

C, N, O abundances and carbon isotope ratios in evolved stars of the open clusters Collinder 261 and NGC 6253*

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ABSTRACT

Context. Investigations of abundances of carbon and nitrogen in the atmospheres of evolved stars of open clusters may provide comprehensive information on chemical composition changes caused by stellar evolution.

Aims. Our main aim is to increase the number of open clusters with determined carbon-to nitrogen and carbon isotope ratios.

Methods. High-resolution spectra were analysed using a differential model atmosphere method. Abundances of carbon were derived using the C₂ Swan (0, 1) band head at 5635.5 Å (FEROS spectra) and the C₂ Swan (1, 0) band head at 4737 Å (UVES spectra). The wavelength interval 7980–8130 Å, with strong CN features was analysed to determine nitrogen abundances and ¹²C/¹³C isotope ratios. The oxygen abundances were determined from the [O I] line at 6300 Å.

Results. The average value of ¹²C/¹³C isotope ratios of Cr 261 is equal to 18 ± 2 in four giants and to 12 ± 1 in two clump stars; it is equal to 16 ± 1 in four clump stars of the open cluster NGC 6253. The mean C/N ratios in Cr 261 and NGC 6253 are equal to 1.67 ± 0.06 and 1.37 ± 0.09, respectively.

Conclusions. The ¹²C/¹³C and C/N values in Cr 261 and NGC 6253 within limits of uncertainties agree with the theoretical model of thermohaline-induced mixing as well as with the cool-bottom processing model.

Key words. stars: abundances – stars: horizontal-branch – open clusters and associations: individual: collinder 261 – open clusters and associations: individual: NGC 6253

1. Introduction

The carbon and nitrogen abundances, C/N, and especially the carbon isotope ratios ¹²C/¹³C are key tools for stellar evolution studies. It is well known that low-mass stars experience the first dredge-up at the bottom of the giant branch (Iben 1965). However, extra-mixing processes become efficient on the red giant branch (RGB) when these stars reach the so-called RGB bump, and modify the surface abundances (Gilroy 1989; Gilroy & Brown 1991; Luck 1994; Charbonnel 1994; Charbonnel et al. 1998; Gratton et al. 2000; Tautvaišienė et al. 2000; Tautvaišienė et al. 2001, 2005; Smiljanic et al. 2009; Mikolaitis et al. 2010, 2011a,b). It is also known that alterations of ¹²C/¹³C and ¹²C/¹⁴N ratios depend on stellar evolutionary stage, mass and metallicity (Charbonnel et al. 1998; Gratton et al. 2000; Chanamé et al. 2005; Charbonnel 2006; Cantiello & Langer 2010; Charbonnel & Lagarde 2010). However, details of these dependences are uncertain; a comprehensive and statistically significant observational data base for stars of different turn-off masses and metallicities is needed to constrain models. In this work, our targets of investigations are the open clusters Collinder 261 and NGC 6253.

Collinder 261 (Cr 261; galactic coordinates $l = 301^{\circ}68, b = -5^{\circ}53$) is one of the oldest open clusters in the Galaxy. Its age

is 5–10 Gyr, depending on the adopted stellar evolution models (Janes & Phelps 1994; Mazur et al. 1995; Gozzoli et al. 1996; Carraro et al. 1998), but the recent investigation of Bragaglia & Tosi (2006) has defined a most probable age of about 6 Gyr. Unlike the majority of old open clusters, which are located in the outer Galactic disk, this cluster is in the inner part, at 7.5 kpc from the Galactic centre and 235 pc below the plane. Despite the old age, the metallicity of this cluster determined from high-resolution spectral studies is close to solar: [Fe/H] = –0.03 (Carretta et al. 2005; De Silva et al. 2007), –0.22 dex (Friel et al. 2003), +0.13 dex (Sestito et al. 2008). De Silva et al., who investigated 12 red giants in Cr 261 using Very Large Telescope (VLT) UVES spectra, emphasised that this cluster is very chemically homogeneous – the intrinsic scatter was estimated to be less than 0.05 dex. The chemical homogeneity of Cr 261 makes this cluster an extremely interesting target for investigating the mixing of sensitive elements such as carbon isotopes and nitrogen, which have not been studied in previous studies.

NGC 6253 (galactic coordinates $l = 335^{\circ}45, b = -6^{\circ}26$) is also quite old of 3–5 Gyr (Piatti et al. 1998; Bragaglia & Tosi 2006; Montalto et al. 2009) and located in the inner part of the Galaxy, at 6.6 kpc from the Galactic centre. The most interesting signature of this open cluster is its high metallicity. Recent high-resolution spectral determinations of [Fe/H] are the following: +0.43 dex (Anthony-Twarog et al. 2010), +0.36 dex (Sestito et al. 2007), +0.46 dex (Carretta et al. 2007). Since

