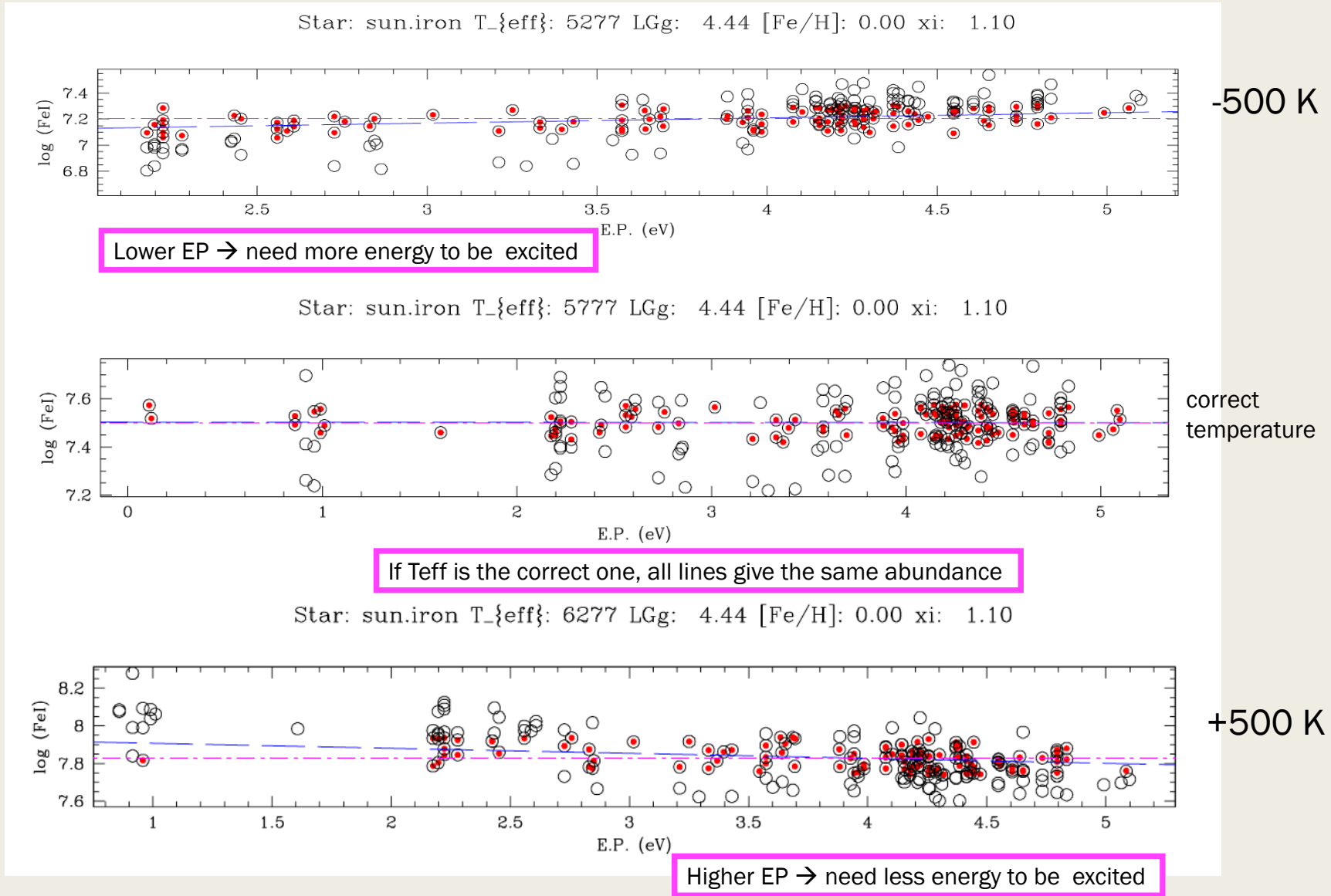
Determination of stellar parameters from spectral analysis

2. Deriving the Pressure (proxy of surface gravity) (from Saha equation):

The surface gravity of a star of mass $M_\star$ and radius $R_\star$ is defined as $g_\star = GM_\star/R_\star^2$, where G is the gravitational constant.

For stellar types F, G or K, we can easily measure elements in two ionization states, like FeI and FeII.

For a given star and a given element, <u>there should be a single value for the abundance, no matter if the abundance is determined from the neutral or the ionized state.</u>

We can then iterate on the gravity of our model until the abundance of Fe I and Fe II are the same, constraining the stellar gravity.

For the hydrostatic equilibrium condition, gravity is related to the gas pressure.

From the Saha equation, **we found that the ratio between FeI and FeII depends on P_e**

$$N_{FeII}/N_{FeI} \propto 1/P_e$$

Assuming that the star is in ionization equilibrium, we can estimate the pressure, and thus the surface gravity

→ **thus the ionization equilibrium is a good tool to derive gravity.**

Determination of stellar parameters from spectral analysis

2. Deriving the Pressure (proxy of surface gravity) (from Saha equation):

Mean of the abundance from neutral iron, FeI

Lines of ionized iron, FeII

-0.4

correct gravity

+0.4
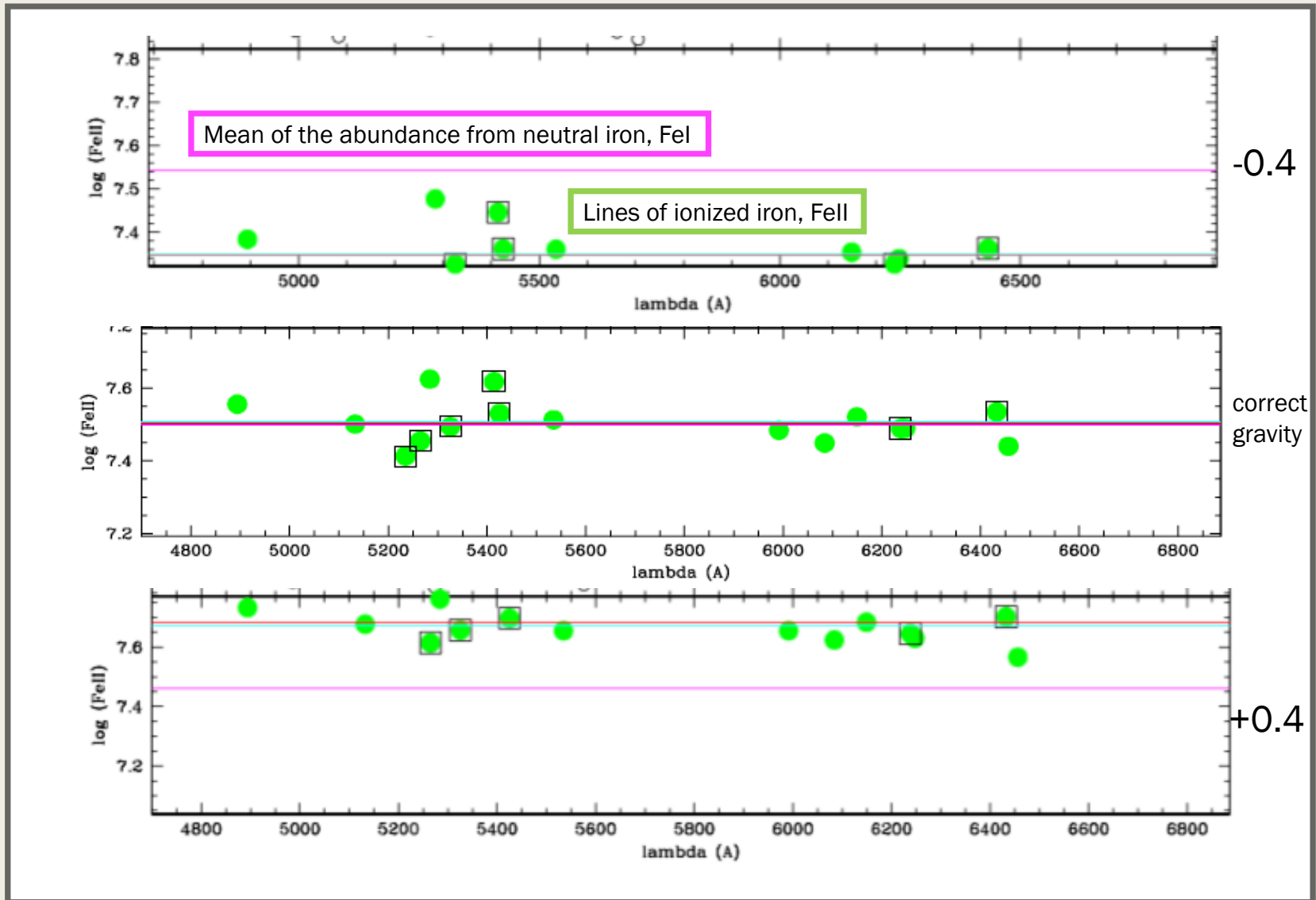
The curve of growth for the abundances

