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MANIFESTATION OF STELLAR EVOLUTION IN METAL-DEFICIENT STARS

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ABSTRACT. Metal-poor stars allow us to establish the early history of the Milky Way, furthermore the stars on advanced evolution stage (e.g. giants, AGB stars etc.) give the opportunity to research the peculiarities of stellar evolution at low metallicity. On the base of the 11m Southern African Large Telescope (SALT) spectra obtained using HRS fibre-fed echelle-spectrograph during 2018 -2020, the atmospheric parameters and elemental abundances of four metal-poor stars HE 1523-0901, HD 6268, HD 121135, and HD 195636 ([Fe/H] ~ -1.5 – -3.0) have been obtained. The iron abundance was determined based on the equivalent widths of absorption lines. The carbon abundance was obtained using the molecular synthesis fitting for the CH (4300-4330 ÅÅ) region, nitrogen from CN at 3883 Å, oxygen from [O] line at 6300 Å and IR triplet at 7770 Å The relationship between the chemical enrichment of stars and their stellar evolution is considered. It may be associated with the processes of mixing inside the stars, and the mechanisms of matter transfer during stellar evolution.

Keywords: stars: abundances – stars: atmospheres – stars: Population II – stars: stellar evolution.

АНОТАЦІЯ. Зорі з бідним вмістом металів дозволяють нам встановити ранню історію Чумацького Шляху, але зорі на просунутій стадії еволюції (наприклад, гіганти, зорі AGB тощо) дозволяють нам вивчати особливості еволюції зір при низькій металевості. На основі спектрів, отриманих за допомогою ешелле-спектрографа з волоконним живленням HRS південноафриканського Великого телескопа (SALT, 11 м) у 2018–2020 рр., досліджено параметри атмосфери та вміст елементів чотирьох бідних на метали зір HE 1523-0901, HD 6268 HD 121135 і HD 195636 ([Fe/H] ~ -1,5 – -3,0) досліджено. Вміст заліза визначали на основі еквівалентної ширини ліній. Вміст вуглецю (і азоту) визначали за допомогою підгонки молекулярного синтезу в області G-смуги CH (4300-4330 ÅÅ), N в області молекулярної смуги CN при 3883 Å, кисню, використовуючи лінії [O] 6300 Å та ІЧ-триплета на 7770 Å. Розглянуто зв'язок між хімічним збагаченням зір і їхньою зоряною еволюцією. Це може бути пов'язано з процесами перемішування всередині зір, тобто з механізмами перенесення речовини в ході їх еволюції. Параметри (log L/L$_\odot$ і [C/H]) зір HE1523-0901, HD6269 відповідають області канонічного змішування, зоря HD 121135 можливо не має впливу канонічного екстра-змішування. Введення можливої корекції за відхилення від термодинамічної рівноваги NLTE для значень вмісту вуглецю не змінює висновків про канонічне екстра-змішування в досліджуваних зорях HE1523-0901, HD6269; зоря 195636, швидше за все, є зорею горизонтальної або висхідної гілки гігантів з деякими особливостями хімічного складу та великою швидкістю обертання.

Ключові слова: зорі: вміст – зорі: атмосфера – зорі: Населення II – зорі: еволюція зір.

1. Introduction

Metal-deficient stars ([Fe/H] <- 1.5) researches can provide information about the early nucleosynthesis of the Galaxy and its chemical evolution as a whole, but the stars on advanced evolution stage (e.g. giants, AGB stars etc.) allow us to study the peculiarities of their stellar evolution at low metallicity. The ratios of the CNO elements, the abundances of which changes as a result of nuclear reactions in case of hydrogen burning in advanced cycles may be associated with the processes of mixing inside the stars, and the mechanisms of matter transfer during the course of stellar evolution (e.g., Gratton *et al.*, 2000; Spite *et al.*, 2006). When the star evolves up giant branch (RGB), the outer convective envelope expands inward and the ensuing mixing episode, called the “first dredge-up” (Iben 1964) to alter the star’s surface light element abundance.