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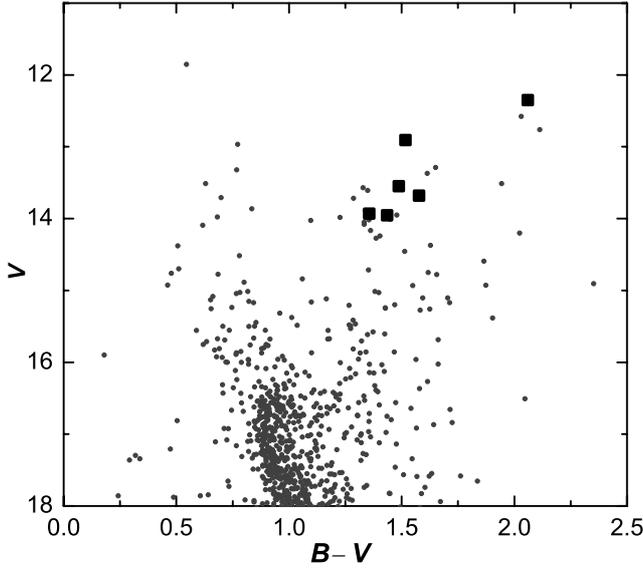


Fig. 1. Colour-magnitude diagram of the open cluster Cr 261. The stars investigated in this work are indicated by the filled squares. The diagram is based on *BVI* photometry by [Gozzoli et al. \(1996\)](#).

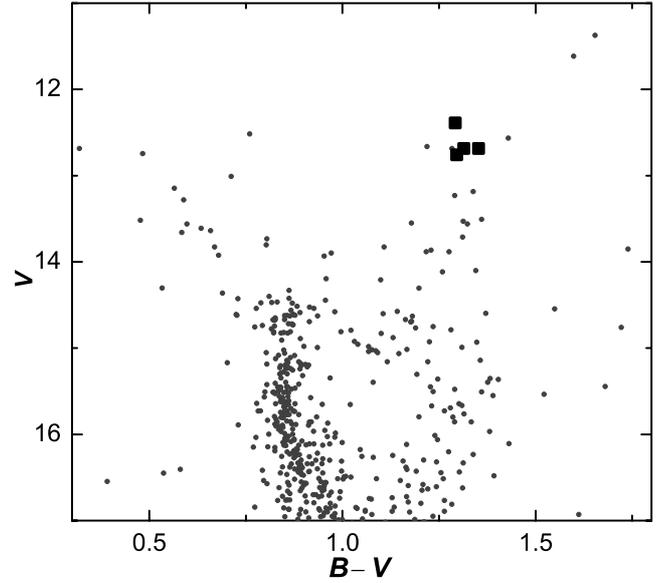


Fig. 2. Colour-magnitude diagram of the open cluster NGC 6253. The stars investigated in this work are indicated by filled squares. The diagram is based on *UBVI* photometry by [Bragaglia et al. \(1997\)](#).

mixing processes depend on stellar metallicities, it is important to have C/N and $^{12}\text{C}/^{13}\text{C}$ ratios determined in metal-rich evolved stars. By now, less than a handful of open clusters with similarly high metal-abundance have been detected in our Galaxy (e.g., NGC 6791, [Gratton et al. 2006](#); NGC 2632, [Pace et al. 2008](#)). This makes NGC 6253 a very attractive target for our study.

Our main aim is to determine detailed elemental abundances of carbon, nitrogen and oxygen, and carbon isotopic $^{12}\text{C}/^{13}\text{C}$ ratios in evolved stars of Cr 261 and NGC 6253 to better understand abundance alterations caused by stellar evolution.

2. Observations and method of analysis

The spectra of six cluster stars of Cr 261 (1045, 1080, 1485, 1871, 2001, and 2105; the identification numbers are from [Phelps et al. 1994](#)) were obtained with the spectrograph FEROS (Fiber-fed Extended Range Optical Spectrograph) mounted on the 1.5 m telescope at the European Southern Observatory (ESO) in La Silla (Chile). The resolving power is $R = 48\,000$ and the wavelength range is $3700 < \lambda < 8600 \text{ \AA}$. Two stars (1080 and 2001) belong to the red clump of the cluster, three stars (1045, 1485 and 2105) are first-ascent giants, and the star 1871 is an RGB-tip giant (see Fig. 1). Depending on the magnitudes, signal-to-noise ratios of the observed spectra lie between 130 and 70. The log of observations and information about reductions were presented in the paper by [Carretta et al. \(2005\)](#).

The spectrum of NGC 6253 3595 was obtained with the same spectrograph FEROS. In the same cluster, the stars 2509, 2885, and 4510 were observed using the UVES spectrograph on the ESO VLT telescope in Paranal (Chile). The identification numbers are from [Bragaglia et al. \(1997\)](#). The spectra cover the wavelength ranges 3560–4840 and 5710–9320 \AA at $R = 43\,000$. Signal-to-noise ratios of the UVES spectra lie between 180 and 120. The log of observations and information about reductions were presented in the paper by [Carretta et al. \(2007\)](#). [Carretta et al.](#) have also observed the star NGC 6253 2508, but its radial velocity was different from the rest of the stars by about 10σ . Even though [Montalto et al. \(2009\)](#) give a high

membership probability for this star based on its proper motion, we neglected NGC 6253 2508 in the analysis. All stars observed in NGC 6253 belong to the red clump of the cluster (see Fig. 2).