Assuming that we derived T_{eff} and $\log g$ –from spectroscopic analysis or for photometric analysis-, we can now use the equivalent widths of different elements/transitions to derive the abundances

For weak lines (first regime) we have:

$$\log\left(\frac{W_\lambda}{\lambda}\right) = \log\left(\frac{\pi e^2}{m_e c^2}\frac{N_i/N}{\mathcal{U}(T)}N_H\right) + \log A + \log(gf\,\lambda) - \frac{5040}{T}\chi + \log(\kappa_\nu)$$

Equivalent width of a line	Constant for a given star	Abundance	transition probability	Effective temp	Absorption coefficient

- For weak lines, the equivalent width varies in a linear way with abundances

- The abundance of an element (A) varies with the inverse of **the temperature**

- The abundance depends linearly on the gf -values.

Determination of abundances:
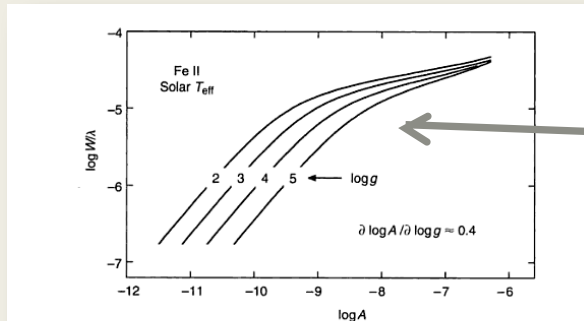# the effect of temperature and gravity

Fig. 16.3. Curves of growth for ions like Fe II are surface-gravity dependent in cool stars.
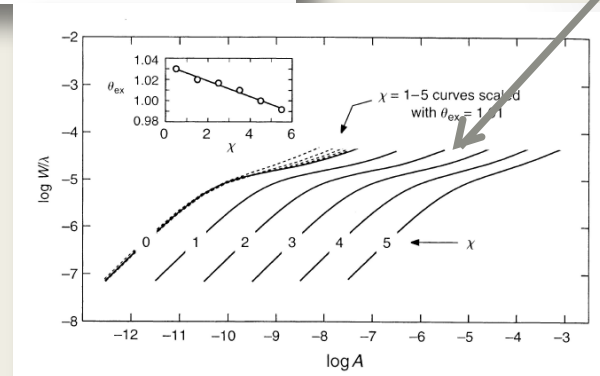
For instance:

The strength of lines of ionized elements depends on the pressure (log g) and so their curve of growth
depends on the pressure/density
→ log g affects ionized species though Kv

The dependence on Teff is even stronger

(from Grey, Lecture on spectral-line analysis)

We need to derive T_{eff} and pressure (related to the surface gravity log g) to correctly measure abundances.

Determination of abundances

Once derived Log g and T_{eff}, from the EWs of absorption lines we can derive the abundances using their theoretical curve of growth [in which we have fixed Teff and log g] → the comparison gives us the abundance

Which elements?
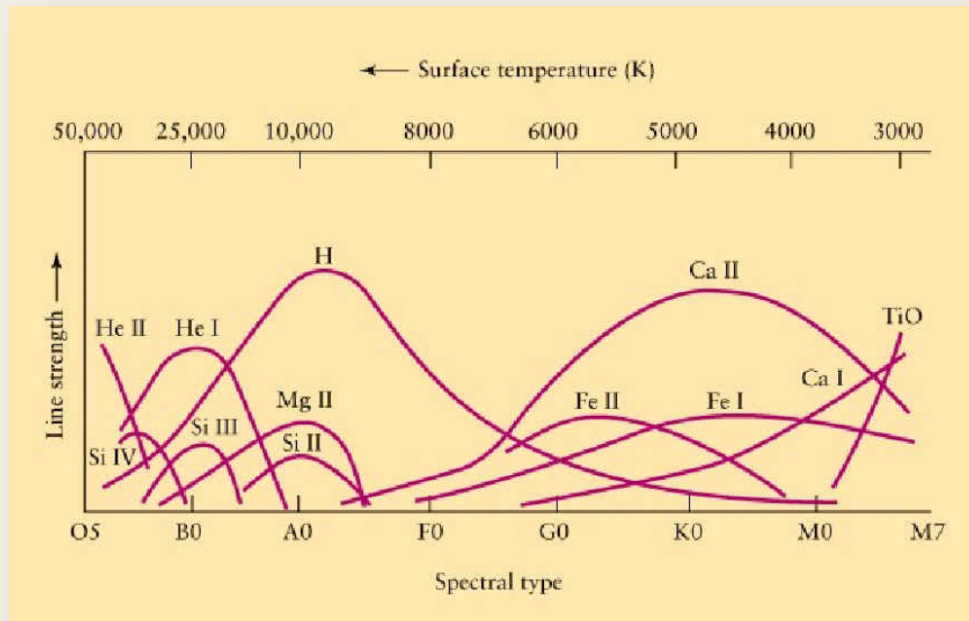
Depending on the T_{eff}, there are different dominating species in the atmospheres of stars.

Limiting the parameter space where our approximations are valid

→ **Iron I and Iron II dominates and allows us both Teff and Log g determination**

Stellar atmosphere models

Thus to solve the Boltzmann and Saha's equations, we must know to the conditions inside the stellar atmospheres, specifically:

- Temperature
- Pressure (or Log g)
- Opacity

The characteristics of the stellar atmospheres are tabulated in several sets of model stellar atmospheres, e.g.:

- Kurucz models: http://kurucz.harvard.edu/grids.html
- MARCS models: http://marcs.astro.uu.se/
- ATLAS modes: http://www.stsci.edu/hst/observatory/crds/castelli_kurucz_atlas.html
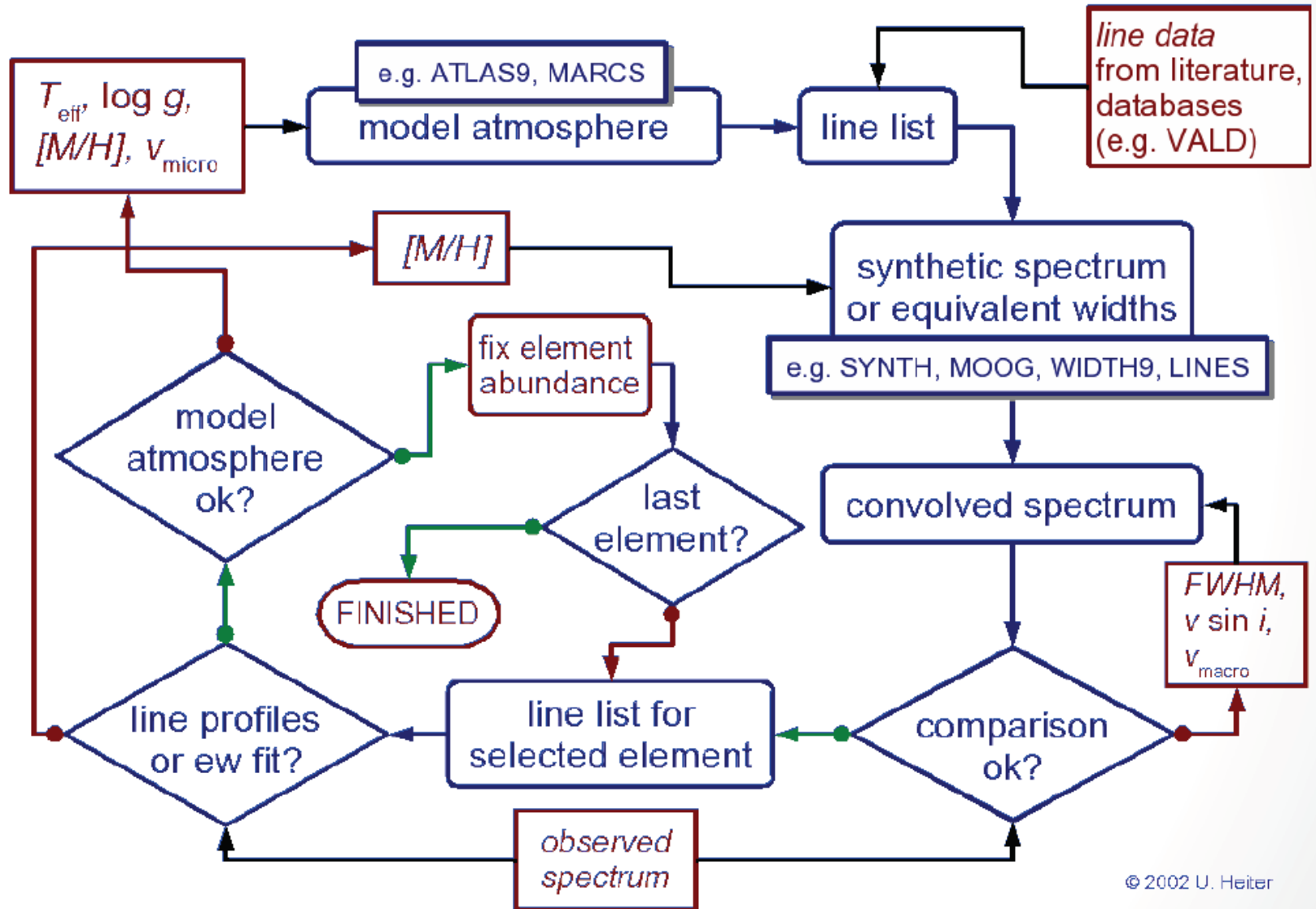
Stellar atmosphere models

