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NLTE CNO abundances in a sample of nine field RR lyr type stars

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For the first time, a direct NLTE analysis of carbon and nitrogen lines in the spectra of nine RR Lyrae stars was carried out. We have determined the abundances of these elements together with oxygen, and have shown that the nitrogen content is increased in metallicity deficient program stars. We conclude that this is a sign of the first dredge up, which occurred at the previous stage of the red giant branch, and brought material processed in an incomplete CNO cycle to the surface of the star. This effect is significantly enhanced by thermohaline (extra-) mixing, which is more effective for metal-poor RR Lyrae stars. This is clearly seen in the plot showing that C/N ration in our sample of stars gradually decreases as metallicity decreases from about –0.2 to –2. Oxygen abundance depends on metallicity in a similar way to what we see in the Population II stars.

KEYWORDS:
Stars: abundances—RR Lyr:instability strip—RR Lyr: abundances—Galaxy: evolution

1 INTRODUCTION

RR Lyrae stars are pulsating giants of A–F spectral classes located on the Horizontal Branch (HB), which cover the rather wide range of metallicities from nearly solar to about [Fe/H]=−3 dex (the most metal-poor field RR Lyr star that we investigated in our series of papers is UY Boo; it has metallicity −2.73, see Wallerstein, Kovtyukh, & Andrievsky 2009).

RR Lyrae stars can be found in globular clusters, as well as in the Galactic field (halo, thick disc and bulge). They are low-mass stars (less that one solar mass), the evolutionary stage of which is determined by the core helium burning, when the helium nuclei are fusing to carbon and oxygen nuclei. In addition, protons are fusing to α-particles in a shell surrounding the stellar core. At the next stage of evolution, the HB star with a carbon core passes to the region of the lower temperatures in the HR diagram. As an asymptotic giant branch star, it has two shell sources of energy release – helium and hydrogen burning shells.

RR Lyrae stars invariably attract attention of astrophysicists engaged in photometric and spectroscopic studies. As a rule, the abundances of α-elements, iron-peak elements and sometimes heavy elements, like strontium, yttrium, barium, were derived in these stars (see, e.g. recent papers by Magurno et al. 2019, 2018).

Of particular interest is the determination in RR Lyrae stars of the abundances of such chemical elements as carbon, nitrogen and oxygen. For instance, the LTE abundances of C and N were derived by Butler, Manduca, Bell, & Deming (1982). These authors showed that the [C/Fe] ratio for 19 field RR
Lyrae stars are typical for unevolved Population II stars. Nitrogen abundance (with indicated uncertainty) was determined only for three stars, and only the upper limit was estimated for the rest of the stars. Later Butler, Laird, Eriksson, & Manduca (1986) reported about NLTE oxygen abundance determination from the near IR O I triplet for the same sample of stars. It should be noted that the reported dependence of [O/Fe] on [Fe/H] (see their Fig. 1) looks rather strange: as [Fe/H] decreases, [O/Fe] decreases too, which is opposite to what is expected for the halo Population II stars.

According to Smith (1995) the overwhelming majority of the field RR Lyrae stars are not components of the binary systems, but recent study of Kervella et al. (2019) based on Gaia DR2 shows that at least 7% of RR Lyrae stars are binaries.

Carbon enhanced metal-poor stars were discovered and studied among RR Lyrae objects (e.g. Kinman, Aoki, Beers, & Brown 2012, Kennedy et al. 2014, Reggiani, Kennedy, Rossi, & Beers 2014, Xia, Zhang, Bi, & Ma 2019, 2020). Those stars are believed to gain high carbon abundance from either thermally pulsing AGB stars, especially from initially more massive companion star in a binary system due to the contamination of their surface with processed material. For example, SDSS J170733.93+585059.7 has been identified as the RR Lyr star in the binary system with an extremely high relative carbon abundance [C/Fe] = +2.79 (Kinman et al. 2012).

Takeda et al. (2006) performed NLTE analysis in order to derive oxygen abundance in a sample of the four RR Lyrae stars. The authors obtained an increased oxygen abundance in their program stars, [O/Fe] is in the range from about 0 to +1, as expected for metal-poor objects. A similar result was obtained by Andrievsky et al. (2018), who derived NLTE oxygen abundances in a sample of 30 Galactic field RR Lyrae stars. [O/Fe] were distributed in the range from 0 to about 1 dex with a typical for the Population II stars dependence on [Fe/H] (metallicity is in the range from 0 to about –3 dex).

