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EVOLUTIONARY EFFECTS IN HELIUM CORE BURNING STAR ATMOSPHERES

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VILNIAUS UNIVERSITETAS

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EVOLIUCINIAI CHEMINĖS SUDĖTIES POKYČIAI HELĮ CENTRE DEGINANČIŲ ŽVAIGŽDŽIŲ ATMOSFEROSE

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INTRODUCTION

First attempts of spectroscopic chemical analysis can be traced back to the early 19th century. In 1814, a young German scientist Joseph von Fraunhofer invented the first spectroscope and discovered first dark lines in the solar spectrum. During the 19th century astronomers collected numerous spectra of various celestial bodies. Those spectra answered one of the most important fundamental philosophical questions of the contemporary science. Spectra proved beyond doubt that all "celestial" objects (Sun, stars, planets, etc.) are all made of the same chemical elements as found on the planet Earth. Yet, 19th century scientists could determine *presence* of a particular chemical element but were not able to measure its *quantity*. Carbon, aluminum, magnesium, silicon, iron and other metals are most abundant elements on the Earth. Spectral lines of those elements are clearly visible in stellar spectra and a chemical composition of meteorites is roughly similar to the chemical composition of Earth rocks. It was easy to make a wrong conclusion that the composition of stars is generally similar to Earth. However, Cecilia Payne in her landmark dissertation published in 1925 estimated abundances of different chemical elements in the solar atmosphere and demonstrated to the skeptical scientific community that most abundant elements in the solar atmosphere are hydrogen and helium. The Payne's dissertation has marked the beginning of modern stellar chemical composition analysis era.

Another critically important milestone in stellar chemical composition studies was the extensive theoretical development of stellar atmospheres by Albrecht Unsöld at Kiel University in 1930ies. Unsöld's efforts culminated in 1941 by the first determination of detailed chemical composition of another star than our Sun (Wilson 1956).

Chemical composition studies of stellar atmospheres are closely related to two fundamental problems of modern astrophysics: abundances of mixing sensitive chemical elements help us to better understand processes in stellar interiors, while studies on the element enrichment in galaxies enable us to understand structure, formation and evolution processes of these galaxies. In the following subsections, the actuality of this thesis work is described in more details.

Mixing processes

Stellar evolution is caused by nuclear reactions in stellar cores slowly changing the internal stellar composition and structure. Mixing processes in stellar interiors can change properties of stellar material and structure, and can influence the stellar evolution. As stellar evolution models are widely used in the modern stellar astrophysics, mixing processes potentially could have a wide impact on various seemingly unrelated astrophysical problems.

Extensive in-depth reviews of observational evidences of various mixing processes, predictions of stellar atmosphere models and physics of mixing inside and outside of the 'standard' model of stellar evolution were published by Pinsonneault (1997), Chanamé et al. (2005) and Charbonnel (2006).

The abundances of certain elements in stellar atmospheres are good indicators of mixing processes:

Lithium-7 isotope is primarily produced in the Big Bang and is most fragile isotope which is destroyed in stellar interiors at temperatures as low as 2.5 x 10^6 K. ^{7}Li abundances are a subject of great theoretical interest. Yet prior knowledge of the initial ^{7}Li abundance is required to measure the amount of ^{7}Li depletion.

Lithium-6, beryllium-9 and boron-10 are produced primarily in cosmic-ray nucleosynthesis processes (Walker at al. 1993). ^{6}Li is also produced in flaring stars (Tatischeff & Thibaud 2007). ^{6}Li is destroyed in even lower temperatures than ^{7}Li, making the ^{6}Li abundance determination of a great challenge to observers. Berrylium and boron are destroyed in much higher temperatures (~5 million K), but the spectral lines useful for beryllium and boron abundance measurements are in the ultraviolet, thus it is difficult to observe them with a sufficient accuracy for abundance determinations and it is difficult to interpret theoretically.

Carbon and nitrogen surface abundances are modified in deep mixing processes. CNO isotope ratios and relative CNO element abundances in the solar surface is dramatically different from the nuclear equilibrium values expected in stellar cores (Pinsonneault 1997). In order to alter the surface CNO abundances, rather deep mixing processes of CNO-processed material are taking place and can be evaluated by examining CNO element abundance ratios and isotope ratios.

According to the so-called 'standard model' of stellar evolution, convection is assumed to be the only mechanism that can drive mixing processes in interior layers of a star (Iben 1965). Because of this limitation, so-called 'first dredge-up' is an only mixing event expected to happen between the main sequence and the tip of the red giant branch (Iben 1965).

As post-main sequence stars travel from the main sequence to the RGB, the surface convection zone expands into deeper layers. At the maximum depth the convection zone reaches deep layers containing the material modified by nuclear reactions and carries it to the surface. This mixing episode is called the 'first dredge-up'. After the first dredge-up event, the convection zone gradually retreats and no more mixing events are expected until the stars reach the asymptotic giant branch (AGB) (Pinsonneault 1997, Gratton et al. 2000).

Extra mixing

Numerous modern observations provide compelling evidences that the standard stellar evolution model is incomplete (Gilroy 1989; Gilroy & Brown 1991; Luck 1994; Charbonnel 1994; Charbonnel et al. 1998; Charbonnel & Do Nascimento 1998; Gratton et al. 2000; Tautvaišienė et al. 2000; Smith et al. 2002; Shetrone 2003; Pilachowski et al. 2003; Geisler et al. 2005; Spite et al. 2006; Recio-Blanco & de Laverny 2007; Smiljanic et al. 2009). The investigations of chemical composition using high–resolution spectra provided strong evidences of additional or 'extra' mixing process in the low–mass red giant branch (RGB) stars. Apparently these processes occur when low–mass stars reach the so–called luminosity bump in the RGB color–magnitude diagram. This extra–mixing process appears to be stellar mass–dependant and is stronger in low mass stars (masses lower than 2 $M_{\rm Sun}$). However, recent open cluster data demonstrate that stars with mases from 2 to 3 $M_{\rm Sun}$ can be also affected by mixing (see Smiljanic et al. 2009, Mikolaitis et al. 2010 for the data compilation). At the RGB bump, surface carbon isotope ratios decrease, lithium and carbon abundances also decrease and nitrogen abundances slightly increase (Boothroyd & Sackman 1999, Charbonnel & Lagarde 2010).

Stellar abundances in a context of Galactic studies

Low mass stars have long lifetimes, comparable to the age of the Galaxy and their atmospheres have preserved much of their original chemical composition. These stars are 'fossils' containing information about chemical composition of galactic material at the moment of birth of these stars. Low mass stars of different ages preserve information about a history of evolution of the chemical abundances in the Galaxy. Because of those reasons, heavy elements are tracers of evolution and structure of our Galaxy.

After primordial nucleosynthesis during the Big Bang occurred, the chemical enrichment of primordial gas (nucleogenesis) was driven by nucleosynthesis in stars defined by stellar evolution processes and environmental processes dictating *what* kinds of stars are formed to enrich interstellar gas. We can try to understand these processes using theoretical models, but the only way to verify those models and truly understand the Galactic history is to look at the 'fossils' and learn their chemical composition. The subject of this thesis work is long lived helium core burning stars located in the Galactic field and open clusters.

The Galactic red clump

Red clump is an easily recognizable feature in the Hertzprung-Russel diagram (HR diagram). Stars form the 'clump', a relatively compact and dense aggregation to the left from the giant branch. First discovered in HR diagrams of open clusters, the red clump is the metal rich counterpart of the horizontal branch, i.e. the red clump is formed by helium-core burning evolved stars.

Cannon (1970) predicted that the red clump stars should also be abundant in the solar neighbourhood. Many photometric studies have tried with varying success to identify such stars in the Galactic field (see Tautvaišienė (1996) for a review), however this task proved to be challenging. We had to wait for the *Hipparcos* astrometric space mission (Perryman et al. 1997). *Hipparcos* determined precise parallaxes and therefore absolute magnitudes of nearby stars and enabled to build the first highly accurate HR diagram of the solar neighbourhood. The presence of red clump stars in the solar neighbourhood was clearly demonstrated in the *Hipparcos* HR diagrams by Perryman et al. (1995). The *Hipparcos* catalogue (Perryman et al. 1997) contains about 600 clump stars with parallax error lower than 10%, and hence an error in absolute magnitude lower than 0.12 mag. This accuracy limit corresponds to a distance of about 125 pc within which the sample of clump stars is complete. Now it is important to investigate their distributions of masses, ages, colours, magnitudes and metallicities, which may provide useful constraints to chemical evolution models of the local Galactic disk. The field red clump stars are bright enough for a very precise spectroscopic determination of their chemical composition; therefore they are excellent targets for the analysis of mechanisms which drive the processed material from the stellar core to the stellar surface and for the study of chemical composition and evolution of our Galaxy.

AIMS OF THE STUDY

Research programme was chosen to serve two scientific purposes: investigations of extra mixing in atmospheres of evolved stars and investigation of chemical composition of Galactic clump stars.

The main aim of this work was an observational study of the evolutionary effects in atmospheres of low–mass helium–core burning stars and evaluation of theoretical models of extra mixing processes in interiors of low–mass helium–core burning stars.

THE MAIN TASKS

1. Determination and interpretation of the main atmospheric parameters and abundances of iron group elements in 62 Galactic clump stars.
2. Determination and interpretation of carbon, nitrogen and oxygen abundances, carbon ($^{12}C/^{13}C$) isotope ratio and mass of 34 Galactic clump stars.
3. Determination and interpreatation of main atmospheric parameters and chemical composition of 9 stars in the open cluster NGC 7789.

SCIENTIFIC NOVELTY

1. The sample of investigated Galactic clump stars was increased and the $^{12}C/^{13}C$ isotope ratio in Galactic clump stars was determined for the first time.
2. Stellar metallicity distribution in the Galactic clump was investigated using available up to date studies. The investigation confirmed the hypothesis that clump stars of the Galaxy are relatively young objects, reflecting mainly the near–solar metallicities developed in the local disk during the last few Gyrs of its history.
3. The use of carbon isotope ratios as the main criterion for the stellar evolutionary status determination in the Galactic clump was suggested.
4. Chemical composition of open cluster NGC 7789 stars was determined with a higher precision and wider chemical element coverage than in previous works. $^{12}C/^{13}C$ isotope ratios in clump stars were determined for the first time.

PRACTICAL IMPORTANCE OF THE DISSERTATION

This work is an experimental (observational) work in fast–evolving fields of (a) mixing in stellar atmospheres of evolved stars and (b) chemical composition of Galactic clump in solar neighborhood:

1. Understanding of extra–mixing processes in stellar interiors is important for a full understanding of internal structure and evolution of stars. Theories and models of extra mixing can only be verified by checking them against observed data. This work represents such data.

2. Observationally based constrains introduced in this work on the Galactic clump will be useful in future attempts to accurately model the Galactic solar neighborhood.

3. An accurate model of Galactic clump population in solar neighborhood is necessary if we desire to use clump star populations as a distance measurement tool for the Local Group galaxies.

4. Near–solar metallicity of the old rich open cluster NGC 7789, determined with high precision, opens a possibility to use it as a standard reference point for future research projects in a similar fashion as M 67 is presently used by the astronomical community.

STATEMENTS PRESENTED FOR DEFENSE

1. Investigated Galactic clump stars form a homogenous sample with the close to solar metallicity. The near-solar metallicity and small iron abundance dispersion ($\sigma_{[Fe/H]}$ = 0.15 dex) of clump stars of the Galaxy obtained in this dissertation confirm the theoretical model of the *Hipparcos* clump by Girardi & Salaris (2001), which suggests that nearby clump stars are (in the mean) relatively young objects, reflecting mainly the near–solar metallicities developed in the local disk during the last few Gyrs of its history.

2. 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) suggest carbon is depleted by about 0.2 dex, nitrogen is enhanced by 0.2 dex and oxygen is close to abundances in dwarfs.

3. The clump stars can be divided into distinct evolutionary groups using the $^{12}C/^{13}C$ criterion. Investigated clump stars fall into two groups in approximately equal numbers.

4. Observed $^{12}C/^{13}C$ ratios of helium–core–burning clump stars show a good agreement with the Cool Bottom Processing (CBP) theoretical model of extra–mixing processes (Boothroyd & Sackman 1999). The thermohaline extra–mixing model by Lagarde & Charbonnel (2009) needs to be complemented by the rotationally induced mixing component in order to agree with the observational data for stars with masses larger than 1.5 M_{sun}.

5. Metallicity of the open cluster NGC 7789 is very close to solar. $^{12}C/^{14}N$ ratio is different in the giants (1.9 ± 0.5 dex) and clump stars (1.3 ± 0.2 dex). $^{12}C/^{13}C$ ratios are similar for all the stars investigated (9 ± 1 dex) and indicate a larger extra–mixing than it is foreseen by currently available theoretical models.

PERSONAL CONTRIBUTION

The author took part in preparations of observational programmes, took part in spectral observations at the Nordic Optical Telescope in La Palma and partially in processing of observed spectra. The author determined the main atmospheric parameters and chemical composition of the programme stars. The author performed the analysis of chemical composition results and drew conclusions.

THESIS OUTLINE

Dissertation consists of Introduction, five Chapters, Conclusions and References.

Observational material is presented in Chapter 1.

Methods used are presented and discussed in Chapter 2.

Main parameters and iron group abundances of Galactic clump stars are presented and discussed in light of Galactic chemical composition in Chapter 3.

Tracers of mixing in stellar atmospheres of Galactic clump stars are presented and discussed in Chapter 4.

Results of chemical composition research of open cluster NGC7789 is presented in Chapter 5.

1. OBSERVATIONAL DATA

Observational data of this work consists of two samples of low-mass core-helium-burning stars: Galactic clump stars and open cluster NGC 7789 stars.

1.1. SELECTION OF GALACTIC CLUMP STARS

The *Hipparcos* catalogue (Perryman et al. 1997) contains about 600 clump stars with parallax error lower than 10%, and hence an error in absolute magnitude lower than 0.12 mag. This accuracy limit corresponds to a distance of about 125 pc within which the sample of clump stars is complete. The *Hipparcos* catalogue stars corresponding to accuracy criteria $\sigma_\pi/\pi < 0.1$ and $\sigma_{B-V} < 0.025$ mag is presented in Fig 1.1. On the diagram, a distinctive red clump is present, approximately centered at B−V ≈ 1.0 and *M*(*Hp*) ≈ 1.0 mag. The Galactic clump star sample was selected by aforementioned accuracy criteria and requirement to belong to the clump structure on the HR diagram. The further selection of individual sample stars was dictated by observational constrains. All candidate programme stars were checked in the available literature and all the stars indicated as binaries or variables were excluded from the sample.

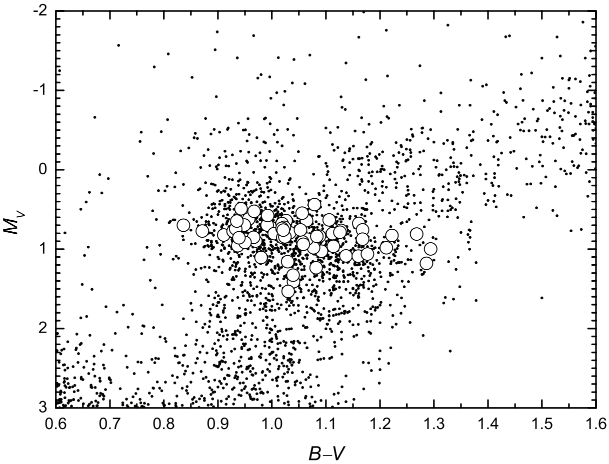

Figure 1.1. Color–magnitude diagram for the Hipparcos catalogue. The programme stars are indicated by open circles.

