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Chemical composition of evolved stars in the open cluster M 67⋆,⋆⋆

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Abstract. High-resolution spectra of six core helium-burning 'clump' stars and three giants in the open cluster M 67 have been obtained with the SOFIN spectrograph on the Nordic Optical Telescope to investigate abundances of up to 25 chemical elements. Abundances of carbon were studied using the C_2 Swan (0,1) band head at 5635.5 Å. The wavelength interval 7980–8130 Å with strong CN features was analysed in order to determine nitrogen abundances and $^{12}C/^{13}C$ isotope ratios. The oxygen abundances were determined from the [O I] line at 6300 Å.

The overall metallicity of the cluster stars was found to be close to solar ([Fe/H]=-0.03 ± 0.03). Compared with the Sun and other dwarf stars of the Galactic disk, as well as with dwarf stars of M 67 itself, abundances in the investigated stars suggest that carbon is depleted by about 0.2 dex, nitrogen is enhanced by about 0.2 dex and oxygen is unaltered. Among other mixing-sensitive chemical elements an overabundance of sodium may be suspected. The mean C/N and $^{12}C/^{13}C$ ratios are lowered to the values of 1.7 ± 0.2 and 24 ± 4 in the giants and to the values of 1.4 ± 0.2 and 16 ± 4 in the clump stars. These results suggest that extra mixing of CN-cycled material to the stellar surface takes place after the He-core flash. Abundances of heavy chemical elements in all nine stars were found to be almost identical and close to solar.

Key words: stars: abundances – stars: atmospheres – stars: horizontal-branch – Galaxy: open clusters and associations: individual: M 67

1. Introduction

The old open cluster M 67 has served as an important sample in the understanding of stellar evolution over almost fifty years. Since the first papers by Becker & Stock (1952), Popper (1954), Johnson & Sandage (1955) work has continued and more than 200 studies were achieved (see, e.g., Burstein et al. 1986, Carraro et al. 1996 and references therein). The advantage that cluster members have to be coeval and identical except for mass and evolutionary state, which can be identified unambiguously, may most efficiently serve for the analysis of changes in mixing-sensitive abundances.

Abundances of carbon and nitrogen are particularly sensitive tests for stellar evolution. The enhancement of CN bands was reported for the M 67 clump stars F84, F141 and F151 already by Pagel (1974). From high-resolution spectra, C and N abundances have been investigated in three giants (Brown 1985) and from moderate-resolution spectra in 19 giants (Brown 1987). Carbon isotope ratios along the giant branch were investigated by Gilroy (1989) and Gilroy & Brown (1991). It was found that C/N and $^{12}C/^{13}C$ ratios in the clump giants and the stars at the tip of the giant branch all have values much lower than predicted in standard models. Charbonnel et al. (1998), however, suggest that the absolute values of C/N ratios obtained by Brown (1987) may have a systematic offset and have to be taken with caution.

High-resolution analyses are very scarce for the oxygen abundances: Griffin (1975) has measured the [O I] line at 6300 Å in one star, but this star (IV-202) is quite cool and the result is uncertain; Cohen (1980) has analysed four stars, but the weaker line of [O I] at 6363 Å was used. In the paper by Cohen (1980), a low value of [Fe/H]= -0.39 for M 67 has been received. This is the same paper that gave a low [Fe/H] value for the globular cluster M 71, which was later increased by +0.5 dex in Cohen (1983). The same correction, if applied to M 67, would yield the [Fe/H] near solar, consistent with more recent determinations (e.g. Nissen et al. 1987, Garcia Lopez et al. 1988, Hobbs & Thorburn 1991, Friel & Boesgaard 1992). In the same paper by Cohen (1980), which is based on photographic data as well as all M 67 abundance works before Brown (1985), abundances of some other elements in M 67 look very extraordinary. The ratios of [Mg/Fe] reach –0.8 dex while the ratios of other α-process element [Si/Fe] are enhanced by about +0.6 dex, [Ba/Fe] are approximately equal to –0.4 dex while for the very similar element lanthanum [La/Fe]≈+0.6 dex.

In this paper, we report a detailed analysis of six core helium-burning clump stars and three giants in M 67 (see Fig. 1 for their location in the HR diagram). The core He-burning stars are the most evolved stars in M 67, their surface abundances reflect

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

⋆⋆ Tables 2 and 3 are only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html

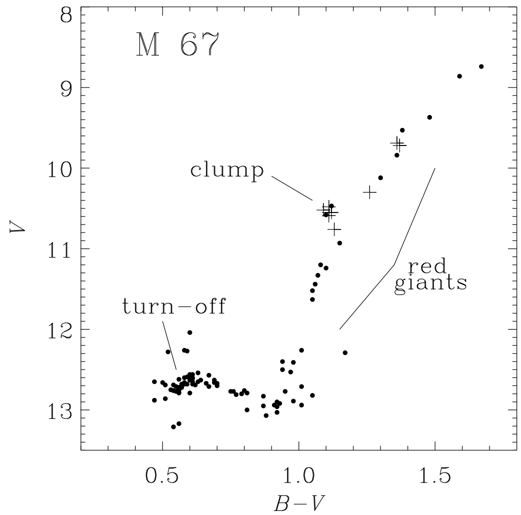

Fig. 1. The colour-magnitude diagram of the open cluster M 67. The red giants and the core He-burning 'clump' stars analysed are indicated by the crosses. The diagram is taken from Mathieu et al. (1986) and cleaned from evident binary stars

effects of the preceding evolution along the red giant branch as well as effects raised by the helium flash. The study aims at a very high internal precision of the abundances, so that even small anomalies in the chemical composition can be revealed.

