Poster Winners

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Mega (metal-poor) not so much : Non-LTE spectroscopic stellar parameters and abundance determination of Ultra metal-poor stars

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Abstract. We present Non-Local Thermodynamic Equilibrium (Non-LTE) abundance corrections for Mg, Ca, and Fe in 12 ultra metal-poor (UMP) stars ([Fe/H] < -4.00). We show that they increase in absolute value toward the lower metallicity up to 0.45 dex for Mg, 0.30 dex for Ca, and 1.00 dex for Fe. This represents a first step toward a full Non-LTE analysis of chemical species in the UMP stars that will enable us to put useful constraints on the properties of the "First" stars.

Keywords. line: formation, stars: abundances, stars: atmospheres, stars: fundamental parameters, stars: Population II

1. Introduction

Chemical elements from the "First" (Population III, or Pop III) stars were ejected at the end of their lifetimes into the interstellar medium and gas forming clouds from which the subsequent Pop II stars were formed (Bromm 2013). Extremely low in metals ([Fe/H] < -3.00, Beers & Christlieb 2005), these low-mass Pop II stars are still around and are thus the rare fossils of the earliest stars, with imprints of their chemical compositions in their atmospheres (Frebel & Norris 2015). A small number of Ultra Metal-Poor (UMP) stars ([Fe/H] < -4.00) have been detected so far (some are listed in Ezzeddine *et al.* 2017). They can be used to directly understand and constrain the Initial Mass Function (IMF) and properties of Pop III stars and first Supernovae (e.g. Tominaga *et al.* 2014). This is done by comparing their abundance patterns to nucleosynthesis yields of Pop III supernova explosions. This highly depends on their derived chemical abundances (e.g. Placco *et al.* 2015, Nordlander *et al.* 2017), which in turn depends on the radiative transfer models and model atmosphere assumptions used in the abundance calculations.

A common practice in chemical abundance studies is the assumption of Local Thermodynamic Equilibrium (LTE) in stellar atmospheres. This condition is mostly valid in collisionally-dominated stellar atmospheres. This is not the case for metal-poor stars, which due to the paucity of metals (electron donors) in their atmospheres, are radiatively dominated. A full Non-Local Thermodynamic Equilibrium (Non-LTE) analysis is thus required.

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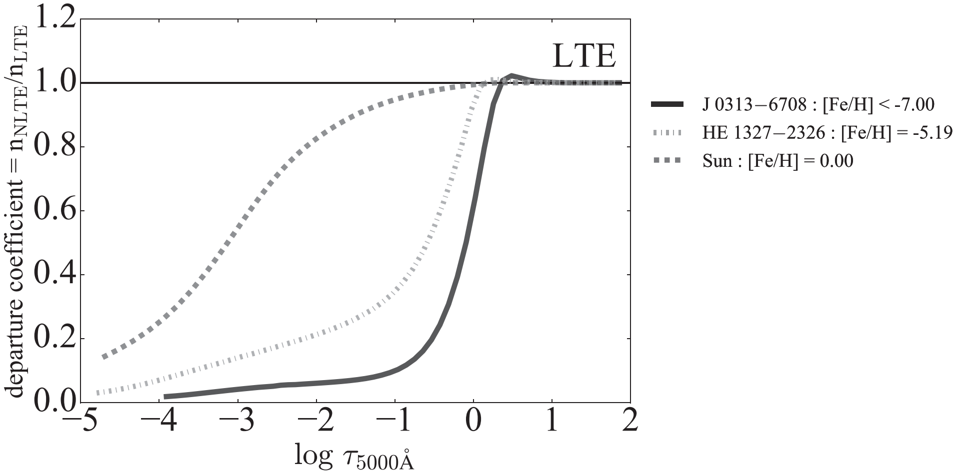

Figure 1. Comparison of departure coefficients of the Fe I ground level as a function of the optical depths log τ_{5000} for the Sun and two UMP stars SMSS J0313−6708 and HE 1327−2326. Departures from LTE are more severe in the UMP stars than in the Sun.

Many studies (Mashonkina *et al.* 2011, Zhao *et al.* 2016, Amarsi *et al.* 2016, Ezzeddine *et al.* 2017) have shown that metal-poor stellar atmospheres can deviate strongly from LTE. This is shown in Figure 1, where the departure coefficients† of the Fe I ground level are represented for the Sun and two UMP stars SMSS J0313−6708 ([Fe/H] < -7.00) and HE 1327−2326 ([Fe/H] $= -5.19$). The departure from LTE as a function of optical depths at 5000 Å (log τ_{5000}) increases toward the lower metallicity stars as compared to the Sun. The Fe I ground level populations in the UMP stars are overpopulated relative to their LTE populations in the line forming region (log $\tau_{5000} \sim -2.0$).

This work is carried out within the project "A uniform non-LTE spectroscopic study of Ultra Metal-poor stars" (Ezzeddine *et al.* 2017, Sitnova *et al.* in prep.) whose aim is to constrain the properties of Pop III stars (IMF, SN explosion energies, early chemical evolution, ..). We present below the Fe, Mg and Ca Non-LTE abundance corrections ($\varepsilon_{\rm Non-LTE} - \varepsilon_{\rm LTE}$) in 12 UMP stars.