1.2. CLUSTER SELECTION

We selected the old open cluster NGC 7789 for investigation because this cluster is quite populous, its colour–magnitude diagram (CMD) shows a well–defined and extended red giant branch (RGB), a prominent "clump" of core–helium–burning stars, many blue stragglers, and a main sequence (see Fig. 1.2). Yet the cluster is located close enough that the cluster clump stars could be observed using relatively modest instrumentation available to the author. For the detailed chemical analysis, we have selected six giants along the giant branch and three clump stars (see Fig. 1.2 for their location in the HR diagram of NGC 7789).

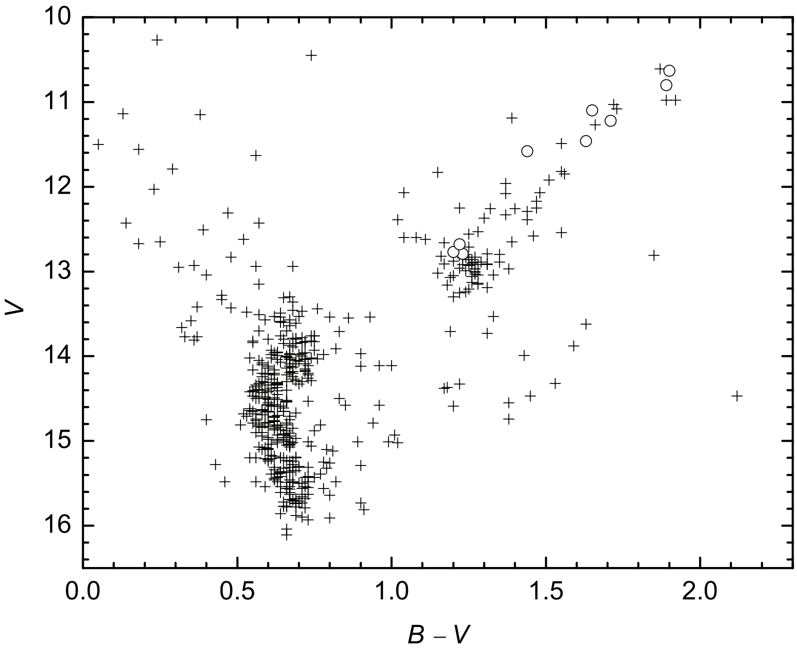

Figure 1.2. The colour–magnitude diagram of the open cluster NGC 7789. The red giants and the core–He–burning "clump" stars analysed in dissertation are indicated by the open circles. The diagram is based on UBV observations by Burbidge & Sandage (1958).

1.3. OBSERVATIONS

Author personally observed on the Nordic Optic Telescope (NOT) located at the Roque de los Muchachos observatory, La Palma, Canary Islands. The observational material was supplemented by 4 other sets of spectra of Galactic clump stars, kindly provided for us by foreign colleagues (described in detail in subsection 1.3.2).

1.3.1. Observations on the Nordic Optical Telescope

Spectra of 17 clump stars and all NGC 7789 stars (6 giants and 3 clump stars) were obtained at the Nordic Optical Telescope (NOT, La Palma) with the SOFIN échelle spectrograph (Tuominen et al. 1999). For clump stars the 2nd optical camera (R ≈ 80,000) was used to observe simultaneously 13 spectral orders, each of 40–60 Å in length, located from 5650 Å to 8130 Å. Two spectrograms were observed for each program star using different CCD positions to improve spectral coverage. Because NGC 7789 stars are fainter than Galactic clump program stars, the 3rd SOFIN optical camera (R ≈ 30,000), was used instead of the 2nd, trading a spectral resolution for a better S/N ratio and spectral coverage. The CCD size covered simultaneously 25 spectral orders, each of 80–150 Å in length, located in the interval of 4500–8750 Å. The typical exposure times were 5 min to 30 min for the field clump stars, depending on a star magnitude and atmospheric conditions. The typical exposure times for the NGC 7789 stars were about 40 min for giants at the tip of the giant branch and 160 min for the clump stars. The S/N ≈ 50 ratio was reached for the faint NGC 7789 clump stars, as those stars pushed instrumentation near to the limit of its capabilities.

The SOFIN CCD images were processed using SOFIN 4A software package using a standard SOFIN procedure (see Ilyin 2000 for details). The procedures included the bias subtraction, cosmic ray removal, flat field correction, scattered light subtraction and extraction of spectral orders. 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. The continuum was subtracted using polynomial approximation. A sample spectrum of the NGC 7789 star K765 is presented in Fig. 1.3. Examples of field clump star spectra are presented in Fig. 1.4.

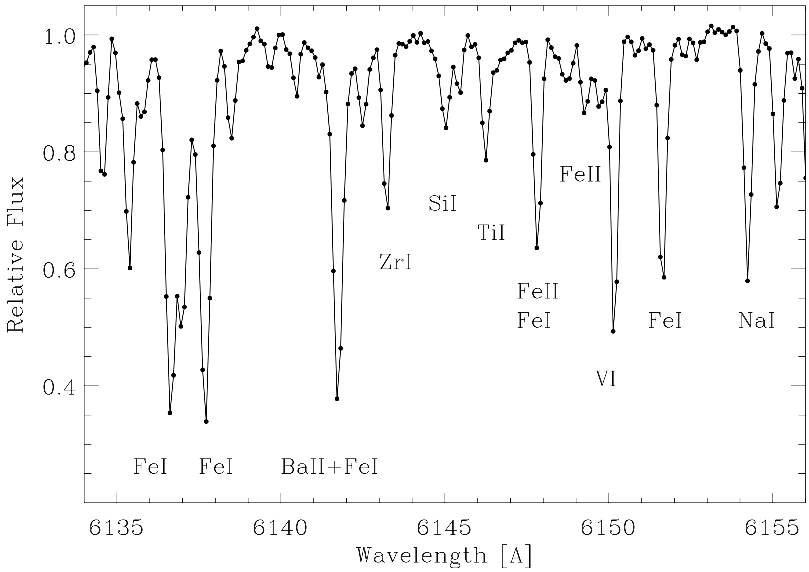

Figure 1.3. Sample spectrum of cluster NGC7789 star K765.

1.3.2. Other spectra

The observational material was supplemented by 4 other sets of spectra of Galactic clump stars, kindly provided for us by our foreign colleagues.

The spectra of 14 stars were observed with the HIRES spectrograph on the 10–m Keck Telescope. A 1.1 x 7 arcsec slit (R ≈ 34,000) was used, and 19 spectral orders located from 5620 to 7860 Å were extracted. The spectra were reduced using *IRAF* and *MAKEE* packages.

The spectra of 17 stars were observed with the long camera of the 1.22 m Dominion Astrophysical Observatory telescope's coudé spectrograph (R ≈ 40,000). The interactive computer graphics program *REDUCE* by Hill et al. (1982) was used to rectify them. The scattered light was removed during the extraction procedure by the program *CCDSPEC* described in Gullivier & Hill (2002).

The spectra for 18 stars in the spectral interval from 6220 Å to 6270 Å were obtained at the Elginfield Observatory (Canada) with the 1.2 m telescope and the high–resolution coudé spectrograph (R ≈ 100,000). Spectra were recorded using an 1872 diode Reticon self–scanned array light detector, mounted in a Schmidt camera, with focal length of 559 mm. See Brown et al. (2008) for further discussion concerning the equipment and operation.

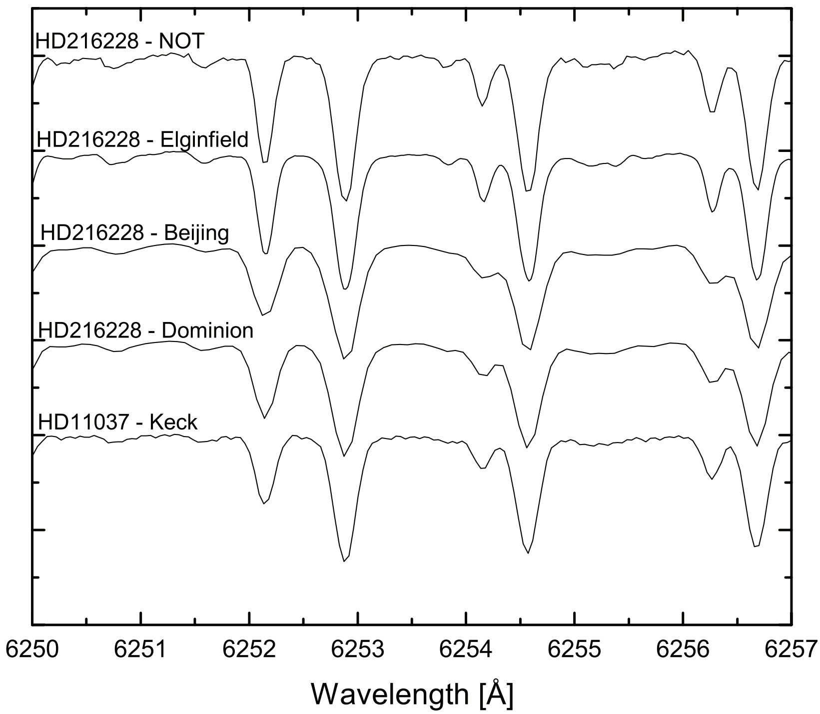

Figure 1.4. The spectrum of the star HD 216228 in the region 6250 to 6257 Å as observed on four different telescopes. Since this star was not observed on the Keck telescope, we present a spectrum of the very similar star HD 11037 instead.

These observational data were supplemented by spectroscopic observations (R ≈ 37,000) of red clump stars obtained on the 2.16 m telescope of the Beijing Astronomical Observatory (China) taken from the literature (Zhao et al. 2001). Examples of the spectra are presented in Fig. 1.4.

2. METHOD OF ANALYSIS

2.1. DIFFERENTIAL MODEL ATMOSPHERE TECHNIQUE

The spectra were analysed using a classical differential model atmosphere technique. The central principle of the differential method is to obtain the abundance of the element in a star A relative to the abundance in a standard comparison star B. A number of systematic errors are expected to be canceled out this way. For instance, one can neutralize systematic errors caused by uncertainties of physical data or by departures from the local thermodynamical equilibrium (LTE) if they are expected to be about the same in the two stars (Cayrel & Cayrel de Strobel 1966).

The Sun was chosen as a comparison star in this work.

The main stellar atmospheric parameters (effective temperature, surface gravity and microturbulence velocity), model atmospheres and atomic (or molecular) data of spectral lines are necessary in order to derive abundances of chemical elements in stellar atmospheres.

2.1.1. Main atmospheric parameters

In this thesis work a spectroscopic method of stellar atmospheric parameter determination was used. The aim was to determine stellar parameters by demanding that abundances derived from different lines of the same element should be identical. Simple indicators of correct atmosphere parameters are available: if there is no abundance dependency on the line excitation potential – the temperature is correct, if abundances derived from neutral and ionized species of the same element agree – stellar surface gravity is deremined well, and if there is no abundance dependency on line equivalent width – the microturbulence velocity is determined correctly.

The preliminary effective temperatures for the stars were determined using the $(B–V)_0$ and $(b–y)_0$ colour indices and the temperature calibrations by Alonso et al. (1999, 2001). The interstellar reddening corrections were calculated using Hakkila et al. (1997) software. For some stars the averaged temperatures also include the values obtained from the infrared flux method (IRFM). Then all the effective temperatures were carefully checked and corrected if needed by forcing Fe I lines to yield no dependency of iron abundance on excitation potential by changing the model effective temperature. Surface gravities were obtained by forcing Fe I and Fe II lines to yield the same [Fe/H] value by adjusting the model gravity. Microturbulence velocity values corresponding to minimal line–to–line Fe I abundance scattering were chosen as correct values (abundances obtained from lines of different equivalent width should be the same). Depending upon the telescope, up to 65 Fe I lines and up to 12 Fe II lines were used for the atmospheric parameter determinations.

Determinations of stellar masses were performed using effective temperatures obtained by author, calculated 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. (1997) software.

2.1.2. Stellar atmosphere models

We used a set of plane parallel, line–blanketed, constant–flux LTE model stellar atmospheres, computed with an updated version of the *MARCS* code (Gustafsson et al. 2008). From the same set we used the solar model atmosphere as well. For the solar model the microturbulent velocity of 0.8 km/s was derived from Fe I lines used in the analysis and the solar abundances taken from Grevesse & Sauval (2000).

2.1.3. Software of calculations

Two software packages (*eqwdth* and *bsyn*), both developed at the Uppsala Astronomical Observatory and kindly provided by Dr. B. Edvardsson, were used to calculate abundance values.

The *eqwidth* package was used to calculate abundances from measured equivalent widths. The equivalent widths of lines were measured by the interactive fitting of a Gaussian profile to a line profile using the *4A* software package (Ilyin 2000).

Abundances of carbon, nitrogen, oxygen, yttrium and europium were determined using the spectrum synthesis *bsyn* package. Several synthetic spectra of the particular star were calculated using different abundances and visually compared to observed spectra (see Sect 2.3 for examples).

Since synthetic spectra modeling calculations are computationally intense, the *bsyn* synthetic spectrum modeling software was adapted (gridified) to run on parallel computing systems (GRIDs) within the framework of the international BalticGrid project. The team of astronomers, including the author, of the Institute of Theoretical Physics and Astronomy of Vilnius University worked on this development (Paper 5 in the list of publications of the author). The author used the gridified package SYNTSPEC integrated with the Migrating Desktop software developed at the Poznan Supercomputing and Networking Center.

2.1.4. Physical input data

The Vienna Atomic Line Data Base (VALD) (Piskunov et al. 1995) was extensively used in preparing the input data for the calculations. 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'Mara (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 (Γ_6) were taken from Simmons & Blackwell (1982). For all other species a correction factor of 2.5 was applied to the classical Γ_6 ($\Delta \log C_6 = +1.0$), following Mäckle et al.

(1975). For lines stronger than W=100 mÅ the correction factors were selected individually by inspection of the solar spectrum.

Cobalt abundances were investigated with hyperfine structure (HFS) effects taken into account. The HFS corrections for all programme stars were kindly provided by Dr. J. Cohen. The LTE spectral synthesis program *MOOG* (Sneden 1973) and the HFS input data adopted from Prochaska et al. (2000) were used for HFS calculation.

We selected an inverse solar spectrum analysis done in Kiev (Gurtovenko & Kostik 1989) as the main source of oscillator strenghs and solar line equivalent widths for the main lines investigated in this study.

We carefully checked available oscillator strength data using the solar atmosphere model for line–to–line scatter of calculated abundances.

2.2. SPECTRAL LINE SELECTION AND MEASUREMENT

Selection of a spectral line set for measurements of spectral line equivalent widths is the arguably most important action in experimental spectroscopy. It would be naive to measure as many spectral lines as possible and expect the averaged abundance derived from these lines to be correct. Most important is to select only unblended lines.

In most cases of experimental science a random measurement error distribution is symmetric in nature. An experimenter can expect (or can design experiment such way) that averaged measurement would approach true measured value by increasing number of measurements. Unfortunately this is not correct in the case of spectral line measurement. Line measurement errors are highly asymmetric: they more often increase than decrease measured line width. Such notable errors are blending and telluric line superposition. To further complicate maters, strength of blending lines and extent of blending are dependant on star atmosphere parameters, i.e. varies from star to star. Similarly, superposition by telluric lines depends on Doppler shift and also varies from star to star.

Because of the aforementioned considerations, we adopted the "quality over quantity" approach when selecting lines for abundance calculations. Inspection of the solar spectrum (Kurucz et al. 1984) and the solar line identifications of Moore et al. (1966) were used to avoid blends and lines blended by telluric absorption lines. All line profiles in all spectra were checked requiring that the line profiles be sufficiently clean to provide reliable equivalent widths. Only lines with equivalent widths between 20 mÅ and 150 mÅ were used for abundance determinations. Calculated abundances were carefully cross–checked. Spectral lines systematically producing outlier abundances in a number of stars, indicating spectral (observational) defect, undetected blends or erroneous atomic data, were rejected as well. The careful selection of spectral lines for the analysis has allowed us to avoid systematic differences in analysis results obtained from the different instruments. E.g., the clump star HD 216228 has been observed on four telescopes, a comparison of the measured equivalent widths (EW) of its Fe I lines is shown in Fig. 2.2.