2. Observations and data reductions

The spectra were obtained at the Nordic Optical Telescope (NOT) with the SOFIN échelle spectrograph (Tuominen 1992) in February of 1995. The 3rd optical camera was used with an entrance slit width of 197 μm, providing a spectral resolving power of $R1 \approx 30\,000$. Three stars (F84, F141 and F151) were also observed with the 2nd optical camera, providing a spectral resolving power of $R2 \approx 60\,000$ (the entrance slit width 68 μm). 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 3rd camera the CCD size covered simultaneously 25 spectral orders, each of 80–150 Å in length, located in the interval of 4500–8750 Å. The 2nd camera gave 15 spectral orders, each of 40–60 Å, in the spectral region from 5650 to 8750 Å. For the F84 and F141 two partly overlapping spectral regions were observed by setting of the échelle and cross-dispersion prism angles in order to extend the wavelength intervals of orders. The concrete numbers of spectrograms received for every star are presented in Table 1. All spectra were exposed to S/N$\geq$ 100.

Reductions of the CCD images were made with the *3A* software package (Ilyin 1996). 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.

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. 179 atomic lines were selected for the analysis in spectra of the 3rd camera and 132 in spectra obtained on the 2nd camera. The line measurements are listed in Tables 2 and 3 (available in electronic form at CDS).

3. Method of analysis and physical data

The spectra were analysed using a differential model atmosphere technique. The *Eqwidth* and *Synthetic Spectrum* program packages, developed at the Uppsala Astronomical Observatory, were used to carry out the calculations of theoretical equivalent widths of lines and synthetic spectra. A set of plane parallel, line-blanketed, flux constant LTE model atmospheres was computed with an updated version of the *MARCS* code of Gustafsson et al. (1975) using continuous opacities from Asplund et al. (1997) and including UV line blanketing as described by Edvardsson et al. (1993). Convection was treated in the mixing-length approximation ($l/H_p = 1.5$).

The Vienna Atomic Line Data Base (VALD, Piskunov et al. 1995) was extensively used while preparing the input data for the calculations. Atomic oscillator strengths for this study were taken mainly from two sources: the first being an inverse solar spectrum analysis done in Kiev (Gurtovenko & Kostik 1989, Gurtovenko et al. 1983, 1985a, 1986), the second being high-precision laboratory measurements done in Oxford (Blackwell et al. 1982, 1983, 1986). The coincidence of these two sets of gf values is very good, and the errors in the least-squares fit do not exceed $\pm\, 0.07$ dex (Gurtovenko et al. 1985b). For Ca I the gf values have been also taken from Smith & Raggett (1981) and for Zr I from Bogdanovich et al. (1996).

Using the gf values and solar equivalent widths of analysed lines from the cited sources we have obtained the solar abundances, later used for the differential determination of abundances in the programme stars. We used the solar model atmosphere from the set calculated in Uppsala (Edvardsson et al. 1993) with a microturbulent velocity of 0.8 $\mathrm{km\ s^{-1}}$, as derived from Fe I lines.

Abundances of carbon, nitrogen and europium were determined using the spectrum synthesis technique. The interval of 5632–5636 Å was synthesized and compared with observations in the vicinity of the $\mathrm{C_2}$ Swan 0–1 band head at 5635.5 Å. The same atomic data of $\mathrm{C_2}$ as used by Gonzalez et al. (1998) were adopted for the analysis. The interval of 7980–8130 Å, containing strong CN features, was analysed in order to determine the nitrogen abundance and $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratios. The molecular data for $^{12}\mathrm{C}^{14}\mathrm{N}$ and $^{13}\mathrm{C}^{14}\mathrm{N}$ 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

Table 1. Atmospheric parameters derived for the programme stars. The last two columns give the resolving powers and number of spectra observed

Star	$T_{\rm eff}$ (K)	log g	[Fe/H]	$v_{\rm t}$ (km s^{-1})	R*	N
F84	4750	2.4	–0.02	1.8	$R1$	3
	4750	2.4	–0.05	1.6	$R2$	3
F105	4450	2.2	–0.05	1.9	$R1$	2
F108	4250	1.7	–0.02	1.8	$R1$	3
F141	4730	2.4	–0.01	1.8	$R1$	2
	4730	2.4	0.01	1.6	$R2$	4
F151	4760	2.4	0.01	1.7	$R1$	2
	4760	2.4	–0.03	1.6	$R2$	1
F164	4700	2.5	0.00	1.8	$R1$	2
F170	4280	1.7	–0.02	1.8	$R1$	3
F224	4710	2.4	–0.11	1.6	$R1$	3
F266	4730	2.4	–0.02	1.7	$R1$	3

* Resolving powers $R1 \approx 30\,000$ and $R2 \approx 60\,000$. See Sect. 3 for more explanations

al. (1984). Parameters of other lines in the intervals of spectral synthesis were compiled from the VALD database. 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.

An interval of 6643–6648 Å, containing the Eu II line at 6645 Å, was analysed in order to determine the europium abundance. 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$A({\rm Eu})_\odot$=0.49, was determined using the same procedure as for other heavy chemical elements. 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.

In addition to thermal and microturbulent Doppler broadening of lines, atomic line broadening by radiation damping and van der Waals damping were considered in the calculation of abundances. Radiation damping parameters for the most of lines were taken from the VALD database. When they were not available at the VALD database, published oscillator strengths of strong lines were used for determination of life times and thus radiation damping for relevant energy levels. Correction factors to the classical van der Waals damping widths (Γ_6) were taken from the literature: Na I: Holweger (1971), Ca I: O'Neill & Smith (1980), Ba II: Holweger & Müller (1974), Fe I: Simmons & Blackwell (1982). For all other species a correction factor of 2.5 was applied to the classical Γ_6 (ΔlogC_6=+1.0), following Mäckle et al. (1975). For lines stronger than W=100 mÅ, the correction factors were selected individually by the inspection of the solar spectrum.

4. Atmospheric parameters and abundances

The effective temperatures were derived and averaged from the intrinsic colour indices $(B–V)_0$ and $(V–K)_0$ using the corresponding calibrations by Gratton et al. (1996). Colour indices have been taken from Houdashelt et al. (1992) and dereddened using E_{B-V}=0.032 according to Nissen et al. (1987) and E_{B-V}/E_{V-K}=3.24 according to Taylor & Joner (1988). For F266 the *B–V* index was taken from Coleman (1982) and *V–K* from Taylor & Joner (1988). The agreement between the temperatures deduced from the two colour indices is quite good, the differences do not exceed 20 K. The gravities were found by forcing Fe I and Fe II to yield the same iron abundances. 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 1.