In our recent paper (Andrievsky et al., 2020) we reported on the results of the determination of C and O NLTE abundances in a sample of 21 RR Lyrae stars from the Galactic field. In all stars studied, carbon showed underabundance comparing to the solar (C/H), while oxygen was found to be overabundant. Its relative abundance [O/Fe] shows a clear dependence on [Fe/H], as expected for the Galactic halo stars.

The theory of stellar evolution predicts that the processes of internal nucleosynthesis in HB stars can only change the surface abundances of such light elements as carbon, nitrogen and oxygen. Since nitrogen abundance in RR Lyrae stars was practically not studied in the past, we decided to carry out the comprehensive NLTE analysis of the carbon, nitrogen and oxygen lines in the spectra of 9 Galactic field RR Lyrae stars.

2 OBSERVATIONS

With the Apache Point Observatory (USA, APO) 3.5-m telescope we observed nine RR Lyrae stars. All spectra have a resolution of 31,000, ranging from from 3,900 to 10,400 Å, with S/N from 70 to 200. Spectra of rapidly rotating hot stars were obtained to facilitate the elimination of atmospheric absorption lines (except very strong lines). Table I shows a list of target stars observed at APO and their properties.

The preliminary data reduction was accomplished using programs in the IRAF package.

3 ABUNDANCE ANALYSIS

For abundance analysis we employed Kurucz (1993) atmosphere models. Atmosphere parameters for each program stars were determined by using Fe I and Fe II lines. As it is commonly adopted in spectroscopic analysis, the effective temperature was derived by requiring that there be no dependence between iron abundance from individual Fe I lines and their excitation potentials. Microturbulent velocity was derived by avoiding dependence between iron abundance from individual Fe I lines and their equivalent widths. Finally, the gravity value was found by keeping equal mean iron abundances from Fe I and Fe II lines. The corresponding mean values of iron abundance from Fe I and Fe II lines give the final [Fe/H] value for a given star. Error analysis was made in the same way as it was described in Andrievsky et al. (2020). In Fig. 1 and Fig. 2 we graphically show the procedure of $T_{\text{eff}}$ and $V_\text{t}$ determination for KX Lyr and RX Eri, and sensitivity of the adopted $T_{\text{eff}}$ and $V_\text{t}$ values to variations within ±150, K and ±0.2 km s$^{-1}$. The change in slopes in both cases can be traced visually. It should be noted that as a reference point we adopted the solar abundance of iron (Fe/H) = 7.48 (Palme, Lodders, & Jones, 2014).

The total list of the iron lines used, their atomic data and equivalent widths are given in the Tables A1 and A2 in Appendix (the full tables are available on-line).

It should be noted that for most of the stars of our program, the atmosphere parameters were first determined in one of our previous work by Andrievsky et al. (2018) using the SME code (Piskunov & Valenti, 2017). These parameters were used as a first approximation for the current standard abundance analysis. For half of the stars, the parameters used turned out to be a good choice, but for the rest of the stars, the parameters were refined.

1IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
TABLE 1 Characteristics of the program stars and abundances of iron, carbon, nitrogen and oxygen. For the reference we give here our NLTE absolute abundances (X/H) of carbon, nitrogen and oxygen in the Sun: 8.43, 7.89 and 8.71 respectively.

| Star  | Period (d) | Type | JD 2450 000+ | $T_{\text{eff}}$ (K) | log $g$ | $V_t$ km s$^{-1}$ | [Fe/H] | [C/Fe] | [N/Fe] | [O/Fe] |
|-------|------------|------|--------------|-----------------|--------|------------------|--------|--------|--------|--------|
| DH Peg | 0.2555     | RRc  | 5192.599     | 6660            | 2.0    | 1.8              | -1.40  | -0.16  | +1.21  | +0.68  |
| RU Psc | 0.3904     | RRc  | 5192.736     | 6420            | 2.0    | 1.8              | -2.03  | -0.41  | +1.06  | +0.78  |
| AV Peg | 0.3904     | RRab | 4995.881     | 6660            | 2.5    | 2.3              | -0.15  | +0.07  | +0.38  | +0.38  |
| RR Gem | 0.3973     | RRab | 5192.782     | 6750            | 2.3    | 2.3              | -0.22  | +0.08  | +0.30  | +0.51  |
| KX Lyr | 0.4409     | RRab | 5280.975     | 6380            | 2.7    | 2.3              | -0.24  | -0.23  | +0.38  | +0.20  |
| RR Leo | 0.4524     | RRab | 4905.848     | 6400            | 2.0    | 2.0              | -1.38  | -0.01  | +0.73  | +0.82  |
| DX Del | 0.4726     | RRab | 5192.782     | 6750            | 2.3    | 2.3              | -0.12  | -0.09  | +0.00  | +0.30  |
| RR Cet | 0.5530     | RRab | 5047.397     | 6790            | 2.1    | 2.6              | -1.48  | +0.04  | +0.73  | +0.97  |
| RX Eri | 0.5872     | RRab | 5521.789     | 6180            | 2.6    | 2.2              | -1.08  | -0.06  | +0.89  | +0.91  |