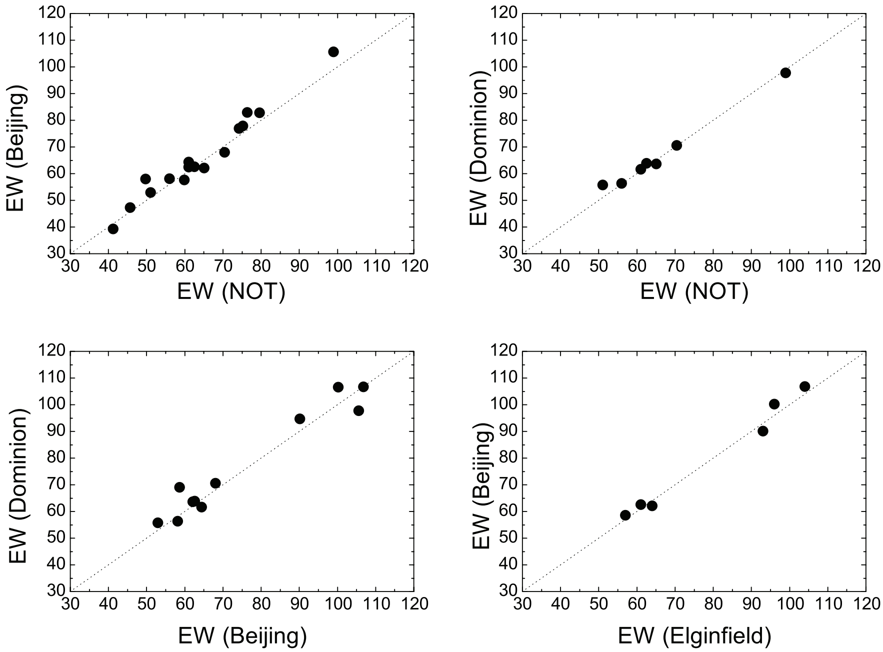

Figure 2.1. Comparisons of equivalent widths of Fe I lines in overlapping spectral regions observed with different telescopes for Galactic clump star HD 216228.

2.3. SPECTRUM SYNTHESIS

Spectrum synthesis technique is preferable when chemical elements are represented in stellar spectra by several week and possibly blended atomic lines or molecular bands. Abundances of carbon, nitrogen, oxygen, yttrium, europium and carbon isotope ratios were determined using the spectrum synthesis technique in this study.

For the carbon abundance determination in stars we used the 5632 – 5636 Å interval to compare with observations of C_2 Swan (0, 1) band head at 5635.5 Å (Fig. 2.2). The same molecular data of C_2 as used by Gonzalez et al. (1998) were adopted for the analysis.

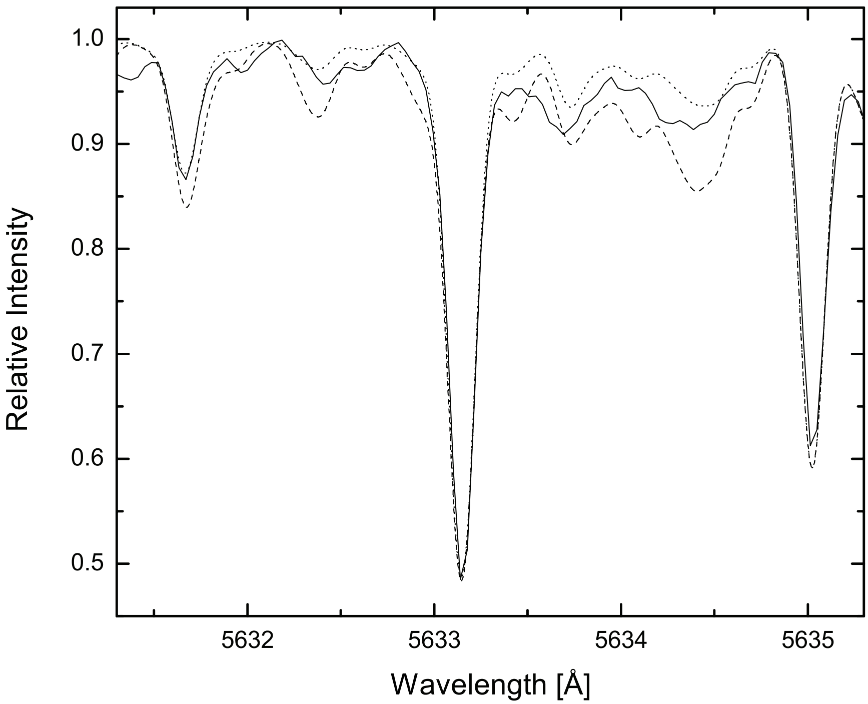

Figure 2.2. Synthetic and observed spectra for the C_2 region near 5635 Å of HD 8763. The solid line shows the observed spectrum and the dotted and dashed lines show the synthetic spectra generated with [C/Fe] = 0 and –0.2

The interval 7980 – 8130 Å contains strong $^{12}C/^{14}N$ and $^{13}C/^{14}N$ features, so it was used for nitrogen abundance and $^{12}C/^{13}C$ isotope ratio analysis. The well known ^{13}CN line at 8004.7 Å was analysed in order to determine $^{12}C/^{13}C$ ratios

(Fig. 2.3). The molecular data for this CN band were provided by Bertrand Plez (University of Montpellier II). All *gf* values of CN were increased by +0.03 dex to fit the model spectrum of solar atlas of Kurucz et. al. (1984).

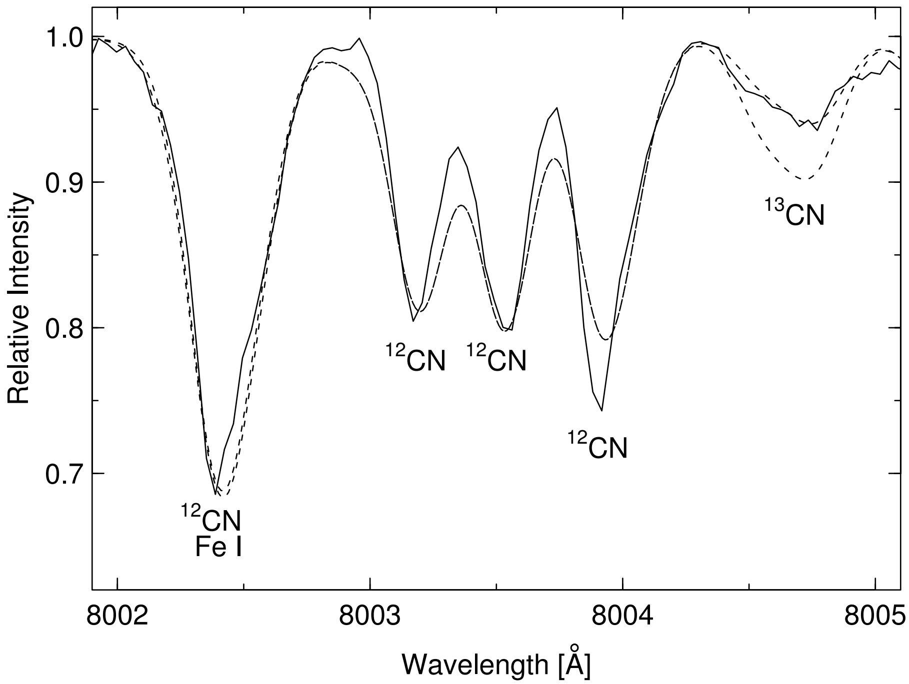

Figure 2.3. Stellar spectrum synthesis example around CN lines in HD2910. The solid line shows the observed spectrum and the dashed lines show the synthetic spectra generated with $^{12}C/^{13}C$ equal to 20 (upper line) and 10 (lower line).

We derived 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) and O I log *gf* = –9.917 value, as calibrated to the solar spectrum (Kurucz et al. 1984).

Stellar rotation for the Galactic clump stars was taken into account when needed, by applying additional rotational profile in convolution process. The values of *v*·sin*i* have been taken from Hekker & Meléndez (2007), De Medeiros et al. (2002) and Glebocki & Stawikowski (2000).

Abundances of yttrium and europium were investigated in spectra of the open cluster NGC 7789. The yttrium abundances were investigated using the Y II line at 5402 Å. The europium abundances were investigated using the Eu II line at 6645 Å with hyperfine structure taken into account. The wavelenght, excitation energy and total log *gf* = 0.12 was taken from Laweler et al. (2001) and the isotopic shifts were taken from Biehl (1976).

2.4. ESTIMATION OF UNCERTAINTIES

Estimation of uncertainties of stellar abundance calculations is not straightforward.

The sources of uncertainty can be divided into two distinct categories. The first category includes the errors that affect a single line (e.g. random errors in equivalent widths, oscillator strengths), i.e. uncertainties of the line parameters. Other sources of observational errors, such as the continuum placement or background subtraction problems also are partly included in the equivalent width uncertainties.

The scatter of the deduced line abundances σ presented in the relevant tables together with abundance results gives an estimate of the uncertainty due to the random errors in the line parameters and measurements. The mean value of the uncertainties in the derived abundances that are caused by random errors is 0.07 dex for the Galactic clump stars and 0.10 dex for the open cluster NGC 7789 stars. Abundances of the NGC 7789 stars have larger errors due to the lower spectral resolution and lower signal-to-noise ratios.

The second category includes the errors which affect all the lines together, i.e. mainly the model errors (such as errors in the effective temperature, surface gravity, microturbulent velocity, etc.).

Typical internal error estimates for the atmospheric parameters are: 100 K for $T_{\rm eff}$, 0.2 dex for log g and 0.3 km·s^{-1} for $v_{\rm t}$. The sensitivity of the abundance estimates to changes in the atmospheric parameters by the assumed errors is illustrated in tables 2.1, 2.2 and 2.3. It is seen that possible parameter errors do not affect the abundances seriously; the element–to–iron ratios, for which we use the neutral species for both and use in our discussion, are even less sensitive.

Table 2.1. *The sensitivity of stellar atmosphere abundances to changes in atmospheric parameters: an example for the star HD 218031.*

Element	**ΔT_{eff} = –100 K**	**Δlog g = +0.2**	**Δ v_t = +0.3 km/s**
V I	–0.17	0.00	–0.08
Cr I	–0.06	0.01	–0.05
Fe I	–0.05	0.04	–0.07
Fe II	0.09	0.11	–0.08
Co I	–0.06	0.06	–0.03
Ni I	–0.05	0.06	–0.05

Table 2.2. *Effects on derived abundances resulting from model changes for the star K665. The table entries show the effects on the logarithmic abundances relative to hydrogen, Δ[A/H].*

Element	**ΔT_{eff} = –100 K**	**Δlog g = +0.3**	**Δ v_t = +0.3 km/s**
C (C_2)	0.02	0.03	0.00
N (CN)	–0.07	0.01	0.00
O ([O I])	0.01	–0.05	–0.01
Na I	–0.09	–0.08	–0.11
Mg I	–0.03	–0.03	–0.08
Al I	–0.05	–0.01	–0.05
Si I	0.02	0.04	–0.04
Ca I	–0.10	–0.01	–0.07
Sc II	0.01	0.14	–0.08
Ti I	–0.14	–0.01	–0.06
V I	–0.16	0.00	–0.06
Cr I	–0.09	–0.01	–0.09
Fe I	–0.07	0.01	–0.09
Fe II	0.08	0.15	–0.12
Co I	–0.09	0.03	–0.05
Ni I	–0.05	0.03	–0.12
Y II	–0.02	0.11	–0.29
Zr I	–0.18	0.00	–0.03
Ce II	0.00	0.13	–0.01
Pr II	–0.02	0.14	–0.01
Eu II	0.00	0.10	–0.01

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. Δ[O/H] = –0.10 causes Δ[C/H] = –0.04 and Δ[N/H] = +0.10; Δ[C/H] = –0.10 causes Δ[N/H] = +0.14 and Δ[O/H] = –0.03. Δ[N/H] = 0.10 has no effect on either the carbon or the oxygen abundances.

Table 2.3. *Effects on derived abundances resulting from model changes for the star HD141680. The table entries show the effects on the logarithmic abundances relative to hydrogen, Δ[A/H].*

Species	**ΔT_{eff} = –100 K**	**Δlog g = +0.2**	**Δ v_t = +0.3 km/s**
C (C_2)	0.02	0.03	0.00
N (CN)	–0.07	0.01	0.00
O ([O I])	0.01	–0.05	–0.01

3. GALACTIC CLUMP POPULATION IN THE SOLAR NEIGHBORHOOD

Almost fifty years passed since Hoyle & Schwatzschild (1955) interpreted the horizontal branch of globular clusters as a sequence of stars with a double energy source: helium burning in the core and hydrogen burning in the shell. It took fifteen years to make a theoretical prediction that the red clump stars should be a prominent feature of the colour-magnitude diagram of stars in the solar nieghbourhood (Cannon 1970), and one more year to find them observationally. “Upgren’s unclassified stars: a new type of G-giant stars?” – that was a title of the outstanding Sturch & Helfer (1971) paper in which they concluded that so-called “unclassified Upgren’s stars” (Upgren 1962) are the field equivalents of the red horizontal branch (RHB) stars of metal-rich globular clusters.

The first large sample of red clump stars belonging both to the Galactic bulge and disk was revealed in Baade’s Window fields using CCD observations of the Optical Gravitation Lensing Experiment (OGLE, Paczyński et al., 1994). However, the main evidence about the presence of red clump stars in the solar neighbourhood was clearly demonstrated in the HR diagrams by Perryman et al. (1995) based on preliminary Hipparcos catalogue.

Since the fist high-resolution spectroscopic study of the RHB star HD175305 by Wallerstein et al. (1979), very few studies of RHB stars and the Galactic red clump stars in the Galactic field were accomplished until beginning of the 21st century. The high-resolution spectra of ten red horizontal-branch stars of the Galactic field have been obtained using the 6m SAO telescope and abundances of up to 22 chemical elements have been determined (Tautvaišienė 1997). This sample constituted a largest up to date high-resolution abundance study of RHB stars located in the Galactic field. Six metal-deficient RHB stars were observed and abundances of up to eight chemical elements were determined by Gratton et al. (2000).

A study of 39 red clump stars was accomplished by Zhao et al. (2001). The main atmospheric parameters and abundances of Fe, Si and Ca were determined. It was found that the stars can be divided into a metal-poor group and a metal-rich group. Unfortunately, the determination of effective temperatures in this work was done using the erroneous temperature calibration by Alonso et al. (1999), which was subsequently corrected by Alonso et al. (2001). Three studies of chemical composition of the Galactic red clump stars were published recently. Chemical composition of 177 clump giants of the Galactic disk were investigated by Mishenina et al. (2006) on a basis of spectra (*R* = 42,000) obtained on the 1.93 m telescope of the Haute Provence Observatoire (France). A sample of 63 Southern hemisphere red clump stars were investigated by Liu et al. (2007). Spectra (*R* = 48,000) were obtained on the 1.52 m ESO telescope (La Silla, Chile). A spectroscopic analysis of a sample of 298 nearby giants, with red clump stars among them, was done by Luck & Heiter (2007) based on high resolution spectra (*R*=60,000) with spectral coverage from 4750 to 6850 Å. Limitations of those studies and comparison of results are discussed in this and following chapters.

