Chemical abundance analysis of the open clusters Cr 110, NGC 2099 (M 37), NGC 2420, NGC 7789, and M 67 (NGC 2682)^{*,**}

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ABSTRACT

Context. The present number of Galactic open clusters that have high resolution abundance determinations, not only of [Fe/H], but also of other key elements, is largely insufficient to enable a clear modeling of the Galactic disk chemical evolution.

Aims. To increase the number of Galactic open clusters with high quality measurements.

Methods. We obtained high resolution ($R \sim 30\,000$), high quality ($S/N \sim 50\text{--}100$ per pixel), echelle spectra with the fiber spectrograph FOCES, at Calar Alto, Spain, for three red clump stars in each of five Open Clusters. We used the classical equivalent width analysis method to obtain accurate abundances of sixteen elements: Al, Ba, Ca, Co, Cr, Fe, La, Mg, Na, Nd, Ni, Sc, Si, Ti, V, and Y. We also derived the oxygen abundance using spectral synthesis of the 6300 Å forbidden line.

Results. Three of the clusters were never studied previously with high resolution spectroscopy: we found [Fe/H] = $+0.03 \pm 0.02$ (± 0.10) dex for Cr 110; [Fe/H] = $+0.01 \pm 0.05$ (± 0.10) dex for NGC 2099 (M 37), and [Fe/H] = -0.05 ± 0.03 (± 0.10) dex for NGC 2420. This last finding is higher than typical literature estimates by 0.2–0.3 dex approximately and in closer agreement with Galactic trends. For the remaining clusters, we find that [Fe/H] = $+0.05 \pm 0.02$ (± 0.10) dex for M 67 and [Fe/H] = $+0.04 \pm 0.07$ (± 0.10) dex for NGC 7789. Accurate (to $\sim 0.5\text{ km s}^{-1}$) radial velocities were measured for all targets, and we provide the first velocity estimate derived from high resolution data for Cr 110, $\langle V_r \rangle = 41.0 \pm 3.8\text{ km s}^{-1}$.

Conclusions. With our analysis of the new clusters Cr 110, NGC 2099, and NGC 2420, we increase the sample of clusters with high-resolution-based abundances by 5%. All our program stars show abundance patterns which are typical of open clusters, very close to solar with few exceptions. This is true for all the iron-peak and *s*-process elements considered, and no significant α -enhancement is found. No significant (anti-)correlations for Na, Al, Mg, and O abundances are found. If anticorrelations are present, the involved spreads must be <0.2 dex. We then compile high resolution data of 57 OC from the literature and find a gradient of [Fe/H] with Galactocentric radius of $-0.06 \pm 0.02\text{ dex kpc}^{-1}$, in agreement with past work and with results for Cepheids and B stars in the same range. A change of slope is seen outside $R_{GC} = 12\text{ kpc}$ and $[\alpha/\text{Fe}]$ shows a tendency to increase with R_{GC} . We also confirm the absence of a significant age-metallicity relation, finding slopes of $-2.6 \pm 1.1 \times 10^{-11}\text{ dex Gyr}^{-1}$ and $1.1 \pm 5.0 \times 10^{-11}\text{ dex Gyr}^{-1}$ for [Fe/H] and $[\alpha/\text{Fe}]$ respectively.

Key words. stars: abundances – Galaxy: disk – open clusters and associations: general

1. Introduction

Open clusters (hereafter OC) are ideal *test particles* in the study of the Galactic disk, providing chemical and kinematical information in different locations for different times. Compared to field stars, they have the obvious advantage of being coeval groups of stars, at the same distance and with a homogeneous composition. Therefore, their properties can be determined with smaller uncertainties. Several attempts have been made to derive two fundamental relations using OC: the *metallicity gradient* along the disk and the *age-metallicity relation* (hereafter AMR) of the disk (e.g., Janes 1979; Panagia & Tosi 1980; Twarog et al. 1997; Friel et al. 2002; Chen et al. 2003; Salaris et al. 2004), but

they were hampered by the lack of large and homogeneous high quality datasets.

In particular, the lack of a *metallicity scale* extending to solar metallicity with comparable precision to that of the lower metallicity regime (i.e., Zinn & West 1984; Carretta & Gratton 1997) represents the main problem from the point of view of (i) the study of the Galactic disk, (ii) tests of stellar evolution models for younger and more metal-rich *simple stellar populations*, and (iii) the use of those stellar populations as templates for extragalactic studies of population synthesis. Of the ~ 1700 known OC (Dias et al. 2002, and updates), only a subset of ~ 140 , i.e., 8% of the total, possesses some metallicity determination. Most of these have been obtained by means of different photometric studies in the Washington (e.g., Geisler et al. 1991, 1992), DDO (e.g., Clariá et al. 1999), Strömgren (e.g., Bruntt et al. 1999; Twarog et al. 2003), UB_V (e.g., Cameron 1985), and IR (e.g., Tiede et al. 1997) photometric systems and passbands, often giving rise to considerable differences from those obtained from spectroscopy (see Gratton 2000, and references therein). In a far smaller number of clusters, abundances have been derived from

* Based on data collected with the fiber spectrograph FOCES at the 2.2 m Calar Alto Telescope. Also based on data from the 2MASS survey and the WEBDA, VALD, NIST, and GEISA online databases.

** Full Table 5 is 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/cgi-bin/qcat?J/A+A/511/A56>

Table 1. Observing logs and program stars data.

Cluster	Star	α_{J2000} (h)	δ_{J2000} (deg)	B (mag)	V (mag)	I_C (mag)	R (mag)	K_S (mag)	n_{exp}	$t_{\text{exp}}^{(\text{tot})}$ (s)	$S/N (\approx 6000 \text{ \AA})$
Cr 110 ^a	2108	06:38:52.5	+02:01:58.4	14.79	13.35	–	–	9.76	6	16200	70
	2129	06:38:41.1	+02:01:05.5	15.00	13.66	12.17	12.94	10.29	7	18900	70
	3144	06:38:30.3	+02:03:03.0	14.80	13.49	12.04	12.72	10.19	6	16195	65
NGC 2099 (M 37) ^b	067	05:52:16.6	+32:34:45.6	12.38	11.12	9.87	–	8.17	3	3600	95
	148	05:52:08.1	+32:30:33.1	12.36	11.09	–	–	8.05	3	3600	105
	508	05:52:33.2	+32:27:43.5	12.24	10.98	–	–	7.92	3	3900	85
NGC 2420 ^c	041	07:38:06.2	+21:36:54.7	13.75	12.67	11.61	12.13	10.13	5	9000	70
	076	07:38:15.5	+21:38:01.8	13.65	12.66	11.65	12.14	10.31	5	9000	75
	174	07:38:26.9	+21:38:24.8	13.41	12.40	–	–	9.98	5	9000	60
NGC 2682 (M 67) ^d	0141	08:51:22.8	+11:48:01.7	11.59	10.48	9.40	9.92	7.92	3	2700	85
	0223	08:51:43.9	+11:56:42.3	11.68	10.58	9.50	10.02	8.00	3	2700	85
	0286	08:52:18.6	+11:44:26.3	11.53	10.47	9.43	9.93	7.92	3	2700	105
NGC 7789 ^e	5237	23:56:50.6	+56:49:20.9	13.92	12.81	11.52	–	9.89	5	9000	70
	7840	23:57:19.3	+56:40:51.5	14.03	12.82	11.49	–	9.83	6	9000	75
	8556	23:57:27.6	+56:45:39.2	14.18	12.97	11.65	–	10.03	3	5400	45

Notes. ^(a) Star names and I_C and R magnitudes from Dawson & Ianna (1998); coordinates and B and V magnitudes from Bragaglia & Tosi (2003); K_S magnitudes from 2MASS. ^(b) Star names from van Zeipel & Lindgren (1921); coordinates from Kiss et al. (2001); B and V magnitudes from Kalirai et al. (2001); I_C magnitudes from Nilakshi & Sagar (2002); K_S magnitudes from 2MASS. ^(c) Star names from Cannon & Lloyd (1970); coordinates from Stetson (2000) and Lasker et al. (1990); B and V magnitudes from Anthony-Twarog et al. (1990); I_C and R magnitudes from Stetson (2000); K_S magnitudes from 2MASS. ^(d) Star names from Fagerholm (1906); coordinates from Fan et al. (1996); B , V and I_C magnitudes from Sandquist (2004); B magnitude for star 286 and R magnitudes from Janes & Smith (1984); K_S magnitudes from 2MASS. ^(e) Star names and V and I_C magnitudes from Gim et al. (1998a); J1950 coordinates from Kustner (1923), precessed to J2000; B magnitudes from Mochejska & Kaluzny (1999); K_S magnitudes from 2MASS.

low-resolution spectroscopy (e.g., Carrera et al. 2007; Warren & Cole 2009), and there have been admirable attempts to obtain large and homogeneous datasets (see Friel & Janes 1993; Friel et al. 2002) in spite of the non-negligible uncertainties involved in the procedure.

A few research groups (see Sect. 6 for more details) are presently obtaining high quality spectra and are deriving more precise abundance measurements. The study of elements other than the iron-peak ones (such as α , s -, and r -process, light elements) allows one to place stronger constraints on the sites of production of those elements (SNe Ia, SNe II, giants, supergiants, and Wolf-Rayet stars) and therefore on their production timescales. These are fundamental ingredients to the chemical evolution modeling of the Galactic disk (Tosi 1982; Chiappini et al. 2001; Colavitti et al. 2009).

For these reasons, we obtained high resolution spectra for a sample of poorly studied old OC. We present here the detailed abundance analysis of five clusters observed during our first run at Calar Alto. Observations and data reductions are described in Sect. 2; the linelist and equivalent width measurements are described in Sect. 3, while the abundance analysis methods and results are presented in Sect. 4; abundance results are then discussed and compared with literature results in Sects. 5–7; finally, we summarize our results and draw our conclusions in Sect. 8.

2. Observational material

Three red clump stars¹ were selected in each of the target clusters using the WEBDA² database (Mermilliod 1995) and the

2MASS³ survey data for the infrared K_S mag (Skrutskie et al. 2006). More details about the references for star names, coordinates and magnitudes can be found in Table 1, while the position of our targets in the color magnitude diagrams (CMDs) obtained from WEBDA are shown in Fig. 1.

Observations were performed between the 1st and 10th of January 2004 with the fiber echelle spectrograph FOCES at the 2.2 m Calar Alto Telescope, in Spain. The sky was generally clear, although a few nights had thin cirrus and sometimes clouds, forcing us to increase the exposure times considerably. All stars were observed in 3–16 exposures lasting 15–90 min each, depending on the magnitude, until a global S/N ratio between 70 and 100 (per pixel) was reached around 6000 Å (Table 1). Each night, we took a sky exposure with an exposure time as long as that of the longest scientific exposure. The sky level was negligible for all exposures with $S/N > 20$, therefore exposures with $S/N < 20$ were neglected and we did not subtract the sky, to avoid adding noise to the spectra. Sky emission lines, even in the red part of the spectrum, only occasionally affected the measurements of some absorption lines, which were discarded. The spectral resolution was $R \approx 30\,000$ for all spectra.

2.1. Data reduction

Data reductions were done with IRAF⁴ within the *imred* and *echelle* packages. The following steps were performed: bias subtraction, flatfielding, order tracing with optimal extraction,

³ <http://www.ipac.caltech.edu/2mass>. 2MASS (Two Micron All Sky Survey) is a joint project of the University of Massachusetts and the Infrared Processing and Analysis Center/California Institute of Technology, funded by the National Aeronautics and Space Administration and the National Science Foundation.

⁴ Image Reduction and Analysis Facility. IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

¹ Although fainter than the brightest giants, red clump stars have the advantage of a higher gravity and temperature that considerably reduces line crowding. Clump stars are also easy to identify even in the sparsest clusters, maximizing the chance of choosing cluster members.

² <http://www.univie.ac.at/webda>

Fig. 1. V , $(B - V)$ Color Magnitude Diagrams of the program clusters (from the WEBDA), with the location of our target stars.

background subtraction, wavelength calibration with the help of a Thorium-Argon lamp, and final merging (and rebinning) of overlapping orders. The one-dimensional spectra obtained from different exposures (with $S/N > 20$) were median-averaged to produce one single high S/N spectrum for each star, used for equivalent width measurements (Sect. 3.3). Finally, the noisy ends of each combined spectrum were cut, allowing for an effective wavelength coverage from 5000 to 9000 Å.

Sky absorption lines (telluric bands of O_2 and H_2O) were removed using the IRAF task *telluric* with the help of two hot, rapidly rotating stars, HR 3982 and HR 8762, chosen from the *Bright Star Catalogue* (Hoffleit & Jaschek 1991). HR 3982 and HR 8762 were observed each night at an airmass not too different from the scientific targets. Residuals of the correction in the red part of the spectrum (for example, from the strong O_2 band around 7600 Å) prevented us from using most of the corresponding spectral regions in our abundance analysis. Also, after 8400 Å, the echelle orders do not overlap anymore and small gaps appear.

2.2. Radial velocities

Radial velocities were measured with the help of DAOSPEC (Stetson & Pancino 2008, see also Sect. 3.3). Measurements were based on ≈ 360 absorption lines of different elements (see Sect. 3) with typical measurement errors on the mean of about 0.1 km s^{-1} . All measurements were performed separately on the one-dimensional spectra extracted from the single exposures for each star, including those with $S/N < 20$, which were not used in the abundance analysis. In this way, we could check that no significant radial velocity variations were present.

Heliocentric corrections were computed with the IRAF task *rvcor*, which bears a negligible uncertainty of less than 0.005 km s^{-1} . Since we did not observe any radial velocity standard and our calibration lamp data were not acquired simultaneously, we used telluric absorption lines to find the absolute zeropoint of our radial velocity measurements. In particular, laboratory wavelengths of the H_2O absorption bands around 5800, 6500, 7000, 7200, 8000, and 8900 Å and the O_2 absorption bands around 6300, 6900, and 7600 Å were obtained from

Table 2. Heliocentric radial velocities measurements and their 1σ errors ($V_r \pm \delta V_r$)_{here} for each program star.

