

Chemical composition of red horizontal branch stars in the thick disk of the Galaxy^{*,**}

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Abstract. High-resolution spectra of 13 core helium-burning stars in the thick disk of the Galaxy have been obtained with the SOFIN spectrograph on the Nordic Optical Telescope to investigate abundances of up to 22 chemical elements. Abundances of carbon were studied using the C₂ Swan (0, 1) band head at 5635.5 Å. The wavelength interval 7980–8130 Å with strong CN features was analysed in order to determine nitrogen abundances and ¹²C/¹³C isotope ratios. The oxygen abundances were determined from the [O I] line at 6300 Å. Abundances in the investigated stars suggest that carbon is depleted by about 0.3 dex, nitrogen is enhanced by more than 0.4 dex and oxygen is unaltered. The ¹²C/¹³C ratios are lowered and lie between values 3 and 7 which is in agreement with “cool bottom processing” predictions (Boothroyd & Sackmann 1999). The C/N ratios in the investigated stars are lowered to values between 0.7 and 1.2 which is less than present day theoretical predictions and call for further studies of stellar mixing processes. Abundance ratios of O, Mg, Eu and other heavy chemical elements to iron in the investigated stars show a pattern characteristic of thick disk stars. The results provide evidence that the thick disk population has a distinct chemical history from the thin disk. The onset of the bulk of SN Ia is suggested to appear at [Fe/H] ≈ −0.6 dex.

Key words. stars: abundances – stars: atmospheres – stars: horizontal-branch – galaxy: formation

1. Introduction

“Uppgren’s Unclassified Stars: A New Type of G-Giant Stars?” – was the title of a paper by Sturch & Helfer (1971) in which *UBVRI* photometry was presented for 17 stars for which Uppgren (1962) could not obtain luminosities. Uppgren (1962) had conducted objective-prism observations with dispersion of 580 Å/mm^{−1} for late-type stars near the north galactic pole. For the G stars, luminosity criteria were the two CN bands at λ3820–80 Å and λ4130–4215 Å. It appeared that for some G stars, luminosity determination from these features was inaccurate. Sturch & Helfer, however, also met with difficulties: the position of stars observed in the *U – B, R – I* diagram matched neither the Hyades nor nearby field dwarfs, nor field giants with *r* < 100 pc, nor M 67 or the giant branches

of a variety of globular clusters. The authors concluded that these unclassified stars probably belong to the field equivalents of the red horizontal branch (RHB) stars of metal-rich globular clusters. This paper marked the beginning of a serious effort to study red horizontal branch stars in the Galactic field (see Tautvaišienė 1996a for a review).

64 G stars from Uppgren’s list were investigated by Rose (1985) using a quantitative three-dimensional spectral classification system employing 2.5 Å resolution spectra in the blue. A number of Uppgren’s unclassified stars were found to be dwarfs. Quite a large group of Uppgren’s G stars were, however, shown to be evolved, based on the strength of their Sr II λ4077 Å line. They were also distinguished from post-main-sequence stars evolving through the same region of the HR diagram because of the unique appearance of their CN λ3883 and 4216 Å bands. It was concluded that a class of red horizontal-branch stars, similar to those in the “metal-rich” globular cluster M 71, has been identified in the Galactic disk. Moreover, it was noticed that these stars have metallicities and kinematics which are common for the “thick disk” of the Galaxy revealed by Gilmore & Reid (1983). Detailed measurements

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* Based on observations obtained at the Nordic Optical Telescope, La Palma.

** Table 1 is only available in electronic at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsweb.u-strasbg.fr/cgi-bin/qcat?J/A+A/380/578>

of kinematic parameters of the stars by Stetson & Aikman (1987) have confirmed that they belong to the thick disk of the Galaxy.

Norris (1987) reported DDO observations for ten of Uggren’s red giants which Rose (1985) identified as RHB stars and presented arguments that these stars could equally well be the core-helium-burning “clump” stars similar to those seen in the old, metal deficient open cluster NGC 2243. Consequently they could be as young as about 5–7 Gyr rather than about 14 Gyr as would follow from their identity to the population of metal-rich galactic disc globular clusters.

Photometric observations and three-dimensional classification in the Vilnius photometric system were carried out for 13 of the Roses’s RHB stars by Tautvaišienė (1996b). The results were photometric spectral types, metallicities, effective temperatures, surface gravities, absolute magnitudes and ages. The stars form a group with mean $[\text{Fe}/\text{H}] = -0.6 \pm 0.1$ which is between -0.7 as evaluated by Rose (1985) and -0.5 as determined by Norris (1987) from the cyanogen excess parameter δ_{CN} . An age of about 10–12 Gyr was ascribed to the group from comparison with model isochrones. This age is intermediate between the ages of the disk globular clusters and the oldest open clusters.

The aim of the present study is to perform a high resolution spectroscopic analysis of 13 red horizontal branch stars which were identified in Uggren’s list by Rose (1985). We expect that C/N and $^{12}\text{C}/^{13}\text{C}$ abundance ratios, and possibly also the abundances of sodium, aluminium and *s*-process elements, will provide information on the extent of mixing processes in these evolved stars. Abundances of other chemical elements will be useful for the interpretation of the chemical evolution of the thick disk of the Galaxy.

2. Observations and data reductions

The spectra were obtained at the Nordic Optical Telescope (NOT) with the SOFIN échelle spectrograph (Tuominen 1992) in 1997. The 2nd optical camera ($R \approx 60\,000$) and the 3rd optical camera ($R \approx 30\,000$) were used. The spectra were recorded with the Astromed-3200 CCD camera (Mackay 1986) equipped with an EEV P88100 UV-coated CCD of 1152×298 pixels operated at the working temperature of 150 K. With the 2nd camera we observed simultaneously 13 spectral orders, each of 40–60 Å in length, located from 5650 Å to 8130 Å and with the 3rd camera we observed 25 spectral orders, each of 80–150 Å in length, located from 4500 Å to 8750 Å. All spectra were exposed to $S/N \geq 100$.

Reductions of the CCD images were made with the *3A* software package (Ilyin 1996, 2000). Procedures of bias subtraction, spike elimination, flat field correction, scattered light subtraction, extraction of spectral orders were used for image processing. A Th-Ar comparison spectrum was used for the wavelength calibration. The continuum was defined by a number of narrow

spectral regions, selected to be free of lines in the solar spectrum.

The lines suitable for measurement were chosen using the requirement that the profiles be sufficiently clean to provide reliable equivalent widths. Inspection of the solar spectrum (Kurucz et al. 1984) and the solar line identifications of Moore et al. (1966) were used to avoid blends. Lines blended by telluric absorption lines were omitted from treatment as well. The equivalent widths of lines were measured by fitting of a Gaussian function. The line measurements are listed in Table 1 (available in electronic form at CDS).

3. Method of analysis

The spectra were analysed using a differential model atmosphere technique. The method of analysis and atomic line parameters are the same as used recently by Tautvaišienė et al. (2000, Paper I), where the chemical composition of evolved stars in the open cluster M 67 was investigated. The *Eqwidth* and *Spectrum* programme packages, developed at Uppsala Astronomical Observatory, were used to carry out the calculations of abundances from measured equivalent widths and synthetic spectra, respectively. A set of plane parallel, line-blanketed, flux constant LTE model atmospheres with solar abundance ratios was computed by M. Asplund (Uppsala Astronomical Observatory) with the updated version of the MARCS code (Gustafsson et al. 1975) using continuous opacities from Asplund et al. (1997) and including UV line blanketing as described by Edvardsson et al. (1993). The solar model atmosphere for the differential analysis was also calculated in Uppsala (Edvardsson et al. 1993).

