The General Assembly of Galaxy Halos: Structure, Origin and Evolution
Proceedings IAU Symposium No. 317, 2015
A. Bragaglia, M. Arnaboldi, M. Rejkuba & D. Romano, eds.
doi:10.1017/S1743921315006791

Impact of NLTE on research of early chemical enrichment of the dwarf galaxies

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Abstract. Based on high-resolution observed spectra, the non-local thermodynamic equilibrium (NLTE) line formation, and precise stellar atmosphere parameters, we present the first complete sample of dwarf spheroidal galaxies (dSphs) with accurate chemical abundances in the very metal-poor (VMP) regime. The obtained stellar elemental ratios are compared with chemical enrichment models, and we show that NLTE is a major step forward for studies of the dSph and the Milky Way (MW) chemical evolution.

Keywords. stars: abundances, galaxies: abundances, galaxies: dwarf, galaxies: evolution

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Studies of chemical abundances of VMP stars provide important clues for better understanding the early chemical enrichment processes of the host galaxy and the onset of star formation. Our research concerns the dSphs orbiting the Milky Way, where individual stars accessible for high-resolution spectroscopy are all giants. The classical LTE assumption commonly applied to stellar abundance analyses is, in particular, questionable for such objects. We aim to revise the chemical abundances of a complete sample of VMP stars in the classical dSphs Sculptor, Sextans, and Fornax and in the ultra-faint dwarf (UFD) galaxy Boötes I based on the NLTE line formation and to test chemical enrichment models. The same methods were used to derive abundances of the MW halo comparison sample.

NLTE calculations were performed for a number of chemical species, using our original model atoms. Inelastic collisions with H I atoms were treated applying accurate rate coefficients for Na I, Mg I, Al I, and Si I and the scaled Drawin formula for the remaining species. In the relevant stellar parameter range, NLTE leads to strengthened lines and negative NLTE abundance corrections for Na I, but to weakened lines and positive corrections for all other chemical species. The amount of NLTE correction varies according to the different species and depends on atmospheric parameters.

The stellar sample includes 10 members of the Scl, Fnx, and Sex dSphs observed by Tafelmeyer *et al.* (2010) and Jablonka *et al.* (2015, JNM15) and 7 Boötes I stars from Norris *et al.* (2010) and Gilmore *et al.* (2013). For comparison with the MW halo, nine cool VMP giants were selected from Cohen *et al.* (2013, CCT13), and three stars from our previous studies. For Boötes I and CCT13 we rely on the published equivalent widths.

Stellar atmosphere parameters. This study is based on non-spectroscopic $T_{\rm eff}$ and log g. The effective temperatures were derived from photometry in the original papers. For the Scl, Fnx, and Sex stars the accurate determination of log g takes advantage of the known distance. We show that, when applying NLTE, the Fe I/Fe II and Ti I/Ti II ionisation equilibria are fulfilled using the adopted $T_{\rm eff}$/log g for all stars, except for the two most

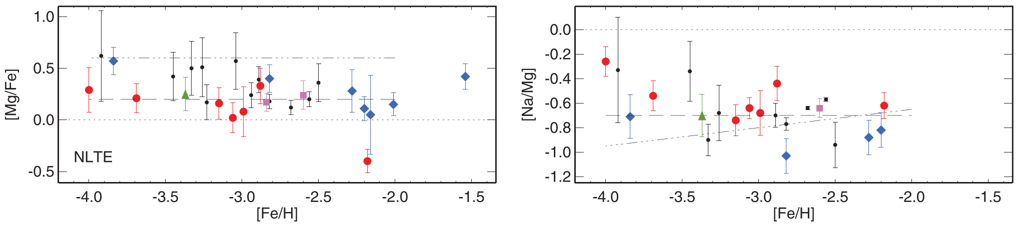

Figure 1. [Mg/Fe] and [Na/Mg] NLTE ratios of stars in the Sculptor (circles), Sextans (squares), Fornax (triangles), and Boötes I (rhombi) dSphs and the MW halo (small circles). The dashed and dash-three-dotted lines indicate the yields of a single supernova of 14.4 $M_{\odot}$ (Lai *et al.* 2008) and the MW chemical evolution calculations of Kobayashi *et al.* (2011), respectively.

MP stars, with [Fe/H] $\leqslant -3.7$. The problem may lie with only two Fe II lines detected and the uncertainty in $T_{\rm eff}$. To make the Fe I and Fe II NLTE abundances agree, their $T_{\rm eff}$ should be increased by 170 and 200 K respectively. The log g of the Boötes I and CCT13 stars were estimated from the YY isochrones at 12 Gyr. We revised log g upward by 0.28 dex for Boo-94 and by 0.1-0.2 dex for the CCT13 stars according to the Fe I/Fe II ionisation equilibrium in NLTE. With respect to the metallicity scale derived from Fe I lines under the LTE assumption, NLTE leads to a shift of +0.2-0.34 dex.

NLTE elemental ratios. Part of our results are displayed in Fig. 1. In line with the previous LTE studies, we find that the dSphs show enhanced Mg and Ca relative to Fe in the VMP regime, with Mg/Fe and Ca/Fe ratios that are similar for different dSphs and similar to those for the MW halo. We improve the average ratios for each galaxy: [Mg/Fe] = 0.18, 0.20, 0.25, 0.26, and [Ca/Fe] = 0.52, 0.36, 0.42, 0.36 for the Scl, Sex, Fnx, Boö I dSphs, respectively. Note that the Scl star ET0381 ([Fe/H] = −2.18) was excluded from the mean ratios (see JNM15 for detailed discussion). Unlike previous studies, Ti is found to follow Fe and reveal no enhancement, within the error bars. NLTE is crucial for accurate determination of elemental ratios involving Na and Al. In NLTE, galaxies with different masses show very similar [Na/Mg] ratios at [Fe/H] > -3.8, while in LTE, they show much less consistent ratios, and the scatter of [Na/Mg] is twice larger in each individual galaxy. Furthermore, [Na/Al] ratios obtained in NLTE are close to solar for galaxies with different masses, while in LTE, Na is strongly enhanced relative to Al, with [Na/Al] > 0.5.

Comparing our results with the nucleosynthesis models (Fig. 1), we conclude that the intermediate-mass (14.4 $M_{\odot}$) SNeII were the dominant source of early chemical enrichment in classical dSphs. For the Boötes I UFD, the statistics of the [Fe/H] $\simeq -3$ stars should be increased.

Acknowledgements. L.M. thanks a support from the International Astronomical Union, the Swiss National Science Foundation (SCOPES project IZ73Z0-152485), the Russian Foundation for Basic Research (14-02-91153-GFEN) of the participation at IAUS317.

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https://doi.org/10.1017/S1743921315006791 Published online by Cambridge University Press