C, N and O abundances in red clump stars of the Milky Way

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ABSTRACT

The Hipparcos orbiting observatory has revealed a large number of helium-core-burning "clump" stars in the Galactic field. These low-mass stars exhibit signatures of extra-mixing processes that require modeling beyond the first dredge-up of standard models. The $^{12}$C/$^{13}$C ratio is the most robust diagnostic of deep mixing, because it is insensitive to the adopted stellar parameters. In this work we present $^{12}$C/$^{13}$C determinations in a sample of 34 Galactic clump stars as well as abundances of nitrogen, carbon and oxygen. Abundances of carbon were studied using the C$_2$ Swan (0,1) band head at 5635.5 Å. The wavelength interval 7980–8130 Å with strong CN features was analysed in order to determine nitrogen abundances and $^{12}$C/$^{13}$C isotope ratios. The oxygen abundances were determined from the [O i] line at 6300 Å. Compared with the Sun and dwarf stars of the Galactic disk, mean abundances in the investigated clump stars suggest that carbon is depleted by about 0.2 dex, nitrogen is enhanced by 0.2 dex and oxygen is close to abundances in dwarfs. Comparisons to evolutionary models show that the stars fall into two groups: the one is of first ascent giants with carbon isotope ratios altered according to the first dredge-up prediction, and the other one is of helium-core-burning stars with carbon isotope ratios altered by extra mixing. The stars investigated fall to these groups in approximately equal numbers.

Key words: stars: abundances – stars: evolution – stars: horizontal-branch.

1 INTRODUCTION

During the last decades, an increasing amount of work has been done in studying the chemical composition of red clump stars of the Galaxy (e.g. McWilliam 1990; Tautvaišienė et al. 2003; Mishenina et al. 2006; Liu et al. 2007; Luck & Heiter 2007; Tautvaišienė & Puzeras 2009; Puzeras et al. 2010). From the Hipparcos catalogue (Perryman et al. 1997) containing about 600 clump stars with parallax error lower than 10% and representing a complete sample of clump stars to a distance of about 125 pc, almost a half of stars are already investigated by means of high resolution spectroscopy.

Among the fundamental questions to which investigations of clump stars should help to find an answer is a mechanism of transport of processed material to the stellar surface in low mass stars. Post-main sequence stars with masses below 2 − 2.5 $M_\odot$ exhibit signatures of material mixing that require challenging modelling beyond the standard stellar theory (reviews by Charbonnel 2006; Chanamé et al. 2005 and references therein). Also it is interesting to find out how many stars in the Galactic clump belong to the first ascent giants and to He-core-burning stars.

Carbon and nitrogen abundances are among most useful quantitative indicators of mixing processes in evolved stars. Because of the first dredge-up abundances of $^{12}$C decrease while abundances of $^{13}$C and $^{14}$N increase (Iben 1965). Depending on stellar mass, metallicity and evolutionary state, these alterations are growing (c.f. Boothroyd & Sackmann 1999; Charbonnel & Zahn 2007; and many other studies).

Three large studies of $^{12}$C, N and O abundances in clump stars have been done recently. Abundances of C, N and O in 177 clump giants of the Galactic disk were determined by Mishenina et al. (2006) on a basis of spectra ($R=42000$) obtained on the 1.93-m telescope of the Haute-Provence Observatoire (France).

A sample of 63 red clump stars, mainly located in the southern hemisphere, was investigated by Liu et al. (2007). Abundances of oxygen were investigated on a basis of spectra ($R=48000$) obtained on the 1.52-m telescope of the ESO (La Silla, Chile).

A spectroscopic analysis of C, N and O ($R=60000$) was done for a sample of nearby giants, with red clump stars...
among them by Luck & Heiter (2007). We selected a subsample of 138 red clump giants based on the luminosity and effective temperature diagram in the Fig. 20 of this paper. All the stars located in the box limited by luminosities log\(L/L_\odot\) from 1.5 to 1.8 and effective temperatures from 4700 K to 5200 K were included in the subsample.

A comprehensive study of \(^{13}\text{C}\) abundances in Galactic clump stars was not done yet. The \(^{12}\text{C}/^{13}\text{C}\) ratio is the most robust diagnostic of deep mixing, because it is very sensitive to mixing processes and is almost insensitive to the adopted stellar parameters.