Stellar atmospheric models are a tabulation of physical parameters used to represent the conditions inside an atmosphere.

Models are typically given as the electronic pressure (Pe), the temperature (T) and the optical depth for photons with λ=5000Å for several layers (~50) of a stellar atmosphere.

It is customary in stellar atmosphere work to use **log g** as equivalent for the pressure in the atmosphere (which can be done if **hydrostatic equilibrium is valid**).


```
TITLE MARCS 35 model for MLT convection testing. Vturb 2.0 km/s
T EFF= 6500. GRAV 2.0 MODEL TYPE= 3 WLSTD= 5000 SPHERICAL, RADIUS= 1.155E+12 cm
1 1 1 1 1 1 1  1 1 1 1 1 1 0 1 0 0 0 0 0 - OPACITY SWITCHES
0.922 0.078 -10.88 -10.89 -9.44 -5.65 -6.26 -4.98 -7.48 -5.80
-7.87 -6.11 -7.67 -6.13 -6.59 -6.50 -6.54 -5.48 -8.96 -7.33
-10.87 -8.74 -10.04 -8.40 -8.65 -6.59 -9.12 -7.81 -7.83 -7.44
-9.16 -8.63 -9.67 -8.69 -9.41 -8.81 -9.44 -9.14 -9.80 -9.54
-10.62 -10.12 -20.00 -10.20 -10.92 -10.35 -11.10 -10.18 -10.58 -10.04
-11.04 -9.80 -10.53 -9.81 -10.92 -9.91 -10.82 -10.49 -11.33 -10.54
-20.00 -11.04 -11.53 -10.92 -11.94 -10.94 -11.78 -11.11 -12.04 -10.96
-11.28 -11.16 -11.91 -10.93 -11.77 -10.59 -10.69 -10.24 -11.03 -10.95
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-20.00 -12.51 -20.00 -20.00 -20.00 -20.00 -20.00 -20.00 -20.00 56
4.75432431E-02, 4571.6, 1.64024E+09, 3.01052E+12, 7.04416E-12, 2.44700E+10,
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.299538255E-01, 4821.7, 1.19096E+10, 3.10038E+13, 6.44878E-11, 1.72482E+10,
.084119260E-01, 4874.9, 1.67679E+10, 4.23195E+13, 8.80230E-11, 1.61355E+10,
```

- depth in column mass or optical depth at standard wavelength
- temperature in K
- number density of free electrons in cm $^{-3}$
- number density of all other particles (except electrons) in cm $^{-3}$
- column: density in g/cm ^{3}

How-to

Observed spectrum

+

Model Atmosphere

↓

Stellar parameters and abundances

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Tools –some examples-

To measure EWs:

- IRAF splot

- Daospec http://www.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/community/STETSON/daospec/

- Ares http://www.astro.up.pt/~sousasag/ares/

Model Atmospheres:

- Kurucz models: http://kurucz.harvard.edu/grids.html

- MARCS models: http://marcs.astro.uu.se/

- ATLAS modes: http://www.stsci.edu/hst/observatory/crds/castelli_kurucz_atlas.html

ATOMIC DATA:

- VALD: http://vald.astro.uu.se/

- NIST: http://physics.nist.gov/PhysRefData/ASD/lines_form.html

Tools –some examples-

to derive abundances:

- MOOG http://www.as.utexas.edu/~chris/moog.html

- ATLAS/SYNTHE (Kurucz) http://kurucz.harvard.edu

- (OS)MARCS: http://marcs.astro.uu.se/

- SME http://tauceD.sfsu.edu/Tutorials.html

- Synspec http://nova.astro.umd.edu/Synspec43/synspec.html

- ISPEC: https://www.blancocuaresma.com/s/iSpec

- THE CANNON: https://www.sdss.org/dr14/irspec/the-cannon

Which elements we can measure:

The main ones are in cool stars:

Alpha-elements: O, Si, Mg, Ca, Ti

Iron-peak elements: V, Sc, Ni, Cr, Fe

Neutron-capture elements: Y, Eu, Ba

Is it enough?

In the previous slides, we have presented the spectral analysis based on several assumptions, in particular LTE, hydrostatic equilibrium, homogeneity of stellar atmospheres.

Reality is much more complex:

■   1D vs 3D results

■   LTE vs NLTE

Homogeneity

- Stellar atmospheres are not homogeneous.

- They can have sunspots, granulations, non-radial pulsations, stellar spots in magnetic stars, clumps and shocks in hot star, winds etc.
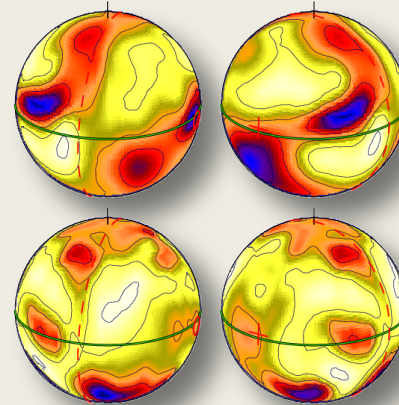
Stationarity→ hydrostatic equilibrium

- The assumption of stationarity is valid in most

- Exceptions: pulsating stars, supernovae, mass transfer in close binaries, etc.
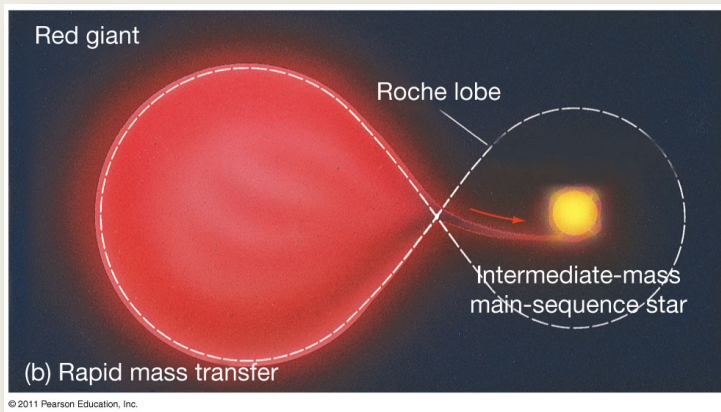
Conservation of energy

- Nuclear reactions and production of energy: stellar interiors
- Negligible production of energy in the stellar atmospheres
- **Energy flux is conserved at any radius**

Local Thermodynamic Equilibrium

- A star is far to be in thermodynamic equilibrium, since the energy is transported from the stellar interior to the surface

