The peculiar Na-O anticorrelation of the bulge globular cluster NGC 6440

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ABSTRACT

Context. Galactic globular clusters (GCs) are essential tools for understanding the earliest epoch of the Milky Way, since they are among the oldest objects in the Universe and can be used to trace its formation and evolution. Current studies using high-resolution spectroscopy for many stars in each of a large sample of GCs allow us to develop a detailed observational picture of their formation and their relation with the Galaxy. However, it is necessary to complete this picture by including GCs that belong to all major Galactic components, including the bulge.

Aims. Our aim is to perform a detailed chemical analysis of the bulge GC NGC 6440 in order to determine if this object has multiple populations (MPs) and investigate its relation with the bulge of the Milky Way and with the other Galactic GCs, especially those associated with the bulge, which are largely poorly studied.

Methods. We determined the stellar parameters and the chemical abundances of light elements (Na, Al), iron-peak elements (Fe, Sc, Mn, Co, Ni), α -elements (O, Mg, Si, Ca, Ti) and heavy elements (Ba, Eu) in seven red giant members of NGC 6440 using high-resolution spectroscopy from FLAMES-UVES.

Results. We found a mean iron content of $[\text{Fe}/\text{H}] = -0.50 \pm 0.03$ dex in agreement with other studies. We found no internal iron spread. On the other hand, Na and Al show a significant intrinsic spread, but the cluster has no significant O-Na anticorrelation nor does it exhibit a Mg-Al anticorrelation. The α -elements show good agreement with the bulge field star trend, although they are at the high α end and are also higher than those of other GCs of comparable metallicity. The heavy elements are dominated by the r -process, indicating a strong contribution by SNeII. The chemical analysis suggests an origin similar to that of the bulge field stars.

Key words. galaxies: clusters: individual: NGC 6440 – stars: abundances

1. Introduction

Globular clusters (GCs) are ideal laboratories to study stellar evolution because they are among the oldest known objects in the Universe. They have been extensively studied with photometry in a wide variety of different photometric systems, and with high-, medium-, and low-resolution spectroscopy.

They were until recently thought to be simple stellar populations (SSP), with all of the stars in a cluster having the same age and initial chemical composition. However, they have proven to be far more complex objects. For example, most Galactic GCs have recently been shown to be characterized by inhomogeneities in the light-element content (C, N, O, Na, Mg and/or Al), that translate to well defined patterns such as O-Na or Mg-Al anticorrelations. This spread is most likely due to the early self-pollution the cluster suffered after its formation, allowing the birth of two or more generations of stars (Gratton et al. 2004). Several kinds of polluters for the light elements have been proposed: intermediate mass asymptotic giant branch (AGB) stars (D’Antona et al. 2002, 2016), fast-rotating massive main sequence (MS) stars (Decressin et al. 2007; Krause et al. 2013) and massive binaries (de Mink et al. 2010; Izzard et al. 2013).

In addition, a few massive GC-like systems such as ω Cen (Johnson et al. 2008; Marino et al. 2011a), M22 (Marino et al. 2011b; Da Costa et al. 2009), M54 (Carretta et al. 2010a) and Terzan 5 (Origlia et al. 2011) show a significant spread in Fe as well. Such clusters must also have been able to retain material ejected from SNeII and/or SNeIa (Marcolini et al. 2009), as well

as material ejected from polluters at lower velocity via stellar winds. This material ejected into the interstellar medium of the GC mixes with the primordial gas to form the second generation of stars, if the appropriate conditions arise (e.g., Cottrell & Da Costa 1981; Carretta et al. 2010b). However, none of the current scenarios are able to satisfactorily reproduce the complex multiple population behavior now known to exist (e.g., Renzini et al. 2015).

Despite the large number of galactic GCs that have been studied with high-resolution spectroscopy, which allows a more detailed understanding of their evolution, the picture is not yet complete, because many galactic GCs, especially those belonging to the bulge of the Milky Way, have not been studied in detail yet, mainly because of the large and often variable reddening, as well as intense field-star contamination, which plague detailed studies.