The effective temperatures for the programme stars were initially taken from Tautvaišienė (1996b), where they were derived using the intrinsic colour index $(Y - V)_0$ of the Vilnius photometric system. For the star BD +28°2079 the $(Y - V)_0$ was taken from Bartkevičius & Lazauskaitė (1997) and the same procedure applied. In the work by Tautvaišienė (1996b) as well as in the work by Norris (1987) the interstellar reddening for these stars was accepted to be zero. Although these stars are located in the direction of the North Galactic Pole, where the reddening should be small, Bartkevičius & Lazauskaitė (1997) have found that some of the stars are affected. We decided to introduce a spectroscopic method to solve the problem. We corrected, when needed, the effective temperatures by achieving the LTE excitation balance in the iron abundance results. For nine stars the effective temperatures were adjusted by -70 – $+110$ K.

The surface gravities were found by forcing Fe I and Fe II to yield the same iron abundances, 47 Fe I and 5 Fe II lines were used. The microturbulent velocities were determined by forcing Fe I line abundances to be independent of the equivalent width. The derived atmospheric parameters are listed in Table 2.

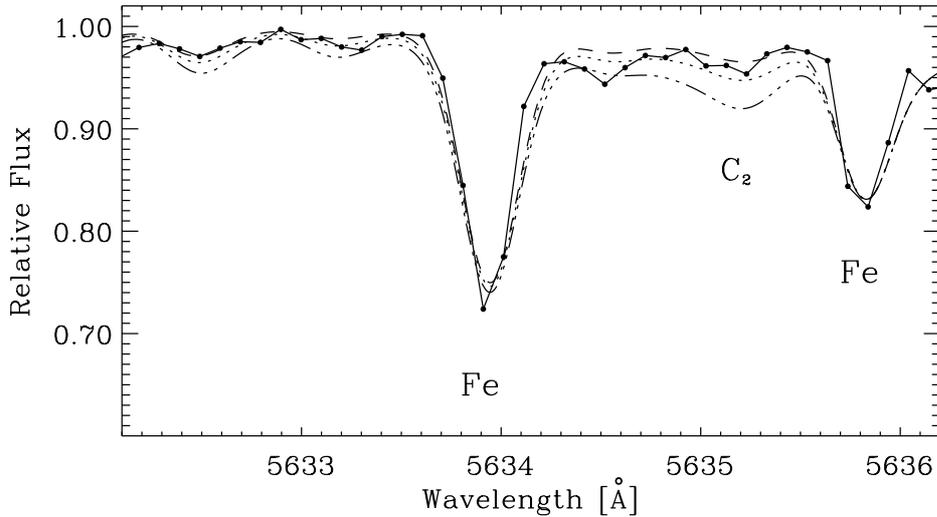


Fig. 1. Synthetic (dashed and dotted curves) and observed (solid curve with dots) spectra for the 1–0 C_2 region near $\lambda 5635 \text{ \AA}$ of BD +34°2371. The syntheses were generated with $[C/H] = -0.3, -0.4,$ and -0.5 (dashed-dotted, dotted and dashed curves, respectively).

Table 2. Atmospheric parameters derived for the field RHB stars. The last two columns give numbers of spectra observed with the resolving power $R1 \approx 30\,000$ and $R2 \approx 60\,000$.

BD/HD	T_e, K	$\log g$	$[Fe/H]$	$v_t, \text{km s}^{-1}$	$R1$	$R2$
+25°2436	4990	2.4	-0.48	1.7	2	2
+25°2459	4980	2.5	-0.35	1.5	1	2
+25°2502	5090	2.2	-0.74	1.3		2
+27°2057	4840	2.1	-0.60	1.7	1	2
+28°2079	4950	2.5	-0.44	2.0	2	
+29°2231	5060	2.5	-0.39	1.9	2	2
+29°2294	5020	2.1	-0.54	1.7	1	
+29°2321	4980	2.3	-0.50	1.9	2	
+33°2280	5000	2.4	-0.48	1.6		1
+34°2371	4980	2.5	-0.18	1.6	1	
+36°2303	4700	1.8	-0.76	2.0	2	
104783	5140	2.4	-0.55	1.5	1	3
105944	5090	2.1	-0.37	1.4	2	

Abundances of carbon and nitrogen were determined using the spectrum synthesis technique. The interval of 5632–5636 Å was synthesized and compared with observations in the vicinity of the C_2 Swan 0–1 band head at 5635.5 Å. The 5635.5 Å C_2 band head is strong enough in our spectra and is quite sensitive to changes of the carbon abundance (see Fig. 1 for illustration). The same atomic data of C_2 as used by Gonzalez et al. (1998) and in Paper I were adopted for the analysis.

The intervals of 7980–8130 Å with $R \approx 30\,000$ and 8380–8430 Å with $R \approx 60\,000$, containing strong CN features, were analysed in order to determine the nitrogen abundance. The $^{12}C/^{13}C$ determination was based on the 8004.728 Å ^{13}CN feature. 11 other weaker ^{13}CN features (λ 7989.45, 8010.4, 8011.2, 8016.35, 8022.65, 8036.15, 8043.2, 8048.3, 8051.8, 8056.4, 8058.2 and 8065.0 Å)

were used for error estimation. The molecular data for $^{12}C^{14}N$ and $^{13}C^{14}N$ were taken from ab initio calculations of CN isotopic line strengths, energy levels and wavelengths by Plez (1999), with all gf values increased by +0.03 dex in order to fit our model spectrum to the solar atlas of Kurucz et al. (1984). The ^{13}CN line wavelengths were, however, adopted from laboratory measurements by Wyller (1966). Parameters of atomic lines in the spectral synthesis intervals were adopted from the VALD database (Piskunov et al. 1995). In order to check the correctness of the input data, synthetic spectra of the Sun were compared to the solar atlas of Kurucz et al. (1984) and necessary adjustments were made to the line data.

Figure 2 illustrates the enhancement of the ^{13}CN line at 8004.7 Å in a spectrum of the star BD +27°2057.

Abundances of oxygen were determined using equivalent widths of the [O I] forbidden line at 6300 Å, widely used in analyses of other late-type stars. This line was recently reexamined in the solar spectrum with a three-dimensional time-dependent hydrodynamical model solar atmosphere and implications of the Ni I blend on oxygen abundances discussed (Prieto et al. 2001). Our test calculations showed that in our sample of stars the influence of the Ni line is very small (oxygen abundance changes do not exceed 0.01–0.03 dex).

The interval of 6643–6648 Å, containing the Eu II line at 6645 Å, was computed in order to determine the europium abundance (see Fig. 3 for illustration). The oscillator strength of the Eu II line, $\log gf = 0.17$, was adopted from Gurtovenko & Kostik (1989). The solar abundance of europium, later used for the differential analysis, $\log A(Eu)_{\odot} = 0.49$, was determined by fitting of the Kurucz et al. (1984) solar flux spectrum. Parameters of other lines in the interval were compiled from the VALD database. CN lines were also included, but none of them seems to affect the europium line significantly.