- However in small volumes, we can assume LTE

- We can consider T(r) as a function of stellar radius

LTE vs. non-LTE

for particular conditions in stellar atmospheres LTE is no more a good approximation….
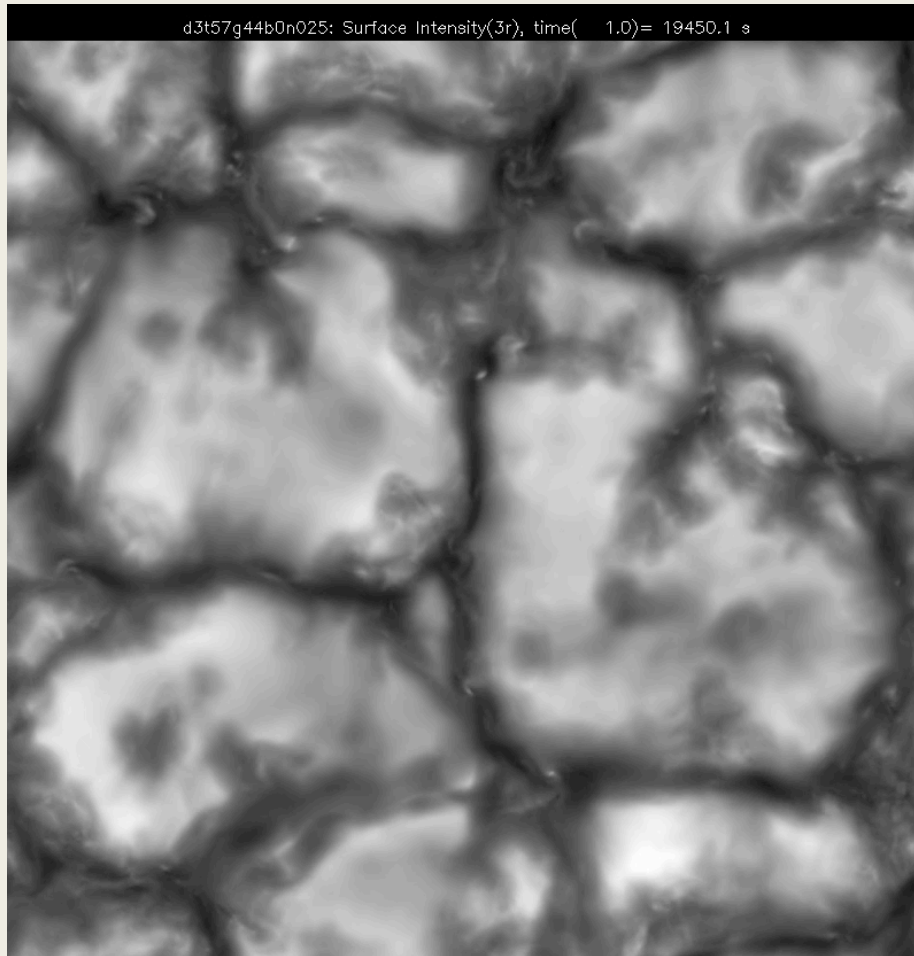
When we have to take non-LTE into account?

■   Rate of photon absorptions >> rate of collisions

■   Stellar atmospheres characterized by:
❑   High temperatures
❑   Low densities
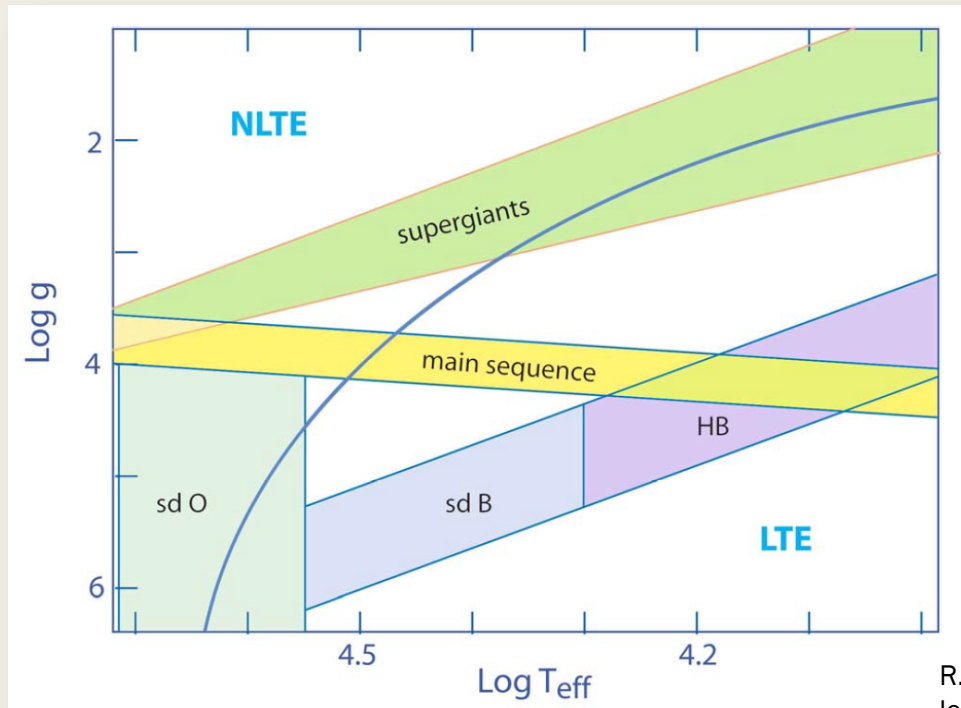
R. Kudritzki
lecture

3D vs. 1D

if we want to consider the three-dimensional structure of the photosphere, taking into account inhomogeneity….

d3t57g44b0n025: Surface Intensity(3r), time(1.0)= 19450.1 s

The stellar photosphere is characterized by:

- convective flows
- pulsating waves
- rotating tornados
- small-scale turbulent motions.

The movie above is produced from a 3D computer simulation of these processes produced by Uppsala astronomers with the CO5BOLD code.

Just like stationary 1D model atmospheres, dynamical 3D models are used to analyse observed stellar spectra, allowing in addition to study the effects of temperature fluctuations and motions.

From these comparisons of observed and synthetic spectra, not only the properties of the stellar atmospheres themselves can be deduced, but also those of the interior and the outer envelope.

https://www.physics.uu.se/research/astronomy-and-space-physics/research/stars/model-atmospheres/

3D vs. 1D

if we want to consider the three-dimensional structure of the photosphere, taking into account inhomogeneity….the line profile changes because of the temperature variations