In this work as well as in other papers of this series ([Mikolaitis et al. 2010, 2011a,b](#)), the ATLAS models with overshooting ([Kurucz 1993](#)) and a computing code by [Gratton \(1988\)](#) were used for the analysis of the spectra. The analysis was differential to the Sun.

The main atmospheric parameters for the observed stars in Cr 261 have been determined spectroscopically by [Carretta et al. \(2005\)](#). We used them in our analysis and present them in Table 1 for convenience.

For the cluster NGC 6253 the atmospheric parameters have been previously determined by [Carretta et al. \(2007\)](#), but they used a photometric method. To make our study as homogeneous as possible, we decided to redetermine them spectroscopically.

The spectroscopic effective temperatures were derived by minimising the slope of the abundances obtained from neutral Fe I lines with respect to the excitation potential. The gravities ($\log g$) were derived by forcing measured neutral and ionised iron lines to yield the same $[\text{Fe}/\text{H}]$ value by adjusting the model gravity. The microturbulent velocities were determined by forcing Fe I abundances to be independent of the equivalent widths of lines. Iron lines were restricted to the spectral range 5500–8000 \AA to minimise problems of line crowding and difficulties in the continuum tracing in the blue region. After the careful selection, the number of Fe I lines was set to 63 and of Fe II to 5. First, using the model atmosphere of the Sun from the same grid of [Kurucz \(1993\)](#) and the microturbulent velocity of 0.9 km s^{-1} , we calculated the solar iron abundance. The atomic parameters and solar equivalent widths of lines were taken from [Gurtovenko & Kostyk \(1989\)](#). These solar iron abundances were used for the differential determination of abundances in the programme stars.

The determined atmospheric parameters and iron abundances for the observed stars in NGC 6253 are presented in Table 1. Differences between the photometric and spectroscopic parameters appeared to be quite small and lie within uncertainties of determinations. There is no systematic difference in T_{eff} ,

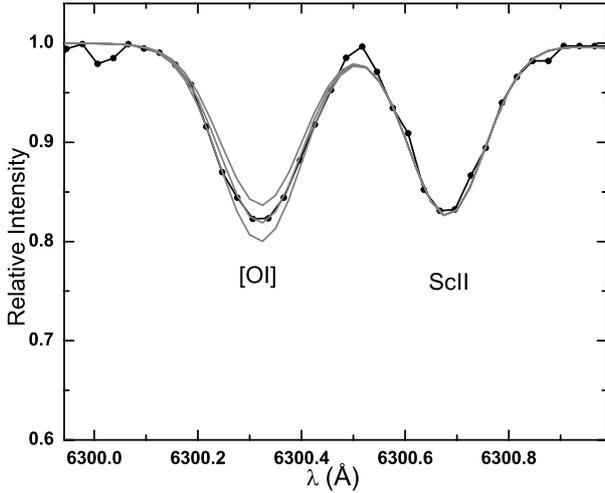


Fig. 3. Fit to the forbidden [O I] line at 6300 Å in Cr 261 1080. The observed spectrum is shown as a solid line with black dots. Synthetic spectra with $[O/Fe] = 0.05, -0.05,$ and -0.15 are shown as solid grey lines.

just a mean scatter of ± 30 K, our $\log g$ values are by about 0.07 dex higher, v_t by about 0.2 km s^{-1} higher, and differences in $[Fe/H]$ do not exceed ± 0.05 dex.

In this work, abundances of ^{12}C , ^{13}C , N, and O were determined using the same method of analysis as in Mikolaitis et al. (2010, Paper I). Here we recall only some details.

For the carbon abundance determination in stars observed with FEROS, we considered observations of the 5632–5636 Å spectral range close to the C_2 Swan (0,1) band head. This spectral interval was not available for the stars observed with UVES, therefore we analysed several lines of the Swan (1,0) bands at 4732.8 Å and 4735.3 Å. This spectral interval was available in the FEROS spectra as well, but we were unable to analyse the C_2 lines at these wavelengths since the S/N ratio was too low.

The interval 7980–8130 Å containing strong $^{12}\text{C}^{14}\text{N}$ and $^{13}\text{C}^{14}\text{N}$ features was used for the nitrogen abundance and $^{12}\text{C}/^{13}\text{C}$ ratio analysis.

We derived the oxygen abundance from synthesis of the forbidden [O I] line at 6300 Å. The gf values for ^{58}Ni and ^{60}Ni isotopic line components, which blend the oxygen line, were taken from Johansson et al. (2003). The [O I] line was not contaminated by telluric lines in the spectra of investigated stars. The solar abundances were taken from Grevesse & Sauval (2000). The carbon, nitrogen and oxygen abundances used in our work are $\log A_C = 8.52$, $\log A_N = 7.92$, and $\log A_O = 8.83$. The solar C/N ratio is 3.98. The $^{12}\text{C}/^{13}\text{C}$ ratio in the solar photosphere is equal to 89 (Coplen et al. 2002). All synthetic spectra were first calibrated to the solar spectrum by Kurucz (2005).

Figures 3–6 display examples of spectrum syntheses for the programme stars. The best-fit abundances were determined by eye.