In this paper we report \(^{12}\text{C}\), \(^{13}\text{C}\), \(^{14}\text{N}\) and \(^{16}\text{O}\) abundances in the 34 clump stars of the Galactic field obtained from the high-resolution spectra. The results are discussed in detail together with results of other studies of the clump stars. The preliminary results of this study were published by Tautvaisienė et al. (2003, 2007, 2010) and Tautvaisienė & Pužeras (2009).

## 2 OBSERVATIONAL DATA

The spectra of 26 stars were obtained at the Nordic Optical Telescope (NOT, La Palma) with the SOFIN échelle spectrograph (Tuominen et al. 1999). The 2nd optical camera \((R \approx 80000)\) was used to observe simultaneously 13 spectral orders, each of 40 – 60 Å in length, located from 5560 Å to 8130 Å. Reduction of the CCD images, obtained with SOFIN, was done using the \(4\mathcal{A}\) software package (Ilyin 2000). Procedures of bias subtraction, spike elimination, flat field correction, scattered light subtraction, extraction of spectral orders were used for image processing. A Th-Ar comparison spectrum was used for the wavelength calibration. The continuum was defined from a number of narrow spectral regions, selected to be free of lines.

This sample of stars was supplemented by spectroscopic observations \((R \approx 37000)\) of 8 red clump stars obtained on the 2.16 m telescope of the Beijing Astronomical Observatory (China) taken from the literature (Zhao et al. 2001). There are more spectra of clump stars presented in this literature source, however not all of them have regions of \(^{12}\text{C}\) Swan \((0,1)\) band head at 5630.5 Å observed, or good quality \(^{13}\text{C}^{14}\text{N}\) bands at 8004 Å. In Fig. 1, we show examples of spectra observed on the Nordic Optical Telescope and the telescope of Beijing Astronomical Observatory.

## 3 METHOD OF ANALYSIS AND PHYSICAL DATA

The spectra were analysed using a differential model atmosphere technique. A program \texttt{BSYN}, developed at the Uppsala Astronomical Observatory, was used to carry out the calculations of synthetic spectra. A set of plane parallel, line-blanketed, constant-flux LTE model atmospheres was computed with an updated version of the \texttt{MARCS} code (Gustafsson et al. 2008). Calibrations to the solar spectrum (Kurucz et al. 1984) was done for all the spectral regions investigated.

For this purpose we used the solar model atmosphere from the set calculated in Uppsala with a microturbulent velocity of 0.8 km s\(^{-1}\), as derived from Fe i lines, and the solar abundances \(\log A_C = 8.52, \log A_N = 7.92, \log A_O = 8.83, \log A_{Fe} = 7.50, C/N = 3.98, \text{^{12}C/^{13}C} = 89\), etc. (Grevesse & Sauval 2000).

For \(^{12}\text{C}\) determination in stars we used 5632 – 5636 Å interval to compare with observations of \(^{12}\text{C}\) Swan \((0,1)\) band head at 5635.5 Å. The same molecular data of \(^{12}\text{C}\) as used by Gonzalez et al. (1998) were adopted for the analysis. This feature was used in several of our previous studies of giants (Tautvaisienė et al. 2000; 2001; 2005).

The interval 7980 – 8130 Å contains strong \(^{12}\text{C}^{14}\text{N}\) and \(^{13}\text{C}^{14}\text{N}\) features, so it was used for nitrogen abundance and \(^{12}\text{C}/^{13}\text{C}\) ratio analysis. The well known \(^{13}\text{CN}\) line at 8044.7 Å was analysed in order to determine \(^{12}\text{C}/^{13}\text{C}\) ratios. The molecular data for this CN band were provided by Bertrand Plez (University of Montpellier II). All \(g\mathcal{f}\) values of CN were increased by +0.03 dex to fit the model spectrum of solar atlas of Kurucz et al. (1984).

We derived oxygen abundance from synthesis of the forbidden \([\text{O}\text{I}]\) line at 6300 Å. The \(g\mathcal{f}\) values for \(^{58}\text{Ni}\) and \(^{60}\text{Ni}\) isotopic line components, which blend the oxygen line, were taken from Johansson et al. (2003) and \([\text{O}\text{I}]\) \(\log g\mathcal{f} = -9.917\) value, as calibrated to the solar spectrum (Kurucz et al. 1984).

