The Metallicity Ladder in Resolved Stellar Populations

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The (surface) chemical composition of a star

**Theoretical scale:**

Mass Fraction normalized to unity: \( X + Y + Z = 1 \)

- First stars in the Universe: 0.75 + 0.25 + 0
- Sun: 0.71 + 0.27 + 0.02

**Observational scale:**

\[
[Fe/H] = \log \frac{A(Fe)}{A(Fe)_\odot}
\]

with \( A(Fe) = \frac{N_{Fe}}{N_{H}} = \text{Nr of Fe atoms} / \text{Nr of H atoms} \)

**Conversion:**

\[
[M/H] = \log \frac{Z}{Z_\odot} = [Fe/H] \quad \text{only if Fe traces all the metals}
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The spectrum of a star

Continuum (Black Body) + Fraunhofer Lines

Increasing $T_{\text{EFF}}$
What is a blackbody?

**DEFINITION:**
A container that is completely closed except for a very small hole in one wall. Any light entering the hole has a very small probability of finding its way out again, and eventually will be absorbed by the walls or the gas inside the container: this is a perfect absorber - all light that enters the hole is absorbed inside.

Eventually the photon finds the hole again and gets out, but this happens only after a lot of bouncing against the walls, i.e., after many interactions with the box material. This is the definition of "thermodynamic equilibrium", a condition that is also fulfilled in (most of) the stellar atmospheres.

By heating the box, one “heats” also the photons in it, and the resulting energy (=frequency) distribution of the outcoming photons also changes, according to the following laws:

**Wien Law**

\[ \lambda_{\text{max}} = \frac{2.9 \times 10^{-3}}{T} \]

**Stefan-Boltzmann Law**

\[ F = \sigma T^4 \]
Spectral Resolution

Resolution is crucial in spectroscopy, not only to separate (resolve) individual spectral lines, but also to define continuum in crowded spectra (=metal rich stars, cold stars)

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However, for fixed exposure time, high R means low S/N, because you spread the same amount of signal over more pixels

And, for a fixed CCD camera, high R means small spectral range, because you have smaller Å/pix, and a fixed amount of pixels
Chemical Abundance determination from HR spectra

a red giant star in the Galactic bulge

Equivalent width (W or sometimes EW)

the width that the line would have if it were a rectangle.

EW (or W) is measured in mÅ
For small optical depths ($\tau_\nu << 1$) it can be demonstrated that:

$$W/\lambda = 8.85 \times 10^{-13} N_i \cdot f_\lambda \cdot \lambda$$

where:

- $N_i$ = column density of element
- $f_\lambda$ = oscillator strength (sort of a transition probability for that line)

[pg. 206 “Atomic Astrophysics and Spectroscopy” Pradhan & Nahar]
From EWs to Abundances

How many atoms of a given element can contribute to a given line?
From EWs to Abundances

How many atoms of a given element can contribute to a given line?

The problem is greatly simplified by the assumption of Local Thermodynamical Equilibrium:

1) The distribution of kinetic energies follows the **Maxwell law**
   
   $f(v) = 4\pi v^2 \left( \frac{m}{2\pi KT} \right)^{3/2} \exp \left( -\frac{mv^2}{2KT} \right)$

   this tells you how many atoms change level due to collisions [they do not produce a line]

2) The distribution of photon energy follows the **Planck’s law**
   
   $B_\nu(T) = \frac{2\nu^3}{c^2} \frac{1}{e^{\nu/kT} - 1}$

   this tells you how photons of a given $\lambda$ (or $\nu$) are available

3) The distribution of electrons among different excitation states follows the **Boltzmann equation**
   
   $\frac{N_i}{N_j} = \left( \frac{g_i}{g_j} \right) \exp \left( -\frac{(E_i - E_j)}{KT} \right)$

   this tells you how many electrons there are in different atomic levels

4) The distribution of atoms among different ionization states follows the **Saha equation**
   
   $\log \frac{N_I}{N_0} = \log \frac{u_I}{u_0} + 2.5 \log T - \frac{5040}{T} \chi_{\text{ion}} - \log P_e - 0.176$

   this tells you how many atoms are ionized
The model atmosphere

what is it? why do we need one?

gives T and $P_e$ of the visible layers of the stellar atmosphere together with its opacity.

hot
hotter
much hotter
way much hotter

100%
70%
30%
1%
The model atmosphere

gives $T$ and $P_e$ of the visible layers of the stellar atmosphere together with its opacity.

Bound-Bound absorption: small - except at those discrete wavelengths capable of producing a transition. i.e., responsible for forming absorption lines. Bound-Free absorption: photoionisation - occurs when a photon has sufficient energy to ionize an atom. The freed $e^-$ can have any energy, thus this is a source of continuum opacity.
Free-Free absorption: a scattering process. A free electron absorbs a photon, causing the speed of the electron to increase. Can occur for a range of $\lambda$, so it is a source of continuum opacity.
Electron scattering: a photon is scattered, but not absorbed by a free electron. A very inefficient scattering process only really important at high temperatures - where it dominates.
The iron distribution of a complex stellar population

In order to derive the Metallicity Distribution Function (MDF) of a SP it is necessary to select a target box that includes stars of all the metallicities present in the system.

One should also make sure that targets are ~ evenly distributed within the box.
The iron distribution of a complex stellar population

Saha et al. (2019)

Optical Spectra

$T_{\text{eff}} = 7325 \text{K}$

HD 2628, A7 III (logg = 3.57)

HD 2665, G5 III (logg = 2.35)

HD 2211 (logg = 2.63)

$T_{\text{eff}} = 5013 \text{K}$

$T_{\text{eff}} = 4731 \text{K}$

$T_{\text{eff}} = 3467 \text{K}$

HD 18478 (logg = 0.60)

K0 III

M4 III

Saha et al. (2019)
The iron distribution of a complex stellar population

Optical Spectra

Saha et al. (2019)

nearIR spectra

Fig. 6.— An image showing continuum normalized APOGEE spectra as a function of stellar spectral type. The earlier spectra are in the K band, while the later spectra are in the M band.
The Metallicity Distribution of the Galactic bulge

**GIBS**: MZ et al. (2017)

- $b \sim -1$
  - MP/tot = 0.53
- $b \sim -2$
  - MP/tot = 0.49
- $b \sim -3.5$
  - MP/tot = 0.33
- $b \sim +4.5$
  - MP/tot = 0.45
- $b \sim -6$
  - MP/tot = 0.51
- $b \sim -8.5$
  - MP/tot = 0.73


**ARGOS**: Ness et al. (2013)
The Metallicity Distribution of the Galactic bulge

MUSE @ VLT
2 hours exposure  1500 stars