3.1. ATMOSPHERIC PARAMETERS AND ELEMENT ABUNDANCES

Table 3.1 presents the adopted atmospheric parameters for our stellar sample, the numbers of Fe I and Fe II lines investigated, the line–to–line scatter and sources of spectral observations used. Some stars were observed on several telescopes. For them the main atmospheric parameters were not redetermined from the new observations, since several checks gave a good agreement. The new observing material was used to increase the number of chemical elements with reliable detections. The elemental abundances relative to hydrogen [El/H] of iron group chemical elements, line–to–line scatters and numbers of lines investigated are presented in Table 3.2

Table 3.1. *Atmospheric parameters of the Galactic clump stars. Observations: 1 – NOT, 2 – Keck, 3 – Dominion, 4 – Eglifield, 5 – Beijing.*

HD	T_{eff}	log g	v_{t}	[Fe/H]	$\sigma_{\mathrm{Fe\,I}}$	$N_{\mathrm{Fe\,I}}$	$\sigma_{\mathrm{Fe\,II}}$	$N_{\mathrm{Fe\,II}}$	Obs.
2910	4730	2.3	1.7	–0.07	0.11	52	0.08	8	5
3546	4980	2.0	1.4	–0.60	0.06	52	0.07	12	5
3627	4360	2.1	1.8	0.01	0.12	31	0.04	3	2
4188	4870	2.9	1.2	0.10	0.07	11	–	1	4
5268	4870	1.9	1.4	–0.48	0.06	47	0.06	8	5
5395	4870	2.1	1.3	–0.34	0.06	54	0.07	10	5
5722	4910	2.3	1.3	–0.14	0.05	45	0.03	5	2
6805	4530	2.0	1.5	–0.02	0.08	39	0.05	6	5
6976	4810	2.5	1.6	–0.06	0.10	49	0.11	8	5
7106	4700	2.4	1.3	0.02	0.07	33	0.07	6	1
8207	4660	2.3	1.4	0.09	0.07	31	0.04	4	1
8512	4660	2.1	1.5	–0.19	0.09	46	0.03	6	5
8763	4660	2.2	1.4	–0.01	0.06	19	0.07	4	1
8949	4650	2.4	1.7	0.02	0.11	51	0.10	8	5
9408	4780	2.1	1.3	–0.28	0.06	33	0.07	6	1
11037	4830	2.3	1.2	–0.02	0.07	44	0.09	5	2
11559	4990	2.7	1.5	0.04	0.08	51	0.03	9	5
12583	4930	2.5	1.6	0.02	0.10	50	0.09	8	5
15779	4810	2.3	1.2	–0.03	0.05	19	0.06	4	1
16400	4800	2.4	1.3	0.00	0.07	34	0.04	5	1
17361	4630	2.1	1.4	0.03	0.09	42	0.05	6	5
18322	4660	2.5	1.4	–0.04	0.07	44	0.06	5	5
19476	4980	3.3	1.5	0.17	0.07	38	0.08	8	5
19787	4760	2.4	1.6	0.06	0.08	41	0.06	7	5
25604	4770	2.5	1.6	0.02	0.08	41	0.04	6	5
28292	4600	2.4	1.5	–0.06	0.09	40	0.05	5	5
29503	4650	2.5	1.6	–0.05	0.09	41	0.06	5	5
34559	5060	3.0	1.5	0.07	0.07	37	0.04	8	5
35369	4850	2.0	1.4	–0.21	0.08	49	0.04	7	5
54810	4790	2.5	0.9	–0.15	0.06	10	–	1	4
58207	4800	2.3	1.2	–0.08	0.06	33	0.05	6	1
61935	4800	2.4	1.2	–0.02	0.06	14	0.04	2	1
74442	4700	2.5	1.2	0.06	0.08	10	–	1	4
82741	4850	2.5	1.0	0.00	0.05	12	–	1	4
86513	4590	2.3	1.1	0.13	0.08	16	0.05	5	3
94264	4730	2.7	1.0	–0.04	0.08	11	–	1	4
95272	4670	2.5	1.3	0.00	0.09	10	–	1	4
100006	4590	2.3	1.2	–0.03	0.10	22	0.09	5	3
104979	4880	2.1	0.9	–0.24	0.06	12	–	1	4
108381	4700	3.0	1.4	0.25	0.09	8	–	1	4
131111	4740	2.5	1.1	–0.17	0.05	34	0.06	6	1
133165	4590	2.3	1.2	–0.05	0.09	19	0.08	5	3

Table 3.1a. *(cont.)*

HD	T_{eff}	log *g*	v_t	[Fe/H]	$\sigma_{Fe\,I}$	$N_{Fe\,I}$	$\sigma_{Fe\,II}$	$N_{Fe\,II}$	Obs.
141680	4900	2.5	1.3	–0.07	0.07	34	0.08	5	1
146388	4700	2.5	1.3	0.18	0.06	31	0.09	6	1
153210	4450	2.3	1.3	0.15	0.09	54	–	1	3
161096	4550	2.5	1.4	0.18	0.11	64	0.07	5	3
163588	4400	2.4	1.4	–0.01	0.11	65	0.04	5	3
169414	4550	2.3	1.5	–0.09	0.09	40	0.08	5	2
172169	4360	2.2	1.5	0.02	0.10	40	0.07	4	2
181276	4940	2.7	1.3	0.13	0.07	31	0.22	2	2
188310	4730	2.5	1.2	–0.11	0.07	11	–	1	2
188947	4760	2.5	1.3	0.06	0.08	58	–	1	3
197989	4760	2.3	1.1	–0.07	0.07	13	–	1	4
203344	4730	2.4	1.2	–0.06	0.06	34	0.04	5	1
207134	4540	2.3	1.6	–0.04	0.01	41	0.07	5	2
212943	4660	2.3	1.2	–0.24	0.05	19	0.08	4	1
216131	4980	2.7	1.3	0.07	0.07	44	0.05	5	2
216228	4740	2.1	1.3	–0.05	0.06	15	0.07	4	1
218031	4780	2.3	1.3	–0.08	0.04	19	0.09	4	1
219916	4980	2.6	1.4	–0.04	0.08	38	0.05	5	2
221115	5000	2.7	1.3	0.05	0.06	18	0.04	4	1
222842	4980	2.8	1.3	–0.02	0.04	18	0.06	4	1

The sample of clump stars investigated form quite a homogeneous sample with no obvious division into metallicity–dependent groups as was suggested by Zhao et al. (2001). The effective temperature ranges from 4300 to 5100 K with the mean value T_{eff} =4750 ± 160 K; log *g* is between 1.8 and 3.3 with the mean value log *g* = 2.41 ± 0.26; the mean microturbulent velocity v_t =1.34 ± 0.19 km·s^{-1}; the metallicity range is from +0.3 to –0.6 dex, however the majority of stars concentrate at the mean value [Fe/H] = –0.04 with a rms deviation about the mean 0.15 dex.

3.2. COMPARISON WITH RESULTS BY MCWILLIAM (1990)

There is an overlap of 35 stars between our sample of clump stars and that of high–resolution spectroscopic analysis by McWilliam (1990). McWilliam & Rich (1994) noted that the McWilliam (1990) study was hampered by the narrow wavelength (6550–6800 Å) coverage and the lack of metal–rich model atmospheres, which caused an underestimation of metallicities for metal rich stars. Our results confirm this; we find for the stars in common

$[Fe/H]_{(McW)} - [Fe/H]_{Our} = -0.13 \pm 0.07$. It is also noticeable that the effective temperature calibrations of McWilliam (1990) and of Alonso et al. (2001), which was used in our work, have a slight systematic temperature determination difference of 50 ± 50 K, the temperatures of McWilliam being lower.

3.3. COMPARISON WITH RESULTS BY ZHAO ET AL. (2001)

A study of 39 red clump giants was carried out by Zhao et al. (2001). Unfortunately, the determination of effective temperatures in this work was done using the erroneous temperature calibration by Alonso et al. (1999), which was subsequently updated by Alonso et al. (2001). Fig. 3.1 demonstrates the consequences of this misunderstanding on a sample of 24 stars reanalysed in our study.

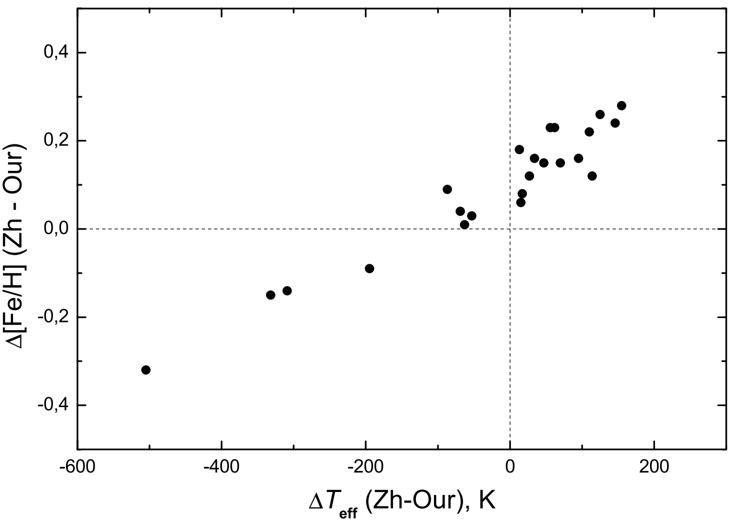

Figure 3.1. The differences of temperature and metallicity caused by the erroneous temperature calibration used by Zhao et al. (2001).

For the stars with [Fe/H] greater than solar, the temperatures and metallicities were overestimated by up to 200 K and 0.2 dex, respectively. For the metal–deficient stars – underestimated by approximately the same values. Considering those stars with no temperature difference, it is also clear that the [Fe/H] values determined in our study are about 0.1 dex lower. This is most likely caused by a very careful selection of unblended lines in our analysis and careful choice of the continuum level in a number of regions.

3.4. COMPARISON WITH RECENT STUDIES

Chemical composition of 177 clump giants of the Galactic disk were investigated by Mishenina et al. (2006) on a basis of spectra (R = 42,000) obtained on the 1.93 m telescope of the Haute Provence Observatoire (France). A sample of 63 Southern hemisphere red clump stars were investigated by Liu et al. (2007). Spectra (R = 48,000) were obtained on the 1.52 m ESO telescope (La Silla, Chile). A spectroscopic analysis of a sample of 298 nearby giants, with red clump stars among them, was done by Luck & Heiter (2007) based on high resolution spectra (R=60,000) with spectral coverage from 4750 to 6850 Å. We selected a subsample of 138 red clump giants for further comparison analysis based on the luminosity and effective temperature diagram provided by Luck & Heiter in their Fig. 20. All stars located in the box limited by luminosities $\log(L/L_{sun})$ from 1.5 to 1.8 and effective temperatures from 4700 to 5200 K were included in the subsample. A number of stars have been investigated in two or more studies. With one exception, iron abundance differences across different papers are negligible and random in nature:

$[Fe/H]_{Our} – [Fe/H]_{LH} = +0.01 \pm 0.06$ (16 stars),

$[Fe/H]_{Our} – [Fe/H]_{L} = +0.04 \pm 0.10$ (8 stars),

$[Fe/H]_{Our} – [Fe/H]_{M} = +0.01 \pm 0.12$ (24 stars),

$[Fe/H]_{L} – [Fe/H]_{LH} = –0.04 \pm 0.04$ (9 stars),

where Our – this work, LH – Luck & Heiter (2007), M – Mishenina et al. (2006), L – Liu et al. (2007). The exception is the clear systematic discrepancy between results of Luck & Heiter and Mishenina et al.: $[Fe/H]_{LH} – [Fe/H]_{M} = +0.07 \pm 0.07$ (41 stars). It is interesting to note that while the systematic difference of [Fe/H] exists between common stars in these two studies, there are no systematic differences between [Fe/H] values in our study and studies by Luck & Heiter and Mishenina et al. Probably this is because the difference between these works is more prominent for the metal–deficient stars, while our common stars are more metal abundant. So, we can not determine which of these studies is right. There are only 3 common stars between Liu et al. and Mishenina et al.

Concerning the agreement of effective temperature and surface gravity determinations, our results are in a very good agreement with the study by Mishenina et al. (2006) despite the different methods of effective temperature determination. So called "spectroscopic" effective temperature values in the work by Luck & Heiter (2007) are systematically higher by almost 100 K, and log *g* by +0.4 dex, however their "physical" determinations are in a good agreement with our work and Mishenina et al. (see also section Methods). Effective temperatures in the work by Liu et al. (2007) are in the mean by about 60 K lower and log *g* by about 0.3 dex higher than in our work, as evaluated from 8 common stars. The systematic difference in temperatures between the studies of Luck & Heiter (spectroscopic) and Liu et al. is 160 K.

Table 3.2a. *Element abundances of the Galactic clump stars: vanadium and chromium.*

HD	[V/H]	σ	N	[Cr/H]	σ	N
2910	0.04	0.10	11	–0.10	0.12	4
3546	–0.46	0.06	12	–0.65	0.07	4
3627	0.23	0.09	6	0.07	0.11	3
4188	0.20	0.07	6	–	–	–
5268	–0.53	0.10	8	–0.55	0.15	2
5395	–0.23	0.04	12	–0.26	0.06	6
5722	–0.17	0.07	6	–0.21	0.05	5
6805	0.19	0.08	8	–0.03	0.08	5
6976	0.07	0.07	9	–0.11	0.05	4
7106	0.25	0.11	13	0.09	0.07	6
8207	0.17	0.09	10	0.18	0.07	4
8512	–0.02	0.06	10	–0.23	0.06	6
8763	0.17	0.08	10	0.04	0.04	2
8949	0.18	0.06	6	–0.16	0.07	4
9408	–0.21	0.06	13	–0.33	0.02	3

Table 3.2a. (cont.)

HD	[V/H]	σ	N	[Cr/H]	σ	N
11037	–0.16	0.07	6	–0.15	0.02	4
11559	0.13	0.06	12	0.06	0.08	5
12583	0.03	0.07	10	–0.02	0.09	4
15779	0.05	0.08	10	0.02	0.02	2
16400	0.01	0.06	13	0.04	0.05	5
17361	0.24	0.03	5	0.08	0.07	4
18322	0.13	0.07	6	–0.10	0.04	5
19476	0.33	0.05	7	0.24	0.08	4
19787	0.08	0.10	11	0.06	0.11	5
25604	0.10	0.09	11	0.03	0.05	5
28292	0.14	0.09	9	–0.11	0.09	5
29503	0.29	0.08	7	–0.06	0.10	5
34559	0.12	0.05	10	0.15	0.08	5
35369	–0.23	0.05	7	–0.20	0.10	4
54810	0.01	0.07	5	–	–	–
58207	0.01	0.07	13	–0.02	0.04	6
61935	0.00	0.05	4	0.08	0.07	3
74442	0.25	0.12	5	–	–	–
82741	0.02	0.07	6	–	–	–
86513	0.06	0.04	10	–	–	–
94264	0.20	0.09	6	–	–	–
95272	0.14	0.10	6	–	–	–
100006	–0.16	0.06	8	–	–	–
104979	–0.33	0.07	7	–	–	–
108381	0.56	0.08	5	–	–	–
131111	0.01	0.07	11	–0.11	0.07	5
133165	–0.09	0.06	7	–	–	–
141680	0.04	0.06	13	0.02	0.08	5
146388	0.40	0.09	11	0.27	0.06	5
153210	0.13	0.13	9	0.07	0.09	7
161096	0.37	0.12	7	0.22	0.09	6
163588	0.03	0.12	9	–0.11	0.18	7
169414	0.20	0.06	5	–0.13	0.10	4
172169	0.38	0.09	6	–0.08	0.07	4
181276	0.03	0.10	8	0.09	0.11	4
188310	0.10	0.08	6	–	–	–
188947	0.29	0.05	17	0.18	0.06	6
197989	0.02	0.08	6	–	–	–
203344	0.06	0.08	12	–0.03	0.13	3
207134	0.26	0.08	6	–0.01	0.12	4
212943	–0.06	0.08	10	–0.21	–	1
216131	–0.02	0.07	7	–0.01	0.06	5

Table 3.2a. (cont.)

