A&A 504, 845–852 (2009)
DOI: 10.1051/0004-6361/200811507

Astronomy & Astrophysics

A spectroscopic study of the open cluster NGC 6475 (M 7)⋆

Chemical abundances from stars in the range $T_{\rm eff}$ = 4500–10 000 K

S. Villanova[1], G. Carraro[2], and I. Saviane[2]

[1] Grupo de AstronomÃŋa, Departamento de Fsica, Casilla 160, Universidad de Concepción, Chile
e-mail: svillanova@astro-udec.cl
[2] ESO, Alonso de Cordova, 3107 Vitacura, Santiago de Chile, Chile
e-mail: [gcarraro;isaviane]@eso.org

Received 11 December 2008 / Accepted 8 June 2009

ABSTRACT

Aims. Clusters of stars are key objects for studying the dynamical and chemical evolution of the Galaxy and its neighbors, and are the most important laboratories to test the theory of stellar evolution. In particular, chemical composition is obtained from different kinds of stars (hot main-sequence stars, cool main-sequence stars, horizontal-branch stars, RGB stars) using different methodologies. Our first aim is to apply these methodologies to the stars of the open cluster NGC 6475 and, by obtaining a census of the most important elements, we will be able to test their consistency. Our second aim is to study the evolution of the surface chemical abundances as a function of the evolutionary phase of a star. We finally want to establish more robust fundamental parameters for this cluster.

Methods. We selected high S/N high resolution spectra of 7 stars of the open cluster NGC 6475 from the ESO database covering the $T_{\rm eff}$ range 4500–10 000 K and of luminosity class V (dwarf) and III (giants). We determined the chemical abundances of several elements. For hot stars ($T_{\rm eff}$ > 9000 K), we applied the Balmer line fitting method to obtain atmospheric parameters, while for cool stars ($T_{\rm eff}$ < 6500 K), the abundance equilibrium of FeI/II lines. For the two groups of stars, the use of different line-lists was mandatory. LTE approximation together with NLTE correction for some elements (C, N, O, Na, Mg) were applied. The abundances of many elements were obtained by measuring of the equivalent width of spectral lines. For those ones having only blended lines (O, He), real spectra were compared to synthetic ones. Hyperfine structure was taken into account for V and Ba.

Results. First of all, we showed that the two methodologies we used give abundances that agree within the errors. This implies that no appreciable relative systematic effects are present for the derived chemical content of cool and hot stars. On the other hand, giants stars show clear chemical peculiarities with respect to the dwarfs affecting light elements (up to Si) and maybe Ba. This can be explained as an evolutionary effect. Then, once we had a new estimation of the metallicity for the cluster ([Fe/H] = +0.03 ± 0.02, [α/Fe] = −0.06 ± 0.02), we fitted suitable isochrones to the CMD of the cluster to obtain the basic parameters ($E(B-V) = 0.08 \pm 0.02$, $(m-M)_0 = 7.65 \pm 0.05$, Age = 200 ± 50).

Key words. Galaxy: open clusters and associations: individual: NGC 6475 – stars: abundances

1. Introduction

Determining metal abundance of individual stars in Galactic open clusters gives useful information on the formation and chemical evolution of a cluster itself, on the importance of convective mixing and rotation in the surface chemical properties of each star, and on the estimate of cluster bulk properties such as distance, reddening, age, and age spread. Very detailed studies are now available, like the ones on Coma Berenices (Gebran & Monier 2008), the Pleiades (Gebran et al. 2008), and Praesepe (Fossati et al. 2007, 2008), for just a few examples.

The ESO archive contains high-resolution spectroscopic data of many stars in Galactic clusters which have been taken for different purposes, but that have never been fully investigated. We searched the archive and found several interesting cases, and present here a detailed analysis of individual high resolution spectra of stars in the open cluster NGC 6475. This cluster was studied before several times (Prosser et al. 1996; Fossati et al. 2007; Meynet et al. 1993; Kharchenko et al. 2005), and it turned out to have a reddening in the range 0.06–0.10 mag and a distance modulus not well constrained but in the range $(m-M)_V$ = 7.0–7.7 mag. Age was found to be in the range 170–220 Myr, and the metallicity is slightly super-solar ([Fe/H] = +0.14 according to Sestito et al. 2003). The cluster possesses both hot stars of spectral type A-B, and evolved red giants of spectral type G-K. However a throughout chemical investigation of both cool and hot stars together has never been performed.

In this paper we describe in detail the techniques for infering abundances for a variety of elements in hot and cool stars (both dwarf and evolved), giving special emphasis to comparing the results for elements belonging to the same group (α, iron peak, or light elements). The results are then used to revise the fundamental parameters of the cluster.

The layout of this paper is as follows. In Sect. 2 we describe the observation material, while in Sect. 3 the build-up of suitable line-lists is illustrated. In Sects. 4 and 5 we discuss the determination of atmospheric parameters for cool and hot stars respectively, and the abundance determination is analyzed in Sect. 6. A brief rewiev of the cluster parameters is finally given in Sect. 7, while the paper conclusions are highlighted in Sect. 8.

⋆ Based on UVES@VLT observations under the Program ID 226.D-5655.

Table 1. Basic parameters for the observed stars.

ID	α(h:m:s)	δ(°:′:″)	V(mag)	$B-V$(mag)	Sp.T.	RV_H(km s^{-1})	$v_e \sin i$(km s^{-1})	T_{eff}(K)	log(g)(dex)	v_t(km s^{-1})
HD 162679	17:53:45.9	–34:47:29	7.16	0.03	B9V	–17.06	37	9962	3.46	0.40
HD 162817	17:54:27.1	–34:28:00	6.11	0.04	B9.5V	–15.66	65	9651	3.29	0.85
HD 162391	17:52:19.8	–34:25:00	5.85	1.10	G8III	–14.51	–	4800	1.60	1.83
HD 162587	17:53:23.5	–34:53:42	5.60	1.09	K3III	–17.18	–	4850	2.10	1.65
JJ10	17:53:54.2	–34:46:08	12.53	0.74	K0V	–14.87	–	5700	4.30	1.10
JJ22	17:53:08.9	–34:45:52	11.11	0.50	F5-G0V	–14.96	–	6300	4.05	1.25
JJ8	17:54:09.7	–34:53:13	13.30	0.87	K5V	–14.83	–	5400	4.50	0.85

2. Observations and data reduction

Observations of stars in the field of the open cluster NGC 6475 were carried out during August 2001 in the context of the ESO DDT Program ID 266.D-5655 (Bagnulo et al. 2003). This program had the aim of observing spectroscopically a large sample of field and cluster stars from ultraviolet (UV) to near infrared (NIR).

