Non-LTE stellar parameters and abundances of metal-poor stars in the Galaxy

Rana Ezzeddine
(JINA-CEE /MIT postdoctoral fellow)

Photo: Magellan Twin Telescopes
credit: Yuri Beletzky
Refresher: What are Metal-poor stars?

- Stellar Archeology: uses stellar relics of the early universe.
- Most metal-poor stars preserve records of “First” Population III stars in their atmospheres.

Cosmic Timeline (Not to Scale)

- low mass Pop II (metal-poor) stars still around
- low mass (0.6-0.8\(M_\odot\)) metal-poor stars
- First Supernovae
- massive First Stars
- First Galaxies
- Pop I and Pop II stars in the Milky way

Now: 13.7 Gyrs

~1 Gyr

~300 Myrs

0 s
Refresher: What are Metal-poor stars?

Astronomers’ Periodic Table

<p>| | | | | | | | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>H: X</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>He: Y</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

With time, more and more of all elements were made!
Refresher: What are Metal-poor stars?

- **Metal-poor**
  
  
  $\text{[Fe/H]} < -1$

- **Very metal-poor (VMP)**
  
  $-3 < \text{[Fe/H]} < -2$

- **Extremely metal-poor (EMP)**
  
  $-4 < \text{[Fe/H]} < -3$

- **Ultra metal-poor (UMP)**
  
  $-5 < \text{[Fe/H]} < -4$

- **Hyper metal-poor (HMP)**
  
  $\text{[Fe/H]} < -5$

- **Mega metal-poor (MMP)**
  
  $\text{[Fe/H]} < -7$ (Keller star 2014)

- **Ridiculously metal-poor**
  
  $\text{[Fe/H]} < -10$

*Beers & Christlieb (2005)*

*Frebel (2018)*
Abundances are not measured BUT determined using approximations:

- Plane-parallel vs. spherical
- Homogeneity
- Stationarity
- Hydrostatic equilibrium
- 1D vs. 3D atmospheres

- Local thermodynamic equilibrium (LTE)

B. Gustafsson, Astronomical Observatory, Uppsala (2009)
REFRESHER: SPECTRAL LINE FORMATION

LTE

- Matter assumed in equilibrium with the radiation field over a finite volume of gas.
- Properties of gas defined by one $T$ at each depth.
REFRESHER: SPECTRAL LINE FORMATION

- **LTE**
  - Matter assumed in equilibrium with the radiation field over a finite volume of gas.
  - Properties of gas defined by one $T$ at each depth.

- **Non-LTE**
  - Photons carry non-local information: Everything depends on everything, everywhere else!

![Diagram showing energy levels and interactions](image)

- Radiative Interaction
- Collisional Interaction
LTE VS NLTE

**LTE**

Fe I

1 line : 1 transition

1 line : 1 transition
LTE VS NLTE

**LTE**

Fe I

1 line : 1 transition

**NLTE**

Iron model atom - Fe I radiative transitions

1 line : 81,162 transitions!

Rana Ezzeddine, PhD, 2015

FORMATO2.0 (Merle et al. in prep)
LTE VS NLTE

LTE

Fe II

1 line : 1 transition

nlow

nhigh
LTE VS NLTE

LTE

1 line : 1 transition

NLTE

Iron model atom- Fell radiative transitions

1 line : 56,981 transitions

Rana Ezzeddine, PhD, 2015
FORMATO2.0 (Merle et al. in prep)
NON-LOCAL THERMODYNAMIC EQUILIBRIUM EFFECTS

departure coefficient = \frac{\text{level population density (NLTE)}}{\text{level population density (LTE)}}

Deviations from LTE increase toward lower metallicities
20 Standard metal-poor halo stars

Ezzeddine et al. (in prep)
NLTE EFFECTS : IRON

Departure from LTE can be severe toward the most metal-poor stars!

\[ \Delta [\text{Fe/H}] = -0.14 \times [\text{Fe/H}]_{\text{LTE}} - 0.15 \]

Ezzeddine et al. (2017)
NLTE EFFECTS : IRON

Departure from LTE can be severe toward the most metal-poor stars!

\[
\Delta [\text{Fe/H}] = -0.14 \times [\text{Fe/H}]_{\text{LTE}} - 0.15
\]

Applies well to less metal-poor stars

\[ \text{Effective temperature} \]

\[ T_{\text{eff}} \]

\[ \text{Fe/H} \]
Agreement between Ca I and Ca II in NLTE vs. LTE in UMP stars! This highlights that NLTE works for extreme cases as well as less metal-poor stars!
TAKE AWAY POINTS

- Stellar abundances are only as good as our models
- Departures from LTE abundances in metal-poor stars can be severe
- Accurate modeling of atmospheres in iron-poor stars (NLTE) is important. Ignoring NLTE effects can:
  - overestimate $T_{\text{eff}}$ ~ 50-600 K
  - underestimate log g ~ 0.2 - 1 dex
  - underestimate [Fe/H] ~ 0.2 - 1.0 dex
  - underestimate [Mg/H] up to 0.5 dex
  - underestimates [Ca/H] from Ca II lines up to 0.5 dex
- NLTE effects important to include in abundance determinations of large samples, i.e., large spectroscopic surveys. Possible with our new dense NLTE metal-poor abundance grid! If interested, talk to me on coffee break :)
3D important for CNO elements: large 3D effects
STEELAR ATMOSPHERES ASSUMPTIONS: IS 1D OKAY VS 3D?

Amarsi et al. (2016)

1D

3D

NLTE

LTE

1D, NLTE better than 3D, LTE!