Cluster	Star	$(V_r \pm \delta V_r)_{\text{here}}$ (km s^{-1})	$(V_r \pm \sigma V_r)_{\text{lit}}$ (km s^{-1})
Cr 110	2108	44.47 ± 0.54	45 ± 8^a
	2129	38.74 ± 0.64	45 ± 8^a
	3144	37.81 ± 0.69	45 ± 8^a
NGC 2099 (M 37)	067	8.79 ± 0.10	8.04 ± 0.19^b
	148	9.05 ± 0.36	8.73 ± 0.19^b
	508	9.40 ± 0.28	8.96 ± 0.19^b
NGC 2420	041	74.23 ± 0.87	79.0 ± 4.2^c
	076	75.49 ± 0.41	75.7 ± 8.6^c
	174	73.66 ± 1.17	68.0 ± 0.9^c
NGC 2682 (M 67)	141	35.23 ± 0.05	33.5 ± 2.3^d
	223	34.92 ± 0.31	33.0 ± 1.1^d
	286	38.90 ± 0.46	33.2 ± 2.0^d
NGC 7789	5237	-51.06 ± 0.99	-57.17 ± 0.23^e
	7840	-49.06 ± 0.81	-49.21 ± 0.28^e
	8556	-53.37 ± 0.81	-54.10 ± 0.32^e

Notes. Literature measurements, when available, are also reported with their uncertainties ($V_r \pm \delta V_r$)_{lit}.

^(a) Cluster average by Carrera et al. (2007), based on 8 stars.

^(b) Mermilliod et al. (2008), superseding Mermilliod et al. (1996).

^(c) Average of measurements by Liu & Janes (1987), Friel et al. (1989) and Scott et al. (1995). ^(d) Average of measurements by Mathieu et al. (1986), Pilachowski et al. (1988), Friel et al. (1989), Friel & Janes (1993), Suntzeff et al. (1992), Scott et al. (1995), Melo et al. (2001), Yong et al. (2005), Yadav et al. (2008). ^(e) Gim et al. (1998b).

the GEISA⁵ database (Jacquinet-Husson et al. 1999, 2005) and we measured their radial velocity in our program stars. The resulting zeropoint corrections, based on 200–250 telluric lines, amount to generally no more than $\pm 1 \text{ km s}^{-1}$ with typical errors in the mean of about 0.5 km s^{-1} , approximately five times larger than those in the radial velocity measurements.

After applying the above corrections, and propagating the corresponding uncertainties, we computed a weighted average of the heliocentric velocities estimates for each exposure (see Table 2). All the program stars appear to be radial velocity members of the observed clusters, the possible exception being star

⁵ <http://ara.lmd.polytechnique.fr/htdOC-public/products/GEISA/HTML-GEISA/>

Table 3. Stellar parameters for the program stars.

Cluster	Star	$T_{\text{eff}}^{(\text{phot})}$ (K)	$T_{\text{eff}}^{(\text{spec})}$ (K)	$\log g^{(\text{phot})}$ (cgs)	$\log g^{(\text{spec})}$ (cgs)	$v_t^{(\text{phot})}$ (km s ⁻¹)	$v_t^{(\text{spec})}$ (km s ⁻¹)	M_{clump} ($M_{\odot}$)
Cr 110	2108	4914 ± 111	4650	2.32 ± 0.16	2.8	1.20 ± 0.02/1.62 ± 0.04	1.4	1.9 ± 0.1
	2129	5056 ± 223	4950	2.53 ± 0.19	2.7	1.17 ± 0.02/1.52 ± 0.06	1.4	1.9 ± 0.1
	3144	5112 ± 258	4800	2.49 ± 0.20	2.8	1.18 ± 0.02/1.49 ± 0.08	1.3	1.9 ± 0.1
NGC 2099 (M 37)	067	4773 ± 119	4550	2.15 ± 0.32	2.7	1.22 ± 0.03/1.68 ± 0.05	1.5	2.7 ± 0.2
	148	4708 ± 116	4550	2.10 ± 0.31	2.7	1.28 ± 0.03/1.72 ± 0.04	1.5	2.7 ± 0.2
	508	4715 ± 115	4500	2.05 ± 0.32	2.8	1.23 ± 0.03/1.72 ± 0.04	1.5	2.7 ± 0.2
NGC 2420	041	4616 ± 77	4850	2.43 ± 0.06	2.6	1.19 ± 0.01/1.76 ± 0.03	1.4	1.4 ± 0.1
	076	4755 ± 103	4800	2.51 ± 0.06	2.6	1.18 ± 0.01/1.69 ± 0.03	1.6	1.4 ± 0.1
	174	4730 ± 77	4800	2.39 ± 0.05	2.6	1.19 ± 0.01/1.71 ± 0.03	1.5	1.4 ± 0.1
NGC 2682 (M 67)	141	4590 ± 100	4650	2.42 ± 0.04	2.8	1.19 ± 0.01/1.78 ± 0.04	1.3	1.3 ± 0.1
	223	4594 ± 100	4800	2.46 ± 0.04	2.8	1.18 ± 0.00/1.78 ± 0.04	1.3	1.3 ± 0.1
	286	4653 ± 103	4850	2.45 ± 0.04	2.8	1.18 ± 0.01/1.75 ± 0.04	1.4	1.3 ± 0.1
NGC 7789	5237	4868 ± 168	4900	2.53 ± 0.15	2.8	1.17 ± 0.02/1.63 ± 0.04	1.2	1.8 ± 0.1
	7840	4759 ± 131	4800	2.47 ± 0.15	2.7	1.18 ± 0.02/1.69 ± 0.04	1.5	1.8 ± 0.1
	8556	4775 ± 135	4900	2.54 ± 0.15	2.9	1.17 ± 0.02/1.68 ± 0.04	1.4	1.8 ± 0.1

2108 in Cr 110, which has a slightly higher velocity than both 2129 and 3144. However, since the value for 2108 is within 3σ of the mean value for the cluster, we decided not to reject this star. We can provide the first radial velocity estimate based on high resolution for Cr 110: $\langle V_r \rangle = 41.0 \pm 3.8$ km s⁻¹. Our determinations are generally in good agreement with literature values within 3σ , except maybe for star 5237 in NGC 7789, which is marginally discrepant with the estimate by Gim et al. (1998b). However, there is perfect agreement between the two studies for the other two stars of NGC 7789, and our estimate appears more consistent with membership of 5237. In conclusion, we considered all the program stars as likely radial velocity members of their respective clusters.

2.3. Photometric parameters

We first computed the dereddened colors⁶ $(B - V)_0$, $(V - I_C)_0$ ⁷, and $(V - K_TCS)_0$ ⁸. The adopted $E(B - V)$ values are indicated in Table 4, where $E(V - I_C)$ was obtained with the reddening laws by Dean et al. (1978), and $E(V - K_TCS)$ with Cardelli et al. (1989). We were then able to obtain T_{eff} and the bolometric correction BC_V for each program star, using both the Alonso et al. (1999) and the (theoretical and empirical) Montegriffo et al. (1998) color-temperature relations, taking into account the uncertainties in the magnitudes and reddening estimates. The average difference between the Alonso et al. (1999) and the Montegriffo et al. (1998) temperatures was $\Delta T_{\text{eff}} = 178 \pm 66$ K (for the empirical calibration of Montegriffo et al. 1998) and $\Delta T_{\text{eff}} = 127 \pm 69$ K (for the theoretical calibration of Montegriffo et al. 1998). We averaged all the above T_{eff} estimates to obtain our photometric reference values and their 1σ uncertainties (Table 3).

⁶ Since R magnitudes are available for less than half of our sample, we decided to ignore them in the following.

⁷ After dereddening, $(V - I_C)$ was also converted into $(V - I_f)$ using the prescription by Bessell (1979), to be used with the color-temperature relations by Alonso et al. (1999).

⁸ We computed the K_TCS magnitudes from the 2MASS TCS magnitudes using the prescription by Kinman & Castelli (2002).

Gravities were obtained from T_{eff} and BC_V using the fundamental relations

$$\log \frac{g}{g_{\odot}} = \log \frac{M}{M_{\odot}} + 2 \log \frac{R_{\odot}}{R},$$

$$0.4 (M_{\text{bol}} - M_{\text{bol},\odot}) = -4 \log \frac{T_{\text{eff}}}{T_{\text{eff},\odot}} + 2 \log \frac{R_{\odot}}{R},$$

where red clump masses were derived using Table 1 of Girardi & Salaris (2001), and are also shown in Table 3. We assumed that $\log g_{\odot} = 4.437$, $T_{\text{eff},\odot} = 5770$ K, and $M_{\text{bol},\odot} = 4.75$, in conformity with IAU recommendations (Andersen 1999). The difference between the Alonso et al. (1999) and the (empirical and theoretical, respectively) Montegriffo et al. (1998) estimates was $\Delta \log g = 0.20 \pm 0.13$ and $\Delta \log g = 0.18 \pm 0.13$. As above, we averaged all our estimates to obtain photometric gravities $\log g^{(\text{phot})}$ (Table 3) and their 1σ uncertainties.

Finally, a photometric estimate of the microturbulent velocities v_t was obtained using the prescriptions of both Ramírez & Cohen (2003), i.e., $v_t = 4.08 - 5.01 \times 10^{-4} T_{\text{eff}}$, and Carretta et al. (2004), i.e., $v_t = 1.5 - 0.13 \log g$. The latter takes into account the systematic effect discussed by Magain (1984) and is on average lower by $\Delta v_t = 0.49 \pm 0.08$ km s⁻¹ than the one by Ramírez & Cohen (2003). However, the correction for the Magain (1984) effect depends strongly on the data quality (i.e., resolution, S/N ratio, number of lines used, $\log gf$ values etc.). Therefore we chose not to average the two estimates, but to use them as an indication of the (wide) v_t range to explore in our abundance analysis (see Sect. 4.1).

3. Linelist, atomic data and equivalent widths

We created a masterlist of absorption lines by visually comparing our spectra with the the UVES solar spectrum⁹ in the range 5000–9000 Å, and with the linelists extracted from the VALD¹⁰ database (Kupka et al. 1999) and the Moore¹¹ (Moore et al. 1966) solar atlas. The masterlist was fed to DAOSPEC,

⁹ http://www.eso.org/observing/dfo/quality/UVES/pipeline/solar_spectrum.html

¹⁰ <http://www.astro.uu.se/~vald/>

¹¹ <ftp://ftp.noao.edu/fts/linelist/Moore>

Table 4. Input cluster parameters.

Cluster	$E(B - V)$ (mag)	$(m - M)_V$ (mag)	log Age (dex)
Cr 110 ^a	0.54 ± 0.03	13.37 ± 0.38	9.23 ± 0.15
NGC 2099 (M 37) ^b	0.27 ± 0.04	11.53 ± 0.19	8.61 ± 0.16
NGC 2420 ^c	0.04 ± 0.03	11.88 ± 0.27	9.47 ± 0.17
NGC 2682 (M 67) ^d	0.04 ± 0.02	9.67 ± 0.11	9.64 ± 0.05
NGC 7789 ^e	0.27 ± 0.04	12.23 ± 0.20	9.21 ± 0.12

Notes. ^(a) Averages of measurements by Tsarevskii & Abakumov (1971), Dawson & Ianna (1998), and Bragaglia & Tosi (2006). ^(b) Averages of measurements by West (1967a), Jennens & Helfer (1975), Lyngå (1987), Mermilliod et al. (1996), Twarog et al. (1997), Kiss et al. (2001), Kalirai et al. (2001), Nilakshi & Sagar (2002), Grocholski & Sarajedini (2003), Bragaglia & Tosi (2006), and Hartman et al. (2008). ^(c) Averages of measurements by McClure et al. (1974), Barbaro & Pigatto (1984), Vandenberg (1985), Lyngå (1987), Anthony-Twarog et al. (1990), Carraro & Chiosi (1994), Demarque et al. (1994), Twarog et al. (1997), Tadross et al. (2002), and Grocholski & Sarajedini (2003). ^(d) Averages of measurements by Racine (1971), Barbaro & Pigatto (1984), Vandenberg (1985), Nissen et al. (1987), Hobbs & Thorburn (1991), Gilliland & Brown (1992), Demarque et al. (1992), Meynet et al. (1993), Montgomery et al. (1993), Carraro & Chiosi (1994), Dinescu et al. (1995), Fan et al. (1996), Twarog et al. (1997), Sarajedini (1999), Tadross et al. (2002), Grocholski & Sarajedini (2003), Vandenberg & Clem (2003), Laugalyis et al. (2004), and Sandquist (2004). ^(e) Averages of measurements by Burbidge & Sandage (1958), Arp (1962), Strom & Strom (1970), Jennens & Helfer (1975), Janes (1977), Claria (1979), Twarog & Tyson (1985), Lyngå (1987), Mazzei & Pigatto (1988), Friel & Janes (1993), Martinez Roger et al. (1994), Janes & Phelps (1994), Twarog et al. (1997), Gim et al. (1998b), Sarajedini (1999), Vallenari et al. (2000), Tadross et al. (2002), and Bartašūtė & Tautvaišienė (2004).

and EW were measured for all our program stars. A first selection was applied to reject all lines measured for 10 stars or less (out of 15) and that had EW systematically larger than 250 mÅ. Later, after performing a rough abundance analysis (see Sect. 4.1), we rejected all lines that inferred systematically discrepant abundances, especially if the formal DAOSPEC relative error ($\delta EW/EW$, Fig. 2) was around 15% or more, and the DAOSPEC quality parameter was above 1.5 (for more details about the DAOSPEC error and quality parameter, see Sect. 3.3). The final linelist, including atomic data and EW measurements for all program stars, contains 358 absorption lines of 17 species, and can be found in the electronic version of Table 5. Atomic data include laboratory wavelengths, excitation potentials, and $\log gf$ values, which are always taken from the VALD database with the exceptions listed below.

3.1. α -elements atomic data

The only α -element for which we had clear problems with the atomic data was magnesium. The lines with $\chi_{\text{ex}} = 5.75$ eV (7060 and 7193 Å) gave discrepant abundances by ~ 1.5 dex with respect to the average of all Mg lines. We compared our VALD $\log gf$ with the NIST¹² database of atomic data and noticed a difference of 1.4 dex for the $\chi_{\text{ex}} = 5.75$ eV lines, while all the other Mg I lines had very similar $\log gf$ values in both databases. The NIST $\log gf$ values abundances of the $\chi_{\text{ex}} = 5.75$ eV lines gave abundances in much closer agreement with the other Mg I lines and the literature Mg abundances for OC, therefore we used the NIST values for those lines, instead of the VALD ones.