FIGURE 1 This explains the procedure of $T_{\text{eff}}$ and $V_t$ determination for KX Lyr and error estimation for adopted atmosphere parameters. Left panel: middle – the best $T_{\text{eff}}$ choice, top – $T_{\text{eff}}$ + 150 K, bottom – $T_{\text{eff}}$ – 150 K. Right panel: middle – the best $V_t$ choice, top – $V_t$ + 0.2 km/s, bottom – $V_t$ – 0.2 km/s.

4.1 CARBON AND OXYGEN NLTE ABUNDANCES

Atomic models of carbon and oxygen, which were used to derive NLTE abundances of these elements in our program stars, are described in details in several papers, see, for instance, Andrievsky et al. (2020) for reference. In that paper we also give the lists of analyzed carbon and oxygen lines, and a description of how we applied spectral synthesis to match the observed profiles of selected lines of the studied ions.
5.1 Nitrogen Abundance Calculations

To find atomic level populations for the atom N I, we employed the code MULTI (Carlsson, 1986). For our aim, this code was modified and adapted by Korotin, Andrievsky, & Luck (1999). MULTI gives a possibility to calculate a single line NLTE profile. It should be noted that the lines of interest as a rule are blended in the real stellar spectra. In order to take the blending into account, we first calculate with MULTI the NLTE departure coefficients for those levels that form the line of interest, and then we include these coefficients in the LTE synthetic spectrum code SYNTHE (Tsymbal, 1996). This enables one to calculate the source function and opacity for each studied line. Simultaneously, the blending lines are calculated in LTE with the help of line list and corresponding atomic data from VALD (Ryabchikova et al., 2015) in the wavelength range of the line under study. This technique is the same as we used for carbon and oxygen lines (Andrievsky et al., 2020).

For the NLTE calculation we use the model of N I atom that was described in Lyubimkov et al. (2011). That model was supplemented with an account for the updated atomic data. In particular, electron collisional rates for the lower 27 levels of N I were taken from Wang, Zatsarinny, & Bartschat (2014), who used the detailed quantum mechanics calculations for this aim.

The adopted nitrogen model atom consists of 39 N I levels, 49 N II levels and the ground state of N III. Moreover, additional atomic levels of LTE populations were included in the equation of the particle number conservation. Among them there are 66 N I levels and four excited N III levels.

Nitrogen abundance in the solar atmosphere was found with the help of equivalent widths of the eight N I lines observed at the center of the solar disc (Biémont, Froese Fischer, Godefroid, Vaeck, & Hibbert, 1990; Grevesse et al., 1990). The authors report that obtained equivalent widths were cleaned of the molecular lines. Our solar nitrogen abundance (N/H) = 7.89 ± 0.04 is in good agreement with the result of Lodders (2019), who gives (N/H) = 7.86 ± 0.12, as well as with result of Lodders (2019), who gives (N/H) = 7.85 ± 0.12.

More information about nitrogen abundance from individual lines in the solar spectrum can be found in Table 3.

To derive NLTE abundances in our program stars we used 12 lines of N I that belong to the four different multiplets. Their parameters were taken from the VALD (Ryabchikova et al., 2015), and they are given in Table 3. All investigated lines to some extent suffer from the NLTE effects. Generally, observed lines become stronger due to the NLTE influence. To describe...
TABLE 2 Nitrogen abundance in the Sun from different N I lines. NLTE corrections are also given.

| Line   | EW(mÅ) | (N/H) | dNLTE |
|--------|--------|-------|-------|
| 7442.29 | 2.6    | 7.84  | -0.02 |
| 7468.31 | 4.9    | 7.92  | -0.02 |
| 8216.33 | 8.6    | 7.90  | -0.03 |
| 8242.38 | 3.9    | 7.89  | -0.03 |
| 8629.23 | 4.5    | 7.84  | -0.03 |
| 8683.40 | 7.8    | 7.85  | -0.04 |
| 8718.83 | 4.2    | 7.93  | -0.03 |
| 9392.79 | 9.5    | 7.96  | -0.03 |

TABLE 3 N I lines.

| λ (Å) | χ (eV) | log gf |
|-------|--------|--------|
| 7442.30 | 10.33  | -0.40  |
| 7468.31 | 10.34  | -0.18  |
| 8184.86 | 10.33  | -0.30  |
| 8188.01 | 10.33  | -0.29  |
| 8216.34 | 10.34  | 0.13   |
| 8223.13 | 10.33  | -0.27  |
| 8629.24 | 10.69  | 0.08   |
| 8683.40 | 10.33  | 0.10   |
| 8686.15 | 10.33  | -0.28  |
| 8703.25 | 10.33  | -0.31  |
| 8711.70 | 10.33  | -0.23  |
| 8718.84 | 10.34  | -0.35  |

In LTE observed profiles of all 12 lines with one adopted nitrogen abundance is practically impossible.