The abundances relative to hydrogen [A/H][1] and σ (the line-to-line scatter) derived for up to 28 neutral and ionized species for the programme stars are listed in Tables 4 and 5.

4.1. Estimation of uncertainties

The sources of uncertainties can be divided into two categories. The first category includes the errors which act on a single line (e.g. random errors in equivalent widths, oscillator strengths), i.e. uncertainties of the line parameters. 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.). The scatter of the deduced line abundances σ, presented in Table 4 and 5, gives an estimate of the uncertainty coming from the random errors in the line parameters. The mean values of σ=0.08 and σ=0.13 are for abundances derived from spectra with $R2$ and $R1$, accordingly. Thus the uncertainties on the derived abundances, which are the result of random errors, amount to approximately these values. There is a small systematic difference between the equivalent widths measured with the two cameras, however the abundance effect is small. Typically 0.03 dex higher abundances are obtained from the lower resolution spectra.

Typical internal error estimates for the atmospheric parameters are: $\pm$ 100 K for $T_{\rm eff}$, $\pm$0.3 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 for the star F141 (Table 6). It is seen that possible parameter errors do not affect the abundances seriously; the element-to-iron ratios, which we use in our discussion, are even less sensitive.

Since abundances of C, N and O are bound together by the molecular equilibrium in the stellar atmosphere, we have investigated also how an error in one of them effect the abundance determination of an other. The $\Delta[{\rm O/H}] = -0.10$ causes $\Delta[{\rm C/H}] = -0.04$ and $\Delta[{\rm N/H}] = 0.10$, the $\Delta[{\rm C/H}] = -0.10$ causes $\Delta[{\rm N/H}] = 0.14$ and $\Delta[{\rm O/H}] = -0.03$. The $\Delta[{\rm N/H}] = -0.10$ has no effect on either the carbon nor the oxygen abundances.

Other sources of observational errors, such as continuum placement or background subtraction problems are partly included in the equivalent width uncertainties discussed at the beginning of this section.

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

Table 4. Abundances relative to hydrogen [A/H] derived from spectra of $R \approx 30\,000$. The quoted errors, σ, are the standard deviations in the mean value due to the line-to-line scatter within the species. The number of lines used is indicated by n.

	F84 (clump)			F105 (giant)			F108 (giant)			F141 (clump)			F151 (clump)		
Ion	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n
C I	–0.22		1	–0.13		1	–0.23		1	–0.18		1	–0.19		1
N I	0.32	0.06	65	0.18	0.03	65	0.20	0.03	65	0.30	0.03	65	0.29	0.03	65
O I	0.03		1	0.09		1	0.00		1	0.03		1	–0.05		1
Na I	0.17		1	0.00		1	0.15		1	0.24		1	0.22		1
Mg I	0.06		1	0.02		1	0.03		1	0.10		1			
Al I	0.08	0.01	2	–0.01	0.07	3	0.16	0.05	2	0.07	0.01	2	0.15	0.06	2
Si I	0.13	0.08	10	0.09	0.08	9	0.03	0.10	9	0.10	0.10	7	0.06	0.06	7
Ca I	0.04	0.16	7	–0.08	0.19	7	0.09	0.18	8	0.08	0.12	7	0.07	0.17	8
Sc I	–0.06	0.11	3	–0.12	0.18	3	–0.12	0.06	2	–0.09	0.22	3	0.03	0.23	3
Sc II	0.10	0.20	9	0.10	0.21	8	0.05	0.20	8	0.08	0.15	9	0.11	0.17	9
Ti I	0.02	0.17	21	–0.07	0.19	22	0.20	0.22	22	–0.04	0.17	20	0.03	0.20	22
Ti II	0.12	0.13	5	0.08	0.24	5	0.10	0.23	5	0.07	0.15	4	0.10	0.16	5
V I	0.12	0.14	17	0.10	0.18	17	0.40	0.14	14	0.08	0.12	17	0.07	0.18	16
Cr I	0.08	0.11	8	0.07	0.22	10	0.22	0.17	10	0.11	0.17	10	0.04	0.20	9
Mn I	–0.10	0.12	2	0.02	0.24	3	–0.06	0.02	2	0.07	0.24	3	0.05	0.23	3
Fe I	–0.02	0.11	29	–0.05	0.12	31	–0.02	0.12	30	–0.01	0.11	31	0.01	0.12	32
Fe II	–0.02	0.04	6	–0.05	0.16	6	–0.02	0.14	6	–0.01	0.12	6	0.01	0.08	6
Co I	0.03	0.14	8	0.11	0.17	8	0.15	0.16	8	0.04	0.19	8	0.09	0.15	8
Ni I	0.05	0.15	22	0.05	0.15	22	0.02	0.17	22	0.04	0.15	22	0.05	0.14	21
Cu I	0.13	0.06	3	0.12	0.03	3	0.18	0.05	2	0.07	0.15	3	0.12	0.12	3
Y II	0.00	0.22	4	0.07	0.25	4	0.11	0.18	3	–0.13	0.15	4	–0.11	0.08	4
Zr I	–0.18	0.11	3	–0.35	0.09	3	–0.13	0.11	3	–0.19	0.19	3	–0.18	0.21	3
Ba II	0.06		1	–0.09		1	0.18		1	0.06		1	0.14		1
La II	0.12	0.04	2	0.20	0.01	2	0.17		1	–0.07		1	0.06	0.13	2
Ce II	0.09	0.02	2	0.06	0.16	3	0.04	0.15	3	0.10	0.09	2	0.10	0.12	2
Sm II	0.05		1	–0.04		1				0.14		1	0.04		1
Eu II	0.10		1	0.20		1	0.00		1	0.10		1	0.10		1
C/N	1.15			1.95			1.50			1.32			1.32		
^{12}C/^{13}C	20	6		20			21	3		16	3		17	3	