First dredge up is expected to be less efficient in metal-poor stars (VandenBerg & Smith 1988; Charbonnel 1994): changes in C and N abundances are very small, and the ^{12}C/^{13}C ratio is expected to remain > 30. Gratton et al. (2000) investigated the mixing along the RGB for $-2 \leq$ [Fe/H] $\leq- 1$ and found that the light elements in lower-RGB stars are in agreement with standard evolutionary models; but in the upper part of the RGB, additional mixing (“second dredge-up”) leads to depletion of carbon and enrichment in nitrogen, but not any O-Na anti-correlation. Later Khan et al. (2018) have indicated that standard stellar models underestimate the depth of efficiently mixed envelopes and an efficiency of significant overshooting increases with a metallicity decreasing.

Spite *et al.* (2006) provided LTE analysis of 32 extreme metal-poor (EMP) giants in order to understand the CNO abundance variations carried out, and found the C–N anti-correlation.

Metal – poor stars with an excess of carbon (CMEP) have aroused special interest, in particular, in the sources of origin of excess of carbon. C underabundance and N overabundance may be associated with canonical extra mixing (e.g., Denissenkov & Pinsonneault, 2008; for the CMEP and CEMP-no stars). Denissenkov & VandenBerg (2003) have proposed to call the thermohaline mixing as an explanation for deep mixing in the envelopes of red giants, because of its universality, as the canonical extra mixing (non-convective) and to use instead of rotational one (e.g. Denissenkov & VandenBerg, 2003) for which viable models to be difficult to construct (e.g. Palacios *et al.*, 2006). To account for extra mixing on the upper giant branch, Stancliffe & Eldridge (2009) used a diffusive prescription for thermohaline mixing based on the work Kippenhahn et al. (1980) and the same parameters choice (introduced by Charbonnel & Zahn, 2007) reproduces the observed abundance trends across a wide range of metallicities, for both CEMP and CEMP-no metal-poor field stars (Stancliffe *et al.*, 2009) and globular cluster stars (Angelou *et al.*, 2011). Placco et al. (2014) for the expected depletion of surface carbon abundance have recomputed of the initial carbon abundance of the stars, using the stellar evolution code (Eggleton, 1971; Stancliffe & Eldridge, 2009). Takeda & Takada-Hidai (2013) carried out the non-LTE analysis of C I lines at 1.068-1.069 μm for metal-poor stars and obtained the mean values of NLTE corrections for [C/Fe] about 0.3 - 0.4 dex.

The purpose of this work is to determine the atmospheric parameters and elemental abundances (carbon, nitrogen, and oxygen, i.e. CNO), which are important parts in the analysis of advanced states, for the stars HE 1523-0901, HD 6268, HD 121135, and HD 195636 ([Fe/H] ~ -1.5 – -3.0), in order to research the relationship between the chemical enrichment and their stellar evolution and mixing processes.

2. Observations and spectrum processing

The main parameters of studied stars were taken from the SIMBAD database (Gaia DR2), in particular:

HE 1523-0901: **B** = 12.37; **V** = 11.50 (SIMBAD); π (mas): 0.2772 [0.0434]; **RV** = -163.608 [0.0045] km s^{-1};

HD 6268: **B** = 9.725; **V** = 9.046 (Zacharias *et al.*, 2012; UCAC4); d = 705.9156 pc; π (mas): 1.4166 [0.0440]; **RV** = 39.52 [0.15] km s^{-1};

HD 121135: **B** =10.14; **V** = 9.37 (SIMBAD); d = 755.00 pc; π (mas): 1.3245 [0.0532]; **RV** = 125.60 [0.23] km s^{-1};

HD 195636: **B** = 10.13, **V** = 9.57 (2000, A&A, 355, 27, UCAC4), π (mas): 1.6074 [0.0681]; **RV** = -258.40 [0.3] km s^{-1}.