In Fig. 3, Fig. 4 and 5 we show observed CNO lines in our program spectra together with synthesized LTE and NLTE profiles. For RU Psc, only the upper limit of the nitrogen abundance can be determined. It should be noted that an error of +/-0.1 dex is inevitable in the abundance derivation process by using SYNTEHEV, because it was done based on simple eye-judgement by trial and error on the computer display.

Table 4 contains for each star and each analyzed C, N, O line resulting abundance and NLTE correction (denoted in the Table as dNLTE). Abundances and NLTE corrections in this Table are given not only for individual lines, but also for groups of lines located within a certain spectral range. We did not use in our analysis the very strong lines. Such strong lines can effectively form in the upper atmosphere layers, where pulsations might create specific turbulent velocity profile, which cannot be modeled in standard calculations. Note that correction dNLTE = LTE abundance – NLTE abundance.

In Table 4 we give NLTE corrections as a specific value, when in the indicated range there is only one line. If there are several lines, we show some range of corrections (say, 0.55 – 0.90). As a rule such lines belong to the same multiplet with different intensities. The entire ensemble of this lines can be described with a single NLTE abundance. However, these lines have different NLTE corrections. It is the range of corrections for different lines from the certain spectral range, and it is shown in this Table. For instance, among the lines of IR oxygen triplet for the star DH Peg, the strongest line has NLTE correction –1.05, while the weakest line has NLTE correction –0.80. Thus, in the Table we indicated the range 0.80–1.05 for the spectral range 7771–7775 Å.

6 | RESULTS AND DISCUSSION

In our previous paper [Andrievsky et al., 2020] we reported about decreased/or near-to-normal carbon abundance in a sample of 21 field RR Lyrae stars. We made a conclusion that no additional carbon is expected to be brought to the stellar surface after the He flash in the RR Lyrae core. Nitrogen abundance was not derived for those stars.

From the top panel of Fig. 6 we see that our current NLTE result confirms our previous conclusion. Middle panel of Fig. 6 shows that NLTE nitrogen abundance is clearly increased in RR Lyrae stars. It is natural to assume that on the surface of the studied stars we see a sign of the material, which was processed in an incomplete CNO-cycle. The bottom panel shows the behavior of the oxygen abundance in RR Lyrae stars, qualitatively typical for the Population II stars. However, two stars with close-to-solar metallicity, AV Peg and RR Gem, show significantly increased oxygen abundance (+0.38 and +0.51 respectively). If we derived the wrong atmosphere parameters for these stars, our metallicity ([Fe/H]) should obviously be incorrect, since parameters can change significantly during the pulsation cycle, while metallicity should be the same within the standard error for each pulsation phase (see, for instance, For, Sneden, & Preston 2011; Liu, Zhao, Chen, Takeda, & Honda 2013). However, we see that our metallicity estimate for AV Peg is almost the same as that obtained by Chadid, Sneden, & Preston (2017). These authors report for AV Peg [Fe/H] = –0.14, while we obtained [Fe/H] = –0.15.

For RR Gem the difference with literature data on [Fe/H] is larger, but still within acceptable limits. Thus, in the paper of Magurno et al. (2018) authors give the value [Fe/H] = –0.41, while our value is 0.19 dex higher. Of course, many factors may affect the abundance value, but such a difference is not critical and cannot significantly reduce the final oxygen abundance.
FIGURE 3 This shows the observed C I lines (at 7113.18, 7115.17 and 7116.99 Å), N I lines (at 8683.40, 8686.15 Å) and O I triplet (at 7772.0, 7774.2, and 7775.4 Å), comparing the synthesized profiles in LTE (dashed line) and NLTE (solid line) computed with the same abundance.