2.1. Estimation of uncertainties

Sources of uncertainty in similar analyses were described in detail and evaluated in our Paper I; that discussion applies also to the stars and instrumentation used here for Cr 261.

Since stars in the open cluster NGC 6253 are more metal-abundant than those in other cluster analysed by us previously, it was interesting to see what the sensitivities to uncertainties of the main atmospheric parameters are. The sensitivity of the

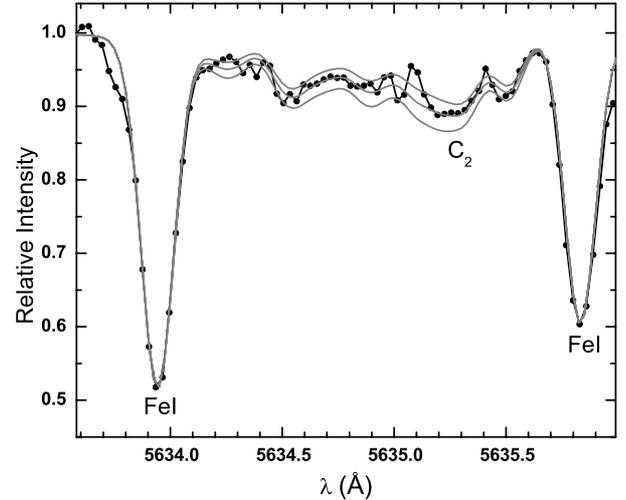


Fig. 4. Small region of Cr 261 2001 spectrum (solid black line with black dots) at C_2 Swan (0,1) band head 5635.5 Å, plotted together with synthetic spectra with $[C/Fe]$ values of -0.10 dex (lower grey line), -0.15 dex (middle grey line) and -0.20 (upper grey line).

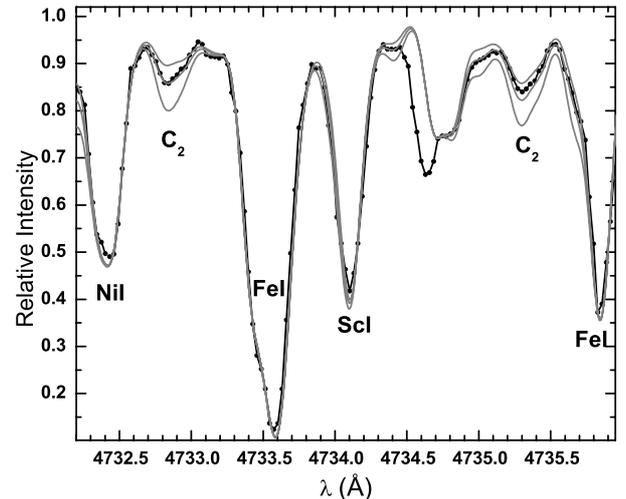


Fig. 5. Small region of NGC 6253 2885 spectrum (solid black line with black dots) with C_2 features, plotted together with synthetic spectra with $[C/Fe]$ values of -0.05 dex (lower grey line), -0.15 dex (middle grey line) and -0.25 (upper grey line).

abundance estimates to variations in the atmospheric parameters for the assumed parameter differences of ± 100 K for T_{eff} , ± 0.3 dex for $\log g$, $\pm 0.3 \text{ km s}^{-1}$ for v_t , and ± 0.1 dex for $[Fe/H]$ is illustrated in Table 2 for the star NGC 6253 2509. Evidently, possible parameter errors do not affect the abundances seriously; the element-to-iron ratios, which we use in our discussion, are even less affected. For Cr 261, the sensitivity of iron abundances to stellar atmospheric parameters were described in Carretta et al. (2005).

Since abundances of C, N, and O are bound together by the molecular equilibrium in the stellar atmosphere, we also investigated how an error in one of them typically affects the abundance determination of another. $\Delta[O/H] = 0.10$ causes $\Delta[C/H] = 0.05$ and $\Delta[N/H] = -0.15$; $\Delta[C/H] = 0.10$ causes $\Delta[N/H] = -0.15$ and $\Delta[O/H] = 0.05$; $\Delta[N/H] = 0.10$ has no effect on either the carbon or the oxygen abundances.

The random errors of elemental abundance determinations mostly depend on the S/N ratio and can be evaluated from the

Table 1. Main parameters and elemental abundances of the programme stars.