The atomic oscillator strengths for stronger lines of iron and other elements were taken from Gurzovenko & Kostik (1989). The Vienna Atomic Line Data Base (VALD, Piskunov et al. 1995) was extensively used in preparing the input data for the calculations. In addition to thermal and microturbulent Doppler broadening of lines, atomic line broadening by radiation damping and van der Waals damping were considered in the calculation of abundances. Radiation damping parameters of lines were taken from the VALD database. In most cases the hydrogen pressure damping of metal lines was treated using the modern quantum mechanical calculations by Anstee & O’Marra (1995), Barklem & O’Mara (1997) and Barklem et al. (1998). When using the Unsöld (1955) approximation, correction factors to the classical van der Waals damping approximation by widths \((\Gamma_6)\) were taken from Simmons & Blackwell (1982). For all other
species a correction factor of 2.5 was applied to the classical \( \Gamma_6 \) (\( \Delta \log C_6 = +1.0 \)), following Mäckle et al. (1975).

Stellar rotation was taken into account when needed. The values of \( v \) have been taken from Hekker & Meléndez (2007), De Medeiros et al. (2002) and Glebocki 
Stawikowski (2000).

Effective temperature, gravity, \([\text{Fe/H}]\) and microturbulent velocity values of the stars have been taken from Puzeras et al., luminosities and Girardi et al. (2000) isochrones. The luminosities were calculated from Hipparcos parallaxes (van Leeuwen 2007), \( V \) magnitudes (SIMBAD database), bolometric corrections calculated according to Alonso et al. (1999) and interstellar reddening corrections calculated using Hakkila et al. (1994) software.

Determinations of stellar masses were performed using effective temperatures obtained by Puzeras et al., luminosities and Girardi et al. (2000) isochrones. The luminosities were calculated from Hipparcos parallaxes (van Leeuwen 2007), \( V \) magnitudes (SIMBAD database), bolometric corrections calculated according to Alonso et al. (1999) and interstellar reddening corrections calculated using Hakkila et al. (1994) software.

3.1 Estimation of uncertainties

The sensitivity of the abundance estimates to changes in the atmospheric parameters by the assumed errors is illustrated for the star HD 141680 in Table 1.

The sensitivity of iron abundances to stellar atmospheric parameters were described in Puzeras et al. (2010).

Since abundances of C, N and O are bound together by the molecular equilibrium in the stellar atmosphere, we have also investigated how an error in one of them typically affects the abundance determination of another. \( \Delta \text{O/\text{H}} = -0.10 \) causes \( \Delta \text{C/\text{H}} = -0.04 \) and \( \Delta \text{N/\text{H}} = 0.10 \); \( \Delta \text{C/\text{H}} = -0.10 \) causes \( \Delta \text{N/\text{H}} = 0.14 \) and \( \Delta \text{O/\text{H}} = -0.03 \). \( \Delta \text{N/\text{H}} = 0.10 \) has no effect on either the carbon or the oxygen abundances.

Abundances of nitrogen were determined from 14–20 lines in the spectra obtained on the Nordic Optical Telescope and from 9–13 lines in the spectra obtained at the Beijinh Astronomical Observatory. The mean scatter of the deduced line abundances is equal to 0.07 dex. This gives an approximate estimate of uncertainties due to random errors of the analysis.

In Fig. 2 and 3, we present several examples of spectral syntheses and comparisons to the observed spectra.

4 RESULTS AND DISCUSSION

The abundances relative to hydrogen \([\text{Ei/H}]\), C/N, \( ^{12}\text{C}/^{13}\text{C} \), stellar masses and suggested evolutionary stages determined for the programme stars are listed in Table 2. For convenience, we also present the main atmospheric parameters of stars (\( T_{\text{eff}} \), log \( g \), \( v \) and \([\text{Fe/H}]\)) determined by Puzeras et al. (2010) as well.

4.1 Comparisons with C, N and O abundances in dwarf stars

The interpretation of the C, N and O abundances can be done by a comparison with abundances determined for dwarf stars in the Galactic disk.