TABLE 4 Abundances and NLTE corrections for all studied lines in the program spectra.

| C I line A | DH Peg | RU Peg | AV Peg | RR Gem | IKX Lyr | RR Lyr | DX Del | RR Crt | RX Eri |
|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| C I line A | (CH) | (NLTE) | (CH) | (NLTE) | (CH) | (NLTE) | (CH) | (NLTE) | (CH) |
| 5025      | 6.87  | 0.18  | 6.32  | 0.18  | 8.27  | 0.22  | 7.96  | 0.13  | 7.10  | 0.21  | 8.06  | 0.16  |
| 5380      | 6.83  | 0.16  | 6.35  | 0.15  | 8.31  | 0.18  | 7.91  | 0.15  | 8.10  | 0.14  | 8.33  | 0.18  |
| 6987      | 6.90  | 0.15  | 6.35  | 0.11  | 8.26  | 0.13  | 8.01  | 0.10  | 7.04  | 0.14  | 8.20  | 0.10  |
| 7111-7119 | 6.87  | 0.16  | 8.07  | 0.11-0.15 | 8.30  | 0.15-0.20 | 7.96  | 0.10-0.11 | 7.00  | 0.18-0.22 | 8.15  | 0.12-0.15 |
| 8355      | 6.82  | 0.42  | 5.95  | 0.40  | 6.02  | 0.65  | 6.96  | 0.58  | 7.25  | 0.63  |
| 9681-9111 | 6.80  | 0.55-0.9 | 5.99  | 0.52-0.83 | 7.07  | 0.75-1.30 | 7.02  | 0.80-1.40 | 7.29  | 0.60-1.08 |
| 9465      | 6.85  | 0.80  | 5.90  | 0.81  | 7.04  | 1.36  | 7.00  | 1.40  | 7.31  | 1.18  |
| 9605-9568 | 6.87  | 0.45-0.6 | 6.05  | 0.50-0.62 | 7.04  | 0.55-1.03 | 6.99  | 0.53-1.00 | 7.29  | 0.45-0.85 |
| Mean      | 6.85  | 0.97  | 6.35  | 0.29  | 7.96  | 0.74  | 8.13  | 0.99  | 7.29  |

| N I line A | (CH) | (NLTE) | (CH) | (NLTE) | (CH) | (NLTE) | (CH) | (NLTE) | (CH) |
|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 8186-8223 | 7.70  | 0.25-0.3 | 6.92  | 0.15-0.20 | 8.10  | 0.15-0.20 | 7.97  | 0.24-0.30 | 8.03  | 0.18-0.2 | 7.27  | 0.15-0.20 | 7.77  | 0.14-0.19 |
| 8629      | 7.70  | 0.26  | 6.10  | 0.20  | 7.97  | 0.30  | 8.00  | 0.19  | 7.25  | 0.19  | 7.77  | 0.16  | 7.14  | 0.21  | 7.70  | 0.18  |
| 8683-8711 | 7.70  | 0.25-0.3 | 6.92  | 0.16-0.20 | 8.15  | 0.16-0.28 | 7.96  | 0.24-0.35 | 8.03  | 0.19-0.2 | 7.24  | 0.18-0.20 | 7.77  | 0.15-0.20 | 7.14  | 0.19-0.22 | 7.70  | 0.15-0.17 |
| Mean      | 7.70  | 0.62  | 6.12  | 0.77  | 8.03  | 0.74  | 7.77  | 0.77  | 7.14  | 0.70  |

| O I line A | (CH) | (NLTE) | (CH) | (NLTE) | (CH) | (NLTE) | (CH) | (NLTE) | (CH) |
|-----------|--------|--------|--------|--------|--------|--------|--------|--------|--------|
| 6138-6158 | 7.89  | 0.07  | 8.91  | 0.06  | 8.85  | 0.11  | 8.67  | 0.05  | 8.18  | 0.04  | 8.63  | 0.07  |
| 6520      | 7.92  | 0.00  | 7.94  | 0.84-0.92 | 9.10  | 1.07-1.15 | 8.67  | 0.75-0.8 | 8.15  | 0.70-0.85 | 8.89  | 0.91-0.98 | 7.42  | 0.70-0.90 |
| 7771-7778 | 7.92  | 0.80-1.0 | 7.46  | 0.41-0.50 | 8.94  | 0.84-0.92 | 10.10  | 1.07-1.15 | 8.67  | 0.75-0.8 | 8.15  | 0.70-0.85 | 8.89  | 0.91-0.98 | 7.42  | 0.70-0.90 |
| Mean      | 7.99  | 0.74  | 7.46  | 0.69  | 8.95  | 0.50  | 8.67  | 0.15  | 8.80  | 0.22  |

Together with our program stars we show in Fig. 6 the stars, which have been analyzed by Gratton et al. (2000). These authors used molecular bands to derive the C and N abundances, as well as forbidden and permitted lines for oxygen. The spectra of stars located at different evolutionary stages were used: main sequence, lower and upper red giant branch and red horizontal branch.