Observations were performed with UVES onboard UT2(Kueyen) telescope in Paranal. Spectra of 32 stars candidate cluster members (selected from the WEDBA database[1]) were obtained using the DIC1(346+580) and DIC2 (437+860) settings with a 0.5″ slit width. The spectra cover the wavelength range 3000–10 000 Å with a mean resolution of 80 000.

Data were reduced using the UVES pipeline (Ballester et al. 2000) where raw data were bias-subtracted, flat-field corrected, extracted using the average extraction method, and wavelength-calibrated. Sky subtraction was applied. Echelle orders were flux-calibrated using the master response curve of the instrument, and an atmospheric extinction correction applied. Finally, the orders were merged to obtain a 1D spectrum. All the reduced spectra can be downloaded from the UVES POP web interface[2].

For our purpose we selected stars with low rotation (v_R < 100 km s^{-1}), allowing the measurement of the equivalent width (EQW) of spectral lines. Our choice left us with 7 members, covering the spectral type range K5-B9 and of luminosity class V (dwarf) and III (giants). The S/N of their spectra vary from star to star and is a function of the wavelength, but it is greater than 200 in the worst case.

Membership was checked by radial velocity measurement obtained using the *fxcor* IRAF, which cross-correlates the observed spectrum with a template having a known radial velocity. As templates we used two synthetic spectra, the former for cool stars and calculated for a typical Sun-like dwarf (T_{eff} = 5777, log(g) = 4.44, v_t = 0.80 km s^{-1}, [Fe/H] = 0.0), and the latter for hot stars and calculated for a typical A0V dwarf (T_{eff} = 9500, log(g) = 4.00, v_t = 1.00 km s^{-1}, [Fe/H] = 0.0). Spectra were calculated using the 2.73 version of SPECTRUM, the local thermodynamical equilibrium spectral synthesis program freely distributed by Richard O. Gray[3].

The error in radial velocity – derived from the *fxcor* routine – is less than 1 km s^{-1}. According to the measured RV_H and to the typical velocity dispersion of open clusters (∼1–2 km s^{-1}), all the selected stars turn out to be members. Finally, for the abundance analysis, each spectrum was shifted to rest-frame velocity and continuum-normalized.

In Table 1 we report the basic parameters of the selected stars: the identification (ID), the coordinates (α, δ), V magnitude, $B-V$ color, Spectral Type (Sp.T.), heliocentric radial velocity (RV_H), rotational velocity for the hot stars ($v_e \sin i$), effective temperature (T_{eff}), gravity (log(g)), and microturbolence velocity (v_t). For determination of rotational velocity and atmospheric parameters see Sects. 4 and 5.

According to the SIMBAD database[4], three of them (HD 162679, HD 162391, and HD 162587) are binaries, but no evidence of a double spectrum was found (no double peak in the cross-correlation function in the radial velocity determination). We conclude that the secondary component must have a negligible influence on the spectral energy distribution, and so no effects on our spectroscopic analysis are expected.

We do not have any information on the other 4 stars, but 3 of them (JJ8, JJ10, JJ22, see Fig. 4) lie in the single-star MS region, well detached from the binary sequence. All of them show no evidence of a double spectrum or double peak in the cross-correlation function when the radial velocity determination was performed. Also in this case we conclude that the secondary component, if present, has a negligible influence on the spectral energy distribution, so no effects are expected on our spectroscopic analysis.

3. The line-lists

Early (hot) and late (cool) type stars in our sample have few spectral lines in common. For this reason we had to build two different line-lists for the purpose of measuring their abundances. Abundances for most of the elements can be obtained by the EQW method in both cases.

The line-list for cool stars was initially taken from Gratton et al. (2003). The log(gf) parameters were then determined again for each element by a solar-inverse analysis to remove the scatter in abundance with respect to the mean value. We measured the equivalent widths from the NOAO solar spectrum (Kurucz et al. 1984) by Gaussian fitting (and using a Voigh profile for the strongest lines) and derived the abundances using a model atmosphere for the canonical solar parameters: T_{eff} = 5777 K, log(g) = 4.44, v_t = 0.80 km s^{-1}, logϵ(Fe) = 7.50 dex. Solar abundances we obtained from this line-list are reported in Table 2 and compared with Grevesse & Sauval (1998).

For some elements (Al and Nd) the agreement was not good ($\Delta A \geq 0.2$ dex); in this case, we calculated again log(gf) values by averaging the data obtained from VALD & NIST[5] atomic parameters databases. Abundances from the new log(gf) parameters showed a better agreement ($\Delta A < 0.1$ dex), and again they were adjusted by solar-inverse analysis. For N and O, whose lines are affected by severe blending with other spectral features, we were forced to apply the spectral synthesis method

[1] http://www.univie.ac.at/webda/

[2] http://www.sc.eso.org/santiago/uvespop/index.html

[3] See http://www.phys.appstate.edu/spectrum/spectrum.html for more details.

[4] http://simbad.u-strasbg.fr/simbad/

[5] VALD and NIST database can be found at http://vald.astro.univie.ac.at/ and http://physics.nist.gov/PhysRefData/ASD/lines_form.html

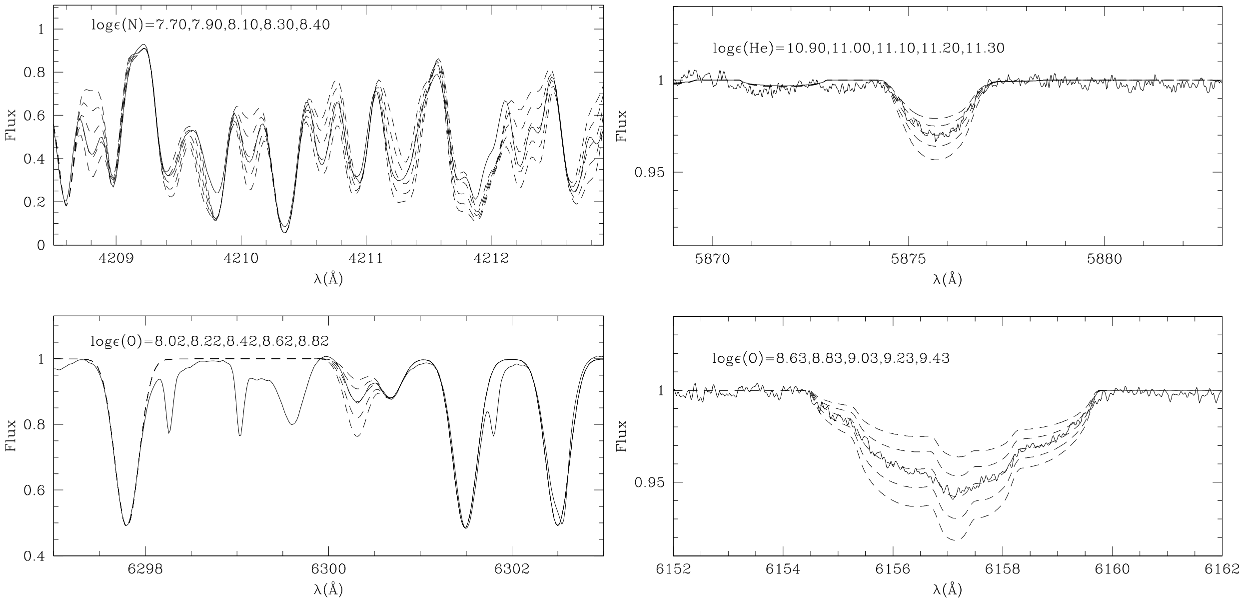

Fig. 1. Example of the spectral synthesis method used to derive N and O for cool stars (applied to #HD 162587 and #162391, *left panel*), and He and O for hot stars (applied to #HD 162817, *right panel*). Continuous lines are the observed spectra, while dashed lines are synthetic spectra. Abundances used in the synthesis are indicated.