5. Relative abundances

The mean abundance of iron, [Fe/H]=-0.03 ± 0.03, is in close agreement with other spectroscopic and photometric determinations: [Fe/H]=-0.05 (Canterna et al. 1986), [Fe/H]=0.06 (Nissen et al. 1987), [Fe/H]=-0.07 (Anthony-Twarog 1987), [Fe/H]=0.04 (Garcia Lopez et al. 1988), [Fe/H]=-0.08 (Friel & Janes 1991), [Fe/H]=0.02 (Friel & Boesgaard 1992), [Fe/H]=-0.09 (Friel & Janes 1993). Along with iron, the abundances of other heavy chemical elements are also very close to solar, as it ought to be in a cluster of almost the same age as the Sun (4.0 Gyr, Dinescu et al. 1995; 4.3 Gyr, Carraro et al. 1996; 4.0 Gyr, Boyle et al. 1998) and located only about 800 pc from it. The small underabundance of zirconium is probably caused by effects of the hyperfine structure.

In Fig. 2 we display the relative abundances of some chemical elements (for stars F84, F141 and F151, the mean values are plotted with double weight for results obtained from the $R2$ spectra). We also display results published for M 67 by other authors. A detailed spectroscopic analysis for IV-202 was done by Griffin (1975) and for T626 by Griffin (1979), for four stars (F105, F170, F224, and F231) by Cohen (1980) and for F164 and F170 by Foy & Proust (1981). The large scatter of the abundance ratios in these early analyses, when present, is most probably due to observational errors caused by photographic data used.

In our study, among mixing-sensitive chemical elements alterations of carbon, nitrogen and sodium are noticeable. In Sects. 5.1 and 5.2 we describe them in more detail.

5.1. Carbon and nitrogen

There are several possibilities to investigate carbon abundances in stars: a low excitation [C I] line at 8727 Å, a number of high excitation C I lines and molecular lines of CH and C_2. 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 the frequently used high excitation C I and CH lines. As it can be seen from results by Clegg et al. (1981), carbon abundances obtained using the high excitation C I lines and CH molecular lines are systematically lower than abundances obtained from the 8727 Å [C I] line. The agreement is present only for results

Table 4. (continued)

	F164 (clump)			F170 (giant)			F224 (clump)			F266 (clump)		
Ion	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n	[A/H]	σ	n
C I	–0.15		1	–0.21		1	–0.30		1	–0.21		1
N I	0.24	0.03	65	0.16	0.03	65	0.10	0.03	65	0.18	0.03	65
O I	–0.04		1	–0.05		1	–0.06		1	–0.01		1
Na I	0.20		1	0.16		1	0.10		1	0.20		1
Mg I	0.10		1	0.05		1	0.07		1	0.13		1
Al I	0.16	0.02	2	0.13	0.01	3	0.07	0.03	2	0.19	0.07	2
Si I	0.07	0.05	9	0.02	0.07	9	0.07	0.05	9	0.07	0.08	9
Ca I	0.07	0.18	8	0.04	0.20	7	–0.14	0.25	8	–0.03	0.19	8
Sc I	–0.16	0.19	3	–0.19	0.05	2	–0.18	0.13	3	–0.13	0.03	2
Sc II	0.09	0.17	9	0.04	0.22	8	0.00	0.19	8	0.06	0.15	9
Ti I	0.03	0.17	20	0.17	0.21	24	–0.16	0.20	23	–0.07	0.18	23
Ti II	0.17	0.09	3	0.17	0.16	5	–0.12	0.17	5	0.03	0.15	5
V I	0.13	0.13	17	0.27	0.17	12	–0.06	0.14	16	–0.06	0.12	17
Cr I	0.07	0.14	8	0.11	0.20	10	–0.07	0.22	9	0.01	0.22	10
Mn I	0.11	0.17	3	0.05	0.28	3	–0.26	0.11	2	–0.01	0.23	3
Fe I	0.00	0.07	32	–0.02	0.14	32	–0.11	0.12	31	–0.02	0.10	31
Fe II	0.00	0.08	6	–0.02	0.14	6	–0.11	0.07	6	–0.02	0.06	6
Co I	0.04	0.16	8	0.08	0.23	8	–0.04	0.17	8	0.01	0.16	8
Ni I	0.06	0.18	22	–0.02	0.19	22	–0.16	0.18	23	0.01	0.13	22
Cu I	0.17	0.07	3	0.19	0.10	2	–0.10	0.19	3	0.04	0.07	3
Y II	0.02	0.23	4	0.14	0.14	4	–0.25	0.10	4	–0.04	0.11	3
Zr I	–0.20	0.15	3	–0.18	0.15	3	–0.11	0.23	3	–0.29	0.20	3
Ba II	0.02		1	0.13		1	–0.18		1	0.03		1
La II	0.17	0.02	2	0.18	0.01	2	–0.01	0.01	2	0.08	0.01	2
Ce II	0.03	0.21	2	0.04	0.12	2	0.02	0.10	2	0.06	0.10	3
Sm II	0.08		1	0.10		1	0.25		1	0.00		1
Eu II	0.00		1	–0.05		1	–0.15		1	0.10		1
C/N	1.62			1.70			1.58			1.62		
$^{12}C/^{13}C$	18	3		30	7		8	3		15	4	

obtained from C_2 molecular lines. A comprehensive discussion on this subject is presented by Gustafsson et al. (1999) and Samland (1998).

Unfortunately, the [C I] 8727 Å line is not suitable for the analysis in spectra of red giants, especially when a probability of increased strengths of CN molecular lines is present. Lambert and Ries (1977) examined CNO abundances in K-type giants and found that the [C I] line was not trustworthy as a C abundance indicator, devoting an Appendix to the problem. Consequently, we decided to use the C_2 Swan (0,1) band head at 5635.5 Å for the analysis. This feature is strong enough in our spectra and is quite sensitive to changes of the carbon abundance (see Fig. 3 for illustration).