Of particular interest for our study is to compare the abundances of C and N in the stars of our program with the abundances of these elements in non-variable HB stars. Following Behr (2003) we can note the various regions in the horizontal branch. The red part of the HB (RHB) with temperature boundaries from about 4500 to 6000 K. At the higher temperatures there is a domain of RR Lyrae type stars. Their
instability strip comprises temperature range from 6000 to 7500 K. Toward the higher temperatures, the cool end of the hot blue HB (BHB) is located. It covers effective temperature range from 7500 to 11500 K. Finally, the hot part of the BHB stretches from 11500 K to the higher temperatures.

There are works devoted to the light elements abundance study in the RHB stars. Among them, for instance, Gratton et al. (2000), who studied ten RHB stars bordering the group of stars in the lower red giant branch. The authors reported about moderately increased nitrogen and decreased carbon abundance in their sample of stars. A similar conclusion was also reached by Tautvaišienė, Edvardsson, Tuominen, & Ilyin (2001), who studied intermediate metal deficient cool core helium burning stars from the Galactic thick disc. Moreover, the authors of that paper gave additional evidence that mixing processes in the giant stars can be metallicity dependent. Both studies used CH and CN molecular bands to determine abundances of carbon and nitrogen. At temperatures of the RHB stars atomic
C and N lines are not visible in their spectra. Since our NLTE analysis of RR Lyrae stars was based on the use of atomic lines, we tried to find the literature spectroscopic information for the stars hotter than RR Lyrae variables. Since, as is known (Michaud, Vauclair, & Vauclair 1983), in the stars hotter than 11500 K atomic diffusion processes can change the surface abundances of elements including carbon and nitrogen, we focused on finding the appropriate spectroscopic data for the stars lying in the temperature range from 7500 to 11500 K. Unfortunately, this temperature range, as a rule, interested specialists mainly because of the helium lines, for which only small fragments of blue spectra were observed.

The necessary data we found in the work of Lambert, McWilliam, & Smith (1992). They investigated three stars, and for one of them (HB stars No. 4408 from M4) one high-resolution spectum in the near-infrared range (from 8080 to 9620 Å) was exposed using CTIO facilities. Fortunately, authors give in their paper equivalent widths of carbon and nitrogen lines. Using the NLTE approximation and published equivalent widths, we estimated absolute carbon abundance for this star (C/H) = 7.19 ± 0.06 that corresponds to [C/Fe] = −0.24. The result for nitrogen is as follows: (N/H) = 7.53 ± 0.10, [N/Fe]=+0.64. It should be noted that average NLTE corrections for investigated lines are significant: −0.04 for carbon, and −0.55 for nitrogen. Note that we used iron abundance for this cluster [Fe/H] = −1.0, as reported by Lambert et al. (1992).

Another good example for us of a star located in HB to the left of the instability strip is HD 161817. Takeda & Sadakane (1997), hereinafter T&S, calculated the CNO abundances in this star and the corresponding NLTE corrections using the NLTE approximation. The authors used two atmosphere models: $T_{\text{eff}}$ = 7500 K, log $g$=3.0, one with [Fe/H]=−1 and another with [Fe/H]=−2. The authors derived resulting metallicity as: (Fe/H)=6.12, i.e. [Fe/H] = −1.38, and the following abundances: (C/Fe)=6.9, (N/Fe)=7.0 and (O/Fe)=7.8. We used calculated model atmosphere for the above parameters and metallicity, [Fe/H] = −1.38. With our NLTE code, atomic models and published equivalent widths from T&S we obtained: (C/Fe)=6.80, (N/Fe)=7.08 and (O/Fe)=7.75. These values are close to the T&S values.

As one can see from Table 5 our corrections and corrections of T&S are close enough, except for nitrogen. We investigated the reason of this discrepancy. First, like T&S, we calculated NLTE and LTE nitrogen abundances for all the lines using two atmosphere models (one for [Fe/H] = −1, and the other for [Fe/H] = −2). Then we compared our results with those of T&S. All results are given in Table 6.

By comparing the NLTE and LTE data from Table 6 we can conclude that we agree with T&S on the NLTE results, while their LTE data (and NLTE corrections, respectively) seem to be incorrect for an unknown reason. Since our LTE data were derived using the MULTI code, we decided to check ourselves and applied Kurucz’s WIDTH6 code with models of 1993 and equivalent widths from T&S. We got the following result: WIDTH6 and MULTI LTE abundances agree within 0.03 dex.