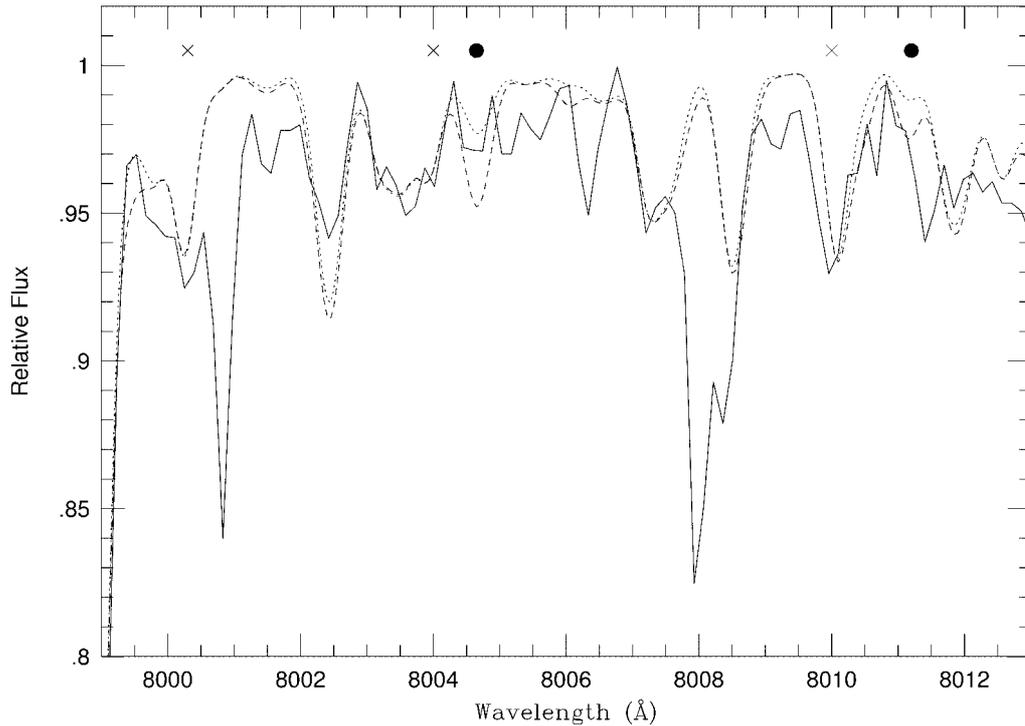


Fig. 2. A small portion of the 8000 Å wavelength interval showing the 8004.7 Å $^{13}\text{C}\text{N}$ feature in the star BD +27°2057. The dotted line shows a synthetic spectrum with $[\text{N}/\text{H}] = -0.28$ and $^{12}\text{C}/^{13}\text{C} = 7$, the dashed line shows a synthetic spectrum with $[\text{N}/\text{H}] = -0.22$ and $^{12}\text{C}/^{13}\text{C} = 3$. The dots indicate features dominated by $^{13}\text{C}\text{N}$, and the crosses mark features dominated by $^{12}\text{C}\text{N}$. Unfitted features belong to the Earth atmosphere.

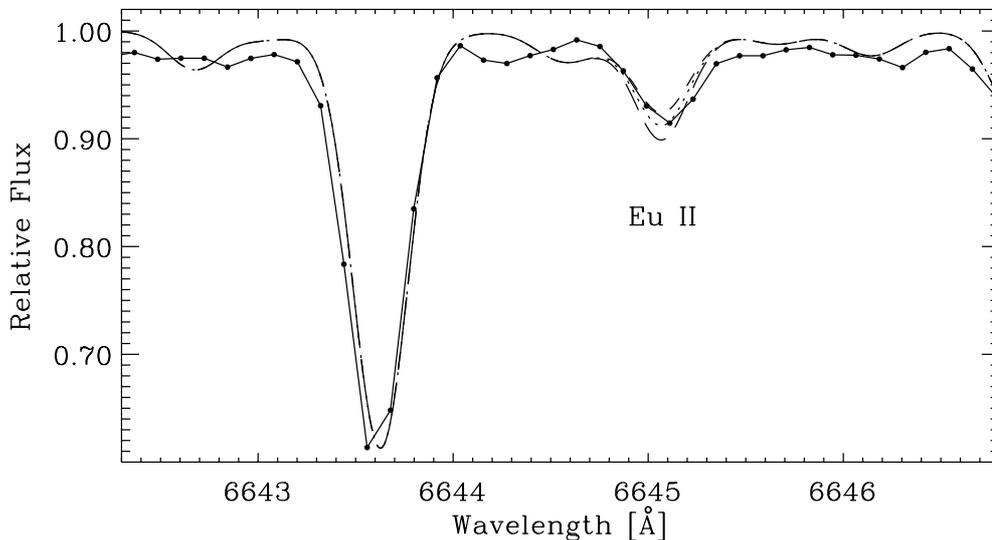


Fig. 3. Synthetic and observed (thick solid curve and dots) spectra for the region around the Eu II line at λ 6645 Å in BD +27°2057. The syntheses are generated with $[\text{Eu}/\text{Fe}] = 0.4, 0.5$ and 0.6 (dashed, dotted and long-dashed curves, respectively).

Typical internal error estimates for the atmospheric parameters are: ± 100 K for T_{eff} , ± 0.3 dex for $\log g$ and ± 0.3 km s $^{-1}$ for v_t . The sensitivity of the abundance estimates to changes in the atmospheric parameters by the assumed errors is illustrated for the star BD +25°2436 (Table 3). It is seen that our estimated parameter

uncertainties do not affect the abundances seriously; the element-to-iron ratios, which we use in our discussion, are even less sensitive. The small differences between the chemical composition of the models and the final abundance results have a negligible effect on the results. The $^{12}\text{C}/^{13}\text{C}$ ratios are not sensitive to the model parameters

Table 3. Effects on derived abundances resulting from model changes for the star BD+25°2436. The table entries show the effects on the logarithmic abundances relative to hydrogen, $\Delta[A/H]$. Note that the effects on “relative” abundances, for example $[A/Fe]$, are often considerably smaller than abundances relative to hydrogen, $[A/H]$.

Ion	ΔT_{eff} −100 K	$\Delta \log g$ −0.3	Δv_t −0.3 km s ^{−1}
C (C ₂)	0.02	−0.03	0.00
N (CN)	−0.10	−0.03	0.00
O I	−0.01	−0.13	0.00
Na I	−0.07	0.01	−0.05
Mg I	−0.04	−0.01	−0.03
Al I	−0.05	0.01	−0.02
Si I	0.01	−0.04	0.03
Ca I	−0.10	0.01	−0.11
Sc I	−0.12	0.00	0.02
Sc II	0.02	−0.13	0.10
Ti I	−0.14	0.01	0.09
Ti II	0.01	−0.12	0.08
V I	−0.16	0.00	0.03
Cr I	−0.11	0.01	−0.09
Mn I	−0.08	−0.01	0.04
Fe I	−0.08	−0.02	0.06
Fe II	0.09	−0.14	0.10
Co I	−0.08	−0.02	−0.02
Ni I	−0.05	−0.03	0.08
Y I	−0.17	−0.01	0.02
Y II	0.00	−0.14	0.13
Zr I	−0.17	0.00	−0.01
Ba II	−0.02	−0.11	0.27
La II	−0.01	−0.13	0.01
Sm II	−0.02	−0.14	0.03
Eu II	0.00	−0.10	−0.01

or errors in the $\log gf$ values since they are determined after fitting the ¹²CN features.