Fig. 2. The behavior of DAOSPEC relative errors $\delta EW/EW$ versus EW is shown (top panel) and the 15% error limit is marked with a dotted line. The behavior of the quality parameter Q is shown versus EW (middle panel) and wavelength (bottom panel), and the $Q = 1.5$ limit is marked with a dotted line. See Sect. 3.3 for more details. In all panels, grey dots represent all the lines measured by DAOSPEC, while black dots represent lines cross-identified with our input linelist.

Another element with uncertain $\log gf$ values is calcium. As an example, for the 9 lines that we use, there is an average difference of $\log gf_{\text{NIST}} - \log gf_{\text{VALD}} = -0.17 \pm 0.18$ dex, which is not statistically significant given the large σ . The NIST $\log gf$ values for those 9 lines also range from D to E, which means that they are largely uncertain. Finally, our solar abundance (Sect. 4.6) gives $[\text{Ca}/\text{H}] = -0.09 \pm 0.03$ (± 0.03) dex if we use the VALD $\log gf$ and $[\text{Ca}/\text{H}] = +0.08 \pm 0.03$ (± 0.03) dex with the NIST ones, which is equally compatible with zero within 3σ . Summarizing, there is large uncertainty in the calcium $\log gf$ determinations, and we should keep in mind that there is an additional ~ 0.2 dex uncertainty in all $[\text{Ca}/\text{Fe}]$ determinations in the literature.

For the synthesis of the [O I]–Ni I blend at 6300 Å, we used the VALD $\log gf$ value for oxygen, but we chose to use the Johansson et al. (2003) $\log gf$ for Ni I at 6300.35 Å, which is lower (-2.11 dex instead of -1.74) and gives oxygen abundances more in line with the other α -elements.

3.2. Heavy element atomic data

For neodymium, we could only find three reliable lines, which apparently did not need any detailed HFS (hyperfine splitting) analysis (Aoki et al. 2001), at 5092, 5249, and 5485 Å. However, the spread in their abundances was quite high (Table 7). The laboratory $\log gf$ value published by Den Hartog et al. (2003)

¹² <http://physics.nist.gov/PhysRefData/ASD/index.html>

Table 5. Equivalent widths and atomic data of the program stars. The complete version of the table is available at CDS. Here we show a few lines to illustrate its contents.

λ (Å)	Elem	χ_{ex} (eV)	$\log gf$ (dex)	Cr 110 – Star 2108			Cr 110 – Star 2129			...	NGC 7789 – Star 8556		
				EW (mÅ)	δEW (mÅ)	Q	EW (mÅ)	δEW (mÅ)	Q		EW (mÅ)	δEW (mÅ)	Q
6696.79	AL1	4.02	-1.42	29.5	2.2	0.289	-9.9	-9.9	-9.999	...	-9.9	-9.9	-9.999
6698.67	AL1	3.14	-1.65	58.0	2.0	0.325	39.0	3.9	0.322	...	39.0	3.7	0.371
7361.57	AL1	4.02	-0.90	44.1	4.0	0.510	39.7	2.7	0.530	...	35.0	3.8	0.370
7362.30	AL1	4.02	-0.75	62.7	3.9	0.577	46.0	1.5	0.217	...	51.4	6.4	0.570
7835.31	AL1	4.02	-0.65	73.7	6.6	0.539	55.5	5.2	0.596	...	63.5	4.7	0.628
7836.13	AL1	4.02	-0.49	87.6	4.1	0.390	77.1	4.1	0.349	...	71.9	3.8	0.420
8772.86	AL1	4.02	-0.32	87.6	5.1	0.957	105.0	7.0	0.650	...	128.4	11.2	1.113
8773.90	AL1	4.02	-0.16	118.6	14.6	0.736	115.0	3.5	0.362	...	110.0	9.8	0.847
5853.67	BA2	0.60	-1.00	121.9	5.5	1.435	121.4	5.4	0.932	...	121.9	8.4	1.210

are very similar to those from VALD, except for the 5485 Å line, where they differ by 0.14 dex. Therefore, since the $\log gf$ values by Den Hartog et al. (2003) slightly reduced the spread in the [Nd/Fe], we used them instead of the VALD ones (see Table 5).

3.3. Equivalent widths with DAOSPEC

The full description of how DAOSPEC works, including comparisons with the literature and several experiments with artificial and real spectra, can be found in Stetson & Pancino (2008). The instructions on how to install, configure and use DAOSPEC can be found in “Cooking with DAOSPEC”¹³. In short, DAOSPEC is a Fortran program that automatically finds absorption lines in a stellar spectrum, fits the continuum, measures EW , and identifies lines with a laboratory linelist; it also provides a radial velocity estimate (Sect. 2.2).

As described in Sect. 3, we used the DAOSPEC errors and quality parameter, Q , to select good absorption lines from our master linelist. Since our spectra are rebinned linearly in wavelength, we scaled the FWHM with λ . Figure 2 shows their behavior. The formal error in the Gaussian fit that DAOSPEC outputs is given by δEW , and $\delta EW/EW$ can be used to select good measurements, since smaller lines are noisier and tend to have higher relative errors. The quality parameter Q , instead, is the result of comparing local residuals around each line with average residuals for the whole spectrum. As a result Q tends to be worse for strong lines, because the Gaussian approximation does not hold so well. Also, Q becomes poorer at the blue side of the spectrum, where the S/N ratio is lower. In the region around 7700 Å, where the residuals of the prominent O₂ telluric band affect the measurements, Q reaches its maximum. The measured EW for our program stars are shown in the electronic version of Table 5 along with the δEW and Q parameter estimated by DAOSPEC.

3.4. EW uncertainties

We used the formal errors in the Gaussian fit computed by DAOSPEC only to reject unreliable measurements from our initial line list. The actual abundance errors due to the EW measurement process itself were instead computed later, as explained in Sect. 4.3.

To compute the EW uncertainty related to the continuum placement, we used Eq. (7) from Stetson & Pancino (2008) to derive the effective uncertainty in the continuum placement

($\pm \Delta C/C$) which was found to be significantly smaller than 1%. We first lowered the “best-fit” continuum level by $\Delta C/C$ and measured the EW s again, obtaining $EW_{(-)}$, then we raised the level by the same amount and measured $EW_{(+)}$. The differences from the “correct” EW measurements, $\Delta EW_{(-)}$ and $\Delta EW_{(+)}$ were averaged to estimate ΔEW for each line. The typical resultant uncertainty, due only to the continuum placement, was approximately constant with EW and $\Delta EW \simeq 1$ mÅ approximately (see also Fig. 2 by Stetson & Pancino 2008). This small uncertainty was neglected because it had a much smaller impact on the resulting abundances than other sources of uncertainty considered in Sects. 4.3 and 4.4.

3.5. Comparison with literature EW

To our knowledge, only one of our target stars was studied before by Yong et al. (2005) and Tautvaišienė (2000), with a resolution and S/N similar to ours, i.e., star 141 in M 67. While Yong et al. (2005) do not publish their EW measurements, we can compare with those by Tautvaišienė (2000). The authors provided two sets of EW , the former derived from a spectrum with $R \simeq 30\,000$, and the latter from a spectrum with $R \simeq 60\,000$. We have 48 lines in common with the $R \simeq 30\,000$ set and 36 with the $R \simeq 60\,000$ set.

Figure 3 shows good agreement between our EW s and the $R \simeq 30\,000$ set. We only found a systematic offset of $EW_{T00} - EW_{\text{DAOSPEC}} = 4.0 \pm 7.3$ mÅ, which corresponds to a continuum placement difference of about 1% (see also Sect. 3.4). A possible trend with EW was visible when comparing our EW s with the $R \simeq 60\,000$ set, with no systematic offset ($\Delta EW = -0.3 \pm 9.3$ mÅ). On the one hand, this means that our continuum placement is in far closer agreement with the $R \simeq 60\,000$ continuum determined by Tautvaišienė (2000) than with the $R \simeq 30\,000$ one. On the other hand, we note that a possible trend is also visible when comparing the Tautvaišienė (2000) measurements at $R \simeq 30\,000$ with those at $R \simeq 60\,000$. In conclusion, we considered our EW measurements to be in good agreement with the Tautvaišienė (2000) ones, given the involved uncertainties (see also Table 6).

4. Abundance analysis

4.1. Best model search

A preliminary abundance determination was done using the photometric parameters (Sect. 4), which allowed us to identify and remove those lines in our list that gave systematically discrepant abundances. We found largely discrepant Fe I and Fe II values

¹³ <http://www3.cadc-ccda.hia-ihp.nrc-cnrc.gc.ca/community/STETSON/daospec/>; <http://www.bo.astro.it/~pancino/projects/daospec.html>

Fig. 3. Comparison of our EW measurements with Tautvaišienė (2000), for star 141 in M 67. The top panel shows the comparison of DAO SPEC EW with the $R \approx 30\,000$ set by Tautvaišienė (2000), based on 48 lines in common. The middle panel show the same comparison, but for the $R \approx 60\,000$ set by Tautvaišienė (2000), based on 36 lines. The bottom panel shows the 15 lines in common between the $R \approx 30\,000$ and the $R \approx 60\,000$ EW sets, considering only the lines included in the two upper panels.

when using the photometric parameters (by ≈ 0.5 – 0.9 dex), indicating that something was wrong with the photometric gravities (Sect. 2.3).

As a second step, we calculated Fe I and Fe II abundances for a set of models with parameters extending more than 3σ around the photometric estimates of Table 3, i.e., about ± 300 – 500 K in T_{eff} , ± 0.3 – 0.6 dex in $\log g$ and ± 0.5 km s $^{-1}$ in v_t , depending on the star. This large grid of calculated abundances was used to refine our photometric estimate of the atmospheric parameters.

We chose the model that satisfied simultaneously (within the uncertainties¹⁴) the following conditions: (i) the abundance of Fe I lines should not vary with excitation potential χ_{ex} ; (ii) the abundance of Fe I lines should not vary significantly with EW , i.e., strong and weak lines should infer the same abundance¹⁵; (iii) the abundance of Fe I lines should not differ significantly from the abundance of Fe II lines; (iv) the abundance of Fe I lines should not vary significantly with wavelength.

Using the spreads in the Fe I and Fe II abundances of various lines, and the uncertainties in the slopes of the above conditions, we estimated the typical 1σ uncertainties in the spectroscopic parameters: about ± 100 K for T_{eff} , ± 0.2 dex for $\log g$, and ± 0.1 km s $^{-1}$ for v_t .

The resulting spectroscopic parameters (Table 3) were always in good agreement with the photometric ones, within the

Table 6. Comparison of our results for star 141 in M 67 with the analysis of Tautvaišienė (2000) and Yong et al. (2005).

Parameter	Here	T00	Y05
Resolution	30 000	30–60 000	28 000
S/N	70–100	≥ 100	30–100
T_{eff} (K)	4650	4730	4700
$\log g$ (dex)	2.8	2.4	2.3
v_t (km s $^{-1}$)	1.3	1.8	1.3
[FeI/H]	$0.06 \pm 0.01(\pm 0.10)$	-0.01 ± 0.02	-0.01 ± 0.02
[FeII/H]	$0.01 \pm 0.03(\pm 0.10)$	-0.01 ± 0.05	0.01 ± 0.03
$[\alpha/\text{Fe}]$	$0.01 \pm 0.01(\pm 0.07)$	0.01 ± 0.03	0.12 ± 0.06
[Al/Fe]	$0.06 \pm 0.06(\pm 0.05)$	0.08 ± 0.01	0.16 ± 0.03
[Ba/Fe]	$0.26 \pm 0.05(\pm 0.06)$	0.07 ± 0.00	0.02 ± 0.00
[Ca/Fe]	$-0.13 \pm 0.02(\pm 0.03)$	0.09 ± 0.05	0.09 ± 0.02
[Co/Fe]	$0.11 \pm 0.02(\pm 0.06)$	0.05 ± 0.07	0.01 ± 0.05
[Cr/Fe]	$0.01 \pm 0.03(\pm 0.06)$	0.12 ± 0.05	–
[La/Fe]	$0.06 \pm 0.05(\pm 0.09)$	-0.06 ± 0.00	0.13 ± 0.03
[Mg/Fe]	$0.29 \pm 0.03(\pm 0.10)$	0.11 ± 0.00	0.18 ± 0.02
[Na/Fe]	$0.10 \pm 0.02(\pm 0.04)$	0.25 ± 0.00	0.24 ± 0.06
[Nd/Fe]	$0.01 \pm 0.29(\pm 0.10)$	–	–
[Ni/Fe]	$0.06 \pm 0.02(\pm 0.03)$	0.05 ± 0.04	0.06 ± 0.03
[O/Fe]	$-0.05 \pm 0.09(\pm 0.08)$	0.04 ± 0.00	0.10 ± 0.04
[Sc/Fe]	$-0.02 \pm 0.08(\pm 0.08)$	0.09 ± 0.05	–
[Si/Fe]	$0.09 \pm 0.02(\pm 0.08)$	0.11 ± 0.04	0.11 ± 0.04
[TiI/Fe]	$-0.07 \pm 0.02(\pm 0.07)$	0.04 ± 0.05	0.05 ± 0.03
[TiII/Fe]	$-0.07 \pm 0.08(\pm 0.06)$	0.11 ± 0.07	–
[V/Fe]	$0.13 \pm 0.04(\pm 0.14)$	0.09 ± 0.03	–
[Y/Fe]	$-0.04 \pm 0.02(\pm 0.12)$	-0.12 ± 0.08	–

Notes. The internal uncertainties are those reported by the authors, where a value of 0.00 means that the abundance calculation was based on one line only.

quoted uncertainties, with a tendency for the spectroscopic gravities to be systematically higher by 0.3–0.5 dex (see above). However, these differences are always easily accommodated within the uncertainty ranges (related to photometric errors, uncertainties in distance moduli and reddenings, and bolometric corrections).

4.2. Abundance calculations

Abundance calculations and spectral synthesis (for oxygen) were performed using the latest version of the abundance calculation code originally described by Spite (1967). We used the model atmospheres by Edvardsson et al. (1993). We also made use of ABOMAN, a tool developed by Rossetti at the INAF, Bologna Observatory, Italy, that allows the semi-automatic processing of data for several objects, using the above abundance calculation codes. ABOMAN performs all the steps needed to choose the best model automatically, and provides all the graphical tools to analyze the results.