Table 2. Abundances for the Sun and Vega as obtained from the line lists used in this work.

El.	Sun	Sun_{GS98}	Vega	$Vega_{Qi01}$
HeI	–	10.99	–	–
CI	8.50	8.52	8.52	8.46
CI_{NLTE}	–	–	8.57	–
NI	7.95	7.92	7.98	8.00
NI_{NLTE}	–	–	7.58	–
OI	8.83	8.83	8.82	9.01
OI_{NLTE}	–	–	8.74	–
NaI	6.37	6.33	6.63	6.45
NaI_{NLTE}	6.32	6.33	6.33	–
MgI	7.54	7.58	7.14	6.81
MgI_{NLTE}	7.56	7.58	–	–
AlI	6.43	6.47	–	–
SiI	7.61	7.55	–	–
CaI	6.39	6.36	5.65	5.41
ScII	3.12	3.17	2.56	2.33
TiI	4.94	5.02	–	–
TiII	4.96	5.02	4.52	4.58
VI_{Hyp}	4.00	4.00	–	–
CrI	5.63	5.67	–	–
CrII	5.67	5.67	5.20	5.19
FeI	7.50	7.50	7.03	6.94
FeII	7.51	7.50	7.01	6.93
CoI	4.85	4.92	–	–
NiI	6.28	6.25	–	–
CuI	4.19	4.21	–	–
ZnI	4.61	4.60	–	–
YII	2.24	2.24	–	–
$BaII_{Hyp}$	2.34	2.13	1.85	0.81
LaII	1.26	1.17	–	–
CeII	1.53	1.58	–	–
NdII	1.59	1.50	–	–

Abundances for the Sun are compared with Grevesse & Sauval (1998) (Sun_{GS98}), those for Vega with Qiu et al. (2001) ($Vega_{Qi01}$).

which compares observed spectra to synthetic ones having different abundances of the studied element. The O abundances were obtained from the 6300 Å forbidden line, and N from CN features due to the $\Delta v = -1$ band of the violet system ($B^2\Sigma$-$X^2\Sigma$) near the bandhead at 4215 Å (see Fig. 1, left panels). Line-lists for the synthesis of the O line and CN bands were taken from the more complete line compilation of SPECTRUM[6].

The list for the CN feature was calibrated on the Sun to match the synthetic spectrum with the NOAO one. In this case a complete calibration procedure would also require a comparison with the spectrum of a late type and well known stars (i.e. Arcturus), in order to adjust the log(*gf*) value of those lines not present in the Sun, but affecting cooler stars such as HD 162391 and HD 162587. This is a very long process to do in future papers. Spectral regions of 0.4 Å width centered at 4209.8 and 4212.0 Å were rejected because of the very poor reproduction of the observed spectrum (see Fig. 1). The reason is that some lines are not identified in the solar spectrum, so we tentatively attributed them to Fe. It appeared to be a bad choice, so we did not include the relative spectral regions in the fitting.

Another effect to consider is the hyperfine structure of the odd-numbered elements such as Sc, V, Co, Cu, Y, and Ba. These elements possess non-zero nuclear spin, which results in considerable splitting of the lines into hyperfine components. According to McWilliam & Rich (1994), this split affects only the shape of the line and not the EQW in the case of weak lines, leaving the derived abundance unaltered. On the other hand, strong lines are desaturated, increasing their EQW, whose final effect is an anomalously greater abundance for the element if no correction is applied.

For Sc, Co, Cu, and Y, we considered only weak lines (EQW $\simeq$ 50 mÅ or lower according to McWilliam & Rich 1994). For V and Ba, only strong lines were available, and we derived their abundances from 6274, 6285, and 6812 Å features for V, and from 5853 and 6496 Å features for Ba, respectively. In both cases spectral synthesis was applied and the hyperfine components were taken from McWilliam & Rich (1994) and

[6] See `http://www.phys.appstate.edu/spectrum/spectrum.htmlandreferencestherein.`

McWilliam (1998). Barium lines also have isotopic components, and for the isotopic ratios we assumed the solar values as described in McWilliam (1998).

As a result of this procedure, all our abundances agree with Grevesse & Sauval (1998) within 0.1 dex, except for BaII for which a difference of ~0.20 dex was found (see Table 2).

The line-list for hot stars was taken from the VALD (Kupka et al. 2000) database for a typical A0V solar metallicity star. log(gf) parameters were then determined as above by an inverse analysis measuring the equivalent widths on a reference spectrum: the Vega spectrum was chosen for this purpose. We measured EQWs on two Vega spectra, the first (4100–6800 Å wavelength range) obtained from the Elodie database (Moultaka et al. 2004), and the second (3900–8800 Å wavelength range) from Takeda et al. (2007). Since Vega is a rotating star, EQWs were obtained from direct integration of spectral features. The measured EQWs were averaged in the common wavelength range (4100–6800 Å). The atmospheric parameters for Vega were obtained in the following way. As for $T_{\rm eff}$, Vega is a primary standard because both angular diameter and bolometric flux are available. From the literature we obtain the following information: $f = 29.83 \pm 1.20 \times 10^{-9}$ W m^{-2}, $\theta = 3.223 \pm 0.008$ mas. Hence, we infer an effective temperature of 9640 ± 100 K.

Since a direct estimate of Vega gravity is not available, we determined log(g) using H Balmer line fitting. We obtained log(g) = 3.97 ± 0.05. The microturbulence velocity was obtained by minimizing the slope of the abundances obtained from FeI lines vs. EQW. We obtained $v_{\rm t} = 1.02 \pm 0.05$ km s^{-1} and logϵ(Fe) = 7.02 dex. The iron content normalized to the Sun results [Fe/H] ~ –0.5, in agreement with previous determinations (Qiu et al. 2001). The Vega abundances we obtained are reported in Table 2 and compared with Qiu et al. (2001) and with the Sun.