The scatter of the deduced line abundances σ , presented in Table 4, gives an estimate of the uncertainty coming from the random errors in the line parameters (e.g. random errors in equivalent widths, oscillator strengths and possible undetected line blends). The approximate value of these uncertainties amounts in the mean to $\sigma = 0.10$ dex. Other sources of observational errors, such as continuum placement or background subtraction problems are partly included in the equivalent width uncertainties. The nitrogen abundance is less dependent on line measurement uncertainties because, depending on the number of spectra observed, the number of CN lines used for the analysis was ranging from 34 to 162.

Since the abundances of C, N and O are tied together by the molecular equilibria in the stellar atmospheres and the abundances were determined in the sequence O (from [O I]) \Rightarrow C (from C₂) \Rightarrow N (from CN), we have investigated how an error in one of them would

typically affect our abundance determinations of the others. Calculations for BD+25°2436: a change of the oxygen abundance of $\Delta[O/H] = -0.10$ would result in $\Delta[C/H] = -0.04$, $\Delta[N/H] = -0.01$ and thus $\Delta[C/N] = -0.03$; a change in $\Delta[C/H] = -0.10$ would cause $\Delta[N/H] = +0.10$, $\Delta[C/N] = -0.20$ and $\Delta[O/H] = -0.03$; $\Delta[N/H] = -0.10$ has no appreciable effect on either the oxygen or the carbon molecular equilibria (except for CN). Note in particular that the C/N ratios are sensitive to the carbon abundance uncertainties squared.

4. Relative abundances

The abundances relative to hydrogen $[A/H]^1$ and σ (the line-to-line scatter) derived for up to 26 neutral and ionized species for the programme stars are listed in Table 4. The abundances of barium are corrected for non-LTE effects by the subtraction of 0.20 dex (see Sect. 4.5 for discussion).

4.1. Carbon and nitrogen

The carbon abundances obtained in our work were compared with carbon abundances determined for dwarf stars in the galactic disk. Gustafsson et al. (1999), using the forbidden [C I] line, performed an abundance analysis of carbon in a sample of 80 late F and early G type dwarfs. Since carbon abundances obtained using the [C I] 8727 Å line and C₂ molecular lines are usually consistent (cf. Clegg et al. 1981), we expect no systematic shift to be present because of the different abundance indicators used. As is seen from Fig. 4, the ratios of [C/Fe] in our stars lie much below the trend obtained for dwarf stars in the Galactic disk (Gustafsson et al. 1999).

Abundances in the investigated stars suggest that carbon is depleted by about 0.3 dex and nitrogen is enhanced by more than 0.4 dex. These abundance alterations of carbon and nitrogen are larger than those we obtained for the clump stars in the old, solar-metallicity open cluster M 67 (Paper I), but smaller than was found for more metal deficient RHB stars by Gratton et al. (2000a). This brings additional evidence that mixing processes are metallicity dependent. The C/N ratios in the investigated stars are lowered to values in the range 0.7 to 1.2 which is less than predicted by present day stellar evolution calculations. Gratton et al. (2000a) receive even smaller C/N ratios for the two red horizontal branch stars with [Fe/H] about −1.5 dex. The ¹²C/¹³C ratios are lowered and lie between values 3 and 7 which indicate extra-mixing processes to be quite strong. Six more metal-deficient RHB stars investigated by Gratton et al. (2000a) show ¹²C/¹³C ratios from 6 to 12.

The theoretical standard stellar evolution of the surface carbon isotopic ratios and carbon to nitrogen ratios along the giant branch was homogeneously mapped by

¹ In this paper we use the customary spectroscopic notation $[X/Y] \equiv \log_{10}(N_X/N_Y)_{\text{star}} - \log_{10}(N_X/N_Y)_{\odot}$.

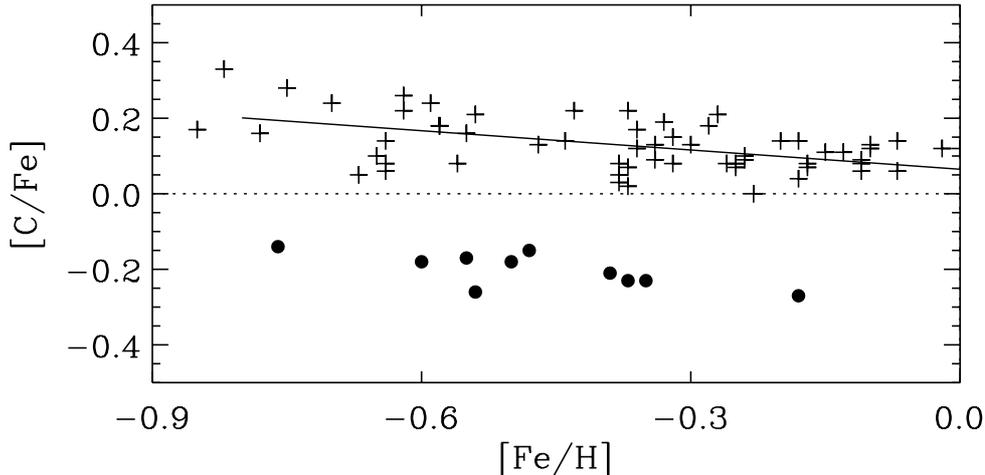


Fig. 4. $[C/Fe]$ as a function of $[Fe/H]$. Results of this paper are indicated by *filled circles*, results obtained for dwarf stars of the galactic disk (Gustafsson et al. 1999) are indicated by “*plus*” signs and the solid line. The relative underabundance in the He-core burning stars is clearly seen.

Charbonnel (1994) and more recently by Girardi et al. (2000) for stellar masses between 1 and $7 M_{\odot}$ and different metallicities. Our investigated field RHB stars are somewhat metal deficient ($Z \approx 0.008$) and have masses approximately 0.8 to $0.9 M_{\odot}$ (Tautvaišienė 1996b). According to Girardi et al. (2000), the C/N and $^{12}C/^{13}C$ ratios in such stars should drop after the first dredge-up episode to values of about 3 and 35, respectively. Charbonnel (1994, extrapolation to $\approx 0.85 M_{\odot}$ in Figs. 2 and 4) predicted similar values after the first dredge-up.

It has long been known that giant stars regularly show much larger evolutionary changes in these abundances than standard models predict, see e.g. Boothroyd & Sackmann (1999) for references. This is the case also for our derived $^{12}C/^{13}C$ and C/N ratios. Because of grave differences between model predictions and observations, Charbonnel (1995), Charbonnel et al. (1998) and Boothroyd & Sackmann (1999) performed calculations of models with deep mixing after the first dredge-up. Boothroyd & Sackmann e.g. fitted a one-parameter recipe for “cool bottom processing” (CBP) after the first dredge-up to the available observations of red-giant abundances. Their CBP results are given for initial stellar masses above $1.0 M_{\odot}$. It is difficult to say what were the initial masses of the stars we investigate. It could be that they lost about $0.1\text{--}0.3 M_{\odot}$ during their evolution on the giant branch (Renzini 1981; Renzini & Fusi Pecci 1988).

The $^{12}C/^{13}C$ ratios determined for the investigated stars are in quite good agreement with “cool bottom processing” predictions (Boothroyd & Sackmann 1999) for low mass stars with $Z = 0.007$. The C/N ratios, however, request the initial mass of the stars to be of about $1.8 M_{\odot}$. The metal-deficient RHB stars investigated by Gratton et al. (2000a) show higher than predicted by CBP $^{12}C/^{13}C$ ratios but even lower C/N ratios. The low C/N ratios may be an indication that CBP is stronger in such stars than the metallicity scaling of models suggest.