Cluster ^{1,2}	Star	<i>V</i> mag	<i>B</i> – <i>V</i> mag	<i>T</i> _{eff} K	log <i>g</i>	<i>v</i> _t km s ⁻¹	[Fe/H]	[C/Fe]	[N/Fe]	σ ³	<i>n</i> ⁴	[O/Fe]	C/N	¹² C/ ¹³ C
Cr 261	1045	13.547	1.487	4470	2.07	1.23	0.00	-0.15	0.23	0.05	16	-0.05	1.66	15
Cr 261	1080	13.952	1.435	4500	2.09	1.23	0.00	-0.15	0.26	0.05	10	-0.05	1.58	11
Cr 261	1485	13.680	1.577	4340	1.76	1.27	-0.06	-0.15	0.23	0.05	16	-0.05	1.66	18
Cr 261	1871	12.350	2.060	3980	0.43	1.44	-0.31	-0.10	0.20	0.04	20	-0.20	2.04	18
Cr 261	2001	13.932	1.356	4580	1.83	1.26	-0.02	-0.15	0.20	0.07	10	-0.10	1.66	13
Cr 261	2105	12.908	1.517	4180	1.59	1.29	-0.08	-0.10	0.24	0.06	16	-0.05	1.78	19
NGC 6253	2509	12.685	1.314	4494	2.57	1.42	0.46	-0.17	0.35	0.03	21	-0.10	1.20	15
NGC 6253	2885	12.656	1.352	4490	2.43	1.38	0.43	-0.23	0.33	0.05	21	-0.20	1.12	17
NGC 6253	3595	12.388	1.292	4535	2.44	1.40	0.44	-0.18	0.27	0.04	19	-0.10	1.39	17
NGC 6253	4510	12.759	1.296	4509	2.52	1.38	0.47	-0.20	0.32	0.03	21	-0.17	1.20	15

Notes. ⁽¹⁾ Star numbers for the cluster Cr 261 were taken from Phelps et al. (1994) and *V*, and *B* – *V* are from Gozzoli et al. (1996). Star numbers, *V*, *B* – *V* for the cluster NGC 6253 were used from Bragaglia et al. (1997) ⁽²⁾ The main atmospheric parameters for the cluster Cr 261 were adopted from Carretta et al. (2005), for the cluster NGC 6253 – determined in this work. ⁽³⁾ The standard deviations in the mean value due to the line-to-line scatter. ⁽⁴⁾ The number of CN molecular features used.

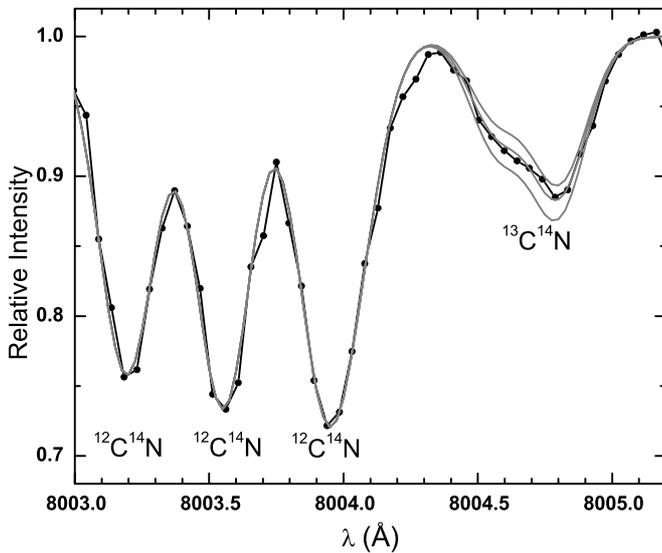


Fig. 6. Small region of NGC 6253 4510 spectrum (solid black line with black dots) including a ¹³C¹⁴N feature. Grey lines show synthetic spectra with ¹²C/¹³C ratios equal to 12 (lower line), 15 (middle line) and 18 (upper line).

star-to-star scatter and line-to-line scatter for an individual star. The star-to-star scatter is very small for the investigated cluster stars, it does not exceed 0.07 dex. The line-to-line scatter in our work is seen in the case of nitrogen abundance determination (Table 1); its mean value is equal to 0.05 dex for Cr 261, and to 0.04 dex for NGC 6253. The typical errors of ¹²C/¹³C and C/N ratios are 2.5 and 0.25, respectively (cf. Charbonnel & Lagarde 2010; Smiljanic et al. 2009; Gilroy 1989).

3. Results and discussion

We determined the abundances of the key chemical elements ¹²C, ¹³C, N, and O for the open clusters Cr 261 and NGC 6253. The abundances relative to iron [E]/[Fe]¹ and σ (the line-to-line scatter) derived for the programme stars are listed in Table 1.

¹ In this paper we use the customary spectroscopic notation [X/Y] ≡ log₁₀(*N*_X/*N*_Y)_{star} – log₁₀(*N*_X/*N*_Y)_⊙.

Table 2. Effects on derived abundances, Δ[A/H], resulting from model changes for the star NGC 6253 2509.

Species	Δ <i>T</i> _{eff} ±100 K	Δ log <i>g</i> ±0.3	Δ <i>v</i> _t ±0.3 km s ⁻¹	Δ[Fe/H] ±0.1	Total
C (C ₂)	0.07	0.05	0.00	0.03	0.09
N (CN)	0.07	0.05	0.03	0.05	0.10
O ([O I])	0.03	0.03	0.00	0.03	0.05
¹² C/ ¹³ C	1.5	1.5	0.0	0.00	2

As already noted by Carretta et al. (2005) (who attributed this to the incomplete adequacy of Kurucz atmospheric models for cool giants), the [Fe/H] value of the star Cr 261 1871, which is located at the red giant branch-tip, is slightly peculiar because it is more than 0.2 dex lower than of other cluster stars. Its carbon and nitrogen to iron ratios are indistinguishable from other stars of this cluster; but the oxygen abundance and C/N ratio slightly differ from the other stars of this cluster. We did not use the [O/Fe] and C/N values of this star when we calculated the average values for the cluster. The value of ¹²C/¹³C, which is less sensitive to the atmosphere parameters, agrees with results for other stars.