Asplund, M. 2005
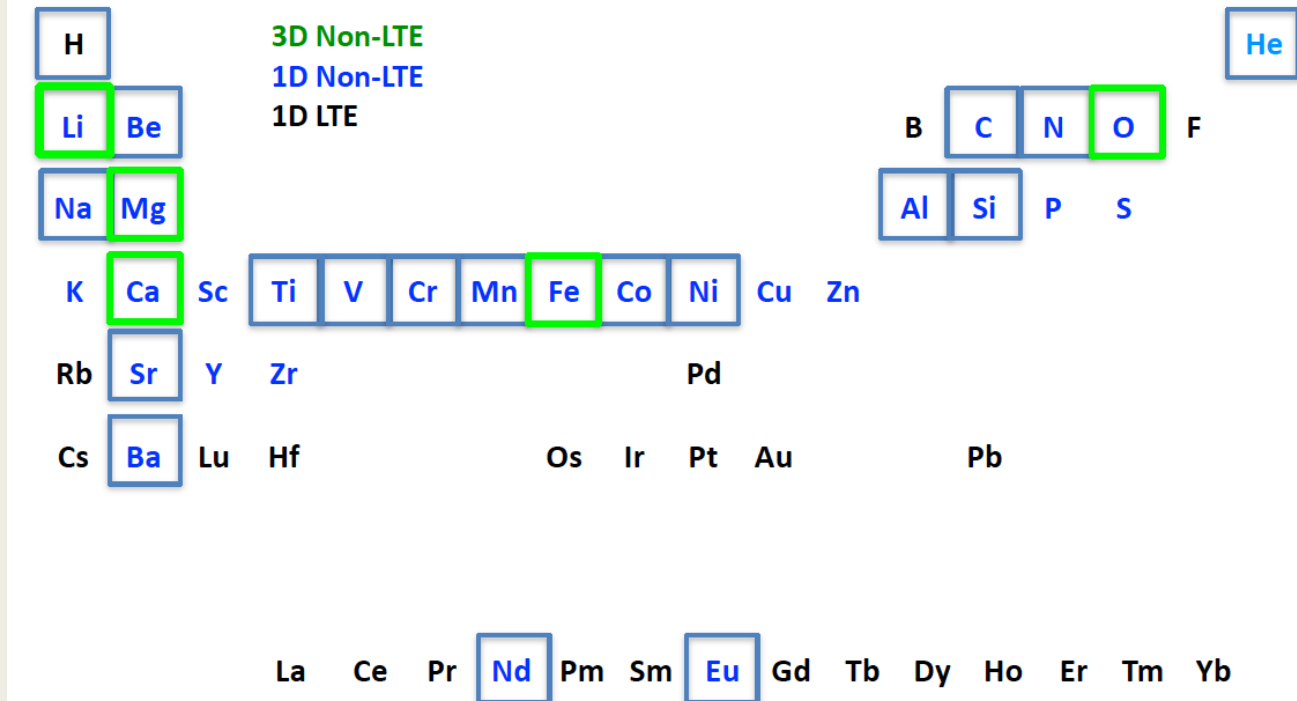Annu. Rev. Astron. Astrophys. 43: 481–530
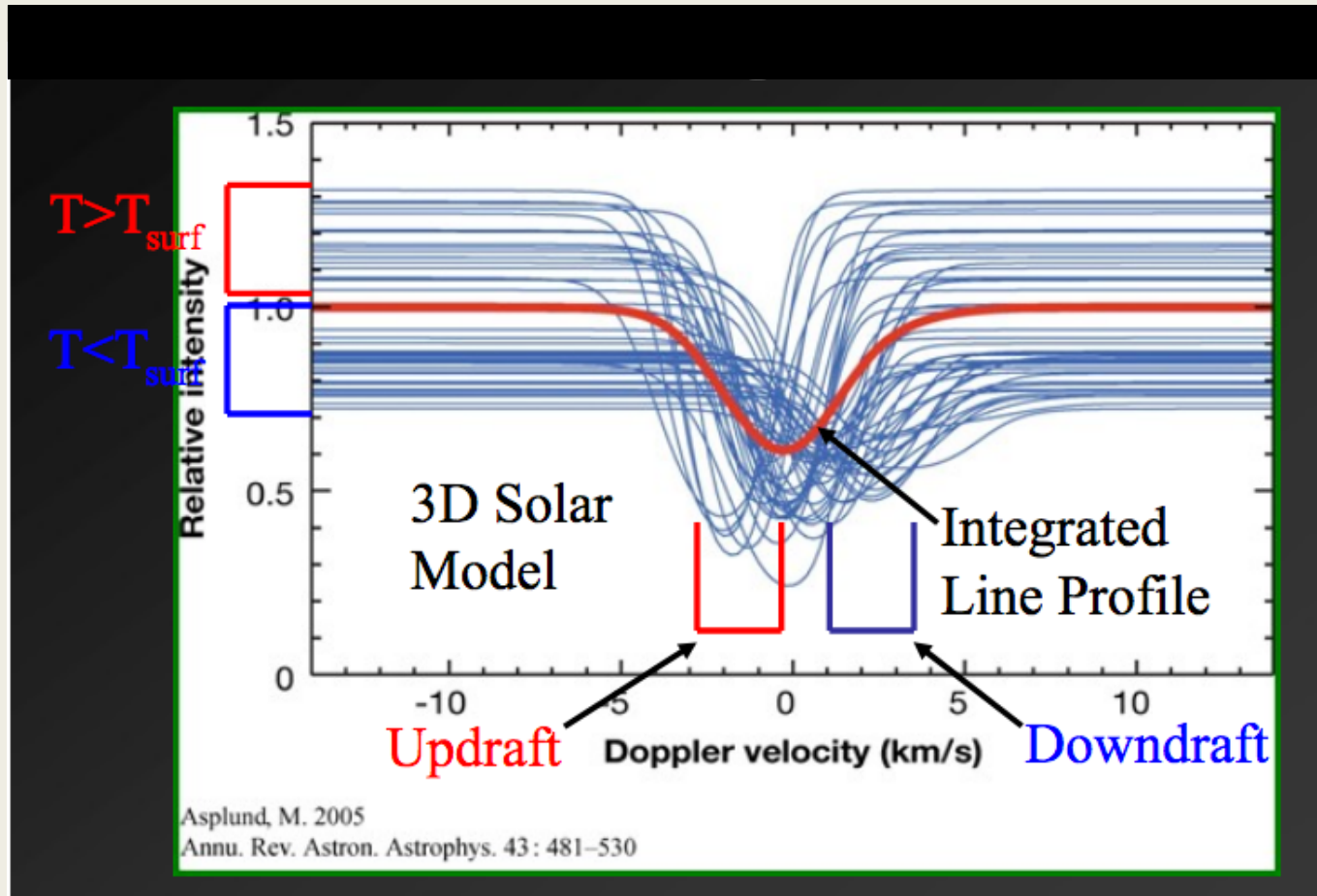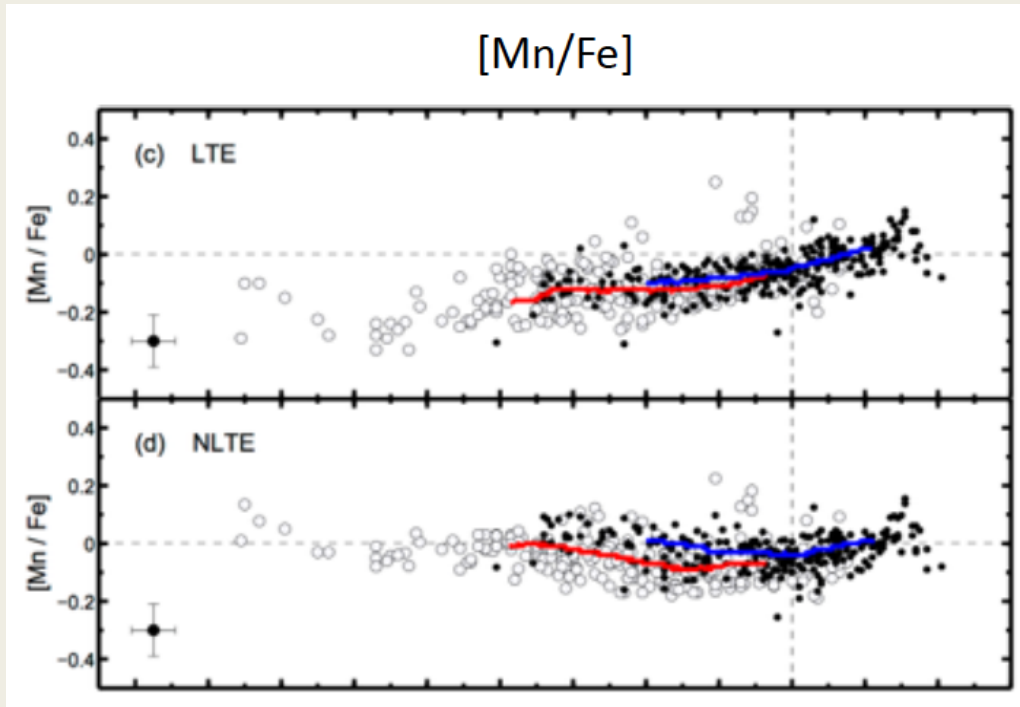
State-of-the-art

Figure from M. Bergemann

For a review on the effects of 3D and NLTE models:
New Light on Stellar Abundance Analyses: Departures from LTE and Homogeneity
M. Asplund
Annual Review of Astronomy and Astrophysics
Vol. 43:481-530 (September 2005)
https://doi.org/10.1146/annurev.astro.42.053102.134001

Effect of NLTE

[Mn/Fe]

(c) LTE

(d) NLTE

Battistini & Bensby (2015)

Our understanding of the mechanisms of production of some elements are related to incorrect abundance measurements

For instance, manganese:

• strong non-local thermodynamic equilibrium effects

• but excellent observational databases

Automactic methods for stellar abundances

Galactic archaeology aims to determine the evolution of the Galaxy from the chemical and kinematical properties of its individual stars.

This requires the analysis of data from large spectroscopic surveys, with sample sizes in tens of thousands at present, with millions of stars being reached in the near future.