HD	[V/H]	σ	N	[Cr/H]	σ	N
216228	0.08	0.07	7	0.00	0.04	2
218031	0.09	0.06	10	–0.07	0.05	2
219916	–0.08	0.08	6	–0.11	0.06	5
221115	0.09	0.05	10	0.08	0.05	2
222842	0.09	0.05	10	0.06	0.05	2

Table 3.2b. *Element abundances of the Galactic clump stars: cobalt and nickel.*

HD	[Co/H]	σ	N	[Ni/H]	σ	N
2910	–0.01	0.08	4	0.03	0.09	32
3546	–0.47	0.07	4	–0.47	0.07	29
3627	0.11	0.08	2	0.04	0.08	10
4188	0.15	–	1	0.18	0.05	2
5268	–0.56	0.07	4	–0.48	0.10	29
5395	–0.28	0.09	4	–0.22	0.07	26
5722	–0.26	0.03	3	–0.18	0.06	22
6805	0.00	0.01	3	0.13	0.11	29
6976	0.05	0.04	2	0.04	0.09	31
7106	0.13	0.08	4	0.08	0.06	15
8207	0.04	0.10	3	0.18	0.08	16
8512	–0.06	0.05	2	–0.03	0.08	25
8763	–0.06	0.07	2	0.05	0.04	9
8949	0.14	0.05	2	0.18	0.09	30
9408	–0.18	0.01	2	–0.26	0.05	17
11037	–0.14	0.00	3	–0.09	0.08	12
11559	0.08	0.05	5	0.12	0.08	29
12583	–0.06	0.04	3	0.05	0.08	30
15779	–0.13	0.06	2	–0.01	0.05	10
16400	–0.07	0.09	3	0.02	0.07	17
17361	0.03	–	1	0.15	0.10	32
18322	0.02	0.06	3	0.05	0.10	30
19476	0.17	0.07	6	0.28	0.08	20
19787	0.03	0.06	4	0.18	0.09	30
25604	0.12	0.09	5	0.16	0.09	32
28292	0.06	0.06	2	0.07	0.10	32
29503	0.15	0.03	3	0.12	0.11	25
34559	0.03	0.06	5	0.15	0.08	32
35369	–0.31	0.08	4	–0.13	0.07	32
54810	–0.05	–	1	–0.13	0.00	2
58207	–0.08	0.08	3	–0.07	0.05	17

Table 3.2b. *(cont.)*

HD	[Co/H]	σ	N	[Ni/H]	σ	N
61935	–	–	–	–0.03	0.04	7
74442	0.28	–	1	0.20	0.08	2
82741	0.06	–	1	–0.04	0.03	2
86513	–	–	–	0.19	0.05	9
94264	0.05	–	1	0.05	0.11	2
95272	0.14	–	1	0.13	0.14	2
100006	–	–	–	0.00	0.06	10
104979	–0.11	–	1	–0.23	0.09	2
108381	0.50	–	1	0.39	0.18	2
131111	–0.20	0.08	3	–0.18	0.05	16
133165	–	–	–	–0.04	0.04	9
141680	–0.02	0.04	4	–0.07	0.05	16
146388	0.14	0.08	3	0.26	0.09	17
153210	0.08	0.05	3	0.24	0.12	12
161096	0.36	0.08	3	0.32	0.15	12
163588	0.01	0.07	3	0.06	0.12	15
169414	0.01	0.02	2	–0.11	0.09	12
172169	0.00	–	1	0.04	0.09	10
181276	–0.08	0.04	3	0.06	0.11	12
188310	–	–	–	0.04	0.07	2
188947	–0.15	0.03	2	0.19	0.08	18
197989	–0.10	–	1	–0.01	0.04	3
203344	–0.02	0.13	3	–0.03	0.06	17
207134	0.05	0.04	3	–0.04	0.09	12
212943	–0.23	0.08	2	–0.22	0.04	9
216131	–0.14	0.02	3	–0.03	0.07	12
216228	–0.07	0.11	2	0.00	0.03	8
218031	–0.11	0.08	2	–0.06	0.04	10
219916	–0.20	0.06	3	–0.12	0.05	12
221115	0.00	0.06	2	0.06	0.04	8
222842	–0.06	0.05	2	–0.01	0.05	9

3.5. METALLICITY DISTRIBUTION IN CLUMP STARS OF THE GALAXY

There have been few attempts to derive typical metallicities for *Hipparcos* clump stars. The first was an indirect method by Jimenez et al. (1998), they obtained –0.7 < [Fe/H] < 0.0. However, they modelled the clump with star formation rate (SFR) strongly decreasing with Galactic age. Consequently, they were considering, essentially, the behaviour of the old clump stars, with masses of about 0.8 – 1.4 M_{sun}. Intermediate–mass clump stars with mass more than 1.7 M_{sun} were absent in their simulations (c.f. Girardi & Salaris 2001). Thus their description of the clump stars was incomplete.

Girardi et al. (1998) considered the full mass range of clump stars, and models with constant SFR up to 10 Gyr ago. They demonstrated that the best fit is achieved with a Galaxy model which in the mean has solar metallicity, with a very small metallicity dispersion of about 0.1 dex.

Girardi & Salaris (2001) collected the spectroscopic abundance determinations for the *Hipparcos* clump stars in the catalogue by Cayrel de Strobel et al. (1997). They found that the histogram of [Fe/H] values is fairly well represented by a quite narrow Gaussian curve centered at [Fe/H] = –0.12 dex and standard deviation of 0.18 dex, as derived by means of a least–squares fit.

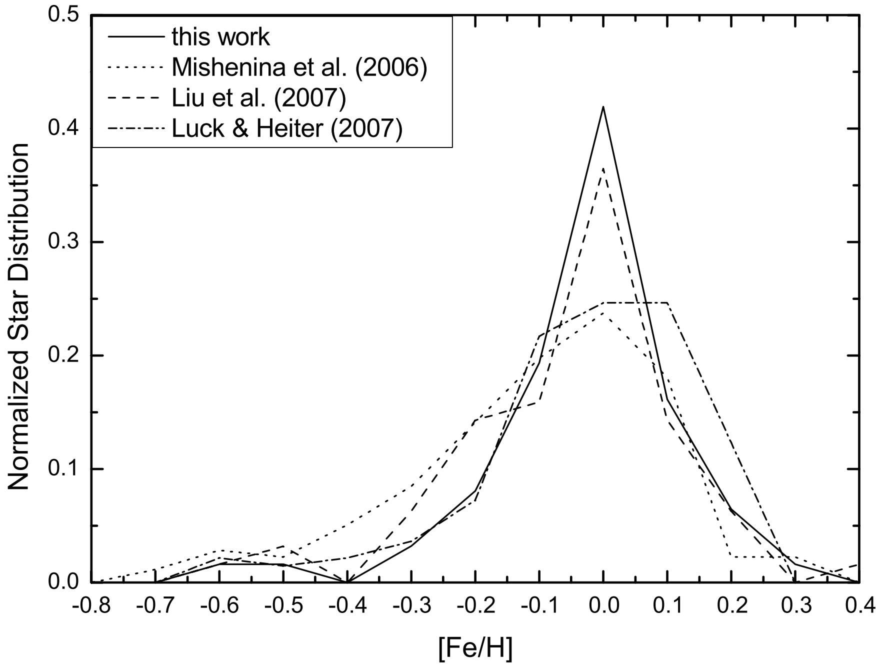

Figure 3.2. Distributions of [Fe/H] in the Galactic clump stars investigated in this work and other studies.

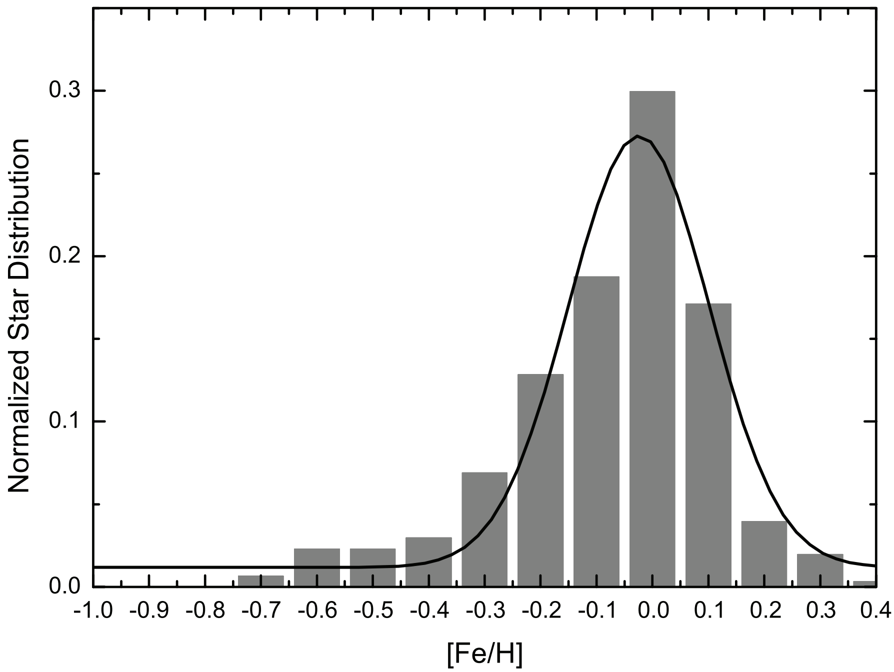

Figure 3.3. Metallicity distribution in the sample of 342 Galactic clump stars (the [Fe/H] values are averaged for the common stars investigated in this study, Mishenina et al. (2006), Liu et al. (2007) and Luck & Heiter (2007).

In the same paper a theoretical simulation of the *Hipparcos* clump was made. Girardi & Salaris (2001) found that the total range of metallicities allowed by their model is quite large (–0.7 ≤ [Fe/H] ≤ 0.3), however the distribution for clump stars is very narrow: a Gaussian fit to the [Fe/H] distribution produces a mean <[Fe/H]> = +0.03 dex and dispersion $\sigma_{[Fe/H]}$ = 0.17. Actually, the [Fe/H] distribution presents an asymmetric tail at lower metallicities, which causes the straight mean of [Fe/H] to be –0.04 dex. The near–solar metallicity and so small $\sigma_{[Fe/H]}$ imply that nearby clump stars are (in the mean) relatively young objects, reflecting mainly the near–solar metallicities developed in the local disk during the last few Gyrs of its history. From the same simulation they determined that the peak of age distribution in the *Hipparcos* clump is at about 1 Gyr. In our study, the results of [Fe/H] determinations in clump stars of the Galaxy confirm the theoretical model by Girardi & Salaris (2001). The metallicity range in our study is from +0.3 to –0.6 dex, however the majority of stars concentrate near the mean value

<[Fe/H]> = –0.04 ± 0.15 dex. A Gaussian fit to the [Fe/H] distribution produces the mean <[Fe/H]> = –0.01 dex and very small dispersion $\sigma_{[Fe/H]}$ = 0.08. In order to see what the metallicity distribution is in all the sample of Galactic clump stars investigated to date using high resolution spectra, we present in Fig. 3.2 metallicity distributions for the samples of Galactic clump stars investigated in this study (62 stars), by Mishenina et al. (177 stars), Liu et al. (63 stars) and Luck & Heiter (138 stars); and in Fig. 4.3, the metallicity distribution in the entire sample of 342 Galactic clump stars is presented. The metallicity values were averaged for the stars with multiple analyses. In the study of Mishenina et al. a special attempt was made to include the metal–deficient stars, so the distribution slightly reflects this selection effect. The [Fe/H] values of clump stars in Fig. 4.3 range from +0.4 to –0.8 dex. A Gaussian fit to the [Fe/H] distribution produces a mean <[Fe/H]> = –0.02 and dispersion $\sigma_{[Fe/H]}$ =0.13 dex, which is in agreement with the theoretical model by Girardi & Salaris (2001).

3.6. ABUNDANCES OF IRON GROUP ELEMENTS

Fig. 3.4 presents the observed [El/Fe] ratios for iron group elements in our sample of stars, always using the neutral species. Nickel abundances always closely follow solar nickel to iron ratios in the Galactic disk. Average nickel abundances are:

[Ni/Fe] = +0.06 ± 0.07 dex in our study,

[Ni/Fe] = +0.11 ± 0.03 dex in Mishenina et al. (2006),

[Ni/Fe] = +0.02 ± 0.05 dex in Liu et al. (2007) and

[Ni/Fe] = +0.01 ± 0.03 dex in Luck & Heiter (2007),

so it can be said that the [Ni/Fe] ratios in clump stars are approximately solar. Vanadium was investigated in our and two other studies. We obtain the mean value of [V/Fe] = +0.11 ± 0.12 dex, Liu et al. derived +0.02 ± 0.10 dex and Luck & Heiter found –0.05 ± 0.09 dex, which means that this element also has solar [V/Fe] ratios. Chromium and cobalt were investigated in our work and by Luck & Heiter. The mean [Cr/Fe] ratios are exactly solar in both studies. [Co/Fe] is enhanced by about +0.07 ± 0.06 dex in the work by Luck & Heiter. In this dissertation, cobalt abundances were investigated with hyperfine structure effects taken into account; we find [Co/Fe] = +0.02 ± 0.11 dex, which is close to solar.

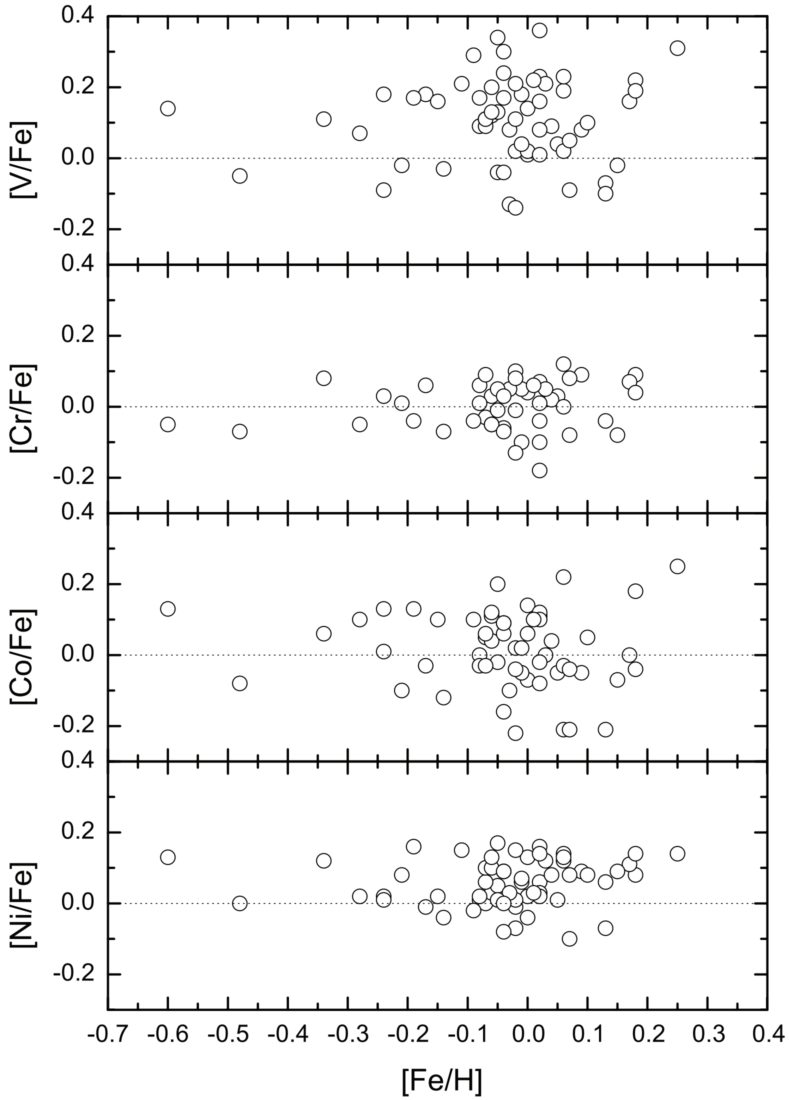

Figure 3.4. Abundance trends of iron group elements.