The spectra of studied stars were obtained using the 11m Southern African Large Telescope SALT (Buckley *et al.,* 2006; O'Donoghue *et al.*, 2006) HRS fibre-fed echelle-spectrograph (Barnes *et al.*, 2008, Bramall *et al.* 2010, Bramall *et al.*, 2012, Crause *et al.*, 2014) during 2018–2021 with medium resolution mode (R~ 31000–41000) and high S/N ratio near 50–220 in the ranges of 3900–8700 ÅÅ. All the data were processed using package developed by authors based on the standard system of astronomical data reduction MIDAS. Further spectra processing such as the continuum establishing, line depth and equivalent width (EW) measurements, etc., was conducted using the DECH30 software package by Galazutdinov G.A. http://gazinur.com/DECH-software.html.

The rotational velocity projection was measured by fitting of the observed spectrum with models from Coelho (2014).

3. Atmospheric parameters determination

The effective temperature T_{eff} was determined, due to the independence of the iron abundances obtained for its given absorption lines from the lower-level potential E_{low} of these lines. Gravity log g was obtained from the ionization equilibrium for the Fe I and Fe II abundances. The microturbulent velocity V_t was obtained from the condition of independence for Fe I lines abundances on their equivalent width EW.

The metallicity [Fe/H] was adopted as the iron abundance determined from the Fe I lines. The selection of the parameters was performed using an iterative procedure.

Table 1 represents the stellar parameters of our researching stars.

Table 1: Our determined stellar parameters

Star	**T_{eff} (K)**	**log g**	**[Fe/H]**	**V_t (km s^{-1})**
HE1523-0901	4450	0.80	-2.82	2.5
HD6268	4700	1.30	-2.56	2.1
HD121135	4950	1.65	-1.37	1.8
HD195636	5450	1.80	-2.75	2.3

In the atmospheres of metal-poor stars the deviations from the Local Thermodynamic Equilibrium (LTE) may influence to the stellar parameters and abundance of iron (see, e.g., Lind *et al.*, 2012). But, for such stars Roederer *et al.* (2014) shown that the Fe II abundance determined in the LTE approaches agree with those ones under non-LTE approximations within 0.02 dex. The obtained results enabled Roederer *et al.* (2014) to adopt the iron abundance derived from the Fe II lines as an indicator of the metallicity [Fe/H]. Our values of the iron abundance obtained from the Fe I and Fe II lines are almost similar, and we used the Fe I abundance as the metallicity [Fe/H] value.

4. Abundances determination

The elemental abundances were determined using the LTE approximation and the atmosphere models by Castelli

& Kurucz (2004). The choice of model for each star was made by means of standard interpolation for T_{eff} and log *g*.

The iron abundances were dermined using EWs of lines and WIDTH9 code by R.Kurucz. C, N, O abundances were calculated employing the synthetic spectrum method by a new version of the STARSP software (Tsymbal, 1996) and new version of the VALD3 line list (Kupka *et al.*, 1999). The carbon abundance were determined using the molecular synthesis fitting in the region of the CH G-band (4300-4330 ÅÅ), nitrogen from CN at 3883 Å, oxygen from [O] line 6300 Å and IR triplet at 7770 Å.

The spectrum synthesis fitting of the CH lines to the observed profiles for star HD 6268 are shown in Fig. 1.

To determine the systematic errors in the abundance estimates due to uncertainties in the atmospheric parameter determinations, we have derived the elemental abundances for the target stars from several models with modified parameters (δTeff= ±100 K; δlog g= ±0.2; δVt= ±0.1). The total uncertainty due to the parameter and EW errors for the Fe I and Fe II are 0.11 and 0.12, respectively. The determination accuracy for C, N, O elements varies from 0.15 to 0.21 dex.

The elemental abundances [El/Fe] presented in Table 2.