Such large samples require **<u>automated analysis techniques</u>** and classification algorithms to obtain robust estimates of the stellar parameter values (and abundances).
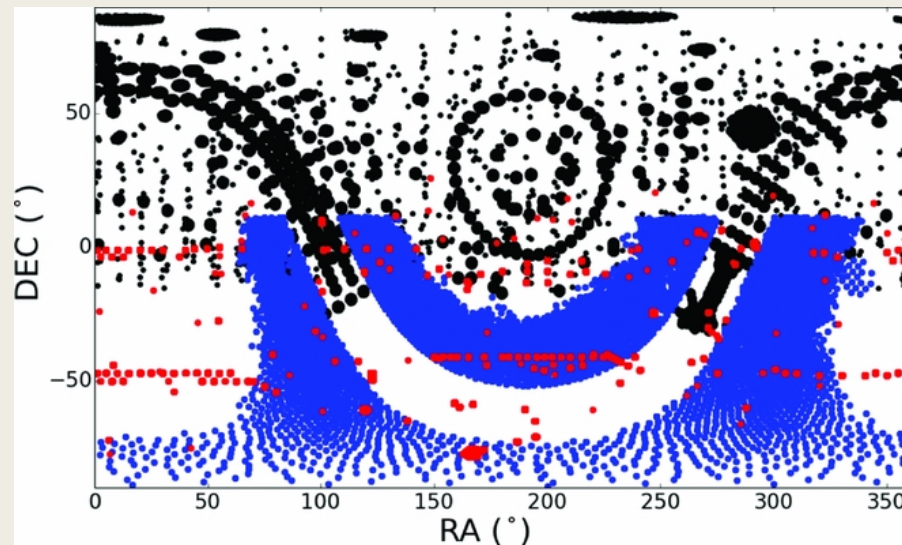
The sky coverage of three different galactic surveys: *APOGEE* (in black), *Gaia-ESO* (in red), and *GALAH* in blue.

Statistical methods for stellar abundances

- Methods based on the **measurement of the EWs** or on the **synthesis of single absorption lines**

- The determination of stellar parameters with these methods relies on the Boltzmann and Saha equations, and they are valid in the limits of LTE (and other approximations)

Pros:

- Stellar parameters and abundances measured with these methods have a **strong physical basis** (ionization and excitation equilibrium for the stellar parameters, curve of growth for the individual abundances)

Cons:

- They work better for high-resolution spectra (to avoid blends between lines, to measure continuum)

- Good knowledge of the atomic physics behind the line formation--> importance of a **proper line list**

New methods for stellar abundances

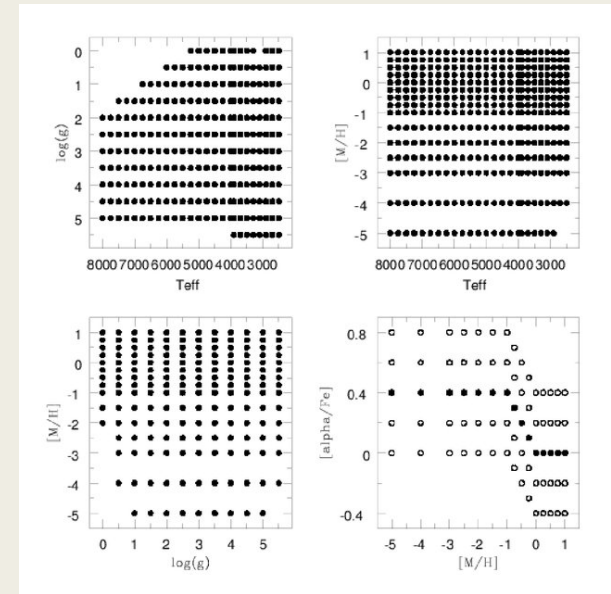**Grid of synthetic spectra: e.g. the Ambre project**

- Comparison of the observed spectrum with a grid of synthetic spectra

- x^2 minimization to find the 'closer' spectrum

- Determination of the stellar paramters

Pros:

- Full automatic and quick analysis

- Can work also at lower resolution

Cons:

- Degeneracy between temperature, gravity and metallicity in some regions of the parameter space

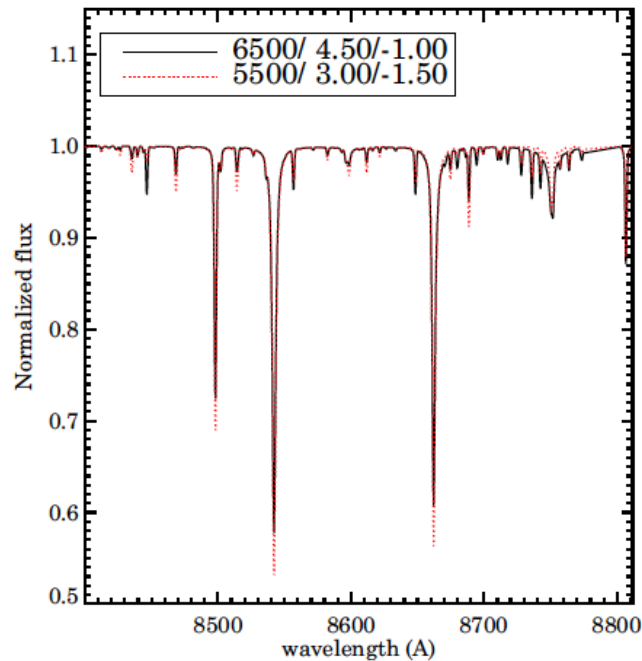- Need of a large spectral range (to avoid degeneracy)

AMBRE project:

designed to automatically analyse the spectral archives of the FEROS, UVES, HARPS and FLAMES instruments with the MATISSE algorithm

New methods for stellar abundances

Grid of synthetic spectra: e.g. the Ambre project

Using only the short spectral range of the spectrograph on board of the Gaia satellite, in some regions of the parameter space there is a strong degeneracy

Fig. 5. Noise-free synthetic spectra showing the degeneracy in parameter space between a hot dwarf star (black, solid line) and a cool giant (red dotted line). The spectra differ significantly only at the cores of the strong lines and at Pa12 (~8750 Å), but their wings differ weakly.

From Kordopatis et al. 2011

New methods for stellar abundances

Using Gaia information to break the degeneracy (for all methods)

From C.C. Worley
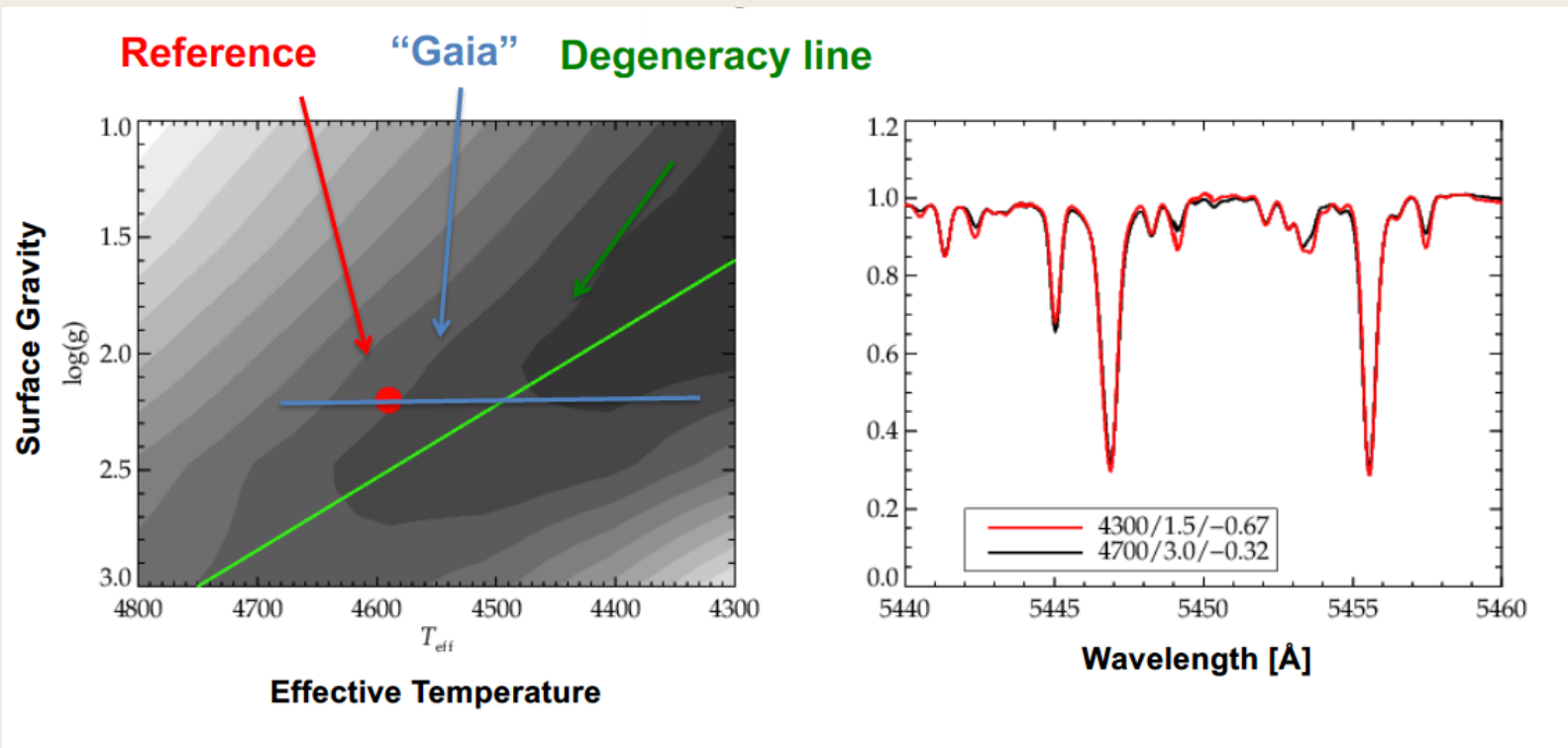
If unappreciated, degeneracies in stellar parameters can introduce biases and systematic errors in derived quantities for stars