4. EVOLUTIONARY EFFECTS IN CLUMP STARS

Exact physical nature of so called extra–mixing is a long standing puzzle of modern astrophysics. The $^{12}C/^{13}C$ isotope 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. But a comprehensive study of ^{13}C abundances in Galactic clump stars was not done yet. In this section we report $^{12}C/^{13}C$ ratio, C, N and 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 elemental abundances relative to hydrogen [El/H], stellar masses and suggested evolutionary stages determined for the programme stars are listed in Table 4.1.

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 studies using the same computing programs and using the forbidden C I line at 8727 Å. Due to its low excitation potential, the C I line should not be sensitive to non–LTE effects and to uncertainties in the adopted model atmosphere parameters, contrary to what may be expected for C I and CH lines. The C_2 line, which was investigated in our work, usually gives compatible results with C I. A comprehensive discussion on this subject is given by Gustafsson et al. (1999) and Samland (1998).

Table 4.1. *Abundances of mixing process tracers in Galactic clump stars. Sp.: 1 – NOT, 2 – Beijing. Evol.: g – first ascent giant, c – He-core-burning star, ∗ – may be a He-core-burning star.*

HD	[Fe/H]	[C/H]	[N/H]	[O/H]	C/N	$^{12}C/^{13}C$	Sp.	Mass	Evol.
2910	–0.07	–0.24	0.19	–0.11	1.46	19	1	1.9	g*
3546	–0.60	–0.92	–0.30	–	0.96	13	1	1.5	c
4188	0.10	–0.08	0.23	0.06	1.95	10	2	2.0	c
5268	–0.48	–	–	–0.33	–	–	1	1.6	c
5395	–0.34	–0.61	–0.04	–0.18	1.08	23	1	1.7	g
6805	–0.02	–0.13	0.09	–0.06	2.39	13	1	1.1	c
6976	–0.06	–0.30	0.15	–0.10	1.42	19	1	2.0	g*
7106	0.02	–0.13	0.35	–0.02	1.32	19	1	1.7	g*
8207	0.09	–0.15	0.37	–0.15	1.20	22	1	1.8	g
8512	–0.19	–0.39	–0.08	–0.23	1.94	10	1	0.8	c
8763	–0.01	–0.15	0.19	–	1.82	14	1	1.5	c
9408	–0.28	–0.50	0.10	–0.23	1.00	14	1	1.3	c
11559	0.04	–0.21	0.21	–0.10	1.51	14	2	2.2	c
12583	0.02	–	–	–0.02	–	7	1	1.9	c
15779	–0.03	–0.25	0.25	–	1.26	19	1	2.2	g*
16400	0.00	–0.28	0.35	–0.14	0.93	20	1	2.1	g*
17361	0.03	–0.26	0.22	–0.11	1.33	23	1	1.6	g
18322	–0.04	–0.23	0.10	0.02	1.86	13	2	1.4	c
19787	0.06	–0.06	0.18	0.12	2.29	15	2	1.8	c
25604	0.02	–0.13	0.19	–0.01	1.90	15	2	1.9	c
28292	–0.06	–0.12	–0.02	0.01	3.16	15	2	1.0	c
29503	–0.05	–0.12	0.21	0.00	1.86	–	2	1.0	c
34559	0.07	–0.13	0.35	0.03	1.32	–	2	2.8	g
35369	–0.21	–0.44	0.12	–0.01	1.20	25	1	1.9	g
58207	–0.08	–0.35	0.21	–0.22	1.10	20	1	1.8	g*
131111	–0.17	–0.32	0.05	–	1.70	30	1	1.3	g
141680	–0.07	–0.30	0.21	–0.02	1.24	16	1	2.0	c
146388	0.18	0.03	0.58	0.04	1.13	22	1	2.0	g
203344	–0.06	–0.15	0.17	0.09	1.92	22	1	1.7	g
212943	–0.24	–0.41	–0.03	–	1.66	30	1	1.1	g
216228	–0.05	–0.30	0.17	–0.19	1.35	15	1	1.7	c
218031	–0.08	–0.33	0.07	–0.12	1.59	13	1	1.7	c
221115	0.05	–0.26	0.39	–0.09	0.89	19	1	2.5	g*
222842	–0.02	–0.31	0.34	–0.16	0.89	25	1	2.4	g

In Fig. 4.1, we show results of [C/Fe] for the stars investigated in our work together with results from other studies of clump stars performed by Mishenina et al. (2006) and by Luck & Heiter (2007). Also we show the results obtained for red horizontal branch stars by Tautvaišienė et al. (2001) and by Gratton et al. (2000). Compared to [C/Fe] values in dwarf stars (Gustafsson et al. and Bensby & Feltzing), it is seen that [C/Fe] in clump stars lie by about 0.2 dex below the abundance trend of dwarfs.

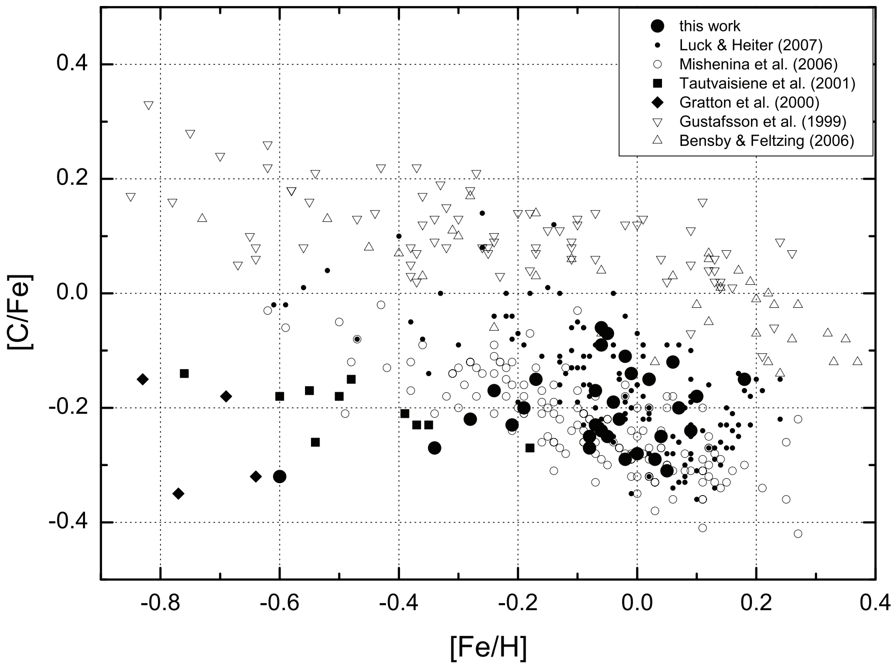

Figure 4.1. Galactic clump abundances: [C/Fe] as a function of [Fe/H]. We show the results for the clump stars investigated in this work, in Mishenina et al. (2006) and in Luck & Heiter (2007). Also we show the results obtained for red horizontal branch stars by Tautvaišienė et al. (2001) and by Gratton 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.

Determinations of nitrogen abundances in Galactic disk stars are not numerous. For metal-abundant stars, as follows from the compilation by Samland (1989), a concentration of [N/Fe] ratios with a rather large scatter lies at the solar value in the [Fe/H] interval from +0.3 dex to about –1.0 dex.

For the comparison of [N/Fe] values, in Fig. 4.2, 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 week N I 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 I lines, however they used the equivalent width method, which gave, to our understanding, slightly overabundant [N/Fe] values.

As it is seen from Fig. 4.2, 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.

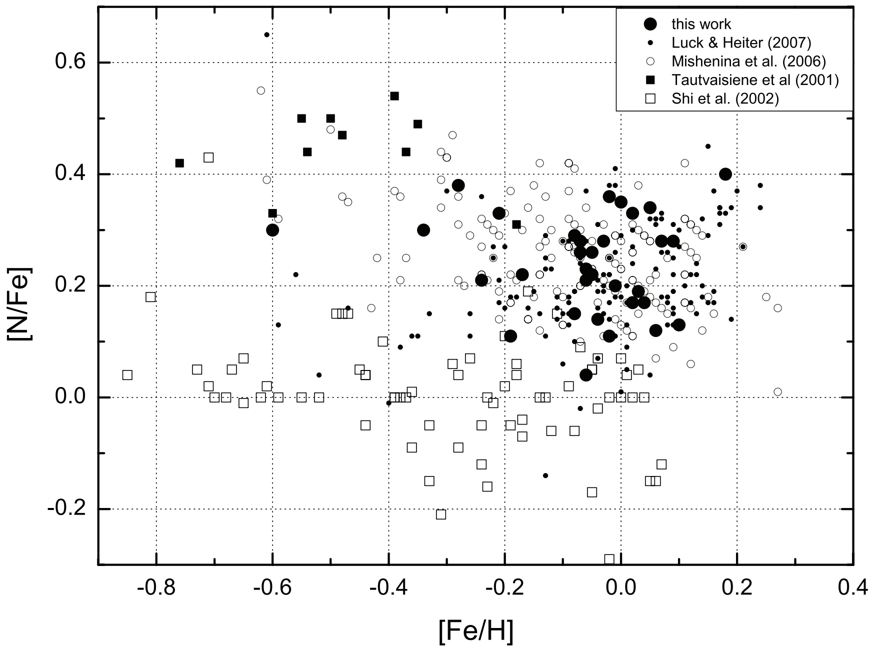

Figure 4.2. [N/Fe] as a function of [Fe/H]. We show the results for the clump stars investigated in this work, in Mishenina et al. (2006) and in Luck & Heiter (2007). Also we show the results obtained for red horizontal branch stars by Tautvaišienė et al. (2001). For the comparison, results obtained for dwarf stars of the Galactic disk (Shi et al. 2002) are presented.

4.2. C, N, O ABUNDANCE DISTRIBUTIONS

Up to date analyses of clump stars of the Galaxy show the following characteristics: [C/Fe] range from –0.4 to 0.1 dex with the maximum at –0.25 dex; [N/Fe] range from 0.0 to +0.5 dex with the maximum at +0.25 dex; [O/Fe] range from –0.2 to +0.3 dex with the maximum number of stars around the solar value. Abundance distribution histograms are presented in Fig. 4.3.

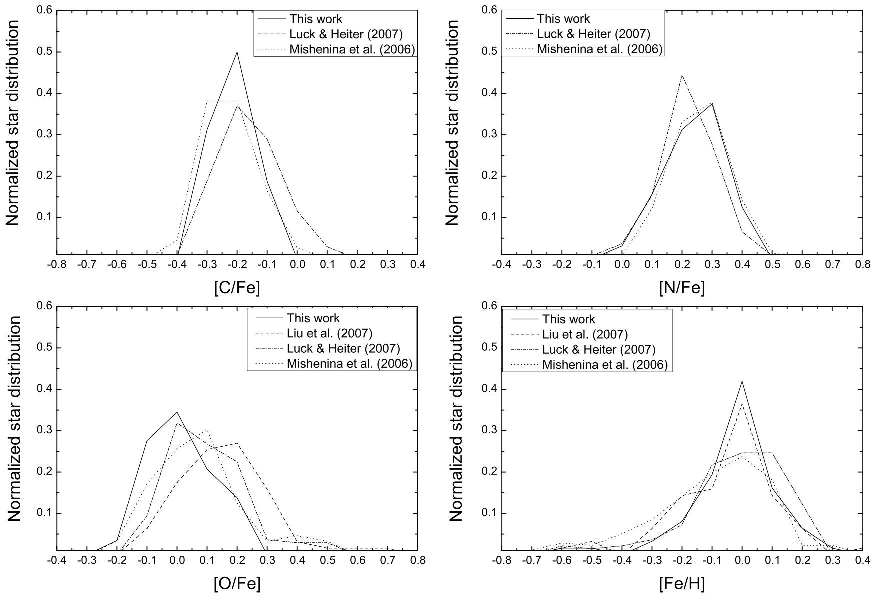

Figure 4.3. C, N, O and [Fe/H] abundance distributions in the samples of Galactic clump stars investigated in this dissertation, by Mishenina et al. (2006), by Liu et al. (2007) and by Luck & Heiter (2007).

4.3. 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. (2006). The modelled trends were computed using the standard mixing length theory. In the left side of Fig. 4.4, 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. (2006). 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 shift.

C/N and $^{12}C/^{13}C$ ratios we compared with the theoretical models by Boothroyd & Sackmann (1999) (the right side of Fig. 4.4) 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 1 M_{sun} 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 $^3He(^3He;2p)^4He$, 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. 4.4) 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.

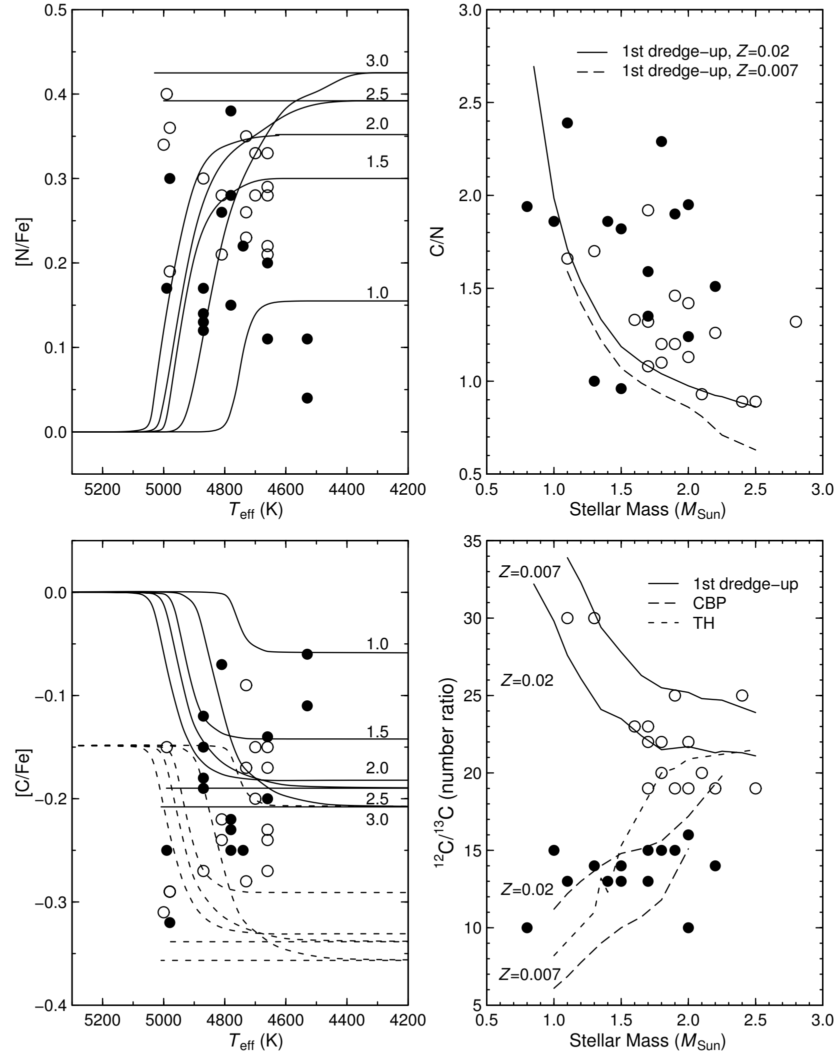

Figure 4.4. On the left side – [C/Fe] and [N/Fe] versus effective temperatures in the sample of Galactic red clump stars compared with the theoretical tracks of abundance variations taken from Mishenina et al. (2006). The theoretical [C/Fe] (dashed lines) are shifted by –0.15 dex (following Mishenina et al. (2006) in order better to represent the majority of metal–deficient stars investigated. On the right side – C/N and $^{12}C/^{13}C$ ratios versus stellar mass. The theoretical curves are taken from Boothroyd & Sackmann (1999) – solid and long dashed lines and Lagarde & Charbonnel (2009) – short dashed line. The stars identified as first ascent giants are shown by empty circles, and the stars identified as helium–core–burning stars – filled circles.