Also in this case we were forced to apply the spectral synthesis method for some elements (He and O, see Fig. 1, right panels). In fact, spectral features of He (5875 Å) and O (6156–6158 Å) are composed by several blended lines of the element. Suitable line-lists for the synthetic spectrum calculation were taken from VALD & NIST databases and the log(gf) values averaged.

It was not possible to derive He abundance for Vega because the target spectral line (5875 Å) was too contaminated by telluric lines.

All the analysis (both for the Sun and Vega, and for the target stars) was performed using the 2007 version of MOOG (Sneden 1973) under the LTE approximation coupled with ATLAS9 model atmospheres (Kurucz 1992). Spectral features affected by telluric contamination were rejected, and C, O, Na and Mg abundances were corrected for NLTE effects when necessary as described in the next sections, while N content for Vega and the hot stars in our sample was corrected as described in Sect. 6.

4. Atmospheric parameters for cool stars

For cool stars (HD 162391, HD 162587, JJ10, JJ22, JJ8), the classical method for obtaining spectroscopic atmospheric parameters is to use the abundances from EQW of FeI/FeII lines. Initial estimates of the atmospheric parameter $T_{\rm eff}$ were obtained from the Sp.T. reported in Table 1 according to the relations given by Straizys & Kuriliene (1981). We then adjusted the effective temperature by removing any trend in the relation between the abundance obtained from Fe I lines and the excitation potential. At the same time, the input log(g) values were set in order to satisfy the ionization equilibrium of FeI and FeII until the relation

$$\log\epsilon({\rm FeII})_\odot - \log\epsilon({\rm FeI})_\odot = \log\epsilon({\rm FeII})_\star - \log\epsilon({\rm FeI})_\star$$

was accomplished.

Finally, the microturbulence velocity was obtained by removing any slope in the relation between the abundance from FeI lines and the reduced EQW. Typical internal errors for this method and the S/N of our spectra are $\Delta T_{\rm eff} \sim 30{-}40$ K, $\Delta\log(g) \sim 0.1$, $\Delta v_{\rm t} \sim 0.05$ km s^{-1} (see Marino et al. 2008). Adopted values for the atmospheric parameters are reported in Table 1.

Abundances for most of the elements were obtained from EQW measurements. None of the cool stars show evidence of rotation, and for this reason EQWs were obtained from Gaussian fitting of spectral features. For N and O abundance we were forced to apply the spectral synthesis method as in the previous section. See Fig. 1 for an example of the synthesis for N and O applied to #HD 162587 and #HD 162391.

In addition as a test we applied the spectral synthesis method to the forbidden blended CI line at 8727 Å to complete the C abundances obtained from EQW of the other unblended C features.

CI-8727 is formed strictly in LTE mode in contrast to the other features ($\lambda = 4775, 5052, 5380$ Å), so our aim was to compare the abundances obtained from the two sets of lines to evaluate possible NLTE effects. We did not find any significant differences (Δ[C/H] < 0.05, in agreement with Takeda & Honda 2005), and therefore we did not apply any NLTE corrections to the derived abundance for this element.

The Na content was derived from the 5682–5688 and 6154–6160 Å doublets, while Mg one from the 5711, 6318, 6319 high excitation lines. Both Na and Mg lines are known to be affected by a non negligible NLTE effect. For this reason abundances obtained in LTE approximation were corrected according to Gratton et al. (1999). Each line was treated separately because the amount of the correction is a function of the EQW, besides the atmospheric parameters of the star. In Tables 2 and 3 we report only the mean LTE and NLTE abundances for the Sun and for our targets, respectively.

Unfortunately, incomplete sources of NLTE correction for Al abundances are available in literature, which provides corrections for dwarf or subgiant stars in the range K0-F5 (Baumueller & Gehren 1997; and Gehren et al. 2004). However, according to Asplund (2005), NLTE corrections for Al are important for metal-poor stars ([Fe/H] < -0.5) and less important at decreasing temperature. Also gravity appears to have a (small) influence on the correction but no data are available for giant stars. Since cool stars in our sample are metal-rich and the two giants (HD 162391 and HD 162587) are very cool ($T_{\rm eff} \sim 4800$ K), we estimate that no NLTE corrections appear necessary for this element.

5. Atmospheric parameters for hot stars

Atmospheric parameters of hot stars (HD 162679, HD 162817) are routinely determined by fitting the Balmer lines of observed spectra with synthetic ones. For our analysis we used a set of ATLAS9 model atmospheres calculated for solar metallicity (roughly the metallicity of the cluster as derived by this study). Starting from these models of atmosphere, we calculated spectra with Lemke's version of the LINFOR program (developed originally by Holweger, Steffen, and Steenbock at Kiel University).

Table 3. Abundances ($\log(N_{\rm el.}/N_{\rm H})$+12) obtained for our stars.