However, in view of the sensitivity of C/N ratios to the carbon abundances, we will not claim that the C/N predictions of Sackmann & Boothroyd are wrong, but rather that the C and N abundances should be checked in further studies employing other atomic and molecular features.

4.2. Sodium and aluminium

Sodium and aluminium are among the mixing-sensitive chemical elements. The star-to-star variations of Na, the existence of Na versus N correlations, and Na versus O anticorrelations in globular cluster red giants have revealed the possibility that sodium and aluminium are produced in red giant stars (see Kraft 1994 and Da Costa 1998 for reviews). It is found also that Na variations exist in all clusters, while Al variations are greater in the more metal-poor clusters (cf. Norris & Da Costa 1995; Shetrone 1996, Paper I).

Pilachowski et al. (1996) determined sodium abundances for 60 metal-poor halo subgiants, giants, and horizontal branch stars using high dispersion spectra and concluded that there is an intrinsic difference between halo field giants and globular cluster giants. The bright giants in the field do not show the sodium excesses seen in their globular cluster counterparts. The $[Na/Fe]$ ratios in field stars show a wide scatter (ranging from -0.6 to nearly $+0.3$) with a slight tendency for $\langle [Na/Fe] \rangle$ to increase with advancing evolutionary stage. In a sample of ten field RHB stars investigated by Tautvaišienė (1997) only two of the more metal rich ($[Fe/H] > -0.5$) stars showed sodium overabundances of $0.2\text{--}0.3$ dex.

The stars in our sample show Na and Al abundances which are typical of unevolved stars in the solar vicinity, as determined from the Na I lines $\lambda 5682.64$ and 6154.23 \AA and Al I lines $\lambda 6696.03$, 6698.66 , 7835.31 and 7836.13 \AA , see Fig. 5. Gratton et al. (2000a) investigated possible non-LTE effects for the Na I lines, and find the probable

Table 4. Abundances relative to hydrogen $[A/H]$ derived for programme stars. The quoted errors, σ , are the standard deviations in the mean value due to the line-to-line scatter within the species. Details on error estimates of the $^{12}\text{C}/^{13}\text{C}$ ratios are described in Sect. 3. The number of lines used is indicated by n .

Ion	BD +25°2436			BD +25°2459			BD +25°2502			BD +27°2057		
	$[A/H]$	σ	n									
C (C ₂)	-0.63		1	-0.58		1			1	-0.78		1
N (CN)	-0.01	0.14	154	0.14	0.11	111				-0.27	0.15	102
O I	-0.25		1	-0.24		1	-0.24		1	-0.25		1
Na I	-0.54	0.01	2	-0.28	0.15	2	-0.72	0.02	2	-0.40	0.10	2
Mg I	-0.21	0.04	2	-0.24	0.09	2	-0.32		1	-0.20	0.10	2
Al I	-0.47	0.06	4	-0.34	0.08	4	-0.68	0.05	3	-0.45	0.03	4
Si I	-0.31	0.12	14	-0.18	0.12	13	-0.48	0.10	6	-0.24	0.11	14
Ca I	-0.36	0.12	7	-0.23	0.12	8	-0.53	0.14	4	-0.39	0.15	7
Sc I	-0.40	0.10	4	-0.31	0.11	4	-0.39		1	-0.56	0.15	4
Sc II	-0.33	0.11	10	-0.20	0.08	11	-0.43	0.16	6	-0.46	0.11	10
Ti I	-0.29	0.12	23	-0.11	0.15	21	-0.57	0.16	6	-0.32	0.13	23
Ti II	-0.26		1	-0.05		1				-0.33		1
V I	-0.40	0.10	17	-0.22	0.12	18	-0.70	0.10	6	-0.50	0.15	18
Cr I	-0.38	0.04	7	-0.23	0.13	7				-0.55	0.09	7
Mn I	-0.46	0.08	3	-0.31	0.09	3				-0.70	0.08	2
Fe I	-0.48	0.12	43	-0.35	0.10	42	-0.74	0.06	18	-0.60	0.12	40
Fe II	-0.48	0.10	5	-0.35	0.13	5	-0.74	0.11	2	-0.60	0.12	5
Co I	-0.41	0.13	10	-0.30	0.14	9	-0.58	0.04	2	-0.47	0.14	8
Ni I	-0.42	0.14	22	-0.24	0.13	20	-0.80	0.09	8	-0.56	0.15	21
Y I	-0.37		1	-0.28		1				-0.53		1
Y II	-0.44	0.03	3	-0.29	0.06	3				-0.46	0.11	2
Zr I	-0.50	0.11	3	-0.32	0.13	4	-0.41	0.06	3	-0.67	0.13	4
Ba II	-0.70	0.07	2	-0.34	0.04	2	-0.69	0.05	2	-0.82	0.03	2
La II	-0.62		1	-0.38		1				-0.68		1
Sm II	-0.53		1	-0.05		1				-0.36		1
Eu II	-0.05		1	-0.05		1				-0.15		1
C/N	0.96			0.76						1.23		
$^{12}\text{C}/^{13}\text{C}$	5	+5/-2		7	+3/-2					5	+2/-2	

corrections not to be larger than about 0.02 dex at the temperatures and gravities of the stars analysed here.

Theoretical explanations for the production of Na and Al have been proposed by Sweigart & Mengel (1979), Langer & Hoffman (1995), Cavallo et al. (1996), Mowlavi (1999), Weiss et al. (2000) and other studies. The nature and extent of the phenomenon is, however, still not well understood.

Prochaska et al. (2000) investigated abundances of Na and Al in 10 thick disk dwarfs and found aluminium to be much more overabundant than sodium. Our sample of thick disk stars does not show such a pattern.

4.3. Oxygen and magnesium

Surface abundances of oxygen and magnesium could be altered in stars only by very deep mixing. E.g., in cluster giants with large aluminium enhancements (~ 1.0 dex) produced by very deep mixing, Mg depletions should then be about ~ 0.2 dex (Langer & Hoffman 1995). Since this is not the case for the investigated stars we will discuss

our results for oxygen and magnesium in the context of the thick disk of the Galaxy.

In Figs. 6 and 7, we plot oxygen and magnesium abundance ratios and compare them with the modeled ratios describing the mean trend of the Galactic thin disk (Pagel & Tautvaišienė 1995). Other results obtained for the thick disk stars in recent studies are displayed as well. Prochaska et al. (2000) analysed a sample of 10 thick disk stars with the HIRES spectrograph on the 10 m Keck I telescope. Unfortunately, the forbidden [O I] $\lambda 6300$ Å line fell in the inter-order gap and the less trustworthy O I triplet lines at 7775 Å had to be used in their analysis. We adopt for the figures the results for 4 thick disk stars from the work by Gratton et al. (2000b). In the same paper a sample of thick disk candidates was selected from the work by Edvardsson et al. (1993). Stars which have $[\text{O}/\text{H}] > -0.5$, $[\text{Fe}/\text{O}] < -0.25$ and $-0.5 < [\text{Mg}/\text{H}] < 0$, $[\text{Fe}/\text{Mg}] < -0.25$ and appropriate dynamical parameters were attributed to the thick disk. While plotted, the data make quite a cloud lying above the semiempirical trends modeled for the thin disk of the Galaxy by Pagel & Tautvaišienė (1995), but this can hardly be used to draw any conclusions about the

Table 4. continued.