As concerns carbon, we selected for the comparison the papers by Gustafsson et al. (1999) and Bensby & Feltzing (2006) since abundances of carbon were determined in these

\[ [X/Y] \equiv \log_{10}(N_X/N_Y)_{\text{star}} - \log_{10}(N_X/N_Y)_{\odot} \]
Figure 4. $[\text{C/Fe}]$ as a function of $[\text{Fe/H}]$. We show the results for the clump stars investigated in this work, in Mishenina et al. (2006) and in Luck & Heiter (2007). Also we show the results obtained for red horizontal branch stars by Tautvaisienė et al. (2001) and by Gratton et al. (2000). For the comparison, results obtained for dwarf stars of the Galactic disk (Gustafsson et al. 1999 and Bensby & Feltzing 2006) are presented.

Figure 5. $[\text{N/Fe}]$ as a function of $[\text{Fe/H}]$. We show the results for the clump stars investigated in this work, in Mishenina et al. (2006) and in Luck & Heiter (2007). Also we show the results obtained for red horizontal branch stars by Tautvaisienė et al. (2001). For the comparison, results obtained for dwarf stars of the Galactic disk (Shi et al. 2002) are presented.
Table 2. Atmospheric parameters and chemical element abundances of the programme stars

| HD   | T eff  | log g | v_t   | [Fe/H] | [C/H] | [N/H] | [O/H] | C/N  | ^{12}\text{C}/^{13}\text{C} | Sp. | Mass | Evol. |
|------|--------|-------|-------|--------|-------|-------|-------|------|------------------|-----|------|-------|
| 2910 | 4730   | 2.3   | 1.7   | –0.07  | –0.24 | 0.19  | –0.11 | 1.46 | 19               | 1   | 1.9  | g*    |
| 3546 | 4980   | 2.0   | 1.4   | –0.60  | –0.92 | –0.30 | –     | 0.96 | 13               | 1   | 1.5  | c     |
| 4188 | 4870   | 2.9   | 1.2   | 0.10   | –0.08 | 0.23  | 0.06  | 1.95 | 10               | 2   | 2.0  | c     |
| 5268 | 4870   | 1.9   | 1.4   | –0.48  | –     | –     | –0.33 | –    | –                | 1   | 1.6  | c     |
| 5395 | 4870   | 2.1   | 1.3   | –0.34  | –0.61 | –0.04 | –0.18 | 1.08 | 23               | 1   | 1.7  | g     |
| 6805 | 4530   | 2.0   | 1.5   | 0.02   | –0.13 | 0.09  | –0.06 | 2.39 | 13               | 1   | 1.1  | c     |
| 6976 | 4810   | 2.5   | 1.6   | –0.06  | –0.30 | 0.15  | –0.10 | 1.42 | 19               | 1   | 2.0  | g*    |
| 7106 | 4700   | 2.4   | 1.3   | 0.19   | –0.39 | –0.08 | –0.23 | 1.94 | 10               | 1   | 0.8  | c     |
| 8207 | 4660   | 2.3   | 1.4   | 0.09   | –0.15 | 0.37  | –0.15 | 1.20 | 22               | 1   | 1.8  | g     |
| 8512 | 4660   | 2.1   | 1.4   | –0.01  | –0.15 | 0.19  | –     | 1.82 | 14               | 1   | 1.5  | c     |
| 9595 | 4990   | 2.7   | 1.5   | 0.04   | –0.21 | 0.21  | –0.10 | 1.51 | 14               | 2   | 2.2  | c     |
| 12583| 4930   | 2.5   | 1.6   | 0.02   | –     | –     | –0.02 | 7    | 1                | 1   | 1.9  | c     |
| 13111| 4740   | 2.3   | 1.2   | –0.03  | –0.25 | 0.25  | –     | 1.26 | 19               | 1   | 1.2  | g     |
| 16400| 4800   | 2.1   | 1.4   | 0.03   | –0.26 | 0.22  | –0.11 | 1.33 | 23               | 1   | 1.6  | g     |
| 17361| 4700   | 2.5   | 1.4   | –0.04  | –0.23 | 0.10  | 0.02  | 1.86 | 13               | 2   | 1.4  | c     |
| 19787| 4660   | 2.6   | 1.4   | 0.06   | –0.06 | 0.18  | 0.12  | 2.29 | 15               | 2   | 1.8  | c     |
| 25604| 4770   | 2.5   | 1.6   | 0.02   | –0.13 | 0.19  | –0.01 | 1.90 | 15               | 2   | 1.9  | c     |
| 28292| 4600   | 2.4   | 1.5   | –0.06  | –0.12 | –0.02 | 0.01  | 3.16 | 15               | 2   | 1.0  | c     |
| 34559| 5060   | 3.0   | 1.5   | –0.07  | –0.13 | 0.35  | 0.03  | 1.32 | –                | 2   | 2.8  | g     |
| 35369| 4800   | 2.1   | 1.4   | –0.21  | –0.44 | 0.12  | –0.01 | 1.20 | 25               | 1   | 1.9  | g     |
| 58207| 4800   | 2.3   | 1.2   | –0.08  | –0.35 | 0.21  | –0.22 | 1.10 | 20               | 1   | 1.8  | g*    |
| 13111| 4740   | 2.5   | 1.1   | –0.17  | –0.32 | 0.05  | –     | 1.70 | 30               | 1   | 1.3  | g     |
| 141680|4900    | 2.5    | 1.3   | –0.07  | –0.30 | 0.21  | –0.02 | 1.24 | 16               | 1   | 2.0  | c     |
| 146388|4700    | 2.5    | 1.3   | 0.18   | 0.03  | 0.58  | 0.04  | 1.13 | 22               | 1   | 2.0  | g     |
| 222842|4980    | 2.8    | 1.3   | –0.02  | –0.31 | 0.34  | –0.16 | 0.89 | 25               | 1   | 2.4  | g     |