El.	HD 162679	HD 162817	HD 162391	HD 162587	JJ10	JJ22	JJ8	$\langle\log\epsilon(\rm El)\rangle$	$\langle$[El./H]$\rangle$
HeI	11.10 ± 0.05	11.10 ± 0.05	–	–	–	–	–	11.10 ± 0.04	+0.11 ± 0.04
CI	8.33	–	7.89 ± 0.05	8.35 ± 0.02	–	–	8.44 ± 0.06	–	–
$\rm CI_{NLTE}$	8.45	–	–	–	–	–	–	8.44 ± 0.01	–0.06 ± 0.01
NI	8.20	–	8.33 ± 0.02	8.10 ± 0.06	7.92 ± 0.04	–	7.92 ± 0.03	7.92 ± 0.02	–0.03 ± 0.02
$\rm NI_{NLTE}$	7.80	–	–	–	–	–	–	–	–
OI	8.97 ± 0.04	9.03 ± 0.05	8.42 ± 0.05	8.69 ± 0.05	8.87 ± 0.05	–	8.90 ± 0.05	–	–
$\rm OI_{NLTE}$	8.83 ± 0.04	8.89 ± 0.05	–	–	–	–	–	8.87 ± 0.02	+0.04 ± 0.02
NaI	6.53 ± 0.05	6.68 ± 0.08	6.84 ± 0.07	6.73 ± 0.04	6.38 ± 0.05	–	6.25 ± 0.03	–	–
$\rm NaI_{NLTE}$	6.23 ± 0.05	6.38 ± 0.08	6.98 ± 0.07	6.80 ± 0.04	6.31 ± 0.05	–	6.19 ± 0.03	6.24 ± 0.05	–0.08 ± 0.05
MgI	7.43	7.61 ± 0.09	7.59	7.60	7.54 ± 0.06	7.45 ± 0.03	7.43 ± 0.04	–	–
$\rm MgI_{NLTE}$	–	–	7.95	7.82	7.58 ± 0.06	7.56 ± 0.03	7.44 ± 0.04	7.53 ± 0.04	–0.03 ± 0.04
AlI	–	–	6.49 ± 0.11	6.33 ± 0.03	6.13 ± 0.03	–	6.14 ± 0.04	6.13 ± 0.01	–0.30 ± 0.01
SiI	–	–	7.72 ± 0.06	7.75 ± 0.03	7.58 ± 0.03	7.52 ± 0.04	7.51 ± 0.02	7.53 ± 0.02	–0.08 ± 0.02
CaI	–	–	6.40 ± 0.10	6.41 ± 0.06	6.44 ± 0.04	6.39 ± 0.05	6.35 ± 0.04	6.40 ± 0.01	+0.01 ± 0.01
ScII	–	3.02	–	–	3.05 ± 0.04	3.04 ± 0.05	3.07 ± 0.06	3.05 ± 0.01	–0.07 ± 0.01
TiI	–	–	4.91 ± 0.05	4.98 ± 0.03	4.90 ± 0.03	4.92 ± 0.05	4.96 ± 0.02	4.95 ± 0.02	+0.01 ± 0.02
TiII	4.87 ± 0.04	4.95 ± 0.04	4.99 ± 0.03	4.93 ± 0.04	4.89 ± 0.02	4.87 ± 0.04	4.91 ± 0.05	4.91 ± 0.02	–0.05 ± 0.02
VI	–	–	3.83 ± 0.01	3.96 ± 0.01	3.92 ± 0.02	–	4.03 ± 0.01	3.94 ± 0.04	–0.06 ± 0.04
CrI	–	–	5.68 ± 0.06	5.72 ± 0.03	5.69 ± 0.02	5.74 ± 0.05	5.65 ± 0.02	5.68 ± 0.02	+0.05 ± 0.02
CrII	5.72 ± 0.05	5.82 ± 0.07	5.72 ± 0.11	5.81 ± 0.06	5.69 ± 0.04	5.66 ± 0.04	5.59 ± 0.02	5.65 ± 0.04	–0.02 ± 0.04
FeI	7.46 ± 0.08	7.55 ± 0.05	7.52 ± 0.01	7.56 ± 0.01	7.54 ± 0.01	7.51 ± 0.01	7.47 ± 0.05	7.53 ± 0.02	+0.03 ± 0.02
FeII	7.47 ± 0.03	7.62 ± 0.03	–	–	–	–	–	7.54 ± 0.07	+0.03 ± 0.07
CoI	–	–	4.87 ± 0.06	4.95 ± 0.06	4.74 ± 0.03	–	4.79 ± 0.02	4.79 ± 0.05	–0.06 ± 0.05
NiI	–	–	6.28 ± 0.04	6.29 ± 0.02	6.21 ± 0.02	6.25 ± 0.02	6.19 ± 0.01	6.22 ± 0.02	–0.06 ± 0.02
CuI	–	–	–	–	3.98	–	4.06 ± 0.05	4.05 ± 0.05	–0.14 ± 0.05
ZnI	–	–	4.63	4.48	4.46 ± 0.02	–	4.48	4.46 ± 0.05	–0.15 ± 0.05
YII	–	–	–	2.40	2.27 ± 0.03	–	2.36 ± 0.05	2.30 ± 0.05	+0.06 ± 0.05
BaII	–	–	2.60 ± 0.05	2.65 ± 0.02	2.46 ± 0.01	–	2.42 ± 0.01	2.44 ± 0.02	+0.13 ± 0.02
LaII	–	–	–	–	–	–	1.39	1.39	+0.13
CeII	–	–	–	1.59	–	–	1.72 ± 0.04	1.71 ± 0.04	+0.18 ± 0.04
NdII	–	–	–	–	–	–	1.95	1.95	+0.31

To achieve the best fit, we used a routine that employs a χ^2 test. The σ necessary for the calculation of χ^2 is estimated from the noise in the continuum regions of the spectra .The fit program normalizes model spectra *and* observed spectra using the same points for the continuum definition. We used the Balmer lines H_β to H_{12} (excluding H_ϵ to avoid the CaII H line) for the fit. The formal errors given by the routine are ΔT = 10–20 K, $\Delta\log(g)$ = 0.005–0.01, which, according to Moehler & Sweigart (2006) are half of the true value. For this reason, we assumed $\Delta T_{\rm eff}$ = 20–40 K and $\Delta\log(g)$ = 0.01–0.02 dex as internal uncertainties for our determinations.

Microturbulence velocity was obtained by removing any trend in the relation between abundance and reduced EQW for FeI and FeII lines and the typical internal error is 0.1 km s^{-1}, obtained as in Marino et al. (2008). The adopted values for the atmospheric parameters are reported in Table 1.

Abundances for most of the elements were obtained from EQW measurements. The selected hot stars show clear evidence of rotation. As a consequence, we refrained obtaining EQWs from a Gaussian fitting, but used a direct integration of spectral features. On the other hand, for some elements (He, O) we were forced to apply the spectral synthesis method as explained in Sect. 3. See Fig. 1 for an example of the synthesis for He and O applied to #HD 162817.

From spectral synthesis we were able to also measure the projected rotational velocity of the stars (reported in Table1) by comparing the shape of the spectral lines with synthetic spectra. The typical rotational velocity error is 3–5 km s^{-1} (obtained by comparing rotational velocities from different lines).

The Na abundance was derived from the 5889–5895 Å doublet known to be affected by strong NLTE effect, and NLTE correction for this element can be large (up to –0.50 dex according to Takeda et al. 2003). For hot stars in our regime a full discussion of NLTE correction for Na-double is found in Mashonkina et al. (2000). A correction of –0.30 dex is required for our targets. Also the O triplet at 6156–6158 Å is affected by NLTE and in this case we applied corrections by Takeda (1997).

The NLTE correction for N, necessary for hot stars, is quite a disputed issue (see Takeda 1992; and Lemke & Venn 1996) discussed in Sect. 6, while C abundances were corrected according to Takeda (1992). No NLTE corrections are available in the literature for He or Mg in our $T_{\rm eff}$ regime; however, the Mg abundances we obtained in LTE approximation agree well with those ones obtained from cool dwarf stars, so we conclude that the NLTE correction is not necessary in this case.

For He we simply give the LTE value because any detailed NLTE treatment is beyond the purpose of this paper. However, in Villanova et al. (2009) we studied a sample of hot globular cluster members in a $T_{\rm eff}$-log(g) regime comparable to the hot stars of the present paper. We found an He content in very good agreement with the primordial value for the Universe, which suggests that, for objects cooler than 10 000 K, NLTE correction for He in not very important. We leave a detailed discussion of this argument to a future paper.