Finally, it should be noted that T&S used solar CNO abundances (C/H)=8.6, (N/H)=8.0, (O/H)=8.9, which is slightly different from the currently adopted values: 8.43, 7.89 and 8.71 respectively.

C,N (and O) abundance data for two hot HB stars are plotted in Fig. 6.

In Fig. 6. we show the distribution of [N/Fe] versus [C/Fe] for all program stars including M4 HB star and HD 161817. There is a fairly clear increase in the relative nitrogen abundance with decreasing carbon abundance. This figure allows us to conclude that we see at the surface of the RR Lyrae stars the results of the previous first dredge up episode that occurred at the RGB, when the material from the incomplete CNO cycle was brought to the upper atmosphere.

In Fig. 8. we show the ratio [C/N] as a function of metallicity. Our data clearly demonstrate a gradual decrease of the relative abundance of C/N as metallicity decreases in a wide range.

Let us briefly discuss Fig. 8. Lagarde et al. (2019) examined the effect of thermohaline mixing on observed surface abundances of carbon and nitrogen (thermohaline instability triggering an effective additional mixing in giant stars was first considered by Charbonnel & Zahn 2007). The authors used a stellar population synthesis model and compared their synthetic data with the observed [C/N] ratios available through abundance determinations from the Gaia-ESO survey. The authors showed that thermohaline mixing is an efficient mechanism that can alter surface abundances of carbon and nitrogen, especially in stars with lower metallicity. Their Fig. 8 shows

### Table 5 NLTE corrections for CNO abundances.

| Line, Å  | T&S    | Present work |
|---------|--------|--------------|
| 9078    | −0.31, −0.61 | −0.55        |
| 9088    | −0.32, −0.62 | −0.55        |
| 9095    | −0.81, −1.23 | −1.05        |
| N I     | 8683   | −0.42, −0.71 | −0.25        |
| 8686    | −0.37, −0.65 | −0.22        |
| 8706    | −0.33, −0.59 | −0.24        |

IR triplet −0.65, −0.78 −0.70

Remark: in T&S corrections for two models are given.
TABLE 6 Toward a solution to the problem of the NLTE nitrogen corrections.

| Line, Å | T&S NLTE mod1 | T&S NLTE mod2 | T&S LTE mod1 | T&S LTE mod2 | Our data NLTE mod1 | Our data LTE mod1 | Our data NLTE mod2 | Our data LTE mod2 |
|---------|---------------|---------------|--------------|--------------|-------------------|------------------|-------------------|------------------|
| 8683    | 7.06          | 6.78          | 7.48         | 7.49         | -0.42             | -0.71            | 6.92              | 7.17             |
| 8686    | 7.16          | 6.89          | 7.53         | 7.54         | -0.37             | -0.65            | 7.07              | 7.29             |
| 8706    | 7.28          | 7.03          | 7.61         | 7.62         | -0.33             | -0.59            | 7.25              | 7.49             |

Remark: our NLTE and LTE abundances (columns 8 and 9) were derived using a single model with [Fe/H] = –1.38. In addition, we obtained LTE abundances using two models, similar to T&S. The results are given in columns 11 and 12.

![FIGURE 7](image7.png)

**FIGURE 7** Relative nitrogen abundance [N/Fe] as a function of [C/Fe]. The star No. 4408 from M4 is designated as an open asterisk symbol, HD 161817 is shown as a solid asterisk symbol. One deviating point KY Lyr is indicated.

![FIGURE 8](image8.png)

**FIGURE 8** The ratio [C/N] as a function of metallicity. The designations are the same as in Fig. 6.

that theoretical prediction of the [C/N] behaviour indicates that this ratio should decrease as metallicity decreases. Partially, this prediction is supported by observations of the cluster stars. For instance, [C/N] data for old globular cluster NGC 1851 and open cluster M 67 do not contradict the above prediction.

Our sample of stars covers the metallicity range from about –0.2 to –2 dex. Correspondingly, [C/N] ratio ranges from about zero to –1.5 dex, which is in good agreement with Lagarde et al. (2019) results from their stellar population synthesis (see their Fig. 8).

7.1 CONCLUSION

We have derived the NLTE abundances of carbon, nitrogen and oxygen in a sample of RR Lyrae stars. The iron content in LTE in these stars ranges from –0.15 to –2.03. The distribution of oxygen abundance in this sample is typical of halo stars: the lower the metallicity, the higher the oxygen abundance. The carbon in our program stars is not increased. Both of these findings are similar to those reported by Andrievsky et al. (2020) for a larger sample of RR Lyrae stars.