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 and first ascent giants in approximately equal numbers. In the last column of Table 4.1, we indicate the predicted evolutionary status of investigated stars. Stars marked with asterisks have $^{12}C/^{13}C$ isotope ratios equal to about 20, and can 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.

5. OPEN CLUSTER NGC 7789

Open clusters are important tools for the study of the Galactic disk as well as for understanding of stellar evolution. Since cluster members initially were of identical chemical composition, all changes in stellar atmospheres are related to internal and external processes of stellar evolution. Changes of the abundances of carbon, nitrogen and oxygen are most often seen in evolved stars. The enhancement of CN bands and altered carbon isotope ratios in evolved stars of open clusters were already reported 30 years ago (e.g. Pagel 1974; McClure 1974); however, the detailed analyses of abundances in stars of open clusters from high–resolution spectra are still necessary for understanding the processes of dredge–up and extra–mixing affecting the chemical composition of atmospheres in evolved low–mass stars. Detailed spectral analyses of CNO elements were undertaken for giants in 20 open clusters by Gilroy (1989), abundances of more than 20 chemical elements in stars of 8 open clusters were analysed by Luck (1994), a number of other clusters to different extents were analysed by Bragaglia et al. (2001), Brown (1985), Brown et al. (1996), Cayrel et al. (1985), Friel et al. (2003), Gratton & Contarini (1994), Hamdani et al. (2000), King & Hiltgen (1996), Peterson (1992), Peterson & Green (1998), Schuler et al. (2003), Smith & Suntzeff (1987), Tautvaišienė et al. (2000) and references therein. In a review on oxygen and α–element abundances in open clusters, Gratton (2000) has reached the conclusion that the results are still scarce and there are no data even for the easiest clusters.

5.1. GENERAL PARAMETERS OF NGC 7789

The open cluster NGC 7789 was selected for this study, because is quite populous, its colour–magnitude diagram (CMD) shows a well–defined and extended red giant branch (RGB), a prominent "clump" of core–He–burning stars, many blue stragglers, and a main sequence. An extensive proper–motion membership analysis of NGC 7789 was carried out by McNamara & Solomon

(1981), who identified 679 probable members brighter than B ≈ 15.5^m. Radial velocity measurements were done by Thogersen et al.(1993), Scott et al.(1995), and Gim et al. (1998a). The age evaluations of NGC 7789 are 1.1 Gyr as determined by Mazzei & Pigatto (1988), 1.2 Gyr (Martinez Roger et al., 1994), 1.3 Gyr (Carraro & Chiosi 1994), 1.6 Gyr (Gim et al. 1998b) or 1.4 Gyr as determined by Vallenari et al. (2000).

Such a populous open cluster is especially useful for testing stellar evolution models. For the detailed analysis, we have selected six giants along the giant branch and three clump stars (see Fig. 1.2 for their location in the HR diagram). Abundances of C, N and O have not been investigated for this cluster previously. From high–resolution spectra, Pilachowski (1985) determined abundances of some metals in a sample of six stars, Pilachowski et al. (1984) investigated lithium abundances and reported an unusually strong lithium doublet 6707 Å line in some giant stars, Sneden & Pilachowski (1986) derived carbon isotope ratios for seven giant stars. We will refer to these papers when discussing our results. The clump stars of this cluster are investigated by means of high–resolution spectroscopy for the first time.

5.2. ABUNDANCES OF NGC 7789

As follows from the nine stars investigated in this work, the mean abundance of iron in NGC 7789, [Fe/H] = –0.04 ± 0.05 dex, is quite similar to solar. The solar metallicity was evaluated for this cluster also from DDO and UBV photometry by Janes (1977). Canterna et al. (1985) obtained a value of –0.05 dex of the overall metallicity from photometry in the Washington system. Some other photometric analyses give sub–solar [Fe/H] values: –0.2 (Jennens & Helfer 1975), –0.25 (Vallenari et al. 2000), –0.35 (Claria, 1979). In most cases, the photometric metallicity evaluations are based on the shape of the colour–magnitude diagram (CMD); thus they have a general limitation, as there is a dependence on interstellar reddening. The color excess E_{B-V} values for NGC 7789 are quite different from one paper to another, being 0.22 in the work by Claria (1979) and 0.32 in the work by Martinez Roger et al. (1994). From the medium–resolution spectra, Friel & Janes (1993) have determined [Fe/H] = –0.26 ± 0.10 dex for this cluster. From the high–resolution spectroscopy of six stars of the cluster, Pilachowski (1985) determined [Fe/H] = –0.1 ± 0.2 dex.

Table 5.1. *Abundances in NGC 7789 stars relative to hydrogen [A/H]. The quoted errors (σ) are the standard deviations of the mean abundance value due to the line–to–line scatter. The number of lines used is indicated by (n).*

	K415 (tip–giant)			K468 (giant)			K501 (giant)		
	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n
C (C2)	–0.22		1	–0.35		1	–0.27		1
N (CN)				–0.06	0.03	65	0.00	0.02	65
O ([O I])	–0.23		1	–0.14		1	–0.12		1
Na I	0.30		1	0.24		1	0.30		1
Mg I	0.17		1	0.01		1	0.23		1
Al I	–0.01	0.07	2	0.12	0.03	2	0.17	0.13	2
Si I	0.08	0.12	4	0.14	0.14	6	0.14	0.11	5
Ca I	–0.02	0.14	3	0.15	0.07	3	0.07	0.07	3
Sc II	–0.10		1	–0.09		1	–0.07		1
Ti I	–0.20	0.08	5	–0.12	0.10	9	–0.07	0.10	8
V I	0.02	0.03	2	0.02	0.10	4	0.24	0.15	4
Cr I	–0.26	0.07	4	–0.13	0.07	4	–0.10	0.09	4
Fe I	–0.03	0.12	17	–0.08	0.10	22	–0.07	0.07	20
Fe II	–0.03	0.05	2	–0.08	0.03	3	–0.07	0.04	4
Co I	–0.06	0.12	3	0.19	0.12	4	0.06	0.02	3
Ni I	–0.10	0.16	12	–0.09	0.14	14	–0.03	0.16	14
Y II	–0.10		1	0.20		1	0.20		1
Zr I	–0.01	0.13	3	–0.24	0.01	2	–0.21	0.10	3
Ce II	–0.10		1	0.09		1	–0.02		1
Pr II				–0.03		1	0.01		1
Eu II	–0.18		1	0.04		1	–0.02		1
C/N				2.04			2.75		
$^{12}C/^{13}C$	9	+–3		10	+6/–4		9	±4	

Table 5.1. (cont.)

	K605 (clump)			K665 (clump)			K669 (giant)		
	[A/H]	Σ	*n*	[A/H]	σ	*n*	[A/H]	σ	*n*
C (C2)	–0.25		1	–0.20		1	–0.30		1
N (CN)	0.33	0.03	65	0.24	0.03	65	0.12	0.03	65
O ([O I])	–0.12		1	–0.11		1	–0.05		1
Na I	0.21		1	0.21		1	0.09		1
Mg I	0.17		1	0.10		1	0.01		1
Al I	0.23	0.05	2	0.10	0.02	2	0.10	0.09	2
Si I	0.12	0.03	6	0.15	0.10	7	–0.01	0.12	7
Ca I	0.18	0.11	4	0.21	0.08	4	–0.01	0.16	3
Sc II	–0.06		1	–0.16	0.03	2	–0.15		1
Ti I	0.02	0.16	14	0.00	0.17	15	–0.22	0.14	8
V I	0.08	0.10	12	0.11	0.09	9	–0.09	0.14	7
Cr I	0.01	0.07	3	0.06	0.01	2	–0.20	0.09	5
Fe I	–0.02	0.08	24	0.00	0.05	19	–0.15	0.10	24
Fe II	–0.02	0.04	4	0.00	0.07	3	–0.15	0.02	3
Co I	0.02	0.05	5	–0.10	0.12	4	0.02	0.04	5
Ni I	–0.04	0.14	12	0.01	0.11	9	–0.11	0.14	15
Y II	0.03		1	0.09		1	0.11		1
Zr I	–0.10	0.08	3	0.19	0.09	2			
Ce II				0.03		1	0.11		1
Pr II									
Eu II	0.08		1	0.10		1	–0.05		1
C/N	1.05			1.45			1.51		
$^{12}C/^{13}C$	10	+9/–5		9	±2		11	+7/–5	

5.3. COMPARISON WITH PREVIOUS STUDIES

The star K765 is in common with the work by Pilachowski (1985). The difference in effective temperature of this star is only 20 K, the value of E_{B-V} is the same in both studies. The logarithm of the surface gravity differs by 0.3 dex, most probably because of differences in its determination. For this reason, or perhaps because we used the method of synthetic spectra, the mean value of [Eu/Fe] in the cluster according to our work is +0.02 dex and according to the work by Pilachowski [Eu/Fe] = +0.3 dex.

Table 5.1. *(cont.)*

	K732 (giant)			K751 (tip–giant)			K765 (giant)		
	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n
C (C2)	–0.20		1	–0.22		1	–0.24		1
N (CN)	0.22	0.03	65				0.21	0.03	65
O ([O I])	–0.10		1	–0.16		1	–0.01		1
Na I				0.18		1	0.27		1
Mg I				0.17		1	0.23		1
Al I	0.20	0.02	2	0.09	0.06	2	0.20	0.09	2
Si I	0.09	0.09	7	0.10	0.14	5	0.10	0.06	7
Ca I	0.16	0.09	3	0.11	0.06	2	0.07	0.02	2
Sc II	0.03		1	–0.04	0.01	2	0.04	0.03	2
Ti I	0.07	0.14	16	–0.12	0.15	6	–0.04	0.12	12
V I	0.03	0.08	10	–0.15		1	0.13	0.13	9
Cr I	0.02	0.03	3	–0.14	0.08	2	–0.10	0.07	3
Fe I	0.02	0.07	22	–0.01	0.11	18	–0.04	0.09	22
Fe II	0.02	0.01	3	–0.01	0.06	3	–0.04	0.07	3
Co I	–0.04	0.14	3	0.07	0.09	2	0.23	0.04	4
Ni I	–0.10	0.12	15	–0.04	0.15	10	–0.04	0.10	13
Y II	0.02		1	0.05		1	0.21		1
Zr I				0.10	0.13	3	–0.11	0.13	3
Ce II				–0.02		1	0.19		1
Pr II	0.15		1	0.01		1	0.08		1
Eu II	0.00		1	–0.20		1	0.06		1
C/N	1.51						1.41		
$^{12}C/^{13}C$	7	±2		8	+6/–3		13	+6/–4	

There are two stars in common (K501 and K669) with the paper by Sneden & Pilachowski (1986). The purpose of this paper was to investigate $^{12}C/^{13}C$ in seven stars, and since this kind of analysis does not require very accurate atmospheric parameter values, the authors did not attempt to be very precise. Our effective temperature for the star K501 is lower by 60 K and for K669 is higher by 80 K, log *g* in our work is lower by 0.4 dex for both stars.

As follows from the present work, the mean abundance of iron in NGC 7789 is quite similar to the metallicity of another open cluster of the Galactic disk M 67 (–0.03, Tautvaišienė et al. 2000), which was analysed by essentially the same technique as used in the present work.

The average cluster abundances and dispersions about the mean values for NGC 7789 are presented in Table 5.2 and discussed in the following subsections. The comparison of the determined elemental abundances has been made with results of field dwarfs of the Galactic disk since the main sequence stars in NGC 7789 have not been investigated yet. The comparison with unevolved field stars may help to reveal evolutionary abundance changes in the evolved stars we investigate in this cluster.

Table 5.2. *Mean cluster abundances of NGC 7789, and standard deviations of abundances.*

Species	[A/H]	$\sigma_{[A/H]}$	[A/Fe]	$\sigma_{[A/Fe]}$
C (C_2)	–0.25	0.05	–0.21	0.03
N (CN) (Giants)	0.07	0.12	0.15	0.13
N (CN) (Clump)	0.26	0.06	0.26	0.08
O ([O I])	–0.12	0.06	–0.07	0.09
Na I	0.23	0.07	0.28	0.07
Mg I	0.13	0.09	0.18	0.07
Al I	0.13	0.07	0.18	0.08
Si I	0.10	0.05	0.14	0.05
Ca I	0.10	0.08	0.14	0.07
Sc II	–0.07	0.07	–0.02	0.07
Ti I	–0.08	0.10	–0.03	0.07
V I	0.04	0.12	0.09	0.12
Cr I	–0.09	0.11	–0.05	0.09
Fe I	–0.04	0.05	–	–
Fe II	–0.04	0.05	–	–
Co I	0.04	0.11	0.09	0.14
Ni I	–0.06	0.04	–0.02	0.05
Y II	0.09	0.10	0.13	0.13
Zr I	–0.05	0.16	–0.02	0.13
Ce II	0.04	0.10	0.09	0.13
Pr II	0.04	0.07	0.08	0.05
Eu II	–0.02	0.11	0.02	0.12
$^{12}C/^{13}C$	9	1		
C/N (Giants)	1.93	0.53		
C/N (Clump stars)	1.34	0.20		

5.4. CARBON, NITROGEN AND OXYGEN

Since the C I 8727 Å line is blended with CN in spectra of red giants, and since the probability of increased strengths of CN molecular lines is present, we analysed the C_2 Swan (0,1) band head at 5635.5 Å. This feature was used in several of our previous studies of giants (Tautvaišienė et al. 2000; 2001).

The evaluation of the carbon abundance can be done by a comparison with carbon abundances determined for dwarf stars in the Galactic disk. Shi et al. (2002) performed an abundance analysis of carbon for a sample of 90 F and G type main–sequence disk stars using the C I lines and found [C/Fe] to be about solar at the solar metallicity.

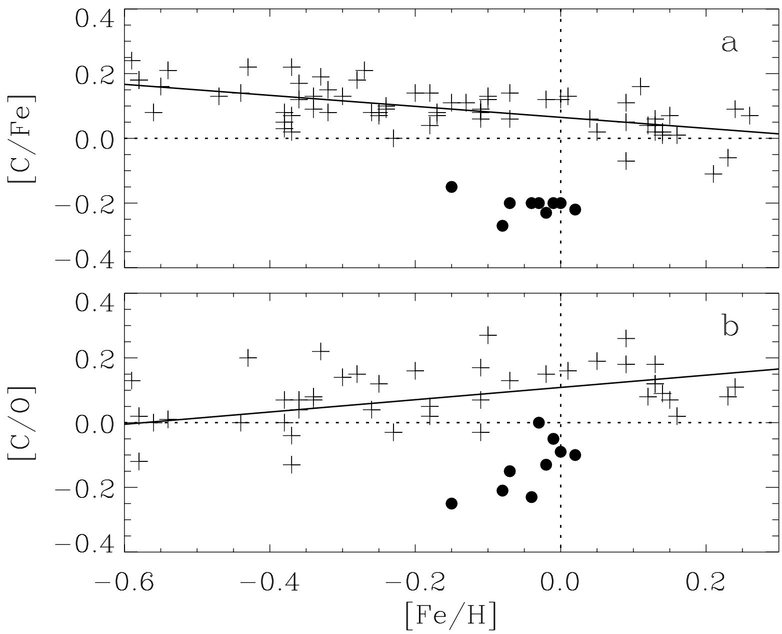

Figure 5.1. [C/Fe] and [C/O] as a function of [Fe/H]. Results of this dissertation are indicated by filled circles, results obtained for dwarf stars of the Galactic disk (Gustafsson et al. 1999) by `plus' signs and the full line.