6. Results of the spectroscopic analysis

The chemical abundances we obtained are summarized in Table 3. Table 3 demonstrates that there is good agreement

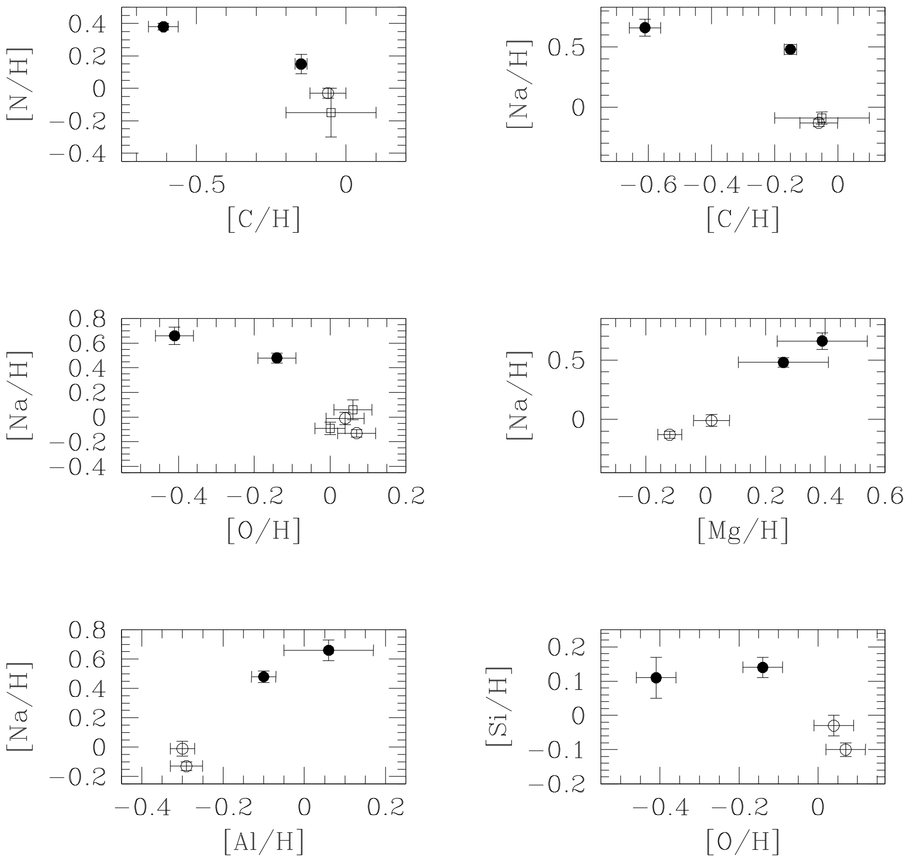

Fig. 2. The correlations N-C, Na-C, Na-O, Na-Mg, Na-Al, and Si-O for our stars. Filled circles are the giants, open ones are the cool dwarf, while open squares are the hot dwarfs.

between hot and cool dwarf stars, as far as the abundances of common elements are concerned, with the mean abundances of the two groups in agreement within 0.10–0.15 dex in the worst case.

Based on this good agreement, we can conclude that HD 162679 and HD 162817 are normal A/B objects, unaffected by deviation of the superficial abundances, which affects peculiar (Ap/Bp) stars. This results agrees with Folsom et al. (2007), where authors find a normal solar chemical composition, within the errors, for HD 162817. On the other hand, Folsom et al. (2007) show that the other NGC 6475 A/B stars in their sample have peculiar composition and present a huge variation in the solar scaled abundances of many elements (from C up to Ba) with respect the mean chemical content of the cluster as traced by cool dwarf or giant stars. This variation can reach the value of ±2.0 dex, depending on the element. Our variation, if present, is lower than 0.10–0.15 dex for all the elements we studied. Because of this we confirm that HD 162679 and HD 162817 do not present surface-abundance peculiarities of Ap/Bp stars. This result can be easily explained by the high rotation of HD 162679 and HD 162817 ($v_e \sin i >$ 35 km s^{-1}), which, according to Hempel & Holweger (2003), mixes the stellar envelope inhibiting diffusion processes that causes chemical anomalies.

Based on this fact we can also affirm that no appreciable differential systematic errors affect the two methods used for abundance analysis that is one of the main aims of this paper. In any case differential systematic errors, if present, are lower than 0.10–0.15 dex for all the chemical abundances we determined.

As for the consistency of our atmospheric parameters for hot stars, Folsom et al. (2007) find for HD 162817 a higher temperature (~300 K) and stronger gravity (~0.1 dex), however in agreement with our values within 1σ. Only rotational velocity is out of the 3σ limits. This is not critical for our results, except in the case of He and O abundances, where spectral synthesis was used. In any case, Fig. 1 shows that the adopted $v_e \sin i$ value reproduces the observed spectrum well.

A second interesting result concerns light elements (from C to Si), which show clear trends (as in Fig. 2) defined by the abundances of the two giants. Those stars turned out to be more C/O-poor and N/Na-rich with respect to the dwarfs. These trends or correlations are similar to those found for GCs, where they seem to be primordial and due to the different composition of the interstellar medium from which stars of different ages were formed (see Gratton et al. 2004, for extensive references) with C/O-poor and N/Na-rich stars representing the younger generation.

In our case, trends are fully explained as an evolutionary effect, due to the migration of light elements produced by the H-burning cycle from deeper regions up to the photosphere after stars have left the MS. However, the two phenomena can be correlated, because the younger generation of C/O-poor and N/Na-rich stars in GCs is thought to be born from material polluted by ejecta of the young massive stars belonging to the older generation. The favorite classes of candidate polluters are three: fast-rotating massive main-sequence stars (Decressin et al. 2007), intermediate-mass AGB stars (D'Antona et al. 2002), and primordial population III stars (Choi & Yi 2007).

In these stars the original superficial abundance of light elements is altered by mixing phenomena concerning products of the H-burning process at high temperature (Langer et al. 1993; Prantzos et al. 2007) like C, N, O, and Na, as is the case of giant stars studied in this paper. In this picture, evolved stars in NGC 6475 could simply be the current version of those AGB intermediate-mass polluter stars present during the first millions of years of a GC lifetime that caused the correlation we see nowadays, and that have now disappeared.

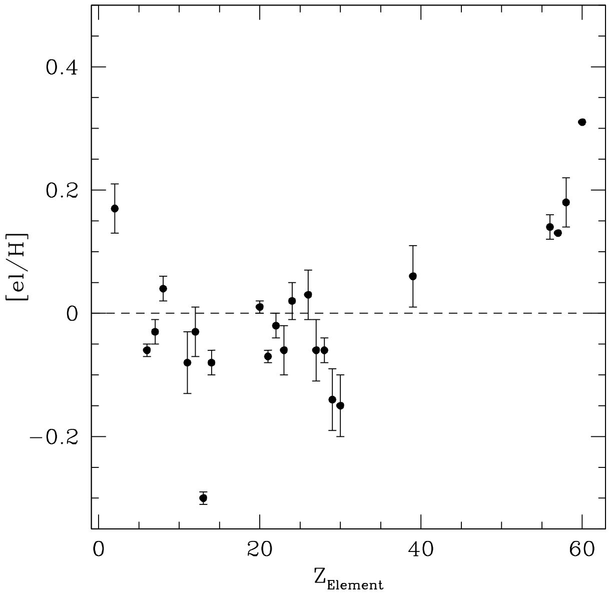

Fig. 3. Abundances of the cluster with respect to the Sun.