When the best model was found for each star, abundances and abundance ratios of all the species of interest were calculated, by averaging the results for each line of that element (Table 7). Abundance ratios were always computed with respect to Fe I. Cluster averages were computed as weighted averages of the results for each star in the cluster and, if necessary, of different ionization stages of each element (Table 8). In all tables, $[\alpha/\text{Fe}]$ is the weighted average of all α -elements abundances.

We can compare our results for star 141 in M 67 (see also Sect. 3.5) with those of Tautvaišienė (2000) and Yong et al. (2005). We find general agreement for both the atmospheric parameters and abundance ratios, with the only significant

¹⁴ We basically considered a slope consistent with zero when the 3σ spread around the fit was larger than the maximum $[\text{Fe}/\text{H}]$ difference implied by the fitted slope at the extremes of the interval covered by the abscissae (be it χ_{ex} , EW or λ).

¹⁵ We decided not to use the Magain (1984) effect, because we prefer to have internally consistent abundances from each line, and the difference in the measurements for the two methods in our case appears small ($\Delta v_t < 0.2$ km s $^{-1}$).

Table 7. Abundance ratios for sigle cluster stars, with their *internal* uncertainties (Sect. 4.3). For *external* uncertainties see Table 9.

Ratio	Cr 110				NGC 2099 (M 37)			NGC 2420	
	Star 2108	Star 2129	Star 3144	Star 067	Star 148	Star 508	Star 041	Star 076	Star 174
[FeI/H]	0.02 ± 0.01	0.05 ± 0.01	0.02 ± 0.01	0.01 ± 0.01	-0.03 ± 0.01	0.07 ± 0.01	-0.07 ± 0.01	-0.06 ± 0.01	-0.03 ± 0.01
[FeII/H]	0.00 ± 0.06	-0.04 ± 0.08	0.00 ± 0.06	-0.01 ± 0.02	-0.07 ± 0.04	0.05 ± 0.06	-0.09 ± 0.06	0.00 ± 0.02	-0.07 ± 0.04
[α/Fe]	-0.02 ± 0.02	0.01 ± 0.02	0.04 ± 0.02	-0.04 ± 0.01	0.00 ± 0.01	0.03 ± 0.01	-0.03 ± 0.01	-0.03 ± 0.01	0.03 ± 0.02
[Al/Fe]	-0.02 ± 0.04	-0.06 ± 0.08	-0.03 ± 0.06	-0.06 ± 0.08	-0.10 ± 0.07	-0.04 ± 0.07	-0.10 ± 0.04	-0.10 ± 0.05	-0.09 ± 0.05
[Ba/Fe]	0.48 ± 0.02	0.49 ± 0.04	0.52 ± 0.06	0.60 ± 0.05	0.55 ± 0.04	0.58 ± 0.04	0.54 ± 0.04	0.58 ± 0.05	0.65 ± 0.02
[Ca/Fe]	-0.08 ± 0.04	-0.04 ± 0.06	-0.09 ± 0.07	-0.06 ± 0.05	-0.08 ± 0.04	-0.09 ± 0.04	-0.08 ± 0.03	-0.11 ± 0.04	-0.08 ± 0.05
[Co/Fe]	0.13 ± 0.05	-0.08 ± 0.04	0.01 ± 0.04	-0.04 ± 0.02	-0.04 ± 0.02	-0.05 ± 0.02	0.10 ± 0.05	-0.02 ± 0.03	0.05 ± 0.03
[Cr/Fe]	0.00 ± 0.04	0.06 ± 0.06	0.03 ± 0.08	-0.01 ± 0.06	0.01 ± 0.05	0.05 ± 0.05	-0.02 ± 0.03	-0.09 ± 0.06	-0.02 ± 0.05
[La/Fe]	0.11 ± 0.09	0.12 ± 0.03	-0.15 ± 0.04	0.08 ± 0.02	0.16 ± 0.08	0.13 ± 0.08	0.23 ± 0.01	0.12 ± 0.09	0.07 ± 0.13
[Mg/Fe]	0.19 ± 0.07	0.01 ± 0.14	0.16 ± 0.08	0.28 ± 0.05	0.26 ± 0.04	0.27 ± 0.03	0.09 ± 0.05	0.10 ± 0.09	0.14 ± 0.08
[Na/Fe]	-0.08 ± 0.02	-0.06 ± 0.08	0.00 ± 0.03	0.08 ± 0.05	0.10 ± 0.04	0.05 ± 0.08	-0.13 ± 0.09	-0.04 ± 0.06	0.02 ± 0.07
[Nd/Fe]	0.05 ± 0.16	0.29 ± 0.13	0.51 ± 0.28	0.23 ± 0.29	0.26 ± 0.25	0.33 ± 0.32	0.12 ± 0.16	0.40 ± 0.28	0.18 ± N.A.
[Ni/Fe]	-0.02 ± 0.02	-0.01 ± 0.02	-0.04 ± 0.03	-0.04 ± 0.03	-0.02 ± 0.02	-0.01 ± 0.02	0.03 ± 0.02	-0.01 ± 0.02	-0.01 ± 0.02
[O/Fe]	0.08 ± 0.08	-0.07 ± 0.12	0.02 ± 0.14	0.12 ± 0.07	0.25 ± 0.15	0.22 ± 0.13	-0.01 ± 0.16	0.24 ± 0.14	0.39 ± 0.33
[Sc/Fe]	0.11 ± 0.05	-0.07 ± 0.06	-0.14 ± 0.10	-0.05 ± 0.05	-0.01 ± 0.07	-0.02 ± 0.12	0.07 ± 0.01	0.11 ± 0.07	0.16 ± 0.06
[Si/Fe]	0.02 ± 0.03	0.04 ± 0.02	0.06 ± 0.03	0.07 ± 0.03	0.11 ± 0.02	0.06 ± 0.03	0.05 ± 0.02	0.05 ± 0.02	0.02 ± 0.03
[TiI/Fe]	0.01 ± 0.03	0.00 ± 0.03	0.01 ± 0.04	-0.10 ± 0.02	-0.10 ± 0.02	-0.07 ± 0.02	-0.06 ± 0.02	-0.09 ± 0.02	0.06 ± 0.03
[TiII/Fe]	0.01 ± 0.13	-0.04 ± 0.07	0.11 ± 0.05	-0.01 ± 0.06	0.00 ± 0.05	0.05 ± 0.08	-0.04 ± 0.23	0.07 ± 0.09	0.12 ± 0.07
[V/Fe]	0.28 ± 0.06	-0.03 ± 0.05	-0.09 ± 0.07	-0.09 ± 0.02	-0.08 ± 0.04	-0.03 ± 0.04	0.11 ± 0.06	-0.08 ± 0.05	0.13 ± 0.04
[Y/Fe]	0.02 ± 0.12	-0.17 ± 0.08	-0.03 ± 0.18	-0.03 ± 0.23	0.09 ± 0.09	0.08 ± 0.20	-0.14 ± 0.14	0.06 ± 0.02	0.02 ± 0.09
Ratio	NGC 2682 (M 67)				NGC 7789				
	Star 141	Star 223	Star 286	Star 5237	Star 7840	Star 8556			
[FeI/H]	0.06 ± 0.01	0.04 ± 0.01	0.06 ± 0.01	-0.01 ± 0.01	0.03 ± 0.01	0.12 ± 0.01			
[FeII/H]	0.01 ± 0.03	0.02 ± 0.05	-0.05 ± 0.04	-0.06 ± 0.05	-0.03 ± 0.07	0.07 ± 0.06			
[α/Fe]	0.01 ± 0.01	-0.03 ± 0.01	-0.05 ± 0.01	-0.02 ± 0.02	-0.02 ± 0.02	-0.08 ± 0.02			
[Al/Fe]	0.06 ± 0.06	0.02 ± 0.05	0.03 ± 0.05	-0.01 ± 0.10	0.05 ± 0.11	-0.13 ± 0.10			
[Ba/Fe]	0.26 ± 0.05	0.27 ± 0.05	0.23 ± 0.05	0.49 ± 0.06	0.36 ± 0.07	0.46 ± 0.03			
[Ca/Fe]	-0.13 ± 0.02	-0.20 ± 0.03	-0.15 ± 0.02	-0.10 ± 0.04	-0.12 ± 0.07	-0.24 ± 0.03			
[Co/Fe]	0.11 ± 0.02	0.05 ± 0.04	0.17 ± 0.04	-0.02 ± 0.04	-0.03 ± 0.02	-0.01 ± 0.03			
[Cr/Fe]	0.01 ± 0.03	-0.01 ± 0.04	0.06 ± 0.05	0.05 ± 0.04	-0.02 ± 0.03	0.16 ± 0.45			
[La/Fe]	0.06 ± 0.05	-0.06 ± 0.06	0.07 ± 0.03	0.14 ± 0.06	0.06 ± 0.07	0.14 ± 0.15			
[Mg/Fe]	0.29 ± 0.03	0.20 ± 0.08	0.23 ± 0.05	0.26 ± 0.07	0.24 ± 0.04	0.13 ± 0.06			
[Na/Fe]	0.10 ± 0.02	-0.02 ± 0.04	0.22 ± 0.08	0.04 ± 0.01	0.09 ± 0.08	-0.15 ± 0.01			
[Nd/Fe]	0.01 ± 0.29	0.10 ± 0.25	0.10 ± 0.21	0.21 ± 0.38	-0.17 ± 0.27	0.35 ± 0.20			
[Ni/Fe]	0.06 ± 0.02	0.04 ± 0.02	0.04 ± 0.02	-0.02 ± 0.02	0.00 ± 0.02	-0.02 ± 0.03			
[O/Fe]	-0.05 ± 0.09	0.09 ± 0.11	0.13 ± 0.10	0.21 ± 0.15	0.13 ± 0.10	0.23 ± 0.20			
[Sc/Fe]	-0.02 ± 0.08	-0.05 ± 0.04	0.01 ± 0.05	0.10 ± 0.09	0.06 ± 0.10	0.08 ± 0.12			
[Si/Fe]	0.09 ± 0.02	0.12 ± 0.02	0.06 ± 0.02	-0.01 ± 0.02	-0.02 ± 0.03	0.03 ± 0.04			
[TiI/Fe]	-0.07 ± 0.02	-0.11 ± 0.02	0.00 ± 0.02	-0.02 ± 0.03	-0.03 ± 0.03	-0.14 ± 0.04			
[TiII/Fe]	-0.07 ± 0.08	0.02 ± 0.06	-0.06 ± 0.13	-0.07 ± 0.29	-0.19 ± 0.17	0.14 ± 0.05			
[V/Fe]	0.13 ± 0.04	0.06 ± 0.04	0.25 ± 0.04	0.05 ± 0.04	-0.01 ± 0.04	-0.16 ± 0.06			
[Y/Fe]	-0.04 ± 0.02	-0.06 ± 0.05	0.00 ± 0.03	0.22 ± N.A.	-0.01 ± N.A.	0.07 ± 0.18			

exception of barium (but see the discussion in Sect. 6.3), calcium (discussed in Sect. 6.2), and titanium. For all the elements discussed, our results, as discussed in Sect. 6, are in broad agreement with the entire collection of high resolution abundances for OC, so we consider our results to be robust.

4.3. Internal abundance uncertainties

Random uncertainties in the *EW* measurement process and in the $\log gf$ determinations were taken into account by averaging the abundances determinations obtained for different lines and using $\sigma/\sqrt{n_{\text{lines}}}$ as the final *internal* error. These are reported in Table 7, and they are of the order of ~ 0.01 dex for Fe I, which had the highest number of lines, and could reach up to ~ 0.2 – 0.3 dex for elements relying on a handful of lines such as Nd, for example. Additional systematic (from line to line) and random (from star to star) uncertainties in *EW* measurements, related to continuum placement, had a negligible impact on the final abundances in our specific case (Sect. 3.4).

For the spectral synthesis of oxygen, the uncertainty in the fit was computed by choosing two spectra, one with abundance higher than the best fitting spectrum, and another one with lower abundance, each chosen to differ by approximately 1σ (of the poissonian noise) from the observed spectrum. The abundance difference of the two “altered” spectra with the best-fit spectrum were averaged together to produce the estimated uncertainty, reported in Table 7 (and in our solar analysis, Table 10).

4.4. Uncertainties due to the choice of stellar parameters

The choice of stellar parameters implies systematic (from line to line) and random (from star to star) uncertainties in the final abundances. To estimate the impact of the stellar parameters choice on the derived abundances, each parameter is usually altered by its estimated uncertainty and the resulting abundance differences with respect to the best model parameter abundance set are summed in quadrature to obtain a global uncertainty. We applied this method to our coolest (508 in NGC 2099) and

Table 8. Average cluster abundances, obtained with the weighted average of the single stars abundances.