Ion	BD +28°2079			BD +29°2231			BD +29°2294			BD +29°2321		
	[A/H]	σ	n									
C (C ₂)				−0.60		1	−0.80		1	−0.68		1
N (CN)				0.15	0.12	162	−0.10	0.14	34	0.00	0.13	93
O I	−0.10		1	−0.22		1	−0.31		1			
Na I	−0.51		1	−0.34	0.09	2	−0.28		1	−0.35		1
Mg I	−0.21		1	−0.18	0.02	2	−0.14		1	−0.26		1
Al I	−0.22	0.03	2	−0.32	0.08	4	−0.46	0.06	2	−0.29	0.12	2
Si I	−0.20	0.12	6	−0.20	0.07	14	−0.30	0.08	8	−0.27	0.08	8
Ca I	−0.22	0.13	5	−0.29	0.17	8	−0.39	0.11	5	−0.41	0.14	7
Sc I				−0.26	0.10	4	−0.48	0.07	3	−0.50	0.15	3
Sc II	−0.19	0.07	8	−0.23	0.09	10	−0.32	0.10	9	−0.33	0.08	8
Ti I	−0.12	0.17	16	−0.18	0.12	22	−0.27	0.13	19	−0.43	0.14	20
Ti II	−0.14		1	−0.30		1	−0.25		1	−0.42		1
V I	−0.17	0.16	12	−0.18	0.12	17	−0.43	0.14	12	−0.49	0.13	14
Cr I	−0.27	0.13	7	−0.39	0.15	8	−0.51	0.13	7	−0.51	0.15	7
Mn I	−0.32	0.12	2	−0.32	0.16	3	−0.70	0.05	2	−0.57	0.08	3
Fe I	−0.44	0.06	25	−0.39	0.12	43	−0.54	0.10	24	−0.50	0.08	27
Fe II	−0.44	0.12	3	−0.39	0.07	5	−0.54	0.12	3	−0.50	0.08	3
Co I	−0.35	0.17	4	−0.28	0.16	9	−0.37	0.12	6	−0.41	0.08	7
Ni I	−0.38	0.10	15	−0.33	0.15	22	−0.45	0.11	21	−0.50	0.12	21
Y I				−0.41		1	−0.53		1	−0.57		1
Y II	−0.43	0.14	2	−0.45	0.11	4	−0.64	0.01	2	−0.56	0.13	4
Zr I	−0.42	0.04	2	−0.29	0.02	3	−0.42	0.15	4	−0.53	0.17	3
Ba II	−0.36	0.03	2	−0.54	0.01	2	−0.67		1	−0.60		1
La II				−0.47		1						
Sm II	−0.06		1	−0.20		1				−0.25		1
Eu II				−0.05		1	−0.28		1	−0.22		1
C/N				0.71			0.79			0.83		
¹² C/ ¹³ C				3.5	+3/−1.5		3	+2/−1		4	+4/−1	

location in terms of metallicity of the transition between the halo and thick disk populations. The high accuracy results for magnesium determined by Fuhrmann (1998) lie at the edge of the distribution. This may be taken as an indication that the transition between the halo phase and the thick disk phase took place around $[\text{Fe}/\text{H}] \approx -0.6$ to -0.5 . Our oxygen and magnesium to iron ratios tend to indicate the onset of supernova of Type Ia (SN Ia) at about $[\text{Fe}/\text{H}] = -0.7$ to -0.6 . We suggest that a model for the halo and thick disk may look much like the model of Pagel & Tautvaišienė (1995), with the difference that the halo phase continued all the way up to $[\text{Fe}/\text{H}] \approx -0.6$ dex.

4.4. Silicon, calcium and titanium

The α -elements silicon, calcium and titanium may also bring information on the thick disk of the Galaxy. A large number of spectral lines with accurate gf -values are available for the analysis which should provide for good abundance precision. Being produced both in Type II and Ia supernova, Si, Ti and Ca may be expected to show smaller overabundances than O and Mg. As is seen from

Fig. 8, abundance ratios of these elements to iron may also exhibit slight overabundances with respect to the mean trend of the thin disk.

4.5. *s*- and *r*-process elements

As already mentioned, the barium abundances in our study are corrected for non-LTE effects by the subtraction of 0.20 dex. Two quite similar Ba II lines $\lambda 6141$ and 6496 \AA were used for the analysis. According to Mashonkina et al. (1999) and Mashonkina & Gehren (2000), the non-LTE correction for the Ba II line $\lambda 6496$ is -0.2 dex on average in the metallicity range $-1 < [\text{Fe}/\text{H}] < 0.1$. Non-LTE effects for the line $\lambda 6141$ were not studied well enough, since this line is too saturated in the solar spectrum to provide an accurate correction. Theoretical non-LTE calculations show that non-LTE effects for this line are not smaller than for $\lambda 6496$, only the weak line $\lambda 5853 \text{ \AA}$ is quite insensitive. In our study, both $\lambda 6141$ and 6496 \AA gave approximately the same barium abundances, so we decided to apply the same correction to both. In the work by Prochaska et al. (2000) three Ba II lines $\lambda 5853$, 6141

Table 4. continued.

Ion	BD +33°2280			BD +34°2371			BD +36°2303			HD 104783		
	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n
C (C ₂)				−0.45		1	−0.90		1	−0.72		1
N (CN)				0.13	0.13	38	−0.34	0.12	92	−0.05	0.14	109
O I	−0.29		1	−0.13		1				−0.14		1
Na I	−0.33	0.02	2	0.02		1	−0.72		1	−0.56	0.11	2
Mg I	−0.28		1	−0.05		1	−0.36		1	−0.23	0.06	2
Al I	−0.41	0.04	4	−0.10	0.07	2	−0.55	0.05	2	−0.54	0.04	4
Si I	−0.29	0.09	7	−0.06	0.06	7	−0.37	0.12	8	−0.24	0.08	15
Ca I	−0.47	0.19	3	−0.07	0.15	7	−0.55	0.13	7	−0.34	0.13	7
Sc I	−0.34		1	−0.10		1	−0.76	0.03	2	−0.56	0.09	2
Sc II	−0.33	0.07	6	−0.06	0.11	9	−0.48	0.12	9	−0.41	0.09	11
Ti I	−0.39	0.08	6	−0.03	0.13	17	−0.51	0.11	20	−0.23	0.14	24
Ti II				0.07		1	−0.48		1	−0.19		1
V I	−0.44	0.08	6	−0.18	0.09	15	−0.70	0.14	15	−0.44	0.11	16
Cr I	−0.36	0.12	2	−0.22	0.10	6	−0.87	0.13	6	−0.52	0.10	7
Mn I				−0.21	0.18	2	−0.89	0.04	2	−0.63	0.04	2
Fe I	−0.48	0.05	24	−0.18	0.08	29	−0.76	0.08	27	−0.55	0.12	39
Fe II	−0.48	0.07	2	−0.18	0.08	3	−0.76	0.08	3	−0.55	0.10	5
Co I	−0.41	0.16	3	−0.16	0.09	7	−0.67	0.12	7	−0.44	0.12	7
Ni I	−0.42	0.15	9	−0.16	0.09	20	−0.72	0.12	20	−0.48	0.13	22
Y I				−0.24		1				−0.47		1
Y II				−0.13	0.11	3	−0.71	0.09	3	−0.48	0.05	2
Zr I	−0.55	0.07	3	−0.22	0.09	4	−0.70	0.09	3	−0.32	0.06	3
Ba II	−0.47	0.08	2	−0.14	0.09	2	−0.70		1	−0.43	0.09	2
La II	−0.42		1							−0.48		1
Sm II				−0.01		1	−0.55		1	−0.41		1
Eu II				0.00		1	−0.20		1	−0.15		1
C/N				1.05			1.10			0.85		
¹² C/ ¹³ C				>5			3	+2/−1		>5		

and 6496 were used, and a typical correction of 0.17 dex was applied.