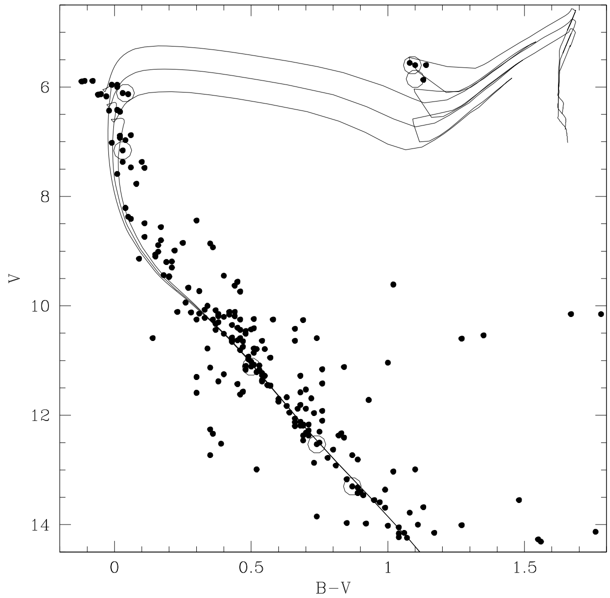

Fig. 4. CMD of NGC 6475. Isochrones of 150, 200, and 250 Myr are plotted. Open circles indicate stars analyzed spectroscopically and confirmed to be cluster members.

According to Table 3 giants also present an overabundance of Ba of ~0.2 dex with respect to the dwarf, but this is more difficult to interpret for us also if some evolutionary mixing phenomenon cannot be ruled out.

The last two columns of Table 3 report the "absolute" and "referred to the Sun" averaged abundances of the cluster as obtained from our 7 stars. Light element and Ba values were calculated by rejecting the two giant stars. Also, N abundance of #HD 162679 was rejected in the calculation of the mean N content because no a priori NLTE correction could be applied. Averaged abundances were calculated using the weighted mean, where the weight w is obtained from the abundance error σ as $w = \sigma^{-2}$. For some elements we could not obtain the error, and we simply assumed $\sigma = 0.15$, which is our upper limit for the error on abundance when a single line is used.

The error on the mean abundance is the r.m.s. divided by the root square of the number of stars used for the calculation, except for N and He, where this procedure gives unreliably low errors. For those elements the error on the mean was assumed to be the mean error on the single star, divided by the square root of the number of stars.

The metallicity of the cluster turns of to be solar or almost solar for most of the elements, especially for the Fe and α (C, O, Mg, Si, Ca, Ti). In particular, the cluster has

$$[\mathrm{Fe/H}] = +0.03 \pm 0.02\ \mathrm{dex},\ \ [\alpha/\mathrm{Fe}] = -0.06 \pm 0.02\ \mathrm{dex}.$$

In spite of this, some elements deviate considerably from the solar composition. Helium turns out to be supersolar by 0.11 dex. This translates into

$$Y = 0.33 \pm 0.02.$$

We underline that He was determined in an LTE approximation, as discussed before. However this value does not sound unreasonable for such a young cluster (Age ~ 200 Myr).

Al turns out to be strongly subsolar (~–0.3 dex). Both Cu and Zn result underabundant by about –0.15 dex, while La, Ce, and Nd are overabundant. Finally s-process elements Y and Ba show a overabundance of ~0.1 dex. The chemical content of the cluster with respect to the Sun is plotted in Fig. 3.

Some additional discussion is needed for the N abundance of the stars HD 162679. For Vega (that has similar parameters as HD 162679), Takeda (1992) and Lemke & Venn (1996) report two different values for the NLTE correction: the former gives –0.8 dex, while the latter –0.4 dex. Comparing the N abundance of HD 162679 with the mean of the dwarf stars (JJ8 and JJ10), we see that a correction of ~–0.3 dex is required to match the two values. We conclude that our data suggest that the right NLTE correction is the one by Lemke & Venn (1996), so we applied this value to our data, both for HD 162679 and to Vega.

Finally, we want to compare our results with Sestito et al. (2003), who determined cluster metallicity from a sample of 30 dwarfs. They give a value of +0.14 ± 0.06 for the Fe content. The agreement with our results is within 1.5σ. We attribute this difference to the methods used. Sestito et al. (2003) obtain temperature and microturbulence from photometry using previously calibrated color-T_{eff} and v_t-T_{eff}-log(g) relations. In contrast with that, our T_{eff} and v_t values were obtained directly from spectra. Therefore it is not surprising that the two results do not agree perfectly.

7. NGC 6475 basic parameters revisited

Based on the detailed chemical analysis detailed in the previous sections, we revise here the cluster fundamental parameter using the Padova suite (Girardi et al. 2000) of stellar models and isochrones. Previous determinations of cluster properties are described in Meynet et al. (1993) and Kharchenko et al. (2005). They derive a logarithmic age of 8.35–8.22, which is compatible with the distance of 280 ± 26 pc determined by Robichon et al. (1999).

The cluster metallicity is basically solar, so that adopting $Z = 0.019$ seems an adequate compromise, provided that the amount of α-element underabundance is almost negligible within the errors. The procedure is highlighted in Fig. 4, where photometric data taken from Prosser et al. (1996) are compared with three solar metallicity isochrones for ages of 150, 200, and 250 Myr.

In general the fit is good, especially for the main sequence. For turn-off and red-clump regions (where the cluster population is not well-defined), the fit is not well-constrained and stars seems to cover a age range between 150 (giants) and

200–250 Myr (TO stars). A reason for this mismatch could be that giant stars do not have the same superficial abundance with respect to the dwarfs due to evolutionary phenomena, which are not considered in the isochrones. The age we derive is therefore 200 ± 50 Myr.

The fit was obtained by shifting the isochrones by $E(B-V) = 0.08$, and $(m-M)_V = 7.65$. A reddening of 0.08 mag is confirmed also by the two-color diagram ($U - B$ vs. $B - V$, not reported here), where the few blue stars with UBV magnitudes are well-fitted by the ZAMS obtained from Padova isochrones shifted by the previously reported reddening. This value lies in the middle of the range given by the literature (0.06–0.10 mag).