In this paper we present a detailed chemical study of the metal-rich GC NGC 6440, located 1.3 kpc away from the center of our Galaxy (Harris 1996). We have analyzed the chemical patterns of seven member stars using high-resolution spectroscopy and obtained the abundances of light-, α -, iron-peak- and heavy elements. The detailed abundance distribution of these elements is compared to that of field stars in several major Galactic components (bulge, disk, halo) as well as other (bulge and non-bulge) GCs.

NGC 6440 is particularly interesting because Mauro et al. (2014) suggested the presence of a possible iron spread in this

cluster, based on low-resolution Ca triplet spectra of eight stars. On the other hand Origlia et al. (2008, hereafter referred to as OR08) have found a homogeneous iron content in a sample of ten stars using high-resolution infrared spectroscopy. In this paper we address this discrepancy.

In addition, Mauro et al. (2012) found two horizontal branches (HBs) in NGC 6440 using data from the VVV survey (Minniti et al. 2010).

This peculiar feature has been found in only three other bulge stellar systems, namely Terzan 5 (Ferraro et al. 2009), NGC 6440, and NGC 6569 (Mauro et al. 2012). While Terzan 5 has been extensively studied in recent years and turns out to be a complex stellar system with multiple stellar populations with different $[\text{Fe}/\text{H}]$ (Origlia et al. 2011; Massari et al. 2014) and age (Ferraro et al. 2016), NGC 6440 and NGC 6569 still need to be fully characterized.

Several chemical analyses have been carried out on NGC 6440 stars using different techniques. However, these studies are far from being complete. For example, OR08 measured light and α elements using IR high-resolution spectroscopy (see Table 5 and Fig. 9). Moreover, there are other studies with low-resolution spectroscopy and photometry (Valenti et al. 2004; Dias et al. 2016a). Our sample, although slightly smaller than the previous studies, was observed with high resolution, which allows us to obtain the abundances of fourteen elements with smaller errors than the previous studies.

In Sect. 2 we describe the observations and data reduction, while in Sect. 3 we explain the methodology we used to calculate atmospheric parameters and chemical abundances. In Sect. 4 we present our result concerning iron-peak elements, alpha elements, the Na-O anticorrelation, the Mg-Al and O-Al relations and heavy element abundances. Our findings are used in Sect. 5 to shed light on the origin of NGC 6440, and finally in Sect. 6 our conclusions are presented.

2. Observations and data reduction

Bright red giant-star candidate stars in NGC 6440 were observed with the fiber-fed multi-object FLAMES facility mounted at the ESO VLT/UT2 telescope in Cerro Paranal (Chile) in period 93A (ESO program ID 093.D-0286, PI S. Villanova). The FLAMES observations analyzed here were conducted using the blue and red arms of the high-resolution spectrograph UVES and allowed for the simultaneous observation of seven stars.

We selected seven targets to be observed with FLAMES-UVES from the membership list of NGC 6440 previously published in Saviane et al. (2012) using FORS2. Their spatial distribution is shown in Fig. 1. Saviane et al. (2012) showed that the stars used in this study are members of NGC 6440 using two criteria: the range of radial velocities of member stars was small and the dispersion in the equivalent widths was comparable to the measurement errors (assuming the intrinsic abundance dispersion in the cluster is small).

These stars belong to the upper RGB, as can be clearly seen in the color-magnitude diagram (CMD) of the cluster (Fig. 2), with the exception of star #5, which apparently is an AGB star. Its chemical pattern shows good agreement with the rest of the sample.

FLAMES-UVES data have a spectral resolution of about $R \approx 47\,000$. The data was taken with central wavelength 580 nm, which covers the wavelength range 476–684 nm. We stacked several spectra in order to increment the S/N. The final stacked S/N is between 25 and 30 at 650 nm.

Fig. 1. Distribution of the stars observed in NGC 6440 (blue filled circles). The yellow large circle is the tidal radius (Harris 1996).

Fig. 2. Color-magnitude diagram of NGC 6440 from the VVV survey corrected by the VVV reddening maps (Gonzalez et al. 2012). The blue filled circles are our observed UVES sample.

Data reduction was performed using the ESO CPL based FLAMES/UVES Pipeline version 5.3.0¹ for extracting the individual fibre spectra. Data reduction includes bias subtraction, flat-field correction, wavelength calibration, and spectral rectification.