The previous high-resolution determination of [C/H] in M 67 giants (F105, F108 and F170) was carried out by Brown (1985), using C_2 lines at around 5110 Å and 4730 Å, and gave the mean value [C/H]=–0.26. Our result for these stars is slightly higher [C/H]=–0.19± 0.04. The mean value for the clump stars is –0.21± 0.05 dex.

The available study of carbon abundances in dwarf stars of M 67 is that by Friel & Boesgaard (1992). Six high excitation C I lines in the spectral region from 7100 Å to 7120 Å were analysed in three F dwarfs and the mean [C/H]=-0.09 ± 0.03 was obtained. This value, probably, would be by about 0.1 dex higher if the low excitation [C I] line would be used instead. Then the [C/H] value in dwarfs of M 67 would be equal to the solar value. Thus, compared with the Sun and with dwarf stars of M 67, the carbon abundance might be depleted by about 0.2 dex in the stars we analysed.

Another evaluation of the carbon abundance can be done by the comparison with carbon abundances determined for dwarf stars in the galactic disk. Gustafsson et al. (1999), using the forbidden [C I] line, have performed an abundance analysis of carbon in a sample of 80 late F and early G type dwarfs. As is seen from Fig. 4, the ratios of [C/Fe] and [C/O] in our stars lie by about 0.2 dex below the trends obtained for dwarf stars in the galactic disk.

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]=0.18 ± 0.02 and from the clump stars [N/H]=0.24 ± 0.08. Neither the carbon depletion, nor the nitrogen enrichment are as large as was reported by Brown (1985). Consequently, the C/N ratios obtained in our work do not re-

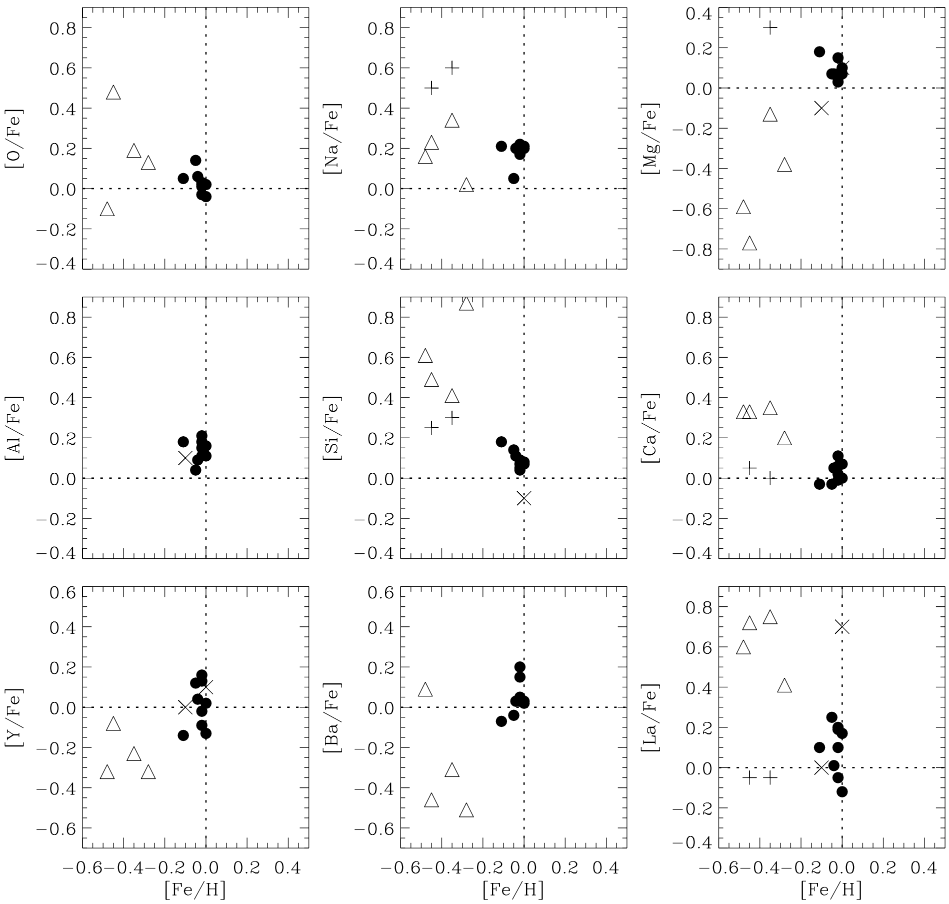

Fig. 2. Element to iron ratios as a function of iron [Fe/H]. Results of this paper are indicated by filled circles, from Griffin (1975, 1979) by 'plus' signs, from Cohen (1980) by triangles and from Foy & Proust (1981) by crosses

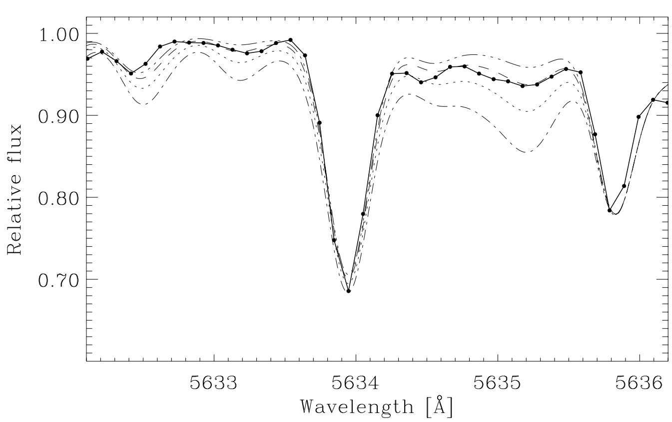

Fig. 3. Synthetic (dashed and dotted curves) and observed (solid curve and dots) spectra for the 1–0 C_2 region near λ5635 of F151. The syntheses were generated with [C/H]=0, –0.1, –0.2, and –0.3