Based on a visual inspection, we estimated errors of 0.02 and 0.05 mag. on reddening and apparent distance modulus, respectively. We inferred a distance of 300 ± 10 pc, in agreement with previous estimates, and this is the value also reported in WEBDA. We underline that reddening and distance of the cluster are very well-constrained by our study, mainly because we could confirm the former parameter obtained by the isochrone fitting by the two-color diagram. On the other hand, age is not well determined because the turn-off and red-clump regions of the cluster are poorly defined.

8. Conclusions

We studied a sample of stars belonging to the open cluster NGC 6475 (M 7) covering a wide range in temperature (4500–13 000 K) and gravities (both dwarf and giants). Spectroscopic data were obtained from the UVES POP database, and the photometric ones from WEBDA database.

Our aim was to determine abundances of a large number of elements (from He to Nd) in different kinds of objects, which require different methodologies. Parameters ($T_{\rm eff}$ and $\log(g)$) for cool MS and Giant stars were obtained by the FeI/II abundance equilibrium method, while for hot MS stars they were determined from the shape of H Balmer lines. For these two group of objects two sets of line-lists were used, calibrated on the Sun and Vega, respectively. Abundances were obtained in LTE aproximation, but NLTE correction from the literature was applied for several elements (C, N, O, Na, Mg) and hyperfine structure was considered for V and Ba.

Abundances of common elements in hot and cool MS stars agree very well (within 0.10–0.15 dex), leading to the conclusion that the methods used for the two kind of objects are not affected by appreciable relative systematic errors. On the other hand, abundances for the two giants stars do not agree with the ones obtained for MS, as far as light elements and Ba are concerned. This indicates that an evolutionary effect changes the photospherical chemical composition when stars leave the MS. These stars could be the current version of those massive polluters present during the first millions of years of a GC lifetime, which altered the chemical composition of the intracluster medium from which they formed as discussed in Sect. 6. This contamination is visible nowadays in the Na-O anticorrelation found to affect almost all GCs.

The cluster turns out to have solar composition ([Fe/H] = +0.03, [α/Fe] = –0.06) within ±0.1 dex for most of the elements. A overabundance was found for He and heavy elements (Ba, La, Ce, Nd), and a strong underabundance for Al.

Finally the cluster parameters were revised. We obtained $E(B-V) = 0.08$, $(m-M)_V = 7.65$, and an age of about 200 Myr.

Acknowledgements. This study made use of ESO, SIMBAD and WEBDA databases.

References

Asplund, M. 2005, ARA&A, 43, 481
Bagnulo, S., Jehin, E., Ledoux, C., et al. 2003, The Messenger, 114, 10
Ballester, P., Modigliani, A., Boitquin, O., & The ESO Paranal Science Operations Team 2000, ESO Messenger, 101, 31
Baumueller, D., & Gehren, T. 1997, A&A, 325, 1088
Choi, E., & Yi, S. K. 2007, MNRAS, 375, L1
D'Antona, F., Caloi, V., Montalbán, J., Ventura, P., & Gratton, R. 2002, A&A, 395, 69
Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., & Ekström, S. 2007, A&A, 464, 1029
Folsom, C. P., Wade, G. A., Bagnulo, S., & Landstreet, J. D. 2007, MNRAS, 376, 361
Fossati, L., Bagnulo, S., Monier, R., et al. 2007, A&A, 476, 911
Fossati, L., Bagnulo, S., Landstreet, J., et al. 2008, A&A, 483, 891
Gebran, M. & Monier, R. 2008, A&A, 483, 567
Gebran, M., Monier, R., & Richard, O. 2008, A&A, 479, 189
Gehren, T., Liang, Y. C., Shi, J. R., Zhang, H. W., & Zhao, G. 2004, A&A, 413, 1045
Girardi, L., Bressan, A., Bertelli, G., & Chiosi, C. 2000, A&AS, 141, 371
Gratton, R., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
Gratton, R. G., Carretta, E., Eriksson, K., & Gustafsson, B. 1999, A&A, 350, 955
Gratton, R. G., Carretta, E., Claudi, R., Lucatello, S., & Barbieri, M. 2003, A&A, 404, 187
Grevesse, N., & Sauval, A. J. 1998, Space Sci. Rev., 85, 161
Hempel, M., & Holweger, H. 2003, A&A, 408, 1065
Kharchenko, N. V., Piskunov, A. E., Röser, S., Schilbach, E., & Scholz, R.-D. 2005, A&A, 438, 1163
Kupka, F. G., Ryabchikova, T. A., Piskunov, N. E., Stempels, H. C., & Weiss, W. W. 2000, Baltic Astron., 9, 590
Kurucz, R. L. 1992, in The Stellar Populations of Galaxies, ed. B. Barbuy, & A. Renzini, IAU Symp., 149, 225
Kurucz, R. L., Furenlid, I., Brault, J., & Testerman, L. 1984, Solar flux atlas from 296 to 1300 nm, National Solar Observatory Atlas, Sunspot, New Mexico: National Solar Observatory
Langer, G. E., Hoffman, R., & Sneden, C. 1993, PASP, 105, 301
Lemke, M., & Venn, K. A. 1996, A&A, 309, 558
Marino, A. F., Villanova, S., Piotto, G., et al. 2008, A&A, 490, 625
Mashonkina, L. I., Shimanskiĭ, V. V., & Sakhibullin, N. A. 2000, Astron. Rep., 44, 790
McWilliam, A. 1998, AJ, 115, 1640
McWilliam, A., & Rich, R. M. 1994, ApJS, 91, 749
Meynet, G., Mermilliod, J.-C., & Maeder, A. 1993, A&AS, 98, 477
Moehler, S., & Sweigart, A. V. 2006, A&A, 455, 943
Moultaka, J., Ilovaisky, S. A., Prugniel, P., & Soubiran, C. 2004, PASP, 116, 693
Prantzos, N., Charbonnel, C., & Iliadis, C. 2007, A&A, 470, 179
Prosser, C. F., Randich, S., & Stauffer, J. R. 1996, AJ, 112, 649
Qiu, H. M., Zhao, G., Chen, Y. Q., & Li, Z. W. 2001, ApJ, 548, 953
Robichon, N., Arenou, F., Mermilliod, J.-C., & Turon, C. 1999, A&A, 345, 471
Sestito, P., Randich, S., Mermilliod, J.-C., & Pallavicini, R. 2003, A&A, 407, 289
Sneden, C. 1973, ApJ, 184, 839
Straizys, V., & Kuriliene, G. 1981, Ap&SS, 80, 353
Takeda, Y. 1992, PASJ, 44, 649
Takeda 1997, PASJ, 49, 471
Takeda, Y., & Honda, S. 2005, PASJ, 57, 65
Takeda, Y., Zhao, G., Takada-Hidai, M., et al. 2003, Chin. J. Astron. Astrophys., 3, 316
Takeda, Y., Kawanomoto, S., & Ohishi, N. 2007, PASJ, 59, 245
Villanova, S., Piotto, G., & Gratton, R. G. 2009, A&A, 499, 755