We subtracted the sky using the Sarith package in IRAF and measured radial velocities using the FXCOR package in IRAF and a synthetic spectrum as a template. The mean heliocentric radial velocity value for our seven targets is $-71.20 \pm 5.49 \text{ km s}^{-1}$.

¹ <http://www.eso.org/sci/software/pipelines/>

Table 1. Parameters of the observed stars.

ID	RA (h:m:s)	Dec (°:′:″)	<i>J</i> (mag)	<i>H</i> (mag)	<i>K_s</i> (mag)	RV _H (km s ⁻¹)	<i>T</i> _{eff} (K)	log(<i>g</i>)	[Fe/H] (dex)	<i>v</i> _t (km s ⁻¹)
1	17:48:56.24	20:20:54.20	11.83	10.66	10.28	-89.59 ± 0.38	4251	1.92	-0.65	1.76
2	17:48:54.47	20:22:41.92	13.51	12.54	12.27	-61.29 ± 0.30	4655	2.31	-0.41	1.96
3	17:48:53.78	20:23:28.50	12.71	11.66	11.35	-50.10 ± 0.41	4429	2.40	-0.51	2.08
4	17:48:55.66	20:21:31.50	12.61	11.48	11.18	-87.16 ± 0.49	4454	2.60	-0.51	1.94
5	17:48:52.63	20:23:06.61	10.89	9.75	9.40	-61.42 ± 0.55	4342	2.50	-0.47	1.56
6	17:48:55.45	20:22:19.20	12.95	11.84	11.55	-71.55 ± 0.84	4435	2.46	-0.45	1.85
7	17:48:50.87	20:21:15.98	12.76	11.70	11.42	-77.28 ± 0.51	4450	2.29	-0.52	2.07

Our velocity dispersion is 14.54 ± 3.90 km s⁻¹. NGC 6440 is a massive GC, with a mass of $5.72 \times 10^5 M_{\odot}$ (Gnedin & Ostriker 1997), so it is expected to have a high-velocity dispersion. Using observational data and dynamical models Gnedin et al. (2002) calculated the velocity dispersion in a large sample of GCs and found in NGC 6440 a velocity dispersion of 18.2 km s⁻¹ at the cluster half-mass radius, one of the larger velocity dispersions among galactic GCs². In addition, our sample is concentrated toward the center of the cluster, therefore our measured velocity dispersion could be somewhat higher than the global value. On the other hand, as we only have seven stars, the uncertainty of the dispersion is large. Our value is in agreement with the dispersion found by OR08 of 10 km s⁻¹. Moreover, Zoccali et al. (2014) determined the velocity of the bulge field stars using GIRAFFE spectra. Along the line of sight to NGC 6440 the velocity of the field stars is ~ 30 km s⁻¹ with a dispersion of ~ 80 km s⁻¹, see Fig. 10 from Zoccali et al. (2014). This average field star velocity is very different from the velocity of our sample. Finally, although stars one and three show the most extreme radial velocities of our sample, their chemical patterns (alpha element, iron peak elements, heavy elements) show good agreement with the rest of the sample, with a low scatter. All these factors suggest a high probability that all the stars of our sample are indeed members of NGC 6440.

The mean radial velocity is in excellent agreement with the values in the literature: Saviane et al. (2012) with the same sample (less star #1_393) found a value of -76 ± 4 km s⁻¹ and Harris (1996) quotes a value of -76.6 ± 2.7 km s⁻¹. Table 1 lists the basic parameters of the selected stars: ID, the J2000 coordinates (RA and Dec), *J*, *H*, *K_s* magnitudes from VVV PSF photometry, calibrated on the system of 2MASS (Mauro et al. 2014; Cohen et al. 2017), heliocentric radial velocity, *T*_{eff}, log(*g*), micro-turbulent velocity (*v*_t) and metallicity from our study. In addition, Table 2 shows the metallicity values from Saviane et al. (2012), Mauro et al. (2014, hereafter referred to as M14) and Dias et al. (2016a). The determination of the atmospheric parameters is discussed in the following section.