The average values of carbon to iron ratios in Cr 261 and NGC 6253 stars are [C/Fe] = -0.13 ± 0.02 and [C/Fe] = -0.20 ± 0.01, respectively. This means that the ratios of [C/Fe] in investigated stars of these clusters lie below the values obtained for dwarf stars of the Galactic disk, which are solar. Shi et al. (2002) performed an abundance analysis of carbon for a sample of 90 F- and G-type main-sequence disk stars using C I and [C I] lines and found [C/Fe] to be about solar at solar metallicity. Roughly solar carbon abundances were found by Gustafsson et al. (1999), who analysed a sample of 80 late-F and early-G type dwarfs using the forbidden [C I] line.

While determining the carbon abundance, we also had to analyse oxygen since carbon and oxygen are bound together by the molecular equilibrium in the stellar atmosphere. The mean oxygen-to-iron abundance ratios in Cr 261 and NGC 6253 stars are [O/Fe] = -0.06 ± 0.02 and [O/Fe] = -0.15 ± 0.05, respectively. These results agree with the oxygen abundances in metal-rich dwarfs (Bensby et al. 2004 and references therein).

The results for C and O also agree well with the values found by Carretta et al. (2005) and Carretta et al. (2007).

The mean nitrogen-to-iron abundance ratios in Cr 261 and NGC 6253 stars are $[N/Fe] = 0.23 \pm 0.02$ and $[N/Fe] = 0.29 \pm 0.03$, respectively. This shows that the nitrogen abundances are enhanced in these evolved stars, since $[N/Fe]$ values in the Galactic main-sequence stars are about solar at the solar metallicity (cf. Shi et al. 2002). The low $[N/Fe]$ values previously found in NGC 6253 by Carretta et al. (2007) were caused by an error in input parameters.

Because we compare the abundances of C, N, and O with results for dwarfs from the literature, some offsets might be present owing to differences in the analysed spectral features, solar abundance scales, or other parameters. However, because we compare element-to-iron ratios, which are less sensitive to systematic errors, our qualitative evaluation of systematic abundance differences should be correct.

The final C/N and $^{12}C/^{13}C$ ratios achieved by the star after the mixing events depend on stellar turn-off masses, which are $1.10 M_{\odot}$ and $1.40 M_{\odot}$ (Bragaglia & Tosi 2006) for Cr 261 and NGC 6253, respectively. The mean C/N ratios in Cr 261 and NGC 6253 are equal to 1.67 ± 0.06 and 1.37 ± 0.09 , respectively.

For clusters in which both first-ascent giants after the red giant branch (RGB) luminosity bump and clump stars were analysed, it is worth to check whether the carbon isotope ratios are similar or not. Two investigated stars in Cr 261 belong to the clump (1080 and 2001) and the remaining stars are giants located above the bump. We see that carbon isotope ratios are lowered more in the clump stars than in the giants. The mean $^{12}C/^{13}C$ ratio is equal to 12 ± 1 in the clump stars and to 18 ± 2 in the giants. The mean $^{12}C/^{13}C$ ratio in four clump stars investigated in NGC 6253 is equal to 16 ± 1 .

The C/N is much less sensitive to mixing processes than $^{12}C/^{13}C$ ratio (Boothroyd & Sackmann 1999; Charbonnel & Lagarde 2010; and references therein). We see this in Figs. 7 and 8. The C/N ratio in clump stars of Cr 261 is by 0.1 lower than in the giants, but this difference lies within the uncertainties of determination.

It is important to increase the number of open clusters of different age and metal abundance with $^{12}C/^{13}C$ ratios determined in giants and clump stars. This may help us to better understand mixing processes in low-mass stars and possible He-flash influence.

4. Comparison with theoretical models

The low-mass stars ($M < 2.5 M_{\odot}$) approach the red giant branch after the turn-off from the main sequence. The convective envelope deepens inside, towards the hydrogen burning shell. The point of the deepest penetration is the end of the first dredge-up. A sharp composition discontinuity is left after this event. The result is the altered surface abundances of 3He and of the main mixing tracers Li, Be, B, C, and N, depending on the initial stellar mass and chemical composition (Charbonnel 1994; Charbonnel & Zahn 2007; Charbonnel & Lagarde 2010; Boothroyd & Sackmann 1999). After the completion of the first dredge-up, canonical mixing models, where the rotation is not included and the convection is the only tool of mixing inside the stellar interior, do not predict any other alterations in the surface abundances until the stars reach the asymptotic giant branch. However, because observations of stars in the Galactic field and open or globular clusters showed signatures of extra-mixing process, new mechanisms of extra-mixing were proposed by a number of scientific groups to describe the