Ratio	Cr 110	NGC 2099	NGC 2420	M 67	NGC 7789
[Fe/H]	+0.03 ± 0.02(±0.10)	+0.01 ± 0.05(±0.10)	-0.05 ± 0.03(±0.10)	+0.05 ± 0.02(±0.10)	+0.04 ± 0.07(±0.10)
[α/Fe]	+0.01 ± 0.03(±0.07)	0.00 ± 0.04(±0.07)	-0.02 ± 0.03(±0.07)	-0.02 ± 0.03(±0.07)	-0.04 ± 0.03(±0.07)
[Al/Fe]	-0.04 ± 0.02(±0.05)	-0.06 ± 0.03(±0.05)	-0.10 ± 0.01(±0.05)	+0.03 ± 0.02(±0.05)	-0.03 ± 0.09(±0.05)
[Ba/Fe]	+0.49 ± 0.02(±0.06)	+0.57 ± 0.02(±0.06)	+0.62 ± 0.07(±0.06)	+0.25 ± 0.02(±0.06)	+0.45 ± 0.05(±0.06)
[Ca/Fe]	-0.07 ± 0.02(±0.03)	-0.08 ± 0.01(±0.03)	-0.09 ± 0.02(±0.03)	-0.16 ± 0.03(±0.03)	-0.18 ± 0.09(±0.03)
[Co/Fe]	+0.01 ± 0.10(±0.06)	-0.04 ± 0.01(±0.06)	+0.03 ± 0.06(±0.06)	+0.08 ± 0.06(±0.06)	-0.02 ± 0.01(±0.06)
[Cr/Fe]	+0.02 ± 0.03(±0.06)	+0.02 ± 0.03(±0.06)	-0.03 ± 0.03(±0.06)	+0.01 ± 0.03(±0.06)	+0.01 ± 0.05(±0.06)
[La/Fe]	+0.03 ± 0.18(±0.09)	+0.09 ± 0.05(±0.09)	+0.23 ± 0.09(±0.09)	+0.05 ± 0.06(±0.09)	+0.11 ± 0.05(±0.09)
[Mg/Fe]	+0.16 ± 0.07(±0.10)	+0.27 ± 0.01(±0.10)	+0.09 ± 0.06(±0.10)	+0.27 ± 0.04(±0.10)	+0.22 ± 0.07(±0.10)
[Na/Fe]	-0.06 ± 0.05(±0.04)	+0.09 ± 0.02(±0.04)	-0.04 ± 0.07(±0.04)	+0.08 ± 0.09(±0.04)	-0.05 ± 0.13(±0.04)
[Nd/Fe]	+0.23 ± 0.20(±0.10)	+0.27 ± 0.05(±0.10)	+0.19 ± 0.17(±0.10)	+0.08 ± 0.05(±0.10)	+0.17 ± 0.30(±0.10)
[Ni/Fe]	-0.02 ± 0.01(±0.03)	-0.02 ± 0.01(±0.03)	+0.00 ± 0.02(±0.03)	+0.05 ± 0.01(±0.03)	-0.01 ± 0.01(±0.03)
[O/Fe]	+0.03 ± 0.08(±0.08)	+0.15 ± 0.08(±0.08)	+0.15 ± 0.18(±0.08)	+0.04 ± 0.10(±0.08)	+0.16 ± 0.06(±0.08)
[Sc/Fe]	+0.01 ± 0.13(±0.08)	-0.03 ± 0.03(±0.08)	+0.07 ± 0.05(±0.08)	-0.03 ± 0.04(±0.08)	+0.08 ± 0.02(±0.08)
[Si/Fe]	+0.04 ± 0.02(±0.07)	+0.09 ± 0.03(±0.07)	+0.04 ± 0.01(±0.07)	+0.10 ± 0.02(±0.07)	-0.01 ± 0.02(±0.07)
[Ti/Fe]	+0.02 ± 0.04(±0.06)	-0.08 ± 0.04(±0.06)	-0.04 ± 0.08(±0.06)	-0.04 ± 0.06(±0.06)	-0.03 ± 0.09(±0.06)
[V/Fe]	+0.05 ± 0.19(±0.14)	-0.08 ± 0.03(±0.14)	-0.05 ± 0.13(±0.14)	+0.15 ± 0.13(±0.14)	-0.01 ± 0.09(±0.14)
[Y/Fe]	-0.10 ± 0.12(±0.12)	+0.07 ± 0.06(±0.12)	+0.05 ± 0.08(±0.12)	-0.05 ± 0.04(±0.12)	+0.08 ± 0.09(±0.12)

warmest star (2129 in Cr 110) and obtained various abundance ratio uncertainties ranging from 0.05 to 0.45 dex, with a typical value around ~0.10 dex.

However, as noted by Cayrel et al. (2004), this method produces a very conservative estimate of the uncertainty, because it neglects the natural correlation between stellar parameters that occurs when the so-called “spectroscopic method” (Sect. 4.1) is adopted. Covariance terms should therefore be included to properly take into account these dependencies among the parameters (see McWilliam et al. 1995, for a detailed treatment of the problem). The practical method proposed by Cayrel et al. (2004) assumes that, among the atmospheric parameters, T_{eff} has by far the strongest effect on the abundance results and, therefore, T_{eff} must be varied by its estimated uncertainty (≈ 100 K in our case, Sect. 4.1). A new “second best” model must then be identified with the new value of T_{eff} by varying v_t and $\log g$ accordingly, to minimize as much as possible the slopes of the relations described in Sect. 4.1. This method naturally and properly takes into account both the main terms of the error budget and the appropriate covariance terms.

We therefore altered the temperature of our hottest and coolest stars (see above) by both +100 K and -100 K. We re-optimized all the parameters and recalculated all the abundance ratios. The final uncertainties are the average of the uncertainties calculated with the higher and lower temperature and are shown in Table 9. The average between the uncertainties in these two cases is taken as a reliable estimate of the impact of the choice of stellar parameters on our abundance ratios. We added these *external* uncertainties between parentheses after each abundance ratio and we summed them in quadrature with the *internal* errors to produce the errorbars in each figure.

4.5. Other sources of uncertainty

The following additional sources of systematic uncertainties are not explicitly discussed here, but should be taken into account when comparing our abundance estimates with other works in the literature:

- systematic uncertainties related to the choice of the solar reference abundances, which are not discussed here. Our abundances can be shifted to any solar reference abundance with the information in Table 10;

Table 9. Uncertainties due to the choice of stellar parameters for the coolest (second column) and the warmest (third column) of our programs stars (see Sect. 4.4).

Ratio	NGC 2099-508 ($T = 4500$ K)	Cr110-2129 ($T = 4950$ K)	Average
[Al/Fe]	±0.04	±0.07	±0.05
[Ba/Fe]	±0.04	±0.08	±0.06
[Ca/Fe]	±0.03	±0.03	±0.03
[Co/Fe]	±0.07	±0.05	±0.06
[Cr/Fe]	±0.09	±0.03	±0.06
[Fe/H]	±0.16	±0.04	±0.10
[La/Fe]	±0.10	±0.07	±0.09
[Mg/Fe]	±0.11	±0.09	±0.10
[Na/Fe]	±0.03	±0.06	±0.04
[Nd/Fe]	±0.09	±0.12	±0.10
[Ni/Fe]	±0.02	±0.03	±0.03
[O/Fe]	±0.10	±0.07	±0.08
[Sc/Fe]	±0.07	±0.09	±0.08
[Si/Fe]	±0.12	±0.03	±0.07
[Ti/Fe]	±0.07	±0.06	±0.06
[V/Fe]	±0.21	±0.07	±0.14
[Y/Fe]	±0.15	±0.08	±0.12

Notes. The average between these two extreme cases (fourth column) is our estimate of the uncertainty due to our choice of stellar parameters.

- uncertainties due to the choice of $\log gf$ values, which can be estimated by comparing our $\log gf$ values with other literature values (see Sect. 3.1);
- uncertainties in the entire analysis due to more sophisticated effects such as, NLTE, HFS, isotope ratios, which are difficult to evaluate in some cases (these are mentioned whenever known or relevant in Sects. 3 and 6);
- small additional uncertainties related to the particular choices of atmospheric model and abundance calculation code.

4.6. The Sun

To test the entire abundance determination procedure, including *EW* measurement, the choice of lines and atomic parameters, and the uncertainty determination criteria, we performed an

Table 10. Solar abundance values.

Element	[X/H] _{derived}	log ϵ_{GS96}	log ϵ_{A05}
Al	$-0.34 \pm \text{N.A.} (\pm 0.05)$	6.47 ± 0.07	6.37 ± 0.07
Ba	$+0.34 \pm 0.02 (\pm 0.06)$	2.13 ± 0.05	2.17 ± 0.07
Ca	$-0.09 \pm 0.03 (\pm 0.03)$	6.36 ± 0.02	6.31 ± 0.04
Co	$+0.05 \pm 0.02 (\pm 0.06)$	4.92 ± 0.04	4.92 ± 0.08
Cr	$+0.02 \pm 0.05 (\pm 0.06)$	5.67 ± 0.03	5.64 ± 0.10
FeI	$+0.01 \pm 0.01 (\pm 0.10)$	7.50 ± 0.04	7.45 ± 0.05
FeII	$-0.03 \pm 0.02 (\pm 0.10)$	7.50 ± 0.04	7.45 ± 0.05
La	–	1.17 ± 0.07	1.13 ± 0.05
Mg	–	7.58 ± 0.05	7.53 ± 0.09
Na	$-0.10 \pm 0.01 (\pm 0.04)$	6.33 ± 0.03	6.17 ± 0.04
Nd	–	1.42 ± 0.06	1.45 ± 0.05
Ni	$+0.01 \pm 0.01 (\pm 0.03)$	6.25 ± 0.01	6.23 ± 0.04
O	$-0.01 \pm 0.07 (\pm 0.08)$	8.87 ± 0.07	8.66 ± 0.05
Sc	$+0.06 \pm 0.02 (\pm 0.08)$	3.17 ± 0.10	3.05 ± 0.08
Si	$-0.08 \pm 0.01 (\pm 0.07)$	7.55 ± 0.05	7.51 ± 0.04
Ti	$+0.03 \pm 0.05 (\pm 0.06)$	5.02 ± 0.06	4.90 ± 0.06
V	$-0.14 \pm 0.02 (\pm 0.14)$	4.00 ± 0.02	4.00 ± 0.02
Y	–	2.24 ± 0.03	2.21 ± 0.02

Notes. The second column shows our derived solar abundance (Sect. 4.6) with its uncertainty (Sect. 4.3). The uncertainty listed for [O/H] is derived from the spectral synthesis fit. The last two columns report our adopted solar abundances (Grevesse et al. 1996) and the values by Asplund et al. (2005), as a reference.

abundance analysis of the Sun, and checked that we obtained solar values for all elements, within the uncertainties. We used the solar spectrum from the ESO spectrograph HARPS, in La Silla, Chile, obtained by observing Ganymede¹⁶. The spectral resolution, $R \simeq 45\,000$, is comparable to ours, while the $S/N \simeq 350$ is much higher.

To measure *EWs*, we used DAOSPEC and the same linelist used for our program stars. We then compared our solar *EWs* with two different literature sets, the first by Moore et al. (1966) and the second by Rutten & van der Zalm (1984). The median difference between our *EW* and the ones by Moore is $EW_{\text{DAO}} - EW_{\text{Moore}} = 0.9 \text{ mÅ}$ (with an interquartile range of $\pm 2.7 \text{ mÅ}$), based on 225 lines in common, while the one with the Rutten & van der Zalm (1984) measurements is $EW_{\text{DAO}} - EW_{\text{RZ84}} = -0.5 \text{ mÅ}$ (with an interquartile range of $\pm 2.1 \text{ mÅ}$), based on 112 lines in common. For completeness, we note that $EW_{\text{Moore}} - EW_{\text{RZ84}} = 1.5 \text{ mÅ}$ (with an interquartile range of $\pm 2.8 \text{ mÅ}$), based on 390 lines in common. We are therefore satisfied with our solar *EW* measurements.

We then performed our abundance analysis (as in Sect. 4.2) by exploring the following atmospheric parameter ranges: $T_{\text{eff},\odot} = 5700\text{--}5800$, in steps of 50 K; $\log g_{\odot} = 4.3\text{--}4.5$, in steps of 0.1 dex; and $v_t = 0.5\text{--}1.5$, in steps of 0.1 km s^{-1} . The resulting best model has $T_{\text{eff},\odot} = 5750 \text{ K}$, $\log g_{\odot} = 4.4$ dex, and $v_t = 0.8 \text{ km s}^{-1}$, in good agreement with the accepted values (Andersen 1999). Our adopted reference solar abundances (Grevesse et al. 1996) are shown in Table 10, along with the abundance ratios derived as described. As can be seen, all the derived abundance ratios are compatible with zero, within the uncertainties, with the exception of Al and Ba. For Al, only one ($\lambda = 6698 \text{ Å}$) very weak ($EW = 18 \text{ mÅ}$) line could be measured in the solar spectrum, while we used about 8 lines in the analysis of our red clump giants. The lines at 6696 and 6698 Å are known to generally infer lower values than the other Al lines

(Reddy et al. 2003; Gratton et al. 2001), so we do not worry too much about our lone 6698 Å¹⁷ solar line giving a low [Al/Fe] result. We discuss Ba in Sect. 6.3. For some elements (La, Mg, Nd, Y), no ratio could be determined either because their lines appear too weak in the sun or because the solar spectrum range (5000–7000 Å) does not contain the lines that we used in this paper.

5. Cluster-by-cluster discussion

5.1. Cr 110

Collinder 110 is a poorly studied, intermediate-age OC located at $\alpha_{J2000} = 06:38:24$ and $\delta_{J2000} = +02:01:00$. We could not find any high resolution spectroscopic study of this cluster in the literature, but photometric studies were conducted by Tsarevskii & Abakumov (1971), Dawson & Ianna (1998) and Bragaglia & Tosi (2003). Reddening, distance, and ages determined by these authors are included in Table 4. Concerning metallicity, while the first two studies assume solar metallicity, Bragaglia & Tosi (2003) find, as a result of their synthetic diagram analysis, two equally good solutions, one at solar metallicity and the other at slightly subsolar metallicity ($Z = 0.008$). A re-evaluation of the same data by Bragaglia & Tosi (2006) favours the slightly subsolar value.

Low resolution spectroscopy using the infrared calcium triplet by Carrera et al. (2007) gave: $[\text{Fe}/\text{H}] = -0.01 \pm 0.07$ dex in the Carretta & Gratton (1997) scale, $[\text{Fe}/\text{H}] = 0.0 \pm 0.3$ dex in the Zinn & West (1984) scale, and $[\text{Fe}/\text{H}] = -0.19 \pm 0.21$ dex in the Kraft & Ivans (2003) scale. Our determination of $[\text{Fe}/\text{H}] = +0.03 \pm 0.02$ (± 0.10) dex is in good agreement with all these estimates, given the large uncertainties involved in photometric and low-resolution spectroscopic metallicity estimates. The other element ratios determined here have no previous literature values with which to compare, but the comparisons in Sect. 6 show that they behave as expected for a solar metallicity OC. Our radial velocity estimate for Cr 110, $\langle V_r \rangle = 41.0 \pm 3.8 \text{ km s}^{-1}$ (Sect. 2.2), is in good agreement with the CaT value determined by Carrera et al. (2007) of $45 \pm 8 \text{ km s}^{-1}$.

5.2. NGC 2099 (M 37)

NGC 2099 (M 37) is located in the Galactic anticenter direction in Auriga $\alpha_{J2000} = 05:52:18$ and $\delta_{J2000} = +32:33:12$. Since it is close-by and appears to be a relatively rich and large cluster, it has been photometrically studied by several authors to derive accurate magnitudes and proper motions, and to complete a census of variable stars (for historical references see Kalirai et al. 2001). All the papers that derived reddening, distance, and age are also cited in Table 4. Photometric studies generally attribute a solar metallicity to NGC 2099 (e.g., Mermilliod et al. 1996). Metallicity estimates based on photometry can only be found in Janes et al. (1988), who infer $[\text{Fe}/\text{H}] = 0.09$ dex, Marshall et al. (2005), who infer $[\text{M}/\text{H}] = +0.05 \pm 0.05$, and Kalirai & Tosi (2004), who infer $Z < 0.02$.