Sp: 1 – NOT, 2 – Beijing. Evol.: g – first ascent giant, c – He-core-burning star, * – may be a He-core-burning star.

For the comparison of [N/Fe] values, in Fig. 5, we show the results of clump stars together with results obtained for dwarf stars by Shi et al. (2002). By means of spectral synthesis they investigated several weak N 1 lines. Reddy et al. (2003) also investigated nitrogen abundances in a sample of 43 F–G dwarfs in the Galactic disk by means of weak N 1 lines, however they used the equivalent width method, which gave, to our understanding, slightly overabundant [N/Fe] values. As it is seen from Fig. 5, in the clump stars investigated, when compared to the Galactic field dwarf stars, the nitrogen abundances are enhanced by about 0.2 dex.

In our study, as well as in Mishenina et al. (2006), in Liu et al. (2007) and in Luck & Heiter (2007), the oxygen abundances in clump stars are similar to those observed in dwarfs (e.g. Edvardsson et al. 1993). In agreement with theoretical predictions the investigated stars do not yet show signs of evolution of the oxygen abundances after the main sequence. This allows to use oxygen abundances of clump stars for Galactic evolution studies.
4.2 Comparisons with theoretical models

In Mishenina et al. (2006), the observational results of [C/Fe] and [N/Fe] were compared with theoretical trends of the 1st dredge-up, computed using the STAREVOL code and presented in the same paper by Mishenina et al. The modelled trends were computed using the standard mixing length theory. In the left side of Fig. 6, we plotted [C/Fe] and [N/Fe] versus effective temperatures in our sample of Galactic red clump stars compared with the theoretical tracks of abundance variations taken from Mishenina et al. The nitrogen overabundances in the clump stars are in agreement with the modeled, however carbon in the observed sample is depleted more than the theoretical model of Mishenina et al. (2006) predicts. In these models neither overshooting, nor undershooting was considered for convection. The atomic diffusion and rotational-induced mixing were also not taken into account. In order to better fit the observational results, the authors simply shifted an initial [C/Fe] by $-0.15$ dex. In our comparison we had to make the same.

C/N and $^{12}$C/$^{13}$C ratios we compared with the theoretical models by Boothroyd & Sackmann (1999) (the right side of Fig. 6) and found a good agreement with the observational data. These models include the deep circulation
mixing below the base of the standard convective envelope, and the consequent "cool bottom processing" (CBP) of CNO isotopes.