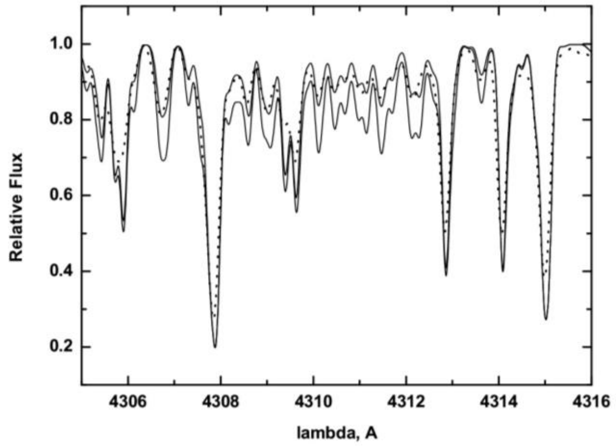

Figure 1: Observed (doted) and calculated (solid lines) spectra in the region of CH lines for star HD 6268.

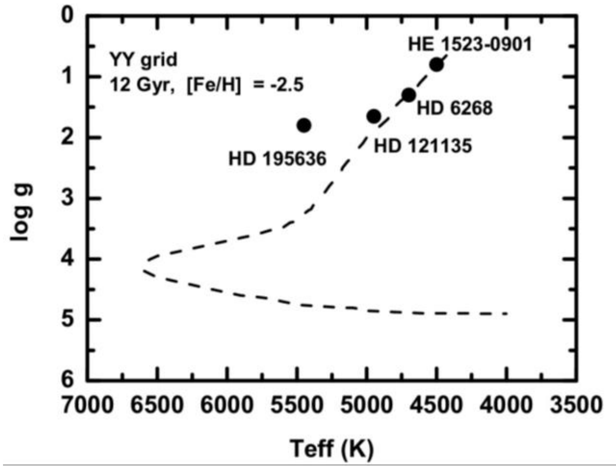

Figure 2: Positions of our stars at evolutionary diagram (Demarque *et al.,* 2004).

5. Results and discussions

We have studied our stars from the point of view of the advanced stages of stellar evolution of metal-poor stars. Positions of our stars at evolutionary diagram (Demarque *et al*., 2004) illustrated in Fig. 2.

5.1 Stellar evolutionary effects

Some elements abundances, such as Li, CNO, Na, Mg and Al change during evolution and by studying them we can assess the evolutionary effects impact on the atmospheres of clusters and field giants (see, e.g. Charbonnel, 1994; Gratton *et al*., 2000; Spite *et al*., 2006). Table 2 presents the abundances of the C, N, and O, obtained in our research.

Table 2: C, N, O abundances

Elem	HE1523	HD6268	HD121135	HD195636
[C/Fe]	-0.82	-0.79	-0.46	-0.79
[N/Fe]	0.78	0.93		
[O/Fe]	0.78	0.92	1.01	1.20
[Fe/H]	-2.82	-2.54	-1.37	-2.78

Spite et al. (2006) performed the LTE analysis of several extreme metal-poor (EMP) giants in order to investigate the CNO abundance and found out a C–N anti-correlation that agreement the hypothesis that the surface abundances could be modified by the CNO processed material from the inner regions.

In case of our investigated star we found the carbon underabundance (Table 2) that may be agreement with the stellar evolution calculations and associated with canonical extra mixing (Denissenkov & Pinsonneault, 2008). Figure 5 in their paper illustrated variations in the surface C and N abundances (red curve, CEMP stars; black curve, CEMP-no stars black curve) due to canonical extra mixing, at that the extra mixing depth does not seems to depend strongly on the metallicity (Denissenkov & VandenBerg, 2003).

To compare our result with calculation of Denissenkov & Pinsonneault (2008) we computed the value of log $L/L_\odot$ based on the classical formula:

$$\mathrm{Log}\, L/L_\odot = \log M^*/M_\odot + 4\log T_{eff}^*/T_{eff\odot} - \log g^*/g_\odot$$

were $T_{eff\odot}$= 5780 K, log $g_\odot$ = 4.44 and assuming that all targets have the same stellar mass M* = $0.85M_\odot$. The values of log $L/L_\odot$ and [C/H] presented in Table 3.