Surprisingly, when considering the wealth of photometric studies, M 37 lacks any low or high resolution spectroscopic study, designed to determine its chemical composition. Our values therefore fill this gap, and show that in all respects this cluster has a typical solar metallicity, with all element ratios close

¹⁶ <http://www.ls.eso.org/lasilla/sciops/3p6/harps/monitoring/sun.html>

¹⁷ Because of the shorter spectral range of the solar spectrum and to spectral defects, we could only measure one Al line in the Sun.

Table 11. Literature abundance determinations for M 67 based on high resolution spectroscopy.

	<i>Here</i>	T00 ^a	S00 ^b	Y05 ^c	R06 ^d	P08 ^e	S09 ^f
$R = \lambda/\delta\lambda$	30 000	30–60 000	30 000	28 000	45 000	100 000	50 000
S/N	50–100	≥ 100	40–70	30–100	90–180	≈ 80	100–300
[Fe/H]	$+0.05 \pm 0.02 (\pm 0.10)$	-0.03 ± 0.04	-0.05 ± 0.01	$+0.02 \pm 0.01$	$+0.03 \pm 0.01$	$+0.03 \pm 0.04$	0.00 ± 0.01
[Al/Fe]	$+0.03 \pm 0.02 (\pm 0.05)$	$+0.14 \pm 0.07$	–	$+0.17 \pm 0.01$	-0.06 ± 0.04	-0.03 ± 0.11	–
[Ba/Fe]	$+0.25 \pm 0.02 (\pm 0.06)$	$+0.07 \pm 0.12$	$+0.21 \pm 0.20$	-0.02 ± 0.03	–	–	–
[Ca/Fe]	$-0.16 \pm 0.03 (\pm 0.03)$	$+0.05 \pm 0.09$	-0.02 ± 0.03	$+0.07 \pm 0.02$	$+0.05 \pm 0.04$	$+0.03 \pm 0.07$	–
[Co/Fe]	$+0.08 \pm 0.06 (\pm 0.06)$	$+0.08 \pm 0.07$	–	–	–	–	–
[Cr/Fe]	$+0.01 \pm 0.03 (\pm 0.06)$	$+0.10 \pm 0.09$	–	–	-0.01 ± 0.04	$+0.03 \pm 0.09$	–
[La/Fe]	$+0.05 \pm 0.06 (\pm 0.09)$	$+0.13 \pm 0.10$	–	$+0.11 \pm 0.02$	–	–	–
[Mg/Fe]	$+0.27 \pm 0.04 (\pm 0.10)$	$+0.10 \pm 0.06$	-0.11 ± 0.08	$+0.16 \pm 0.02$	-0.01 ± 0.03	–	–
[Na/Fe]	$+0.08 \pm 0.09 (\pm 0.04)$	$+0.19 \pm 0.08$	-0.05 ± 0.05	$+0.30 \pm 0.03$	$+0.04 \pm 0.07$	-0.02 ± 0.07	–
[Ni/Fe]	$+0.05 \pm 0.01 (\pm 0.10)$	$+0.04 \pm 0.08$	$+0.04 \pm 0.06$	$+0.08 \pm 0.02$	-0.01 ± 0.04	-0.02 ± 0.07	–
[O/Fe]	$+0.04 \pm 0.10 (\pm 0.03)$	$+0.02 \pm 0.06$	-0.02 ± 0.08	$+0.07 \pm 0.02$	-0.04 ± 0.01	-0.07 ± 0.09	–
[Sc/Fe]	$-0.03 \pm 0.04 (\pm 0.08)$	$+0.10 \pm 0.06$	–	–	–	–	–
[Si/Fe]	$+0.10 \pm 0.02 (\pm 0.07)$	$+0.10 \pm 0.05$	–	$+0.09 \pm 0.03$	$+0.03 \pm 0.04$	-0.03 ± 0.06	–
[Ti/Fe]	$-0.04 \pm 0.06 (\pm 0.06)$	$+0.04 \pm 0.13$	–	$+0.12 \pm 0.02$	-0.03 ± 0.04	-0.02 ± 0.11	–
[V/Fe]	$+0.15 \pm 0.13 (\pm 0.14)$	$+0.15 \pm 0.16$	–	–	–	–	–
[Y/Fe]	$-0.05 \pm 0.04 (\pm 0.12)$	$+0.01 \pm 0.14$	–	–	–	–	–

Notes. ^(a) Tautvaišienė (2000), from 6 red clump stars. ^(b) Shetrone & Sandquist (2000), from 4 turn-off stars (we ignored blue stragglers). ^(c) Yong et al. (2005), from 3 red clump stars. ^(d) Randich et al. (2006), from 8 dwarfs and 2 slightly evolved stars. ^(e) Pace et al. (2008), from 6 main-sequence stars. ^(f) Santos et al. (2009), from 3 red clump giants and 6 dwarfs.

to zero within the uncertainties. On the other hand, radial velocity determinations for this cluster have been quite numerous (Sect. 2.2) and appear in good agreement with our determination.

5.3. NGC 2420

NGC 2420 ($\alpha_{J2000} = 07:38:23$ and $\delta_{J2000} = +21:34:24$) has always been considered the definitive example of the older, moderately metal-deficient OC beyond the solar circle. Several good quality imaging studies appeared already in the 60 s and 70 s (Sarma & Walker 1962; West 1967b; Cannon & Lloyd 1970; van Altena & Jones 1970; McClure et al. 1974, 1978, to name a few), and more recent photometries appeared in a variety of photometric systems (the most cited being Anthony-Twarog et al. 1990). Its intermediate status between the solar-metallicity OC near the sun and the clearly metal-deficient population of globular clusters indicated it early on as a potential transition object between the two populations, with metallicity determinations – both photometric and spectroscopic – placing it at an [Fe/H] value around the one of 47 Tuc (e.g., Pilachowski et al. 1980; Cohen 1980; Canterna et al. 1986; Smith & Suntzeff 1987). Photometric studies infer somewhat higher [Fe/H] values, ranging from -0.5 to -0.3 dex (e.g., Twarog et al. 1997; Friel et al. 2002; Anthony-Twarog et al. 2006), but still significantly lower than the value of [Fe/H] = -0.05 ± 0.03 (± 0.10) dex that we found here.

However, both Cohen (1980) and Pilachowski et al. (1980) noted that NGC 2420 should be significantly more metal-rich than the globular clusters they analyzed, i.e., M 71 (Cohen 1980) and 47 Tuc (Pilachowski et al. 1980), by some ≈ 0.5 dex. Since they placed M 71 and 47 Tuc around [Fe/H] = -1.3 , they consequently placed NGC 2420 at [Fe/H] = -0.6 . The resolution of their spectra ($R < 10\,000$) was much lower than ours, but if we trust their analysis in a relative sense, and consider more recent metallicity estimates for 47 Tuc and M 71 (-0.76 and -0.73 , respectively, Harris 1996), we would then place

NGC 2420 around [Fe/H] ≈ -0.1 or -0.2 . Having said that, it is surprising that there are no modern high resolution studies of a cluster that was considered so important in the past. The highest spectral resolution employed to study NGC 2420 is $R \approx 15\,000$ (Smith & Suntzeff 1987), with a spectral coverage of only 200 Å, giving [Fe/H] = -0.57 . Only the preliminary work of Freeland et al. (2002) suggested a higher, slightly sub-solar [Fe/H] value for NGC 2420. We also note that our [Fe/H] brings NGC 2420 more in line with other OC in the Galactic trends discussed in Sect. 7. Also, we cannot ignore the similarity with the case of NGC 7789 (Sect. 5.5), where analyses of high resolution spectroscopy by Tautvaišienė et al. (2005) and us provide much higher abundances than the previous photometric and low/medium-resolution studies. Clearly, additional high resolution spectroscopy with modern instruments, possibly with $R \approx 50\,000$ and $S/N \approx 100$ is needed for this cluster.

5.4. NGC 2682 (M 67)

Among the old OC, M 67 ($\alpha_{J2000} = 08:51:18$, $\delta_{J2000} = +11:48:00$) is quite close to us, with low reddening (Table 4) and solar metallicity, so it is one of the most well studied open clusters, and a good target when searching for solar twins and analogs (Pasquini et al. 2008). Since the first pioneering studies at the beginning of XX century, a few hundred papers have been published to date (see Burstein et al. 1986; Carraro et al. 1996; Yadav et al. 2008, for more references). Therefore, we have included M 67 in our sample because it acts as a fundamental comparison object that enables us to place our measurements in a more general framework.

Among the vast literature on M 67, there are several determinations of its metallicity, with various methods (e.g., Demarque 1980; Cohen 1980; Foy & Proust 1981; Janes & Smith 1984; Burstein et al. 1984, 1986; Brown 1987; Garcia Lopez et al. 1988; Cayrel de Strobel 1990; Hobbs & Thorburn 1991; Friel & Boesgaard 1992; Friel & Janes 1993; Janes & Phelps 1994;

Table 12. Literature abundance determinations for NGC 7789 based on high resolution spectroscopy.

	<i>Here</i>	T05 ^a
$R = \lambda/\delta\lambda$	30 000	30 000
S/N	50–100	≥ 50
[Fe/H]	$+0.04 \pm 0.07(\pm 0.10)$	-0.04 ± 0.05
[Al/Fe]	$-0.03 \pm 0.09(\pm 0.05)$	$+0.18 \pm 0.08$
[Ca/Fe]	$-0.18 \pm 0.09(\pm 0.03)$	$+0.14 \pm 0.07$
[Co/Fe]	$-0.02 \pm 0.01(\pm 0.06)$	$+0.09 \pm 0.14$
[Cr/Fe]	$+0.01 \pm 0.05(\pm 0.06)$	-0.05 ± 0.09
[Mg/Fe]	$+0.22 \pm 0.07(\pm 0.10)$	$+0.18 \pm 0.07$
[Na/Fe]	$-0.05 \pm 0.13(\pm 0.04)$	$+0.28 \pm 0.07$
[Ni/Fe]	$-0.01 \pm 0.01(\pm 0.10)$	-0.02 ± 0.05
[O/Fe]	$+0.16 \pm 0.06(\pm 0.03)$	-0.07 ± 0.09
[Sc/Fe]	$+0.08 \pm 0.02(\pm 0.08)$	-0.02 ± 0.07
[Si/Fe]	$-0.01 \pm 0.02(\pm 0.07)$	$+0.14 \pm 0.05$
[Ti/Fe]	$-0.03 \pm 0.09(\pm 0.06)$	-0.03 ± 0.07
[V/Fe]	$-0.01 \pm 0.09(\pm 0.14)$	$+0.09 \pm 0.12$
[Y/Fe]	$+0.08 \pm 0.09(\pm 0.12)$	$+0.13 \pm 0.13$

Notes. ^(a) Tautvaišienė et al. (2005), from 6 giants and 3 red clump giants.

Friel et al. 2002; Balaguer-Núñez et al. 2007; Marshall et al. 2005, to name a few), all typically converging to a solar value. high resolution abundance determinations have been derived for both giants and dwarfs, with many studies being devoted to light elements such as lithium and beryllium and their implications for mixing theories (Pasquini et al. 1997; Jones et al. 1999; Randich et al. 2007).

Table 11 shows a comparison of our results with some of the most recent high resolution ($R \geq 20\,000$) determinations (Tautvaišienė 2000; Shetrone & Sandquist 2000; Randich et al. 2006; Pace et al. 2008; Santos et al. 2009). The overall comparison is extremely satisfactory for all elements, except maybe for Mg, Na, Ba, and Ca (see also Sect. 3.1). For Mg, Na, and Ba, the large spread in literature demonstrates the difficulties in measuring these elements. For Ca, we see that our value is marginally lower than other literature determinations. As explained in Sect. 3.1, this is most probably due to the large uncertainties on the calcium $\log gf$ values.

5.5. NGC 7789

NGC 7789 ($\alpha_{J2000} = 23:57:24$ and $\delta_{J2000} = +56:42:30$, or $l = 115.53$ and $b = -5.39$) is a rich and intermediate-age OC, with a clearly defined giant branch, a well-populated main-sequence turnoff, and a substantial population of blue stragglers (McNamara 1980; Twarog & Tyson 1985; Milone & Latham 1994). Several photometric studies have been carried out (some examples are Kustner 1923; Reddish 1954; Burbidge & Sandage 1958; Janes 1977; Martinez Roger et al. 1994; Jahn et al. 1995; Gim et al. 1998a; Vallenari et al. 2000; Bartašiūtė & Tautvaišienė 2004; Bramich et al. 2005) and its parameters are reasonably well known.

Abundance determinations obtained from photometry and low/medium-resolution spectroscopy all give subsolar values around $[\text{Fe}/\text{H}] \simeq -0.2$ (Pilachowski 1985; Friel & Janes 1993; Schönberner et al. 2001; Friel et al. 2002), i.e., much lower than our $[\text{Fe}/\text{H}] = 0.04 \pm 0.07 (\pm 0.10)$ dex. However, a more conforing comparison with Tautvaišienė et al. (2005) is shown in Table 12. Their spectra have a resolution and S/N that is similar to ours, and most abundance ratios in common show excellent agreement. Minor discrepancies arise for some elements such as Ca (but see the discussion in Sects. 3.1 and 5.4), Al (but they

Fig. 4. Comparison between our iron-peak element results (large black dots), the high resolution measurements of other OC listed in Table 13 (large dark grey dots), and field stars belonging to the thin Galactic disc (light grey dots, Reddy et al. 2003) and to the thick Galactic disc (tiny light grey dots, Reddy et al. 2006). Errorbars on our results are the quadratic sum of internal uncertainties and uncertainties due to the choice of stellar parameters (Sect. 4).

used only one doublet while we used four), Na, and O. Since they do not list their $\log gf$ values, and other ingredients of the abundance analysis were similar to ours, we cannot explain the Na-O discrepancies, but we suspect that they must be caused by $\log gf$ differences.