- Gaia, measuring distance, can help to estimate the absolute luminosity of the stars, and thus their gravity
  → breaking the degeneracy (using the definition of surface gravity GM/R^2 and the Stefan-Boltzmann equation $L \propto R^2\, T^4$)

New methods for stellar abundances

Data driven methods: *The Cannon* (Ness et al. 2015)

- *The Cannon* is a data-driven method to determine stellar parameters and abundances (and more generally, stellar labels) for stars in large surveys.

- *The Cannon* relies on a subset of reference stars in the survey, with known labels. These labels can come from high resolution analyses from any wavelength regions and from comparisons with the most up to date stellar models.

- *The Cannon* then uses the reference objects with known labels to build a model that relates stellar labels to stellar flux at each wavelength.

- That model is then used to infer the stellar labels for the remaining stars in the survey (Ness et al. 2015).

- *The Cannon* is named after Annie Jump Cannon, who pioneered producing stellar classifications without physical models.

From The Data-Driven Approach to Spectroscopic Analyses, M. Ness

New methods for stellar abundances

Data driven methods: *The Cannon* (Ness et al. 2015)

Pros:

- Can be used to put together data from different surveys (if there are a good number of stars in both surveys to built up a common scale)

- Relates stellar flux to stellar labels (stellar parameters and abundances, but also mass and ages)

- Can be used to transfer label from high-resolution to low-resolution surveys

Cons:

- Need a good reference set (training set)

- Generally, you obtain the same kind of stars you put in the reference set

- The link with physics underlying the formation of stellar spectra is hidden (it is still there…in the training set…)

From The Data-Driven Approach to Spectroscopic Analyses, M. Ness

New methods for stellar abundances

Data driven methods: *The Cannon* (Ness et al. 2015)

→ Transferring the information from APOGEE survey (R~28000) to LAMOST (R~2000) with The Cannon
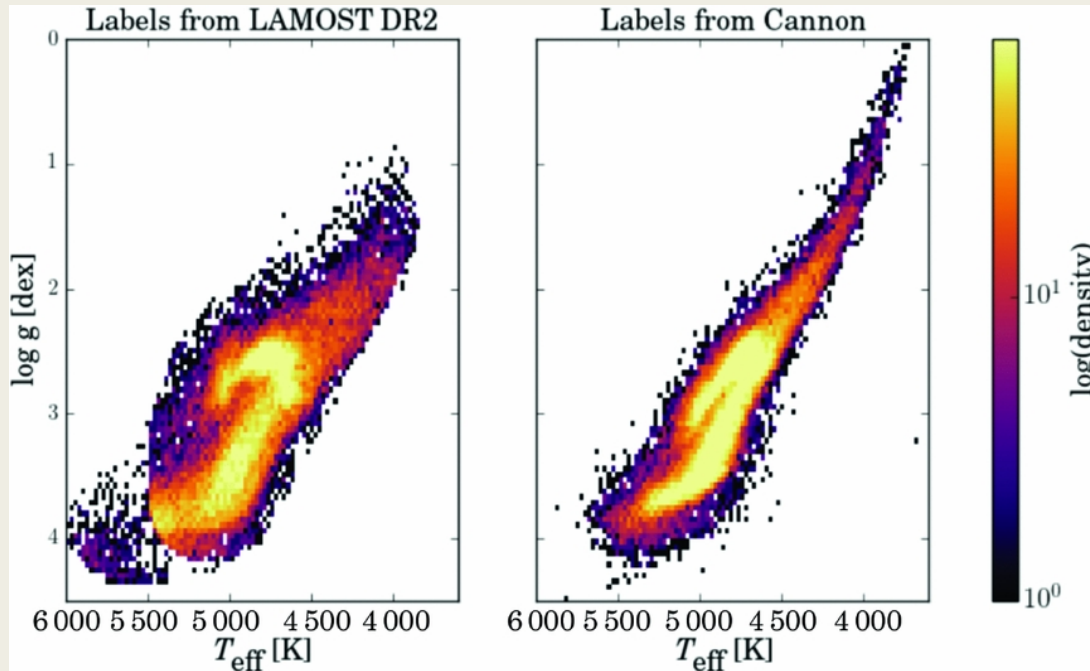
With the Cannon there are plans to put on the same scale (using stars in common):

- 300 000 SEGUE stars
- *GALAH* (which has currently observed 300 000 stars with the aim to observe 1 million stars)
- *APOGEE* (which has currently observed 300 000 stars with the aim to observe 450 000 stars)

From [The Data-Driven Approach to Spectroscopic Analyses](#), M. Ness

New methods for stellar abundances

Neural networks: Leung & Bovy (2019) and others (see also Fabbro et al. 2019)

Deep learning using artificial neural networks (ANNs) is getting increasing attention from astronomers, because of its great potential for data-driven astronomy and its recent successes in many fields such as computer vision, voice recognition, machine translation, etc.

Progress in ANNs in astronomy:

- Big data (large photometric –SDSS, LSST; astrometric –Gaia; spectroscopic –Gaia-ESO, APOGEE, LAMOST and future surveys, …)
- Cheap availability of fast computational hardware (graphics processing units (GPUs) → computer for gaming, which are also ideal for ANNs!)
- Advances in the methodology of ANNs
- Availability and accessibility of software platforms implementing this technology (free codes from ANNs, like **Tensorflow** (Abadi et al. 2016), **keras** (Chollett et al 2015), and **astroNN** (Leung & Bovy 2019))

The application to high-resolution spectra:

- With a training set of data (~1000 stars) analyzed with more traditional means, ANNs **can process high-resolution spectra faster and more reliably than other methods**

New methods for stellar abundances

Neural networks: Leung & Bovy (2019) and others (see also Fabbro et al. 2019)

There is no need to pre-program any knowledge in an ANN, i.e., neural networks consist of random weights at the initial training stage.