Abundance ratios of *s*- and *r*-process-dominated (in the Solar system, Burris et al. 2000) elements to iron as a function of iron [Fe/H] for the thick disk stars analysed in the recent studies are presented in Fig. 9. For a comparison, the modeled abundance trends of the Galactic thin disk by Pagel & Tautvaišienė (1997) are shown. As is the case for oxygen and the α elements, these elements fit the models for the thin disk reasonably well if we shift the onset of SN Ia from [Fe/H] = −1.1 to −0.6 dex. Since europium is an almost pure *r*-process element and supposedly produced with oxygen and magnesium in stars exploding as core-collapse supernovae, the thick-disk Eu abundance trend differ quite dramatically from the thin-disk one and may be very useful for population studies. [Eu/Fe] ratios obtained in our sample of thick disk stars and in ten more stars analysed by Prochaska et al. (2000) and Mashonkina & Gehren (2000) bring quite a

clear indication that the thick disk population is chemically discrete from the thin disk.

5. Summary and conclusions

More than ten years have passed since the high-resolution spectroscopic study by Barbuy & Erdelyi-Mendes (1989), in which a spread in [O/Fe] ratios at $-0.8 < [\text{Fe}/\text{H}] < -0.5$ was proposed to be an indication of a thick disk phase in the chemico-dynamic evolution of the Galaxy. However, further studies by observers and theoreticians did not bring accurate enough characterization of the thick disk of the Galaxy (cf. Pagel 2001; Bernkopf et al. 2001; Nissen 1999; Chiappini et al. 1997; Robin et al. 1996). The thick disk still needs to be revisited by new observations.

We have presented a detailed chemical abundance analysis of 13 core helium-burning low-mass stars, representatives of the thick disk of the Galaxy. Abundances

Table 4. continued.

Ion	HD 105944		
	[A/H]	σ	n
C (C ₂)	-0.60		1
N (CN)	0.07	0.13	77
O I	-0.29		1
Na I	-0.24		1
Mg I	-0.17		1
Al I	-0.34	0.02	2
Si I	-0.31	0.11	8
Ca I	-0.19	0.12	6
Sc I	-0.27	0.04	2
Sc II	-0.28	0.11	9
Ti I	-0.28	0.14	19
Ti II	-0.15		1
V I	-0.36	0.11	14
Cr I	-0.41	0.14	7
Mn I	-0.40	0.12	2
Fe I	-0.37	0.08	30
Fe II	-0.37	0.06	3
Co I	-0.38	0.11	8
Ni I	-0.37	0.14	20
Y I			
Y II	-0.54	0.06	3
Zr I	-0.29	0.10	2
Ba II	-0.20	0.03	2
La II			
Sm II	-0.17		1
Eu II	-0.16		1
C/N	0.85		
¹² C/ ¹³ C	3.5	+4/-2	

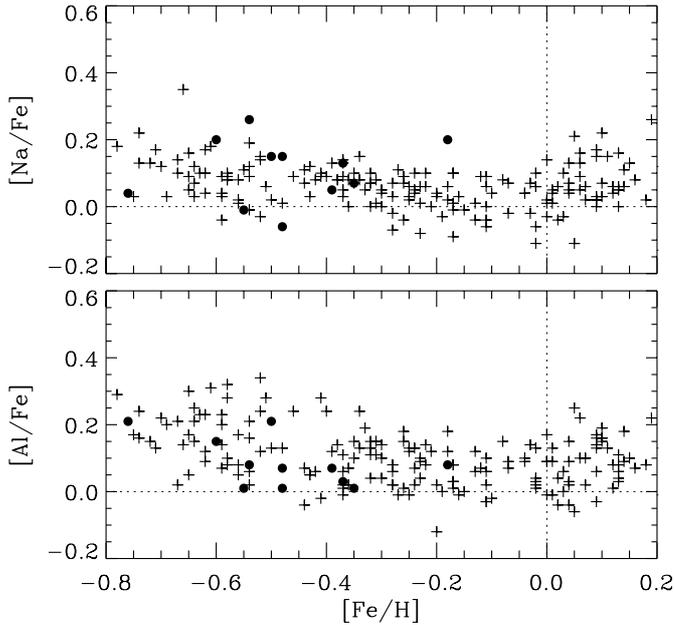


Fig. 5. [Na/Fe] and [Al/Fe] ratios as a function of iron [Fe/H]. Results for the field RHB stars investigated in the present work are indicated by *filled circles*, for the Galactic disk stars investigated by Edvardsson et al. (1993) by *crosses*.

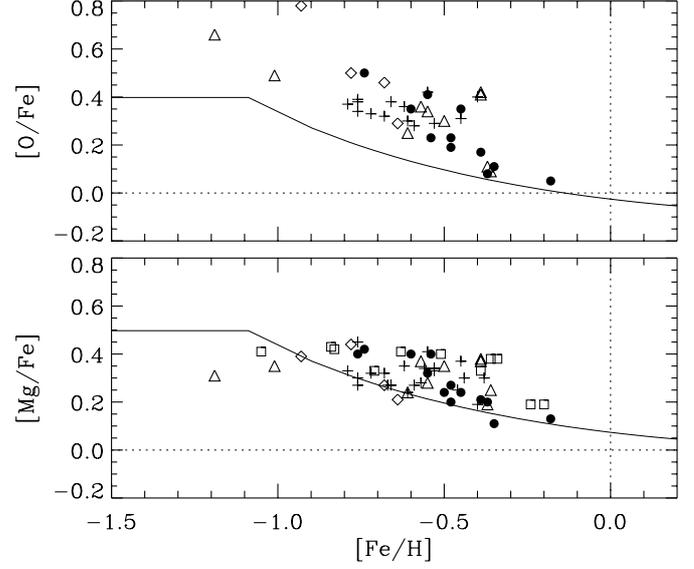


Fig. 6. [O/Fe] and [Mg/Fe] ratios as a function of iron [Fe/H] for the thick disk stars analysed in recent studies: *filled circles* – the present work; *triangles* – Prochaska et al. (2000); *rhombs* – Gratton et al. (2000b); *crosses* – Edvardsson’s et al. (1993) dwarfs with $R_m \leq 7$ kpc, reanalysed and selected to be the thick disk stars by Gratton et al. 2000b; *squares* – Fuhrmann (1998). The solid lines show the model of the Galactic thin disk (Pagel & Tautvaišienė 1995).