6. Discussion of abundance ratios

We compared our abundance ratios with data from the literature, which were assembled as follows. For the Milky Way field stars, we used the thick and thin Galactic disc measurements from Reddy et al. (2003) and Reddy et al. (2006), who performed homogeneous abundance calculations of a few hundred F/G dwarfs selected from the Hipparcos catalogue. We added abundance ratios, based on high resolution spectroscopy, for 57 old OC from various literature sources (Table 13). When more than one determination was available for one cluster, we simply plotted them all to obtain a realistic idea of the uncertainties involved in the compilation.

6.1. Iron-peak element ratios

When compared with literature data (Fig. 4), our iron-peak elements appear all solar and in good agreement with the results for the Galactic disc and other OC. In particular, cobalt and

Table 13. Literature sources and [Fe/H] values for high resolution ($R \geq 15\,000$) based abundance ratios of old OC.

Cluster	[Fe/H]	Reference	Cluster	[Fe/H]	Reference
Be 17	-0.10	Friel et al. (2005)	NGC 2141	-0.26	Yong et al. (2005)
Be 20	-0.61	Yong et al. (2005)		0.00	Jacobson et al. (2009)
	-0.30	Sestito et al. (2008)	NGC 2158	-0.03	Jacobson et al. (2009)
Be 22	-0.32	Villanova et al. (2005)	NGC 2243	-0.48	Gratton & Contarini (1994)
Be 25	-0.20	Carraro et al. (2007)	NGC 2324	-0.17	Bragaglia et al. (2008)
Be 29	-0.44	Carraro et al. (2004)	NGC 2360	+0.07	Hamdani et al. (2000)
	-0.18	Yong et al. (2005)		+0.04	Smiljanic et al. (2009)
	-0.31	Sestito et al. (2008)	NGC 2420	-0.57	Smith & Suntzeff (1987)
Be 31	-0.40	Yong et al. (2005)	NGC 2447	+0.03	Hamdani et al. (2000)
Be 32	-0.29	Bragaglia et al. (2008)		-0.01	Smiljanic et al. (2009)
Be 66	-0.48	Villanova et al. (2005)	NGC 2477	+0.07	Bragaglia et al. (2008)
Be73	-0.22	Carraro et al. (2007)	NGC 2506	-0.20	Carretta et al. (2004)
Be75	-0.22	Carraro et al. (2007)	NGC 2660	+0.04	Bragaglia et al. (2008)
Blanco 1	+0.04	Ford et al. (2005)	NGC 3532	+0.04	Smiljanic et al. (2009)
Cr 261	-0.22	Friel et al. (2003)	NGC 3680	-0.04	Pace et al. (2008)
	-0.03	Carretta et al. (2005)		+0.04	Smiljanic et al. (2009)
	-0.03	De Silva et al. (2007)	NGC 3960	+0.02	Bragaglia et al. (2008)
	+0.13	Sestito et al. (2008)	NGC 5822	+0.04	Smiljanic et al. (2009)
Hyades	+0.13	Sestito et al. (2003)	NGC 6134	+0.15	Carretta et al. (2004)
	+0.13	Paulson et al. (2003)		+0.12	Smiljanic et al. (2009)
	+0.13	De Silva et al. (2006)	NGC 6253	+0.46	Carretta et al. (2007)
IC 2391	-0.03	Randich et al. (2001)		+0.36	Sestito et al. (2007)
IC 2602	-0.05	Randich et al. (2001)	NGC 6281	+0.05	Smiljanic et al. (2009)
IC 2714	+0.12	Smiljanic et al. (2009)	NGC 6475	+0.14	Sestito et al. (2003)
IC 4756	-0.15	Jacobson et al. (2007)	NGC 6633	+0.07	Smiljanic et al. (2009)
	+0.04	Smiljanic et al. (2009)	NGC 6791	+0.40	Peterson & Green (1998)
IC 4651	+0.11	Carretta et al. (2004)		+0.35	Origlia et al. (2006)
	+0.10	Pasquini et al. (2004)		+0.39	Carraro et al. (2006)
	+0.12	Pace et al. (2008)		+0.47	Carretta et al. (2007)
M 11	+0.10	Gonzalez & Wallerstein (2000)		+0.30	Boesgaard et al. (2009)
M 34	+0.07	Schuler et al. (2003)	NGC 6819	+0.09	Bragaglia et al. (2001)
M 67	-0.03	Tautvaišienė (2000)	NGC 6939	0.00	Jacobson et al. (2007)
	-0.01	Yong et al. (2005)	NGC 7142	+0.08	Jacobson et al. (2008)
	+0.03	Randich et al. (2006)	NGC 7789	-0.04	Tautvaišienė et al. (2005)
	+0.03	Pace et al. (2008)	Pleiades	-0.03	Randich et al. (2001)
Mel 66	-0.38	Gratton & Contarini (1994)		+0.06	Gebran & Monier (2008)
	-0.33	Sestito et al. (2008)	Praesepe	+0.04	Friel & Boesgaard (1992)
Mel 71	-0.30	Brown et al. (1996)		+0.12	Pace et al. (2008)
NGC 188	+0.01	Randich et al. (2003)	Rup 4	-0.09	Carraro et al. (2007)
NGC 1817	-0.07	Jacobson et al. (2009)	Rup 7	-0.26	Carraro et al. (2007)
NGC 1883	-0.20	Villanova et al. (2007)	Saurer 1	-0.38	Carraro et al. (2004)
	-0.01	Jacobson et al. (2009)	Tom 2	-0.45	Brown et al. (1996)
NGC 2112	-0.10	Brown et al. (1996)		-0.28	Frinchaboy et al. (2008)

chromium are in the closest agreement and have the smallest spreads. Although Sc, V, and Co are known to possess HFS that may lead to an increased scatter and an overestimated ratio, they do not appear to differ significantly from solar for our target stars, so we did not attempt any detailed HFS analysis. Nevertheless, the effect of increased scatter and overestimated abundances are visible, especially for vanadium, both in our data and in the disc stars, as well as in the other clusters from the literature.

A puzzling effect is seen in Fig. 4 in the [Ni/Fe] ratio. All the data for disc stars are very close to solar ($\langle[\text{Ni}/\text{Fe}]\rangle = -0.02 \pm 0.02$), and so are our determinations ($\langle[\text{Ni}/\text{Fe}]\rangle = 0.00 \pm 0.03$), but the other OC high resolution data appear slightly enhanced ($\langle[\text{Ni}/\text{Fe}]\rangle = 0.06 \pm 0.04$), lying systematically above the disc ones. Such a ≈ 0.05 dex offset is well within the uncertainties of abundance determinations in general, but since it appears systematic in nature, we are still left without a clear explanation. Our [Ni/Fe] ratios are slightly lower than

the other OC determinations, although still compatible within the uncertainties.

6.2. α -element ratios

We obtained abundances of Ca, Mg, O, Si, and Ti. As can be seen from Fig. 5, Si and Ti appear practically solar, within their respective uncertainties, and in very good agreement with literature determinations for both the disc stars and those of the other OC. For O, Ca and Mg we instead find marginally discrepant enhancements.

For O, we note that the spread in both our data and that of the literature is greater than in any other α -element. This is partly due to the well known problems of determining O from the single 6300 Å line, or the 6363 Å weak line, or from the IR triplet at 7770 Å (which requires NLTE corrections). Moreover, some literature works use Solar reference abundances that are as high as 8.93, which may explain some of the lowest [O/Fe]

Fig. 5. Comparison between our α -element ratios and the literature ones. Symbols are the same as in Fig. 4.

literature estimates. Given the large spread, the tendency of our [O/Fe] measurements to lie on the upper envelope of the other OC high resolution data is probably irrelevant. Solar O enhancements would probably be more in line with those of the other α -elements, while the subsolar values found generally in the literature suggests Wolf-Rayet as additional contributors of O, with a stronger metallicity dependence of the O yields (McWilliam et al. 2008).

In the case of Ca, our values are marginally inconsistent with the bulk of field and OC literature determinations. A few literature measurements of OC ratios are however as low as our values. These inconsistencies could be explained by the large uncertainties in the literature $\log gf$ values for calcium lines (~ 0.2 dex, see discussion in Sect. 3.1). Given these large additional uncertainties, we finally conclude that [Ca/Fe] is basically compatible with solar values in all the clusters examined.

Concerning Mg, we know already that the $\log gf$ values of some lines are still not very well determined (Sect. 3.1). We also know (Gratton et al. 1999) that some lines require NLTE corrections. We could find no correction factors for the lines that we were able to measure in our spectra, but we noticed that those lines examined by Gratton et al. (1999), which have χ_{ex} values similar to our lines, require NLTE corrections of about $+0.1$ – 0.5 dex. This correction would make our [Mg/Fe] values even higher, reaching an enhancement of 0.2 – 0.6 dex with respect to solar. Another possibility is that our lines have a non-negligible HFS, because they are dominated by odd isotopes, but we could find no further information in the literature. We only noted that other authors find such relatively high values of [Mg/Fe] in OC (such as Bragaglia et al. 2008).

Fig. 6. Comparison between our s-process elements ratios and the literature ones. Symbols are the same as in Fig. 4, except for the black star-like symbols in the top [Ba/Fe] panel, which represent the revision of Ba abundances with spectral synthesis performed by D’Orazi et al. (2009).

When the average $[\alpha/\text{Fe}]$ values are calculated, however, all the program stars and the cluster averages appear perfectly compatible with solar, within the relatively small uncertainties, as expected (see Tables 7 and 8). The $[\alpha/\text{Fe}]$ ratio is discussed also in Sect. 7.

6.3. Heavy element ratios

We measured the heavy s-process elements Ba, La, and Nd and the light s-process element Y. Lanthanum does not require any synthesis to take into account HFS, since the three lines that we used are always in the linear part of the curve of growth, and Fig. 6 shows indeed good agreement with the sparse literature values. Yttrium and neodymium are also in agreement with the literature data, although the measurements of Nd in OC are few in number and exhibit significant scatter. Our values of [Nd/Fe] have a tendency to lie towards the upper envelope of the disc stars, but this is not significant if we consider the large uncertainties involved (see also the discussion in Sect. 3.2).

Concerning Ba, we find high values in both our program stars and the Sun itself (Sect. 4.6). The same result has been found by other authors (e.g., Bragaglia et al. 2008). While a detailed study of the barium abundance is beyond the scope of the present paper, we note that recently D’Orazi et al. (2009) used a detailed HFS analysis of barium in OC to show that the overabundance can thus be reduced by roughly ~ 0.2 dex. Looking at Fig. 6, we can see that our [Ba/Fe] values are in general slightly higher than the literature OC data, which in turn have a huge spread. Data from D’Orazi et al. (2009), who revised the Ba abundances for 20 OC using spectral synthesis to take HFS into account, are towards the lower envelope of the OC abundances (open stars in

Fig. 7. Comparison between our $[\text{Na}/\text{Fe}]$ and $[\text{Al}/\text{Fe}]$ ratios and the literature values. Symbols are the same as in Fig. 4.

Fig. 6). As can be seen, some $[\text{Ba}/\text{Fe}]$ enhancement remains in their high quality data, which is apparently well correlated with the cluster ages (see their Fig. 1). However, no clear explanation is available yet, since the current evolution models and yields do not reproduce the data correctly at young ages, where the enhancement is higher and more uncertain (up to $[\text{Ba}/\text{Fe}] \approx 0.6$ dex for ages around 10^8 yr).

To summarize, most of the $[\text{Ba}/\text{Fe}]$ enhancement that we see in our measurements should be produced by HFS effects, but some could be real (up to 0.2 dex, see Fig. 2 by D’Orazi et al. 2009). A hint of a negative slope of $[\text{Ba}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$ in OC appears, that is not apparent among disc stars. Further studies similar to that of D’Orazi et al. (2009) are necessary for large samples of disc and OC stars to place firmer constraints on the chemical evolution of Ba in the Galactic disc.

6.4. Ratios of Na and Al and anticorrelations

We also derived Na and Al abundances, since these elements are quite easy to measure in OC and there is a vast body of literature measurements to compare with. Figure 7 shows that for Al there is general agreement between our data, the disc ratios, and the OC ratios, although there is a large scatter in the literature data. The NLTE corrections for the four Al doublets and the type of stars studied here could not be found in the literature. Baumüller & Gehren (1997) give corrections for hotter ($T_{\text{eff}} > 5000$) and higher gravity ($\log g > 3.5$) stars, which suggest that either the corrections are negligible, or they are slightly negative at lower temperatures and gravities.

In the case of Na, the spread in the literature data is even larger, and there are data points with both significant Na enhancement and typical solar values. Part of the scatter depends on the need for NLTE corrections. According to Gratton et al. (1999), the 5682–5688 Å and the 6154–6160 Å doublets with $EW \approx 100$ mÅ both require corrections of about ≤ 0.05 – 0.10 dex, for solar stars such as those considered here. The NLTE-corrected abundances should be higher than the LTE-uncorrected ones: this should bring our $[\text{Na}/\text{Fe}]$ LTE measurements to closer agreement with literature measurements. If the observed enhancement in $[\text{Na}/\text{Fe}]$ should prove to be real for OC, this would set OC stars completely apart from disc stars (De Silva et al. 2009). If the large spread were in addition intrinsic, this would suggest that light element chemical anomalies are similar, although much less pronounced, to those found in globular clusters.

Fig. 8. A search for (anti)-correlations of Al, Mg, Na and O among our targets stars. The four panels show different planes of abundance ratios, where stars belonging to each cluster are marked with different symbols. Dotted lines show solar values, solid lines show linear regressions and the typical uncertainty (~ 0.1 dex) is marked on the lower right corner of each panel.

Together with Mg and O (and C and N), Al and Na show puzzling (anti)-correlations in almost all of the studied Galactic globular clusters (Gratton et al. 2004). The most interesting property of the chemical anomalies, is that they have never been found outside globular clusters. They are not present in the field populations of the Milky Way and its surrounding dwarf galaxies, and they have only more recently been found in Fornax and LMC clusters (Letarte et al. 2006; Johnson et al. 2006; Mucciarelli et al. 2009). Dedicated searches for anticorrelations in OC include that of Martell & Smith (2009), on the strength of CH and CN bands in NGC 188, NGC 2158, and NGC 7789, that of Smiljanic et al. (2009), based on high resolution spectroscopy of C, N, O, Na, and $^{12}\text{C}/^{13}\text{C}$ and that of De Silva et al. (2009), which compiles and homogenizes literature Na-O high resolution data. No clear-cut sign of any anticorrelation has yet been found.