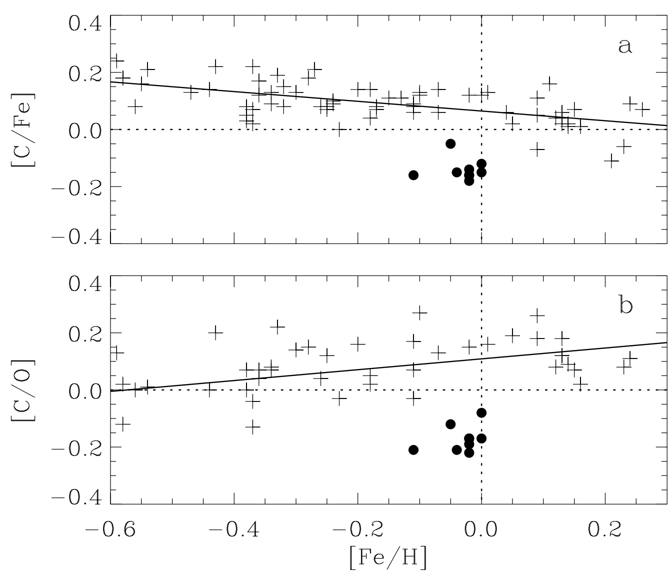

Fig. 4a and b. [C/Fe] **a** and [C/O] **b** as a function of [Fe/H]. Results of this paper are indicated by filled circles, results obtained for dwarf stars of the galactic disk (Gustafsson et al. 1999) by 'plus' signs and the full line

quest large extra-mixing processes in order to be explained. The mean C/N ratios are lowered to the value of 1.72 in the giants and to the value of 1.44 in the clump stars.

In our work, $^{12}C/^{13}C$ ratios were determined for all programme stars from the (2,0) $^{13}C^{14}N$ line at 8004.728 Å with a laboratory wavelength adopted from Wyller (1966). Fig. 5 illustrates the enhancement of ^{13}CN line at 8004 Å in spectra of F164 and F224. The star F224 has the lowest value $^{12}C/^{13}C$=8, among stars investigated in our work. For F84, F141 and F151, the ^{13}CN line at 8381.06 Å were observed at higher resolution, but due to the weakness of the line we can for F84 and F141 only

Table 5. Abundances relative to hydrogen [A/H] and σ derived from spectra of $R \approx 60\,000$. The quoted errors are the standard deviations in the mean value due to the line-to-line scatter within the species. The number of lines used is indicated by n

		F84		F141		F151	
Ion	n	[A/H]	σ	[A/H]	σ	[A/H]	σ
O I	1	0.01		0.02		0.04	
Na I	3	0.16	0.09	0.20	0.15	0.18	0.11
Mg I	4	0.02	0.15	0.06	0.13	0.01	
Al I	6	0.03	0.06	0.13	0.09	0.06	0.11
Si I	11	0.04	0.14	0.07	0.13	0.05	0.14
Ca I	9	0.00	0.11	–0.04	0.13	–0.03	0.17
Sc I	1	0.06	0.07	0.03	0.04	0.01	0.10
Sc II	6	0.02	0.10	0.02	0.08	0.05	0.08
Ti I	16	0.00	0.08	0.03	0.09	0.00	0.07
V I	7	0.03	0.08	0.10	0.06	0.13	0.10
Cr I	6	–0.02	0.07	0.04	0.07	0.04	0.13
Mn I	2	0.07	0.12	0.02	0.09		
Fe I	26	–0.05	0.04	0.01	0.06	–0.03	0.08
Fe II	4	–0.05	0.05	0.01	0.06	–0.03	0.01
Co I	3	–0.02	0.05	0.00	0.07	0.02	0.08
Ni I	17	–0.05	0.09	0.01	0.09	0.01	0.08
Rb I	1	0.02		–0.02			
Zr I	5	–0.17	0.09	–0.14	0.10	–0.19	0.09
Ba II	3	–0.04	0.02	0.01	0.03	–0.05	0.00
La II	1	–0.11		–0.14		–0.10	

Table 6. Effects on derived abundances resulting from model changes for the star F141. The table entries show the effects on the logarithmic abundances relative to hydrogen, Δ[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	$\Delta T_{\rm eff}$ -100 K	$\Delta \log g$ $+0.3$	$\Delta v_{\rm t}$ $+0.3{\rm km\ s}^{-1}$
C I	0.02	0.03	0.00
N I	–0.07	0.01	0.00
O I	0.01	–0.05	–0.01
Na I	–0.09	0.00	–0.11
Mg I	–0.03	–0.01	–0.07
Al I	–0.03	0.01	–0.06
Si I	0.05	0.04	–0.05
Ca I	–0.11	0.01	–0.12
Sc I	–0.11	–0.01	–0.04
Sc II	0.02	–0.05	–0.09
Ti I	–0.16	0.00	–0.07
Ti II	0.01	0.07	–0.11
V I	–0.15	0.00	–0.10
Cr I	–0.10	0.00	–0.08
Mn I	–0.07	0.00	–0.13
Fe I	–0.05	0.02	–0.11
Fe II	0.12	–0.06	–0.09
Co I	–0.05	–0.02	–0.03
Ni I	–0.01	–0.02	–0.10
Cu I	–0.06	0.02	–0.16
Rb I	–0.11	0.00	–0.02
Y I	0.01	0.09	–0.12
Zr I	–0.18	0.00	–0.02
Ba II	–0.02	–0.02	–0.19
La II	–0.02	–0.04	–0.03
Ce II	–0.01	0.08	–0.07
Sm II	–0.02	0.08	–0.10
Eu II	0.00	0.10	–0.01

confirm that the ${}^{12}{\rm C}/{}^{13}{\rm C}$ ratios are consistent with the values derived from the 8004.7 Å feature, while for F151 we are not able to derive any useful information of the isotope ratio from this line.