3. Atmospheric parameters and abundances

The analysis of the data was performed using the local thermodynamic equilibrium (LTE) program MOOG (Snedden 1973).

Atmospheric models were calculated using ATLAS9 (Kurucz 1970) and the line list for the chemical analysis is the same described in previous papers (e.g., Villanova & Geisler 2011). *T*_{eff}, *v*_t, and log(*g*) were adjusted and new atmospheric models calculated iteratively in order to remove trends in excitation potential and equivalent width versus abundance for

Table 2. Iron abundances from different authors.

ID.	[Fe/H] _{this_work}	[Fe/H] _{S12}	[Fe/H] _{M14}	[Fe/H] _{D16}
1	-0.65 ± 0.05	-0.06 ± 0.16	-0.37 ± 0.14	-0.32 ± 0.16
2	-0.41 ± 0.05	-0.07 ± 0.16	-0.14 ± 0.14	-0.40 ± 0.20
3	-0.51 ± 0.05	-0.50 ± 0.16	-0.57 ± 0.14	-0.21 ± 0.09
4	-0.51 ± 0.05	-0.28 ± 0.16	-0.46 ± 0.14	-0.15 ± 0.16
5	-0.47 ± 0.05	-0.43 ± 0.16	-0.52 ± 0.14	-0.55 ± 0.16
6	-0.45 ± 0.05	-0.12 ± 0.16	-0.33 ± 0.14	–
7	-0.52 ± 0.05	-0.34 ± 0.16	-0.45 ± 0.14	–

References. S12: Saviane et al. (2012); M14: Mauro et al. (2014); D16: Dias et al. (2016a).

*T*_{eff} and *v*_t respectively, and to satisfy the ionization equilibrium for log(*g*). FeI and FeII were used for this latter purpose. The [Fe/H] value of the model was changed at each iteration according to the output of the abundance analysis. In Fig. 4 we show the good agreement between our stellar parameters and an isochrone of similar metallicity as we derive ([Fe/H] = -0.5 dex) and age of 13 Gyr (Dotter et al. 2008).

The reddening in this cluster is a significant factor to be addressed because of its position inside the Galactic bulge. The mean color excess in the Harris catalog is $E(B - V) = 1.07$ (Harris 1996), similar to that of Valenti et al. (2004), $E(B - V) = 1.15$. Additionally there is a strong and complex differential reddening (Fig. 5). In our case the stellar parameters were found directly from the spectra, as explained above, so our measurement of abundances is not affected by the effects of reddening.

The chemical abundances for Ca, Ti, Fe, Co and Ni were obtained using equivalent widths (EWs) of the spectral lines; a more detailed explanation of the method we used to measure the EWs is given in Marino et al. (2008). For the other elements (O, Na, Mg, Al, Si, Sc, Ni, Mn, Ba and Eu), whose lines are affected by blending, we used the spectrum-synthesis method. We calculated five synthetic spectra having different abundances for each line, and estimated the best-fitting value as the one that minimises the rms scatter. We show in Fig. 3 an example of the method for two lines (oxygen and aluminum). Only lines not contaminated by telluric lines were used. The adopted solar abundances we used are reported in Table 3.

An internal error analysis was performed by varying *T*_{eff}, log(*g*), [Fe/H], and *v*_t and redetermining abundances of star #3, assumed to be representative of the entire sample. Parameters were varied by $\Delta T_{\text{eff}} = +40$ K, $\Delta \log(g) = +0.24$, $\Delta [\text{Fe}/\text{H}] = +0.03$ dex, and $\Delta v_t = +0.08$ km s⁻¹, which we estimated as our typical internal errors. The amount of variation of the parameter was calculated using three stars representative of our sample (#1, #3, and #2) with relatively low, intermediate, and high

² <http://dept.astro.lsa.umich.edu/~ognedin/gc/vesc.dat>

Fig. 3. Spectrum synthesis fits for oxygen (star #3) and aluminum (star #4) lines respectively. The dotted line is the observed spectrum and the solid color lines show the synthesised spectra corresponding to different abundances.