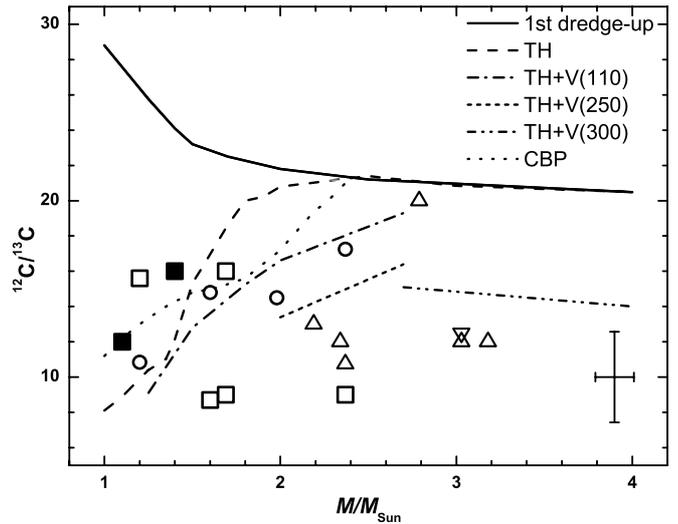


Fig. 7. Average carbon isotope ratios in clump stars of open clusters as a function of stellar turn-off mass. The results of this work are marked by filled squares; from Mikolaitis et al. (2010, 2011a,b) and Tautvaišienė et al. (2000); Tautvaišienė et al. (2005) – open squares; from Smiljanic et al. (2009) – open triangles; from Luck (1994) – reversed open triangle; from Gilroy (1989) – open circles. The models of the first dredge-up, thermohaline mixing (TH) and rotation-induced mixing (V) are taken from Charbonnel & Lagarde (2010). The CBP model of extra-mixing is taken from Boothroyd & Sackmann (1999). A typical error bar is indicated (Charbonnel & Lagarde 2010; Smiljanic et al. 2009; Gilroy 1989).

observed surface abundances in various types of stars (see reviews by Chanamé et al. 2005; Charbonnel 2006; recent papers by Denissenkov 2010; Lagarde et al. 2011; Palmerini et al. 2011; Wachlin et al. 2011; Angelou et al. 2012 and references therein).

In Figs. 7 and 8 we compare the determined $^{12}C/^{13}C$ and C/N ratios in clump stars of Cr 261 and NGC 6253 with theoretical models and results obtained for other open clusters. The mean values of the $^{12}C/^{13}C$ and C/N ratios in the clump stars of Cr 261 are 12 ± 1 and 1.62 ± 0.04 , respectively. The clump stars have accumulated all chemical composition changes that have happened during their evolution along the giant branch and during the helium flash, therefore they are very suitable for a comparison. A compilation of recent $^{12}C/^{13}C$ and C/N ratios in clump stars of open clusters has been provided by Mikolaitis et al. (2011a). In addition, we include the results by Mikolaitis et al. (2011b) and this work. Two models of extra-mixing are compared: the thermohaline-induced mixing (TH) model (Charbonnel & Lagarde 2010), and the cool-bottom processing (CPB) model by Boothroyd & Sackmann (1999).

The cool-bottom processing model, which includes a deep circulation mixing below the base of the standard convective envelope was proposed more than a decade ago (Boothroyd et al. 1995; Wasserburg et al. 1995; Boothroyd & Sackmann 1999, and references therein). In this model, an extra-mixing takes material from the convective envelope, transports it down to regions hot enough for some nuclear processing in the outer wing of the H-burning shell, and then transports it back up to the convective envelope. For the computations of the extra-mixing the “conveyor-belt” circulation model was used. The temperature difference between the bottom of mixing and the bottom of the H-burning shell was considered a free parameter, to

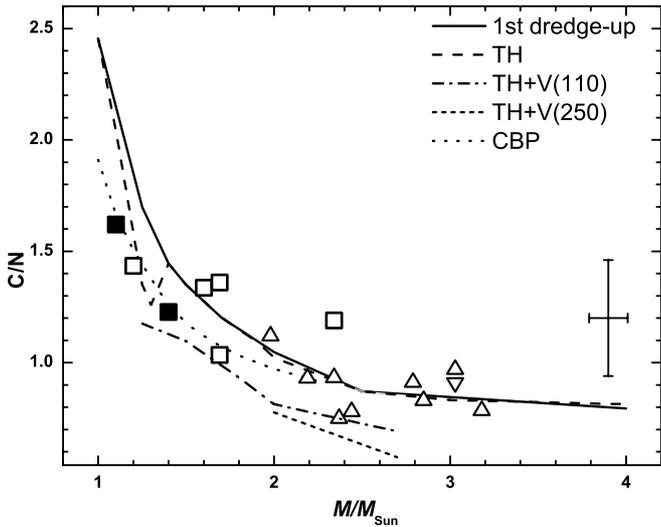


Fig. 8. Average carbon-to-nitrogen ratios in clump stars of open clusters as a function of stellar turn-off mass. The meaning of symbols are as in Fig. 7.

be determined by comparison with the observations, to M 67 (Gilroy 1989; Gilroy & Brown 1991), in particular.