If we make the usual (anti)-correlation plots for our five OC (Fig. 8), we find no clear sign of chemical anomalies, and in all four plots the spread in each ratio is still compatible with the typical uncertainty in our measurements, which is of the order of 0.1–0.2 dex, depending on the element. In particular, in the $[\text{O}/\text{Fe}]$ – $[\text{Na}/\text{Fe}]$ plane, all 15 stars roughly occupy the solar region around zero that in Fig. 5 by Carretta et al. (2006) contains only normal only (see also De Silva et al. 2009). A possible exception to this total absence of correlations is the $[\text{Na}/\text{Fe}]$ – $[\text{Al}/\text{Fe}]$ plane, where a hint of a correlation can be discerned. Statistically, this is not significant and small variations in T_{eff} could induce a similarly weak correlation. For this reason, anticorrelations are usually a more robust sign of chemical anomalies. In light of the discussion by Smiljanic et al. (2009) about a Na-O anticorrelation, our Na-Al results is suggestive. If future studies show that some chemical anomalies of these elements are present in Galactic OC, our analysis (together with that of Smiljanic et al. 2009) implies that they must be of a much

Fig. 9. Trends in $[\text{Fe}/\text{H}]$ (*top panel*) and $[\alpha/\text{Fe}]$ (*bottom panel*) with Galactocentric Radius. Light grey dots in the *top panel* are OC from Friel et al. (2002), grey dots are the OC compiled in Table 13 and black dots are our data. NGC 2420 estimates by us and Smith & Suntzeff (1987) are connected with a thick dotted line. A linear fit with its uncertainty range is drawn across all points in both panels.

smaller extent than in globular clusters, i.e., 0.2–0.3 dex at most in $[\text{Al}/\text{Fe}]$, $[\text{Mg}/\text{Fe}]$, $[\text{Na}/\text{Fe}]$, and $[\text{O}/\text{Fe}]$ for the kind of clusters studied here. In any case, the lack of relations for OC would point towards one or more of the following environmental causes for the presence of anticorrelations in globular clusters: (i) relatively low metallicity (below solar); (ii) a dense local environment; (iii) total cluster mass of the order of $\sim 10^4 M_\odot$ or more; (iv) an undisturbed position in the Galaxy (e.g., away from the disc, see also Carretta 2006).

7. Galactic trends

As said earlier, OC are fundamental test particles in the study of the chemical evolution of the Galactic disc, and as such, they produce two of the strongest constraints on chemical models: the Galactic radial trends and the age-metallicity relation (AMR). Since a careful homogenization of literature data (including not only element ratios, but also ages and Galactocentric radii) is beyond the scope of the present paper, we used the literature data of Table 13, averaging all estimates for a single cluster together. We complemented our results with data by Friel et al. (2002) for those OC lacking high resolution measurements. Using 28 OC in common between the two datasets, we found an average offset of $[\text{Fe}/\text{H}] = -0.16 \pm 0.13$ dex, in the sense that the measurements by Friel et al. (2002) are on average lower than those based on high resolution data. We corrected Friel et al. (2002) data by this amount before plotting them. We extracted OC ages from the compilation of Dias et al. (2002)¹⁸, and for the Galactocentric radii (R_{GC}) data we used primarily Friel et al. (2002),

¹⁸ We are aware that at least in the case of NGC 6791, the age given by Dias et al. (2002) is quite different from other literature estimates (citations in Table 13), being lower by at least 2 Gyr. However, building a homogeneous age scale is a non-trivial task, which is beyond the scope of the present paper.

Fig. 10. Trends in $[\text{Fe}/\text{H}]$ (*top panel*) and $[\alpha/\text{Fe}]$ (*bottom panel*) with cluster ages. Symbols are the same as in Fig. 9.

complemented by the WEBDA, and obtained data points for the few missing clusters from the papers of Table 13. The resulting radial trends and AMR for $[\text{Fe}/\text{H}]$ and $[\alpha/\text{Fe}]$ (computed as in Sect. 4.2) are plotted in Figs. 9 and 10 and discussed below.

7.1. Trends with Galactocentric radius

The trends in the abundances with Galactocentric radius R_{GC} provide strong constraints on the models of Galactic chemical evolution as far as the disc formation mechanism is concerned¹⁹. It is now widely accepted (see for example Twarog et al. 1997; Friel et al. 2002; Yong et al. 2005; Sestito et al. 2008; Magrini et al. 2009) that there is a clear trend of decreasing metallicity, measured by $[\text{Fe}/\text{H}]$, with increasing R_{GC} . Such a trend is clearly detected not only in OC, but also in field stars (B-stars and Cepheids), H II regions, and planetary nebulae²⁰ (see Chiappini et al. 2001; Andrievsky et al. 2004; Yong et al. 2005; Lemasle et al. 2008, for some reviews of literature data).

The first large studies of homogeneous OC abundances (summarized in the review by Friel 1995), found that old OC (older than the Hyades) extend outwards in the disc, much farther out than young OC, and they found a clearly defined slope out to $R_{\text{GC}} \approx 16$ kpc. The spread about this slope was at the time ~ 0.2 dex, i.e., generally compatible with (or perhaps slightly larger than) the measurement uncertainties. This slope follows naturally from most Galactic chemical evolution models (Tosi 1982, 1988; Matteucci & Francois 1989; Tosi 1996; Chiappini et al. 2001; Andrievsky et al. 2004; Colavitti et al. 2009; Magrini et al. 2009), when different star formation and infall rates are assumed for the inner and outer disc. To reproduce most of the observational constraints, a differential disc formation

¹⁹ A far stronger constraint would be the variation in this trend with age. Such a study is at the moment not possible, given the small number of clusters studied with high resolution in a homogenous way.

²⁰ However, we know of at least one dataset in which PNe show flat trends in oxygen and neon abundances with R_{GC} (Stanghellini et al. 2006).

mechanism is often assumed, in which either the inner disk formed first and then grew in radius (inside-out formation) or the whole disk evolved simultaneously, but with a far more intense (and sometimes fast) evolution in its central, denser parts. A prediction of all models is that the metallicity gradient should change with time (although different models predict very different time changes; Tosi 1996) and some predict that it should flatten out at large radii. Indeed, the first studies of anticenter and distant clusters (Carraro et al. 2004; Yong et al. 2005; Carraro et al. 2007; Sestito et al. 2008) showed that after $R_{GC} \approx 12$ kpc, the relation flattens to around a value of $[Fe/H] \approx -0.3$ dex.

Not much can be said with the present data about the slope variation with time, but the exact value of the slope has been a matter of some debate. As said, earlier studies found a value of around -0.09 ± 0.01 dex kpc $^{-1}$, or -0.07 ± 0.01 dex kpc $^{-1}$ for the homogenous measurements by Friel et al. (2002). An alternative interpretation of a different data compilation (Twarog et al. 1997) describes the trend as two disjoint plateaux, one around solar metallicity comprising OC within $R_{GC} \approx 10$ kpc, and a second one at $[Fe/H] \approx -0.3$ outside the solar circle. More recent work based on high resolution compilations of OC data (Sestito et al. 2008) find a steeper slope of -0.17 ± 0.01 dex kpc $^{-1}$ within $R_{GC} < 14$ kpc, which still holds when considering only the 10 clusters analyzed homogeneously by that group. A sort of bimodal distribution is observed in their Fig. 9, where between the very steep slope of the inner clusters and the plateau of the outer ones there is a small gap that is almost devoid of OC ($9 < R_{GC} < 12$ kpc).

Our results are plotted in Fig. 9, where we consider the trend in $[Fe/H]$ and $[\alpha/Fe]$ with R_{GC} . We do see a distinct slope in the inner clusters and a flattening out for the outer ones. However, our sample contains ~ 15 more OC than that of Sestito et al. (2008), and most of them (including our five determinations) fall into the gap around $9 < R_{GC} < 12$ kpc, discussed above. With the addition of these clusters, we find a gentler slope of -0.05 ± 0.01 dex kpc $^{-1}$, in good agreement with previous work (Friel 1995; Friel et al. 2002) and with the disk Cepheids within $R_{GC} \approx 11$ kpc (Andrievsky et al. 2004; Lemasle et al. 2008). If we exclude the clusters outside $R_{GC} = 12$ kpc and remove the low resolution OC data from Friel et al. (2002), the slope does not steepen significantly, becoming -0.06 ± 0.02 dex kpc $^{-1}$. The flattening also does not seem so abrupt as in Fig. 9 by Sestito et al. (2008). The paucity of OC in the flat part of the relation (we have only Be 20, Be 22, Be 29, and Saurer 1 in our compilation) surely calls for more high resolution studies, since as the data stand now, they look compatible with both a plateau and a gradual change in slope. We note that NGC 2420 (already discussed in Sect. 5.3) was found to have $[Fe/H] = -0.57$ dex by Smith & Suntzeff (1987), based on $R \approx 16000$ spectra, while we find -0.05 dex, in much better agreement with the global Galactic trend. This goes in the direction of filling the gap in the Sestito et al. (2008) compilation, and also in the Twarog et al. (1997) dataset, pointing more towards a gentle and continuous decrease in $[Fe/H]$.

The trend in α -enhancement with R_{GC} is also of some importance, because it constraints the role of SNe Type Ia and II and their relative contributions. Yong et al. (2005) found a tendency for the α -enhancement to increase with R_{GC} , as did Magrini et al. (2009), who found this tendency to be in good agreement with their chemical evolution model. Model A by Chiappini et al. (2001) also predicted an increase in $[\alpha/Fe]$ with R_{GC} . In our compilation, the trend appears as a weak slope that is perfectly compatible with a flat distribution at the 1σ level. This, together with the study of slope changes with time, is one typical case in which

a high quality, homogeneous analysis of ~ 100 OC could provide a clear and definitive answer.

7.2. Trends with age

In spite of all models predicting an evolution of disk metallicity with time, albeit maybe only in the first Gyrs, and that this variation is indeed observed in disk stars (Reddy et al. 2003; Bensby et al. 2004), there appears to be no correlation at all between old OC abundances and ages (see the review by Friel 1995). More recent results have not changed this picture substantially. If confirmed, the lack of an AMR in OC would point towards a different source of chemical enrichment for OC stars (Yong et al. 2005) with respect to the disk stars. In essence, the metallicity of OC stars seems to be more dependent on the location in which they formed, than by the time at which they formed.

What we find here is quite encouraging, although still not statistically significant. We recall that our compilation includes 57 high resolution abundance determinations, plus a handful of low resolution determinations by Friel et al. (2002). Although we have made no attempt to homogenize the data, except for a -0.16 dex correction to the low resolution abundances, this sample is $\sim 50\%$ larger than any compilation presented before (see e.g., Sestito et al. 2008; De Silva et al. 2009; Magrini et al. 2009) and shows that the community is proceeding fast in filling up the gaps in our knowledge of OC. Figure 10 indeed shows a weak trend of decreasing $[Fe/H]$ and increasing $[\alpha/Fe]$ with increasing age. The slopes are very gentle at most and are still compatible with no trends at all. Nevertheless, if these trends exist, we can place some constraints on them: for $[Fe/H]$, the gradient should not be significantly greater than $-2.6 \pm 1.1 \times 10^{-11}$ dex Gyr $^{-1}$ and for $[\alpha/Fe]$ no greater than $1.1 \pm 5.0 \times 10^{-11}$ dex Gyr $^{-1}$.

8. Summary and conclusions

We have analyzed high resolution spectra of three red clump giants in five OC, three of them lacking any previous high-resolution-based chemical analysis. Given the paucity of literature data, such a small sample is enough to increase the entire body of high resolution data for OC by $\approx 5\%$. To compare our results with the literature, we have compiled chemical abundances based on high resolution data of 57 clusters from the literature. Given the rapid progress in the field, this sample is $\sim 50\%$ larger than previous literature compilations (e.g., Friel et al. 2002; Sestito et al. 2008; Magrini et al. 2009). The main results drawn from the analysis of our five clusters are:

- We provide the first high-resolution-data based abundance analysis of Cr 110 ($[Fe/H] = +0.03 \pm 0.02$ (± 0.10) dex), NGC 2099 ($[Fe/H] = +0.01 \pm 0.05$ (± 0.10) dex) and NGC 2420 ($[Fe/H] = -0.05 \pm 0.03$ (± 0.10) dex), which previously had only measurements based on low resolution data, and the $R \approx 16000$ analysis by Smith & Suntzeff (1987); our new determination of the metallicity of NGC 2420 places data for this cluster in far closer agreement with global Galactic trends.
- The abundances found for NGC 7789 ($[Fe/H] = +0.04 \pm 0.07$ (± 0.10) dex) and M 67 ($[Fe/H] = +0.05 \pm 0.02$ (± 0.10) dex) are in good agreement with past high resolution studies.
- We provide the first high-resolution-data based radial velocity determination for Cr 110 ($\langle V_r \rangle = 41.0 \pm 3.8$ km s $^{-1}$).
- We found that all our abundance ratios, with few exceptions generally explained by technical details of the analysis procedure, are near-solar, as is typical of OC with similar

properties; we also found solar ratios for Na, which is generally found to be overabundant, and for O, which is generally found to be underabundant.

- We detected no significant anticorrelation (or correlation) among Na, Al, Mg, and O, in general agreement with past and recent results, and we can say that if these correlations are indeed present in OC, they must be far less extended than in globular clusters, amounting to no more than 0.2–0.3 dex at most.

With our compilation of literature data, we could also examine global Galactic trends, which are extremely useful in constructing chemical evolution models for the Galaxy in general and the Galactic thin disc in particular. For the metallicity gradient, we found a slope of -0.06 ± 0.02 dex kpc $^{-1}$ considering only high resolution data within $R_{GC} = 12$ kpc. Our compilation contains data, including our own determinations, that fill the small gap around 9 kpc $< R_{GC} < 12$ kpc and point towards a gentle and continuous decrease, rather than either a two-step decline such as in Twarog et al. (1997) or a steep slope as in Sestito et al. (2008). We do find a flattening at $R_{GC} > 12$ kpc and a hint of an increasing $[\alpha/Fe]$ towards the outer disk. Concerning the AMR, we do not find any strong evidence for it, and we just note some very mild trends. If an AMR is indeed present among OC, it must be very weak and we provide upper limits to its slope in both $[Fe/H]$ and $[\alpha/Fe]$.

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