Gustafsson et al. (1999), using the forbidden C I line, made an abundance analysis of carbon for a sample of 80 late F and early G type dwarfs. As is seen from Fig. 5.1, the ratios of [C/Fe] and [C/O] in our stars lie by about 0.2 dex below the trends obtained for dwarf stars of the Galactic disk analysed in this study. There is no noticeable difference in carbon abundances between giant and clump stars investigated.

The wavelength interval 7980 – 8130 Å, with 65 CN lines selected, was analysed in order to determine the nitrogen abundances. The mean nitrogen abundance, as determined from the giants, is [N/H]= 0.07 ± 0.12 dex and from the clump stars [N/H]= 0.26 ± 0.06 dex.

Determinations of nitrogen abundances in Galactic disk stars are not numerous. For metal–abundant stars, as follows from the compilation by Samland (1989), a concentration of [N/Fe] ratios with a rather large scatter lies at the Solar value in the [Fe/H] interval from +0.3 dex to about –1.0 dex. Reddy et al. (2003) investigated nitrogen abundances in a sample of 43 F–G dwarfs in the Galactic disk by means of weak N I lines. At a value of [Fe/H] of about –0.2 dex, which was well represented in their sample, [N/Fe] is about 0.2 dex. There were few stars of solar metallicity investigated in this study. Nevertheless, the authors make the extrapolation that at solar metallicity [N/Fe] values should be solar. In the work by Shi et al. (2002) [N/Fe] values in the main–sequence stars are also about solar at the solar metallicity. Thus, in the NGC 7789 stars investigated, when compared to the Galactic field dwarf stars, the nitrogen abundances are enhanced. Also it is noticeable that the enhancement is larger in the clump stars: [N/Fe] =0.15 ± 0.13 in the giants and [N/Fe] =0.26 ± 0.08 in the clump stars. Consequently, the mean C/N ratios are lowered to the value of 1.93 ± 0.53 dex in the giants and to the values of 1.34 ± 0.20 dex in the clump stars. As follows from the Solar carbon and nitrogen abundances accepted in our work – log A_C = 8.52 and log A_N = 7.92 (Grevesse & Sauval 2000) – the solar C/N = 3.98. The $^{12}C/^{13}C$ ratios were determined for all programme stars using the (2,0) $^{13}C/^{14}N$ feature at 8004.728 Å with a laboratory wavelength adopted from Wyller (1966). We find that the mean $^{12}C/^{13}C$ ratios are lowered to about the same value of 9 in the giants and clump stars investigated. Ratios of $^{12}C/^{13}C$ were investigated for seven stars in NGC

7789 by Sneden & Pilachowski (1986). They found carbon isotope ratios in the range 10 – 30. The same carbon and nitrogen changes are seen in atmospheres of giant stars in the Galactic field and in clusters (c.f. Weiss & Charbonnel 2004; Charbonnel 2003; Smith & Martell 2003; Gratton et al. 2000 and references therein).

5.5. SODIUM AND ALUMINIUM

Sodium and aluminium are among the chemical elements for which observations of abundance anomalies are also present. The O–Na anticorrelation has been observed among the brightest red giants in Galactic globular clusters for a long time (see Kraft 1994; Da Costa 1998; Denissenkov & Herwig 2003 and references therein). An overabundance of Na could appear, due to the deep mixing from layers of the NeNa cycle of H burning. Extensive theoretical studies of deep mixing in stellar atmospheres have been made by Denissenkov & Weiss (1996), Denissenkov & Tout (2000), Denissenkov & Herwig (2003) and references therein. However, the explanation of abundance changes by deep mixing has recently been challenged by the determination of an O – Na anticorrelation in less evolved stars down to the main sequence (Gratton et al. 2001; Thevenin et al. 2001; Ramirez & Cohen 2002). The stars in our sample, as determined from the Na I lines at 5682.64 Å and 6154.23 Å, show a slight overabundance of sodium (Fig. 5.2). Aluminium was investigated using Al I lines at 7835.30 Å and 7836.13 Å. [Al/Fe] values within the errors agree well with the results from the field dwarf stars (Fig. 5.2). The majority of other open clusters also have enhanced [Na/Fe] ratios. Looking at the correlation of [Na/Fe] ratios with the Galactocentric distances of the clusters, presented recently by Friel et al. (2003), it is interesting to notice that [Na/Fe] is larger for open clusters with smaller Galactocentric distances. The result of [Na/Fe] in NGC 7789 with R_{GC}=9430 ps fits well to this correlation.

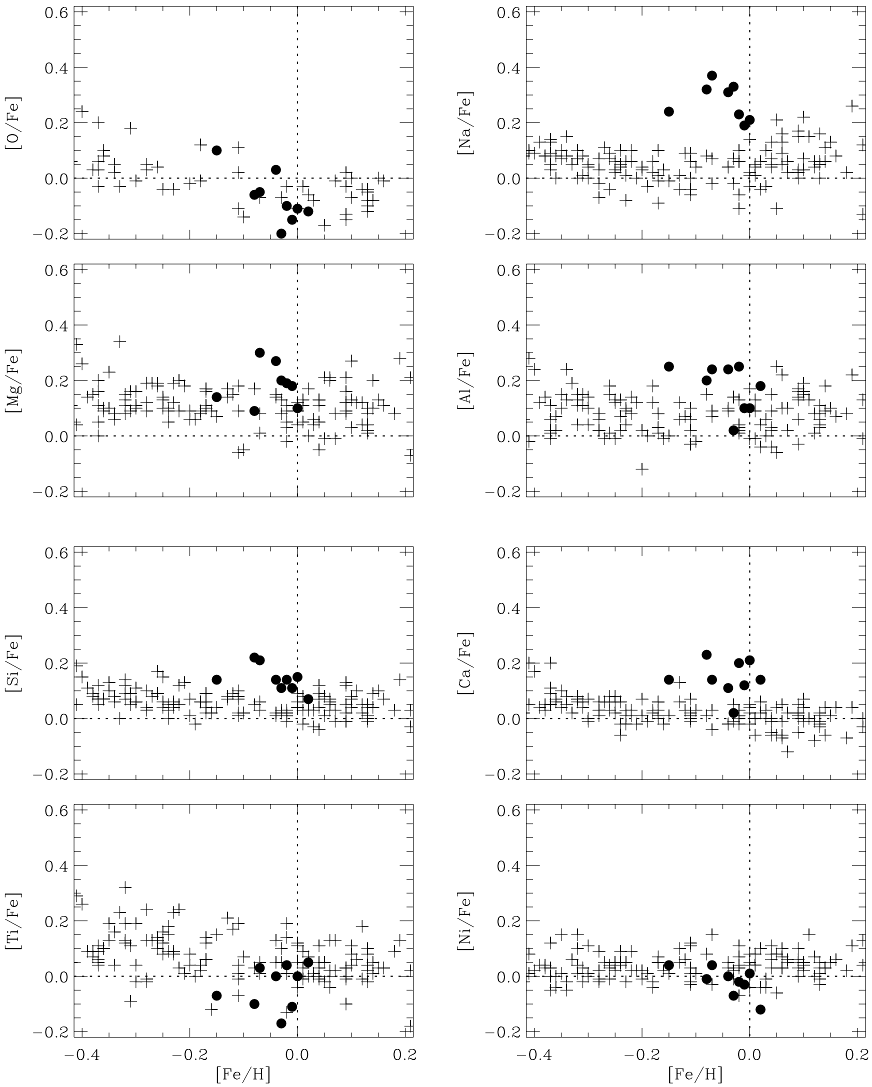

Figure 5.2. Element to iron ratios as a function of iron [Fe/H]. Results of this dissertation paper are indicated by filled circles, results obtained for dwarf stars of the galactic disk (Edvardsson et al. 1993) by `plus' signs.

5.6. ALPHA–ELEMENTS: MG, SI, CA AND TI

According to observations of the main sequence stars in the Galactic disk, abundance ratios of α–process elements to iron at the solar metallicity are solar or slightly higher. In the study by Edvardsson et al.(1993) [Mg/Fe], [Si/Fe] and [Ti/Fe] for almost all of the stars lie slightly above the solar ratio, [Ca/Fe] are solar (see Fig. 5.2). In the study of Reddy et al. (2003), [Mg/Fe] and [Si/Fe] values are above the solar, while [Ca/Fe] and [Ti/Fe] are exactly solar. For purpose of this study, author defined:

[α/Fe] = ¼ ([Mg/Fe]+[Si/Fe]+[Ca/Fe]+[Ti/Fe]).

Averge NGC7789 [α/Fe] value is 0.11 ± 0.08 dex. From the comparison of the individual elements with the Galactic disk field sample of Edvardsson et al. (1993) (Fig. 5.2) it can be suspected that abundances of Si and Ca are slightly higher than in the field dwarfs. The mean [α/Fe] ratios in a majority of open clusters investigated are higher than in the Sun, the overabundance of silicon is most noticeable (c.f. Brown et al. 1996; Bragaglia et al. 2001; Friel et al. 2003).

5.7. IRON GROUP AND HEAVIER ELEMENTS

In the NGC 7789 stars investigated the abundances of iron group chemical elements are close to solar (see Table 5.1) and have much less scatter around the mean values than in the work by Pilachowski (1985). In our spectra there are not many lines for the analysis of abundances of *s*– and *r*–process elements. For the determination of the yttrium abundances we used the spectral synthesis of the Y II line at 5402 Å, the abundance of zirconium was determined using equivalent widths of Zr I lines at 6127.48, 6134.57 and 6143.18 Å , and the abundance of cerium was determined using only one line at 6043.38 Å . The analysis gave a scatter around the mean cluster abundances of these *s*–process dominated elements of 0.13 dex with the mean abundances close to solar. Two *r*–process–dominated chemical elements, Pr II and Eu II, were investigated in our work. The praseodymium abundance was determined using the Pr II line at 5322.71 Å and the europium abundance from the Eu II line at 6645 Å. The abundances obtained for these elements are also close to solar.

5.8. FINAL REMARKS

The change in the surface composition of a star ascending the giant branch is predicted by theoretical calculations. When a star evolves up the giant branch its convective envelope deepens and CN–cycle products are mixed to the surface of the evolving star, causing the surface $^{12}C/^{13}C$ and $^{12}C/^{14}N$ ratios to drop. These ratios decrease with increasing stellar mass and decreasing metallicity. Extra–mixing processes may become efficient on the red giant branch when stars reach the so–called luminosity function bump, and may modify the surface abundances (see Charbonnel et al. 1998 for more discussion). The first and only evidence on the evolutionary state at which this non–standard mixing actually starts and how effective it is has to come from observations. Stars of different masses and metallicities are affected by extra–mixing to a different extent (c.f. Boothroyd & Sackmann 1999). In the open cluster M 67 (Tautvaišienė et al. 2000), evidence for extra–mixing in first–ascent giants was not found (the mass of turn–off stars in this cluster is about 1.2 M_{sun}). In the M 67 giants investigated, the mean $^{12}C/^{13}C$ ratio is lowered to the value of 24 ± 4, and the $^{12}C/^{14}N$ ratio to the value of 1.7 ± 0.2, which is close to the corresponding predictions of the first dredge–up (Boothroyd & Sackmann 1999). Evidence of extra–mixing has been detected only in the clump stars observed. Their mean $^{12}C/^{13}C$ = 16 ± 4 and $^{12}C/^{14}N$ =1.4 ± 0.2 agree well with predictions of extra–mixing by Boothroyd & Sackmann (1999). In NGC 7789 we also investigate the first–ascent giants located above the red giant bump and more evolved clump stars. This provides information on chemical composition changes along the evolutionary sequence. In NGC 7789 with the mass of turn–off stars of about 1.6 M_{sun} (Faulkner & Cannon 1973), the mean $^{12}C/^{14}N$ ratios are also different, in the giants $^{12}C/^{14}N$ = 1.9 ± 0.5 and in the clump stars 1.3 ± 0.2; however, the $^{12}C/^{13}C$ ratios are very similar for all the stars investigated, 9 ± 1, and indicate a larger extra–mixing than it is foreseen by Boothroyd & Sackmann (1999) for stars of a similar turn–off mass. Note that according to theoretical predictions of extra–mixing (Boothroyd & Sackmann 1999), changes of $^{12}C/^{14}N$ ratios in solar metallicity stars lower C/N ratios after the 1st dredge–up by not more than 0.1 dex in stars of all the masses modelled (1.00 – 2.25 M_{sun}). However, the differences of C/N ratios in giants and clump stars of the open clusters M 67 and NGC 7789 are larger. The question of whether this disagreement is caused by observational or theoretical reasons, or perhaps by effects of helium–core–flash, still has to be answered. We hope that the results presented in this work will contribute to answering the fundamental questions of stellar evolution.

RESULTS AND CONCLUSIONS

Galactic clump: main parameters, iron group abundances and metallicity distribution

The main atmospheric parameters (effective temperature, surface gravity, miroturbulent velocity) and abundances of iron peak elements (vanadium, chromium, cobalt, iron and nickel) were determined for 62 Galactic red clump stars revealed in the Galactic field by the *Hipparcos* orbiting observatory.

Conclusions:

1. The clump stars form a homogeneous sample with the mean value of temperature $T_{\rm eff}$ = 4750 ± 160 K, of surface gravity log g = 2.41 ± 0.26 and the mean value of metallicity [Fe/H] = –0.04 ± 0.15.

2. The Galactic clump star distribution by iron abundance is quite narrow and close to Gaussian function. A Gaussian fit to the [Fe/H] distribution produces the mean <[Fe/H]> = –0.01 and dispersion $\sigma_{\rm [Fe/H]}$ = 0.08. The iron group element to iron abundance ratios in the investigated clump giants are close to solar.

3. The near–solar metallicity and small dispersion of $\sigma_{\rm [Fe/H]}$ of clump stars of the Galaxy obtained in this work confirm the theoretical model of the *Hipparcos* clump by Girardi & Salaris (2001), which suggests that nearby clump stars are (in the mean) relatively young objects, reflecting mainly the near–solar metallicities developed in the local disk during the last few Gyrs of its history.

Galactic clump: mixing processes

^{12}C/^{13}C isotope ratios were determined for 34 Galactic red clump stars as well as abundances of nitrogen, carbon and oxygen.

Conclusions:

1. 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.

2. 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 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.

3. Observed $^{12}C/^{13}C$ ratios of helium–core–burning clump stars are consistent with the cool–bottom–processing model of extra–mixing (Boothroyd & Sackman 1999). The thermohaline extra–mixing model by Lagarde & Charbonnel (2009) needs to be complemented by the rotationally induced mixing component in order to agree with the observational data for stars with masses larger than 1.5 M_{sun}.

Chemical composition of the open cluster NGC 7789

Element abundances and isotope ratios $^{12}C/^{14}N$ and $^{12}C/^{13}C$ (extra–mixing indicators) were determined in NGC 7789 stars. 3 clump stars and 6 red giants located above the red giant branch bump were investigated.

Conclusions:

1. Overall metallicity of the cluster was found to be very close to solar metallicity.

2. $^{12}C/^{14}N$ ratio was found to be different in the giants (1.9 ± 0.5 dex) and clump stars (1.3 ± 0.2 dex).

3. $^{12}C/^{13}C$ isotope ratios were found to be similar for all the stars investigated (9 ± 1 dex) and indicate a larger extra–mixing than it is foreseen by currently available theoretical models.

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