The model of thermohaline instability induced mixing is based on ideas of Eggleton et al. (2006) and Charbonnel & Zahn (2007). Eggleton et al. (2006) found a mean molecular weight (μ) inversion in their $1 M_{\odot}$ stellar evolution model, occurring after the so-called luminosity bump on the RGB, when the hydrogen-burning shell reaches the chemically homogeneous part of the envelope. The μ -inversion is produced by the reaction ${}^3\text{He}({}^3\text{He}, 2p){}^4\text{He}$, as predicted by Ulrich (1972). It does not occur earlier, because the magnitude of the μ -inversion is low and negligible compared to a stabilising μ -stratification. Following Eggleton et al. 2006; Charbonnel & Zahn (2007) computed stellar models including the prescription by Ulrich (1972) and extended them to the case of a non-perfect gas for the turbulent diffusivity produced by that instability in a 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 the hydrogen-burning shell and induces surface abundance modifications in red giant stars.

The thermohaline instability induced mixing is widely used in oceanology. It is used to model the regions of cooler, less salty water below the warmer water where the salinity is higher because of the evaporation from the surface. The so-called “long fingers” of the warmer water penetrate the cooler water; mixing occurs when the heat excess is exchanged (e.g., Schmitt 1983, 2003; Ruddick 2003; Kunze 2003; Radko 2010).

In Figs. 7 and 8 we can see that the ${}^{12}\text{C}/{}^{13}\text{C}$ and C/N values in Cr 261 and NGC 6253 agree within limits of uncertainties with the theoretical models of extra-mixing, as well as with other observational studies. The mean ${}^{12}\text{C}/{}^{13}\text{C}$ ratio of stars in NGC 6253 lie slightly above the solar metallicity models in accordance with the theory. However, there are no models computed for supersolar metallicities and there are no other observed clusters with lower metallicities and the same turn-off mass as NGC 6253, therefore we cannot judge the agreement quantitatively. In comparison to the most metal-deficient cluster in our sample NGC 2506, which has $[\text{Fe}/\text{H}] = -0.24$ and turn-off mass

$1.7 M_{\odot}$, the ${}^{12}\text{C}/{}^{13}\text{C}$ ratio of NGC 6253 is higher by 5. We need more observational data to determine the sensitivity of extra-mixing on metal abundance. As we already emphasised in our previous studies (Mikolaitis et al. 2011a,b), the ${}^{12}\text{C}/{}^{13}\text{C}$ values in the clump stars with turn-off masses of 2–3 M_{\odot} in most of the investigated clusters are lower than predicted by the available models and need modelling of stronger extra-mixing.

Charbonnel & Lagarde (2010) also computed the models of rotation-induced mixing for stars at the zero age main sequence (ZAMS) with rotational velocities of 110 km s^{-1} , 250 km s^{-1} and 300 km s^{-1} . Typical initial ZAMS rotation velocities were chosen depending on the stellar mass based on observed rotation distributions in young open clusters, see Gaige (1993). The convective envelope was supposed to rotate as a solid body through the evolution. The transport coefficients for chemicals associated to thermohaline and rotation-induced mixings were simply added in the diffusion equation and the possible interactions between the two mechanisms were not considered. The rotation-induced mixing modifies the internal chemical structure of main sequence stars, although its signatures are revealed only later in the stellar evolution. These models lie closer to the observational data but still not close enough.

As an alternative to the pure ${}^3\text{He}$ -driven thermohaline convection, the model of magneto-thermohaline mixing was proposed by Denissenkov et al. (2009). On the basis of three-dimensional numerical simulations of thermohaline convection, it was suggested that the salt-finger spectrum might be shifted towards larger diameters by a toroidal magnetic field (Denissenkov & Merryfield 2011).

Wachlin et al. (2011) have computed full evolutionary sequences of red giant branch stars close to the luminosity bump and also found that thermohaline mixing is not efficient enough for fingering convection to reach the bottom of the convective envelope of red giants. To reach the contact, the diffusion coefficient has to be artificially increased by about four orders of magnitude.

5. Summary

With this work we have added two more open clusters with carbon-to-nitrogen and carbon isotope ratios determined from high-resolution spectra to the study of evolutionary dominated changes of chemical composition in low mass stars. The average value of ${}^{12}\text{C}/{}^{13}\text{C}$ isotope ratios in four giants of Cr 261 is equal to 18 ± 2 and to 12 ± 1 in two clump stars; it is equal to 16 ± 1 in four clump stars of the open cluster NGC 6253. The mean C/N ratios in Cr 261 and NGC 6253 are equal to 1.67 ± 0.06 and 1.37 ± 0.09 , respectively. The cluster Cr 261 provided the data point for stars with the lowest turn-off mass ($1.1 M_{\odot}$), while the cluster NGC 6253 – for most metal-rich stars ($[\text{Fe}/\text{H}] = +0.46$).

The ${}^{12}\text{C}/{}^{13}\text{C}$ and C/N values in Cr 261 and NGC 6253 within limits of uncertainties agree with the theoretical model of cool-bottom processing (Boothroyd & Sackmann 1999) and with the recently computed model of thermohaline-induced mixing (Charbonnel & Lagarde 2010).

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