2. Method

Non-LTE atmospheric stellar parameters ($T_{\rm eff}$, log g, [Fe/H] and ξ_t) were first determined using individual Fe I and Fe II Non-LTE abundances whenever available following Ezzeddine *et al.* (2017). Consequently the Fe Non-LTE corrections Δ[Fe/H] $=$ $[{\rm Fe/H}]_{\rm NLTE} - [{\rm Fe/H}]_{\rm LTE}$, were determined based on the average abundance differences between LTE and Non-LTE from all individual Fe lines. The Mg and Ca corrections, Δ[Mg/H] and Δ[Ca/H], were similarly obtained from individual Mg I and Ca I lines.

The coupled radiative transfer and statistical equilibrium equations were solved based on the accelerated lambda iteration method (Rybicki & Hummer 1991,1992). 1D MARCS model atmosheres (Gustafsson *et al.* 1975,2008) were used. The DETAIL code (Butler & Griddings 1985) was used for Mg and Ca, while MULTI2.3 (Carlsson 1986,1992) was used for Fe. The opacity package in DETAIL was updated as described by Mashonkina

† The ratio of the Non-LTE level population to its LTE counterpart ($b^i = n^i_{\rm Non-LTE}/n^i_{\rm LTE}$) for an atomic level i.

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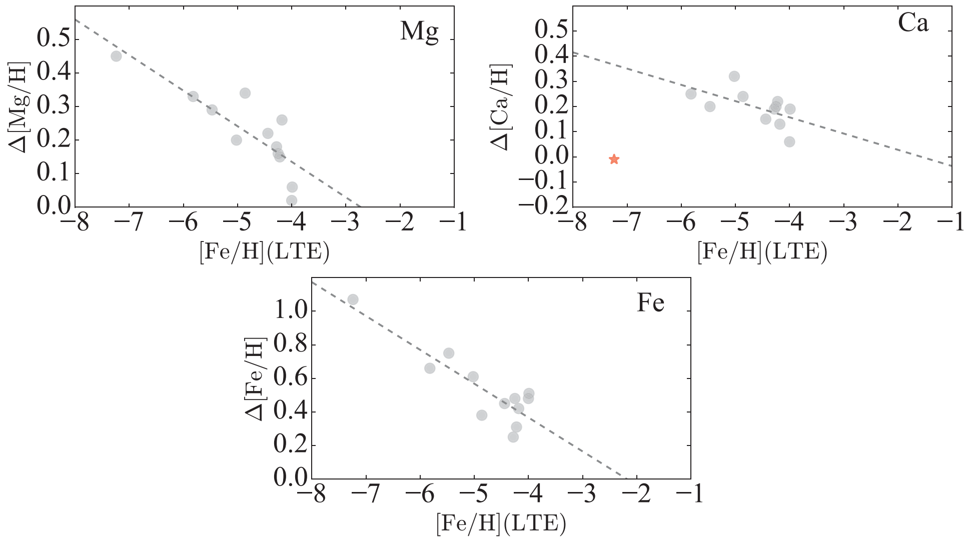

Figure 2. Non-LTE abundance corrections for Mg, Ca and Fe in 12 UMP stars as a function of [Fe/H](LTE). The corrections show increasing trends toward lower metallicities (dashed lines). The red star in the second panel is the correction obtained for SMSS J0313−6708 from Ca II lines (Δ[Ca II/H] = −0.01).

et al. 2011. Line background opacity was included in MULTI2.3 based on the MARCS opacity package.

NLTE calculations for Mg and Ca were performed using the methods presented by Mashonkina (2013) & Mashonkina *et al.* (2017) respectively, where accurate data on inelastic collisions with hydrogen atoms from Barklem *et al.* (2012) and Mitrushchenkov *et al.* (2017) were applied. The NLTE calculations for Fe are based on the work done in Ezzeddine *et al.* (2017).

Abundances are based on equivalent widths for Fe and spectral synthesis for Mg and Ca. The theoretical spectra for Mg and Ca are computed with the code SYNTHV-NLTE (Ryabchikova *et al.* 2015) that uses the departure coefficients from DETAIL. In turn, SYNTHV-NLTE is integrated within the IDL BINMAG3 code† written by O. Kochukhov, allowing to determine the best fit to the observed line profiles.

3. Non-LTE effects on Fe, Mg and Ca

The NLTE corrections for Mg, Ca and Fe for the 12 UMP stars are shown in Figure 2 as a function of [Fe/H](LTE).

The corrections show increasing trends toward decreasing [Fe/H](LTE), in agreement with previous studies. The corrections are up to 0.45 dex for Mg, 0.30 dex for Ca and 1.00 dex for Fe. This can be understood as due to the shift of the ionization-recombination balance towards more efficient ionization at lower metallicities, thus de-populating the lower levels relative to LTE (Mashonkina *et al.* 2011, Lind *et al.* 2012). It is important to note that the corrections can also be dependent on other stellar parameters especially $T_{\rm eff}$ and $\log g$. Such dependencies are further investigated e.g. in Sitnova *et al.* 2015. Further details of this work will be presented in coming publications.

† `http://www.astro.uu.se/~oleg/download.html`

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4. Conclusions

We present Non-LTE calculations for Mg, Ca and Fe in 12 UMP stars of [Fe/H] < -4.00 using comprehensive and up-to-date atomic models. Large departures from LTE were found, with Δ[Mg/H], Δ[Ca/H] and Δ[Fe/H] up to 0.45 dex, 0.32 dex and ~ 1 dex, respectively. The corrections show strong linear correlations with [Fe/H](LTE), with increasing trends toward lower metallicities.

These results provide an important step towards a full Non-LTE analysis of chemical species in the UMP stars to put useful constraints on Pop III star properties by comparing the stellar Non-LTE abundances to Pop III SN explosion yields.

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