Ratios of ${}^{12}{\rm C}/{}^{13}{\rm C}$ were investigated for stars in M 67 by Gilroy (1989) and Gilroy & Brown (1991). There are six stars in common with Gilroy (1989) and one with Gilroy & Brown (1991). Except for two stars (F84 and F170), our ${}^{12}{\rm C}/{}^{13}{\rm C}$ ratios agree within errors of uncertainties. The mean difference between our values and these by Gilroy & Brown is equal to 3 ± 4. In their study, Gilroy & Brown rule out mixing during the He-core flash because the two stars, F108 and F170, had ${}^{12}{\rm C}/{}^{13}{\rm C}$ ratios similar to the clump stars. In our study however, a small difference can be suspected. We find the mean ${}^{12}{\rm C}/{}^{13}{\rm C}$ ratios lowered to the value of 24 ± 4 in the giants and to the value of 16 ± 4 in the clump stars.

The standard theoretical evolution of the carbon isotopic ratio and carbon to nitrogen ratio along the giant branch was homogeneously mapped by Charbonnel (1994) for stellar masses between 1 and 7 $M_{\odot}$, and for different values of metallicity. For a 1.25 $M_{\odot}$ star (approximately the turn-off mass of M 67), with initially solar composition the predicted ${}^{12}{\rm C}/{}^{13}{\rm C}$ and ${}^{12}{\rm C}/{}^{14}{\rm N}$ ratios at the end of the first dredge-up phase are about 22.7 and 1.6, respectively (Charbonnel 1994, Figs. 2 and 4 (it is not explaned in the paper why values in Table 2 and Figs. 7 and 8 are different from those presented in Figs. 2 and 4, so we decided to use homogeneous ones)). The predicted values are in good agreement with our results for the giant stars. The clump stars, however, may well show an additional decrease caused by an extra mixing process (see Fig. 6).

5.2. Sodium

The stars in our sample, as determined from the Na I lines λ 5682.64, 6154.23 and 6160.75 Å show a slight overabundance of sodium (see Fig. 7).

Overabundances of sodium in red giants have long been considered as being of a primordial origin (see, e.g., Cottrell & Da Costa 1981). However, 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 a possibility of sodium to be produced in red giant stars (Cohen 1978, Peterson 1980, Drake et al. 1992, Kraft et al. 1995, 1997 and references therein). Norris & Da Costa (1995) have concluded that Na variations exist in all clusters, while Al variations are greater in the more metal-poor clusters. Theoretical explanations for the production of Na and Al have been proposed by Sweigart & Mengel (1979), Denissenkov & Denissenkova (1990), Langer & Hoff-

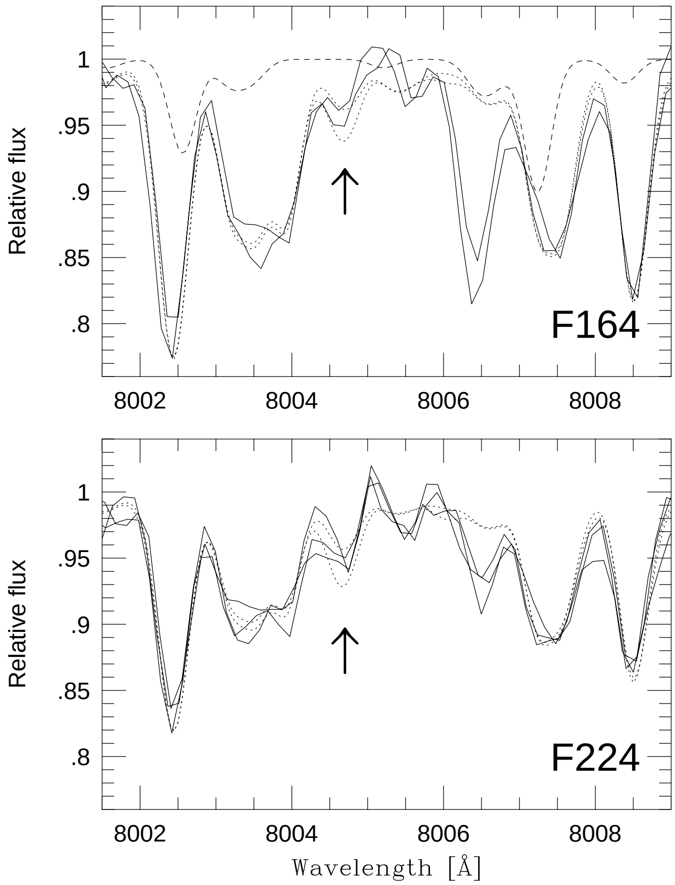

Fig. 5. A small portion of the 8000 Å wavelength interval showing the 8004.7 Å ^{13}CN feature in F164 and F224. In the upper panel, the solid lines show the 2 observed spectra for F164, the dotted lines show two synthetic spectra with ^{12}C/^{13}C ratios of 10 and 20, the dashed line shows a synthetic spectrum without any CN lines. In the lower panel, the solid lines show the 3 observed spectra for F224, and the dotted lines show two synthetic spectra with ^{12}C/^{13}C ratios of 5 and 10

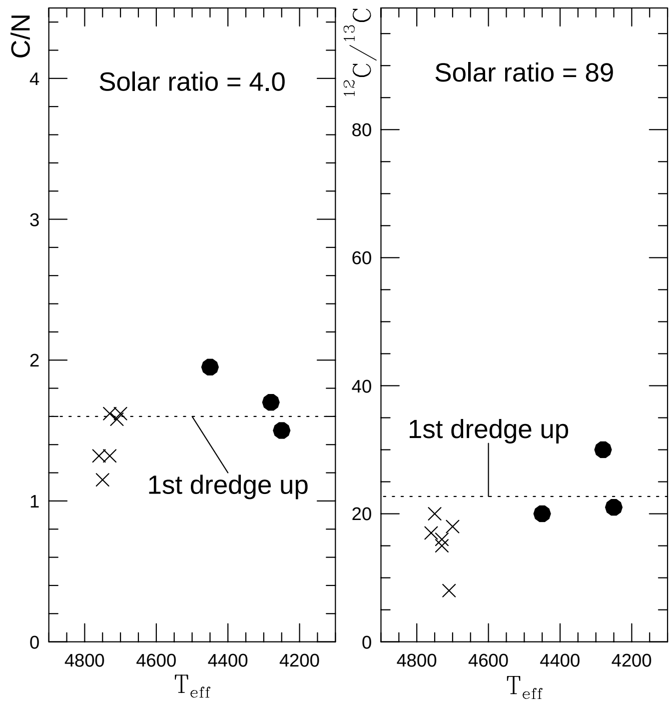

Fig. 6. C/N and ^{12}C/^{13}C abundance ratios for giants (*filled circles*) and clump stars (*crosses*). The dotted lines show predictions from Charbonnel (1994). We suggest that the diagram shows that extra mixing takes place after the He-core flash

man (1995), Cavallo et al. (1996) and other studies; however, the origin and extent of the phenomenon is not well understood.