Nitrogen is clearly overabundant in the studied RR Lyrae stars; its abundance increases with decreasing carbon abundance. Thus, we conclude that our stars exhibit material on their surface that was processed in an incomplete CNO cycle, when the stars passed the RGB stage, and then mixed due to convection with atmospheric gas during the first dredge up.

The ratio [C/N] distribution versus [Fe/H] for our program RR Lyrae type stars is similar to that observed for halo population giants, where the surface C and N abundances are effectively altered by additional mixing induced by thermohaline instability. Our result on RR Lyrae stars shows that this process is active, and confirms the conclusion that thermohaline mixing becomes more effective in the giant stars with lower metallicity (Lagarde, Charbonnel, Decressin, & Hagelberg, 2011).

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APPENDIX A: ON-LINE MATERIAL
TABLE A1  Equivalent widths of the used iron lines and corresponding abundances for DH Peg, RU Psc, AV Peg, RR Gem, KX Lyr. Atomic data are from VALD.

| Lambda   | Ion | EPL   | log $gf$ | DH Peg | RU Psc | AV Peg | RR Gem | KX Lyr |
|----------|-----|-------|----------|--------|--------|--------|--------|--------|
| 4602.001 | Fe I | 1.608 | −3.153   | −      | −      | −      | 31.722 | −      |
| 4602.941 | Fe I | 1.485 | −2.208   | −      | 10.525 | −      | −      | −      |
| 4620.521 | Fe II| 2.828 | −3.190   | −      | 16.537 | −      | −      | −      |
| 4625.045 | Fe I | 3.241 | −1.270   | −      | −      | −      | 75.739 | −      |
| 4690.138 | Fe I | 3.686 | −1.680   | −      | −      | −      | 24.733 | −      |
| 4713.453 | Fe II| 2.891 | −3.100   | −      | 16.533 | −      | −      | −      |
| 4733.592 | Fe I | 1.485 | −2.987   | −      | −      | −      | 38.706 | −      |
| 4736.773 | Fe I | 3.211 | −0.670   | −      | 18.553 | −      | 106.731| −      |
| 4741.530 | Fe I | 2.832 | −2.000   | −      | −      | −      | 38.720 | −      |
| 4745.800 | Fe I | 3.654 | −1.269   | −      | −      | −      | 42.723 | −      |
| 4788.757 | Fe I | 3.237 | −1.810   | −      | −      | −      | 35.730 | −      |
| 4917.230 | Fe I | 4.191 | −1.179   | −      | −      | 53.757 | 34.743 | 39.735 |
| 4923.927 | Fe II| 2.891 | −1.319   | −      | −      | −      | −      | −      |
| 4924.770 | Fe I | 2.279 | −2.240   | 9.613  | −      | −      | 60.731 | 81.737 |

TABLE A2  Atomic data, equivalent widths of iron lines and corresponding abundances for RR Leo, DX Del, RR Cet, RX Eri.

| Lambda   | Ion | EPL   | log $gf$ | RR Leo | DX Del | RR Cet | RX Eri |
|----------|-----|-------|----------|--------|--------|--------|--------|
| 4598.117 | Fe I | 3.283 | −1.569   | −      | −      | −      | 26.653 |
| 4602.941 | Fe I | 1.485 | −2.208   | −      | −      | −      | 85.655 |
| 4619.288 | Fe I | 3.603 | −1.030   | −      | −      | −      | 31.639 |
| 4620.521 | Fe II| 2.828 | −3.190   | −      | −      | −      | 59.635 |
| 4625.045 | Fe I | 3.241 | −1.270   | −      | −      | −      | 28.625 |
| 4728.546 | Fe I | 3.654 | −1.280   | −      | −      | −      | 25.655 |
| 4733.592 | Fe I | 1.485 | −2.987   | −      | −      | −      | 27.634 |
| 4736.773 | Fe I | 3.211 | −0.670   | −      | −      | −      | 75.641 |
| 4741.530 | Fe I | 2.832 | −2.000   | −      | −      | −      | 15.626 |
| 4745.800 | Fe I | 3.654 | −1.269   | −      | −      | −      | 15.628 |
| 4892.859 | Fe I | 4.218 | −1.289   | −      | −      | 33.744 | −      |
| 4893.820 | Fe II| 2.828 | −4.266   | −      | −      | 52.731 | −      |
| 4917.230 | Fe I | 4.191 | −1.179   | −      | 43.748 | −      | −      |
| 4924.770 | Fe I | 2.279 | −2.240   | 78.742 | −      | 29.635 | −      |
| 4950.106 | Fe I | 3.417 | −1.669   | 8.628  | −      | −      | 15.646 |