In order to achieve learning:

- error signals representing the agreement between the true output and the ANN output for (a subset of) the training set is back-propagated through the neural network;
- the connection strength of the synapses is adjusted to obtain better agreement between truth and prediction.
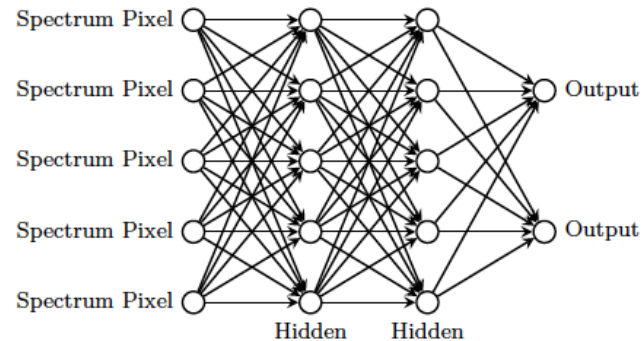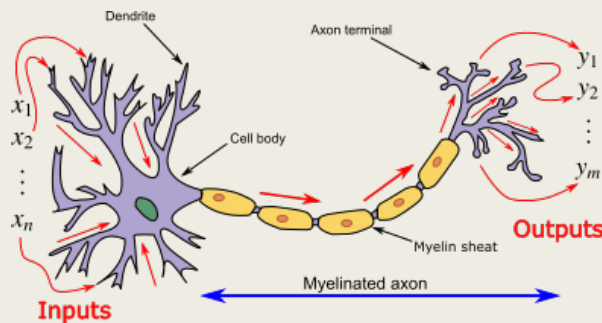

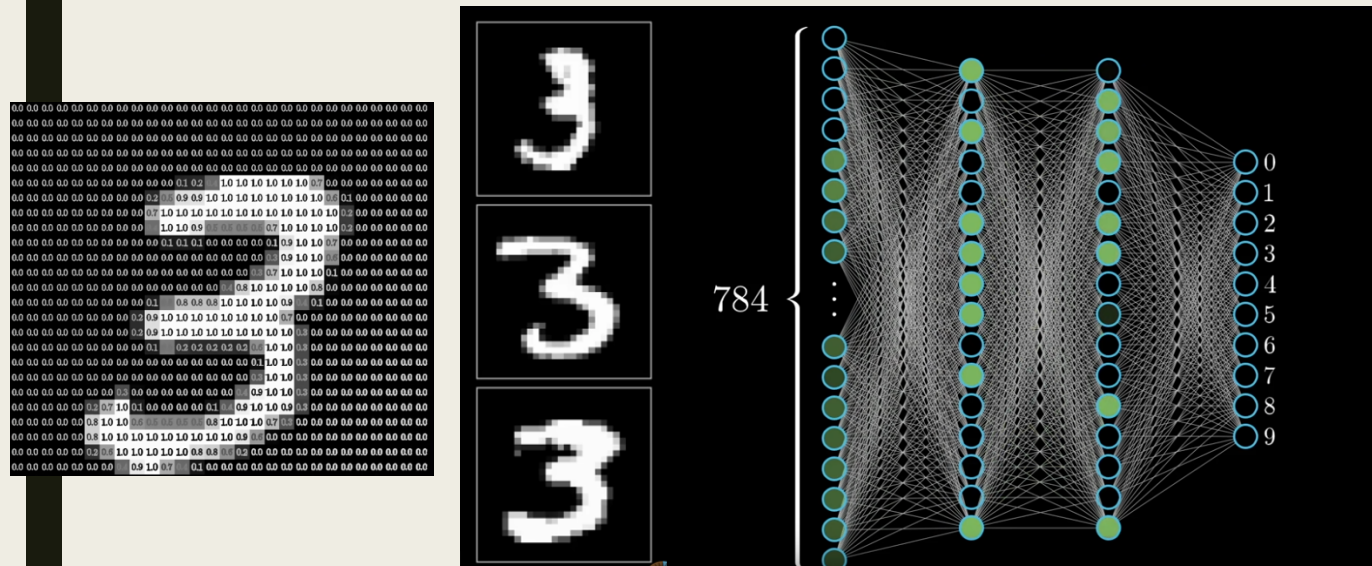**Figure 1.** A simple multilayer neural network.

- The ANNs 'learn' with the training set
- The ANNs is then applied to the whole set
- It can discover features and results that are unexpected

New methods for stellar abundances

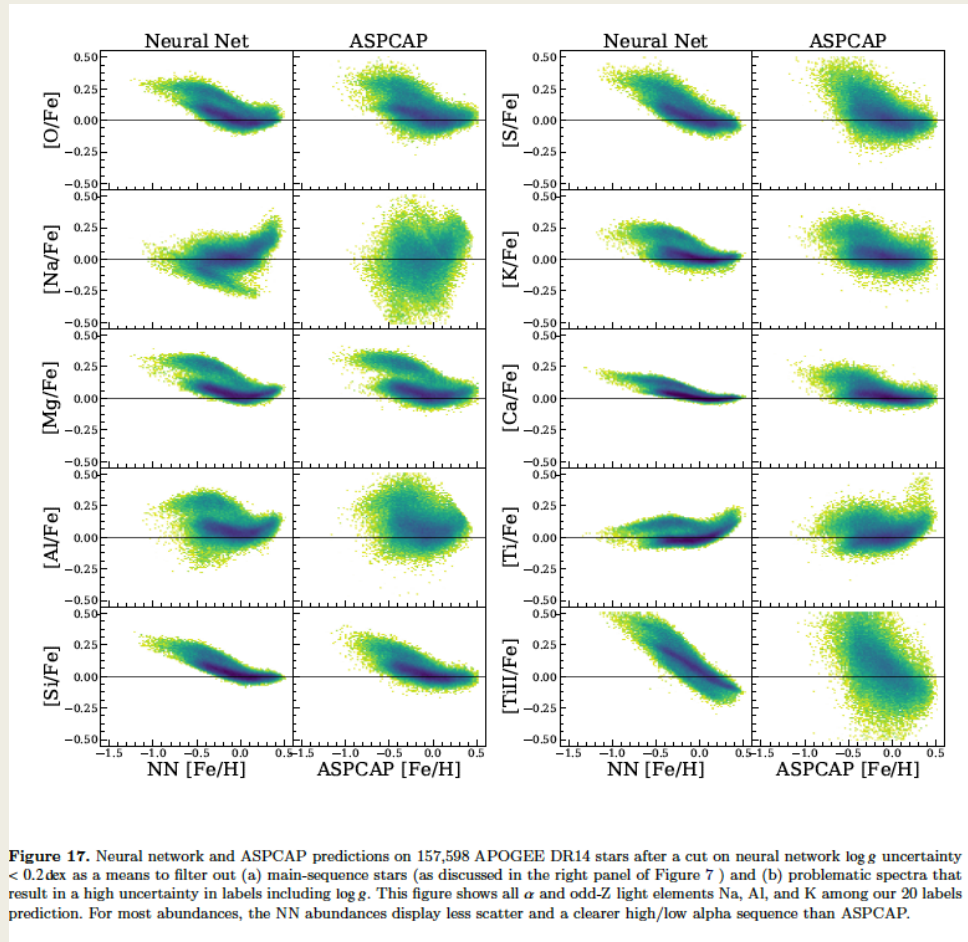**Neural networks: Leung & Bovy (2019) and others (see also Fabbro et al. 2019)**

- An example, to understand how neural nets work, is how our brain is able to recognize hand-written letter and numbers, and associate them with their 'true' value

- Similar to the work done by an ANNs to go from high-resolution spectra to low resolution spectra

Matrix to quantify how a hand-written digit can be associated with a number

New methods for stellar abundances

Neural networks: Leung & Bovy (2019)

Figure 17. Neural network and ASPCAP predictions on 157,598 APOGEE DR14 stars after a cut on neural network log *g* uncertainty < 0.2 dex as a means to filter out (a) main-sequence stars (as discussed in the right panel of Figure 7) and (b) problematic spectra that result in a high uncertainty in labels including log *g*. This figure shows all α and odd-Z light elements Na, Al, and K among our 20 labels prediction. For most abundances, the NN abundances display less scatter and a clearer high/low alpha sequence than ASPCAP.

- ANNs applied to the APOGEE sample

- Abundance ratios obtained with the neural net and with ASPCAP (pipeline of APOGEE for the abundances)

- For most elements the results of the neutral net are even tighter than the official results of APOGEE

New methods for stellar abundances

Neural networks and in general data driven methods

Pros and Cons:

- They are very similar to the ones of the other data driven methods

- We need always to start from a well calibrated training set

- In the training set we must transfer all our knowledge of stellar and atomic physics

→ So the physics (of stellar atmospheres) is still there, but is very hidden

→ When using the data-driven methods we should not forget which kind of objects we are dealing with

Now we know…

- How to measure stellar parameters from spectral analysis
- How to use equivalent widths of different elements and transitions to infer their abundance

….but

- We also know that in the standard analysis there are many simplifications (1D, LTE, etc.)
- New techniques are going towards more sophisticated 3D and NLTE analysis

..and

- For large samples we need to consider other methods
- Based on good training sets
- Data driven
- Fast and automatic

Measuring elemental abundance from stellar spectra is the input for the next step…understanding the chemical evolution of our Galaxy, acting as Galactic Archeologists.
But first, we want to know where/when/how the different elements are produced.