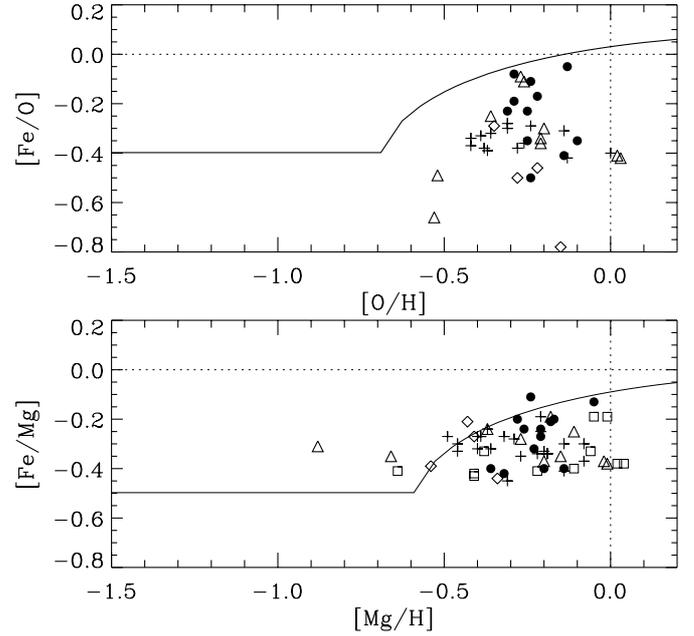


Fig. 7. Run of [Fe/O] vs. [O/H] and [Fe/Mg] vs. [Mg/H] ratios for the stars of Fig. 6.

in the investigated stars show that carbon is depleted by about 0.3 dex, nitrogen is enhanced by more than 0.4 dex, the ¹²C/¹³C ratios are lowered to values from 3 to 7 and C/N ratios to values from 0.7 to 1.2. These abundance ratios can only be accounted for by stellar evolution calculations if extra mixing, e.g. “cool bottom processing”

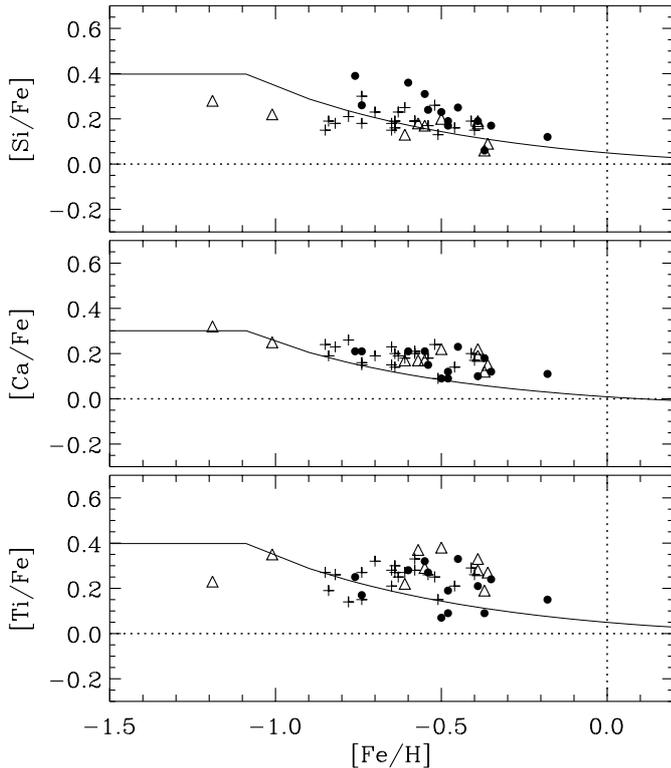


Fig. 8. [Si/Fe], [Ca/Fe] and [Ti/Fe] ratios as a function of iron [Fe/H] for the thick disk stars analysed in recent studies. The meaning of symbols as in Fig. 6.

(Boothroyd & Sackmann 1999), after the first dredge-up episode is prescribed.

In agreement with other studies of field core-helium-burning stars, our stars do not show enhanced overabundances of Na and Al.

Abundance ratios of O, Mg, Eu and other heavy elements to iron in the investigated stars provide further evidence that the thick disk population had a different chemical history as compared to the thin disk (cf. Fuhrmann 1998; Gratton et al. 2000b; Prochaska et al. 2000). We propose that the time-scale for metal enrichment was short for the thick disk population, and that SN Ia started to contribute with iron-peak nuclei only after the overall metallicity reached $[\text{Fe}/\text{H}] \approx -0.7$ or -0.6 dex.

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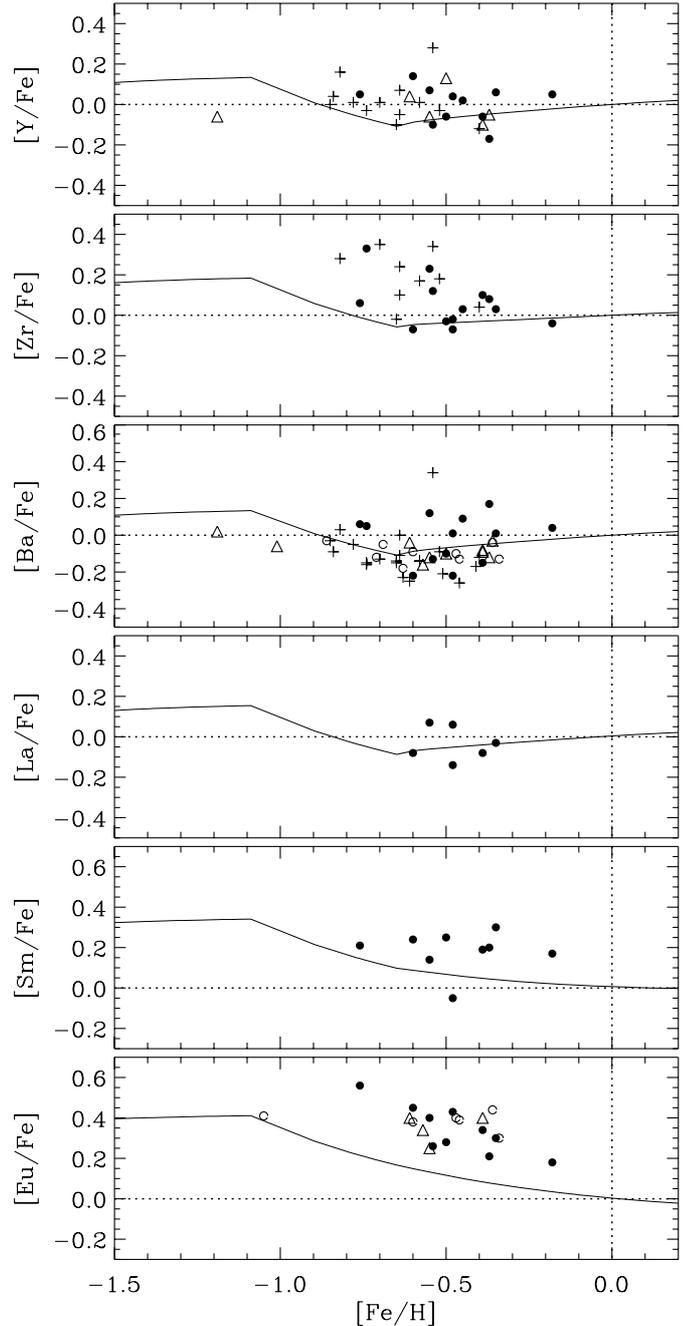


Fig. 9. Abundance ratios of the *s*-process dominated (Y, Zr, Ba and La) and *r*-process dominated (Sm and Eu) elements to iron as a function of iron [Fe/H] for the thick disk stars analysed in recent studies. The meaning of symbols as in Fig. 6, *open circles* represent results by Mashonkina & Gehren (2000). The solid line shows the model of the Galactic thin disk (Pagel & Tautvaišienė 1997).

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