Recently Eggleton et al. (2006) found a mean molecular weight (μ) inversion in their 1M_☉ stellar evolution model, occurring after the so-called luminosity bump on the red giant branch, when the H-burning shell source enters the chemically homogeneous part of the envelope. The μ-inversion is produced by the reaction $^4$He($^3$He, 2p)$^7$He, as predicted by Ulrich (1972). It does not occur earlier, because the magnitude of the μ-inversion is small and negligible compared to a stabilizing μ-stratification.

The work by Eggleton et al. (2006) has inspired Charbonnel & Zahn (2007) to compute stellar models including the prescription by Ulrich (1972) and extend them to the case of a non-perfect gas for the turbulent diffusivity produced by that instability in stellar radiative zone. They found that a double diffusive instability referred to as thermohaline convection, which has been discussed long ago in the literature (Stern 1960), is important in evolution of red giants. This mixing connects the convective envelope with the external wing of hydrogen burning shell and induces surface abundance modifications in red giant stars (Lagarde & Charbonnel 2009).

In our $^{12}$C/$^{13}$C and stellar mass plot (Fig. 6) we show the thermohaline model (TH) by Lagarde & Charbonnel (2009) as well. It fits to our observational results well at lower masses but at larger masses the theoretical $^{12}$C/$^{13}$C ratios could be slightly lower. Nevertheless, we are sure that the thermohaline model is a promising model to be developed. Cantiello & Langer (2010) reported that thermohaline mixing is also present in red giants during core He-burning and beyond.

The comparison with theoretical models shows that according to $^{12}$C/$^{13}$C isotope ratios, the stars fall into two groups: the one with carbon isotope ratios altered according to the 1st dredge-up prediction, and the other one with carbon isotope ratios altered by extra mixing. The stellar positions in the $^{12}$C/$^{13}$C versus stellar mass diagram as well as comparisons to stellar evolutionary sequences in the luminosity versus effective temperature diagram by Girardi et al. (2000) show that stars fall to groups of helium-core-burning stars and about 100 first ascent giants in approximately equal numbers. In the last column of Table 2, we indicate the predicted evolutionary status of investigated stars. By asterisks are marked stars which have $^{12}$C/$^{13}$C isotope ratios equal to about 20, and which could belong to helium-core-burning stars as well, especially if compared to the model of thermohaline mixing.

In the paper by Mishenina et al. (2006), according to nitrogen abundance values, the authors have suggested 21 helium-core-burning stars, about 54 candidates to helium-core-burning stars and about 100 first ascent giants.

4.3 Summary

In this work we present $^{12}$C/$^{13}$C determinations in a sample of 34 Galactic clump stars as well as abundances of nitrogen, carbon and oxygen, obtained using high-resolution spectra observed on the Nordic Optical telescope ($R \approx 80000$) and at the Beijing Astronomical Observatory ($R \approx 37000$). The obtained stellar abundances together with results of other studies of Galactic clump stars (Mishenina et al. 2006; Liu et al. 2007 and Luck & Heiter 2007) and of red-horizontal-branch stars (Tautvaišienė et al. 2001 and Gratton et al. 2000) were compared with determinations of C, N and O abundances in dwarf stars of the Galactic disk.

The mean abundances in the investigated clump stars suggest that carbon is depleted by about 0.2 dex, nitrogen is enhanced by 0.2 dex and oxygen is close to abundances in dwarfs.

The stellar positions in the $^{12}$C/$^{13}$C versus stellar mass diagram as well as comparisons to stellar evolutionary sequences in the luminosity versus effective temperature diagram by Girardi et al. (2000) show that the stars fall into two groups: the one is of first ascent giants with carbon isotope ratios altered according to the 1st dredge-up prediction, and the other one is of helium-core-burning stars with carbon isotope ratios altered by extra mixing. The stars investigated fall to these groups in approximately equal numbers.

And finally, we would like to point out that thermohaline convection is a fundamental physical process and is important in evolution of red giants. However, most probably thermohaline mixing is not the only physical process responsible for surface abundance anomalies in red giants (c.f. Cantiello & Langer 2010). We hope that the results presented in this work will contribute to answering fundamental questions of stellar evolution.

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