Table 3: log $L/L_\odot$ and [C/H] of studied stars

Star	log $L/L_\odot$	[C/H]
HE1523-0901	2.42398	-3.44
HD 6268	2.43898	-3.38
HD121135	2.05406	-1.88
HD195636	1.74023	-3.54

With these values of [C/H] and log L/L$_{\odot}$ the investigated stars, excepted HD 195636, were located in the black curve which corresponds to canonical extra mixing for non-C-enhanced extremely metal-poor stars with the prediction reported in the afore-mentioned study (their Fig. 5).

Placco *et al.* (2014) for the expected depletion of surface carbon abundance have recomputed the initial carbon abundance of the stars, using the stellar evolution code (Eggleton, 1971; Stancliffe & Eldridge, 2009), a grid of 0.8 M$_{\odot}$ stellar evolution models with a range of initial compositions, [Fe/H] = -1.3, -2.3, -3.3, and -4.3 and for each of these metallicities the values of [C/Fe] = -0.5, 0.0, +0.5, 1.0, respectively. We used their data and taken the correction Δ from Placco *et al.* (2014), recalculated the carbon value [C/Fe] for our targets and eventually obtained the following initial carbon values [C/Fe]$_{\mathrm{ini}}$ (Table 4).

Table 4: log L/L$_{\odot}$ and corrected [C/Fe] of studied stars

Star	**log L/L$_{\odot}$**	**Δ**	**[C/Fe]$_{\mathrm{ini}}$**
HE1523-0901	2.42398	0.90	+0.28
HD 6268	2.43898	0.50	-0.32
HD121135	2.05406	0.35	-0.11
HD195636	1.74023	0.10	-0.69

5.2 The individual target results

Star HE1523-0901 has a small excess of carbon, whereas HD6269 and HD121135 have a small C deficit. Star HD195636 has a large carbon deficit, taking into account this mixing corrections not upper part RGB.

Takeda & Takada-Hidai (2013) using NLTE analysis of C I lines at 1.068–1.069 μm have obtained the mean values of NLTE corrections for [C/Fe] about 0.3–0.4 dex. Used these corrections for our stars, we can see from Fig. 5 (Denissenkov & Pinsonneault, 2008, see their Fig. 5), that new values will move, but remain near the calculated curve, that it does not change our conclusions about the canonical extra-mixing in studied HE1523-0901, HD6269 stars; but the star HD 121135 changes its position and turns out to be far from the calculated curve.

The star HD 195636 have [C/Fe] = -0.79, [O/Fe] = 1.16; Preston (1997) noted that “the low gravity and low metallicity derived from spectrum analysis, and weakness of all CH molecular lines combine to suggest that HD 195636 is in an evolutionary state near the transition between the horizontal branch and asymptotic giant branch (RHB/AGB)”. An additive argument by Preston (1997), is a rotational velocity of HD 195636 (Vsini = 25 km/s), the value at 2 times greater than may be if blue horizontal branch axial rotators in globular clusters conserve envelope angular momentum during horizontal branch evolution. We also have a low carbon value, initial [C/Fe] = -0.69, which is lower than our other stars.

The position HD 195636 on the evolutionary diagram (see Fig. 2) confirms Preston's opinion.

6. Conclusion

- The atmospheric parameters and abundances of some key elements, as C, N, O for four target stars were determined to analyze the mixing;
- Such parameters as log L/L$_{\odot}$ and [C/H] for HE1523-0901 and HD6269 correspond to the region of canonical mixing (Denissenkov & Pinsonneault, 2008), thereas HD 121135 may not be a subject to canonic mixing;
- The initial carbon values [C/Fe] were obtained using mean value of corrections from Placco *et al.* 2014;
- The introduction of a possible NLTE correction (Takeda & Takada-Hidai, 2013) for the value of carbon abundance does not change the conclusions about the canonical extra-mixing in the studied HE1523-0901 and HD6269 stars;
- The star HD195636 is more likely to be a horizontal or ascending giant branch star, with some chemical composition peculiarities.

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