For the stars in our sample, the overabundance of sodium is not followed by a noticeable overabundance of aluminium and underabundance of oxygen. This confirms the conclusion by Norris & Da Costa (1995) that Al variations are not that great as of Na in metal-rich stars. The overabundance of Na could appear due to the deep mixing from layers of the NeNa cycle, which lie higher than ON-processed regions in red giants (cf. Cavallo et al. 1996). Shetrone (1996), from the analysis of red giants in the globular cluster M 71, also concluded that either Al and Na are created in different nucleosynthesis processes, or the NeNa cycle can occur without the ON or MgAl cycles.

5.3. 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 $^{12}\mathrm{C}/^{13}\mathrm{C}$ and $^{12}\mathrm{C}/^{14}\mathrm{N}$ 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 modify the surface abundances (see Charbonnel et al. 1998 for more discussion). In case of M 67, this may happen starting from $\log L/L_{\odot}$=1.64 (Charbonnel 1994), however the first and only evidence on the evolutionary state at whish this non-standard mixing actually becomes effective has to come from observations. The giants F108 and F170 ($\log L/L_{\odot} \approx 2.3$), observed in our work, do not show obvious effects of the extra mixing. Other bright M 67 giants such as T626 and IV-202 are not investigated since have quite low membership probabilities (19% and 51%, respectively, as quoted by Sanders 1977) and are rather cool (continuum placement in their spectra would be at best difficult). In our work, the extra-mixing processes seem to show up in the clump stars observed (Fig. 6), however here the He-core flash may be responsible.

The role that the He-core flash may play in producing surface abundance changes still has to be investigated. The theoretical calculations indicate that the nature of nucleosynthesis and mixing depend upon the degree of degeneracy in the He-core and, hence, intensity of the explosion: intermediate flashes produce the most mixing (Despain 1982, Deupree 1986, Deupree & Wallace 1987, Wallace 1988 and references therein). Due to the numerical difficulties in treating such a violent event, the He core-flash remains an event of interest to theorists. The observa-

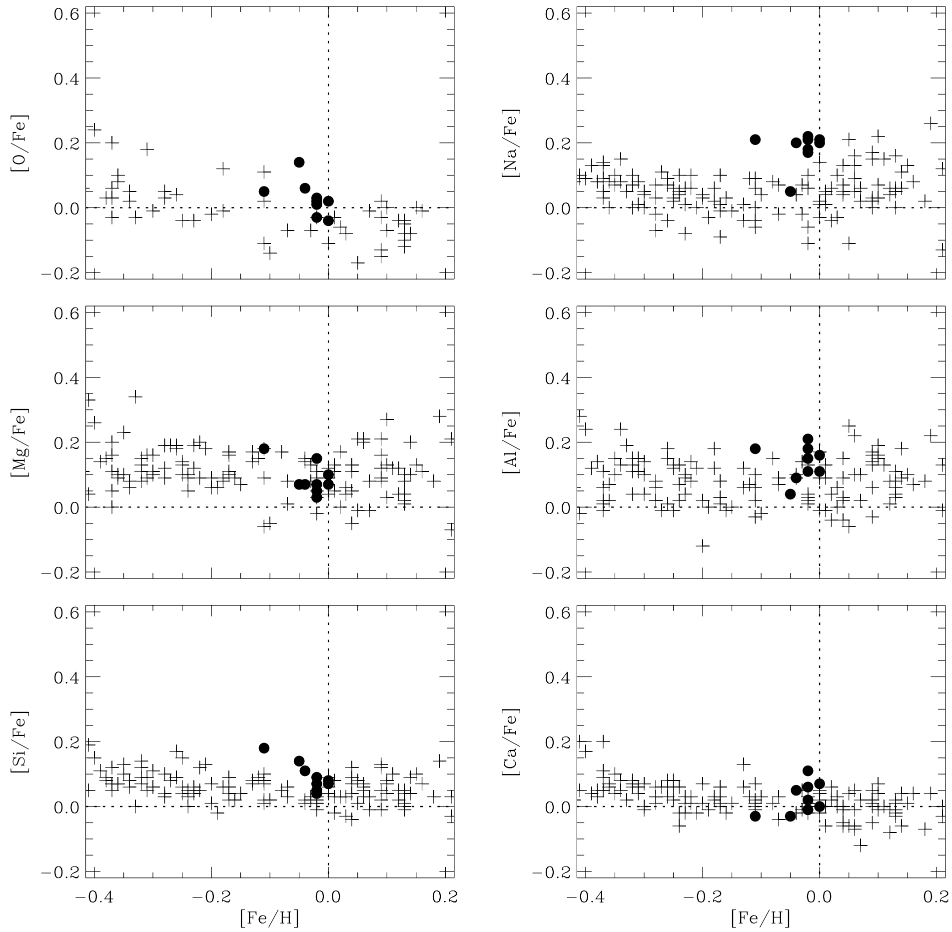

Fig. 7. Element to iron ratios as a function of iron [Fe/H]. Results of this paper are indicated by *filled circles*, results for the Galactic disk stars investigated by Edvardsson et al. (1993) by *crosses*

tional data for giants and clump stars of M 67 in our work show a slight increase of abundance changes in more evolved clump stars. New precise observational data are necessary in understanding effects of the He-core flash and other open questions of chemical evolution of stars.

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