Fig. 4. $\log g$ vs. $\log T_{\text{eff}}$ for our sample of seven stars. The over-plotted isochrone has a metallicity of -0.5 dex, $[\alpha/\text{Fe}] = +0.40$ dex and age of 13 Gyr (Dotter et al. 2008).

effective temperature, respectively, according to the procedure that was performed by Marino et al. (2008), which we use in this study.

The error introduced by the uncertainty on the EW ($\sigma_{S/N}$) was calculated by dividing the rms scatter by the square root of the number of the lines used for a given element and a given star. For elements whose abundance was obtained by spectrum-synthesis, the error is the output of the fitting procedure.

Fig. 5. VVV reddening map for NGC 6440 (Gonzalez et al. 2012). The large blue circle is the tidal radius and small circle is the half light radius. The blue filled circles are our observed UVES sample.

Finally the error for each $[X/\text{Fe}]$ ratio as a result of uncertainties in atmospheric parameters and $\sigma_{S/N}$ are listed in Table 4. The total internal error (σ_{tot}) is given by:

$$\sigma_{\text{tot}} = \sqrt{\sigma_{T_{\text{eff}}}^2 + \sigma_{\log(g)}^2 + \sigma_{v_t}^2 + \sigma_{[\text{Fe}/\text{H}]}^2 + \sigma_{S/N}^2}. \quad (1)$$

In Table 4 we compare the total internal error for each element with the observed error (standard deviation of the sample).

4. Results

In this section, we discuss our results in detail. In addition, we compare them with the literature, and also do a general comparison with bulge globular clusters analyzed up to this moment.

4.1. Iron

We found a mean $[\text{Fe}/\text{H}]$ value for the cluster of

$$[\text{Fe}/\text{H}] = -0.50 \pm 0.03 \text{ dex.}$$

The observed scatter is consistent with that expected solely from errors and thus we find no evidence for any intrinsic Fe abundance spread. However, star #1 of our sample has a difference of 0.12 dex compared to the average. In order to decide whether this is a peculiar star, or if there is a real intrinsic dispersion, a larger sample would be needed. Hereafter we have highlighted this star in most plots to check for any other peculiarities. We now discuss how our result compares to the literature.

Saviane et al. (2012), who selected the targets we analyze in this paper, measured CaII triplet equivalent widths of all stars. They applied the metallicity scale from Carretta et al. (2009a) and found an average of $[\text{Fe}/\text{H}] = -0.25 \pm 0.16$ for eight stars in NGC 6440. In Table 2 we list the metallicities of Saviane et al. (2012) for our stars. If we use the new metallicity scale of Dias et al. (2016a,b), the average is $[\text{Fe}/\text{H}] = -0.28 \pm 0.14$. This is compatible with our results within 1.5σ . No evidence of intrinsic Fe abundance spread was found, in agreement with our findings.

Table 3. Abundances of the observed stars.

Element	1	2	3	4	5	6	7	Cluster ¹	Sun	N° lines
[O/Fe]	0.57 ±0.04	0.43 ±0.05	0.57 ±0.05	0.52 ±0.04	0.57 ±0.05	0.67 ±0.06	0.30 ±0.04	+0.52 ± 0.05	8.83	1
[Na/Fe] _{NLTE}	0.15 ±0.06	0.21 ±0.09	0.48 ±0.09	0.44 ±0.08	0.53 ±0.07	0.85 ±0.07	1.05 ±0.08	+0.53 ± 0.12	6.32	2
[Mg/Fe]	0.41 ±0.05	0.44 ±0.08	0.39 ±0.05	0.37 ±0.06	0.24 ±0.04	0.47 ±0.06	0.29 ±0.06	+0.37 ± 0.03	7.56	3
[Al/Fe]	0.58 ±0.04	0.32 ±0.04	0.34 ±0.04	0.81 ±0.04	0.64 ±0.04	0.56 ±0.03	0.69 ±0.04	+0.56 ± 0.07	6.43	2
[Si/Fe]	-0.05 ±0.07	0.67 ±0.08	0.13 ±0.08	0.13 ±0.09	0.02 ±0.06	0.24 ±0.09	0.26 ±0.07	+0.20 ± 0.09	7.61	2
[Ca/Fe]	0.69 ±0.07	0.19 ±0.05	0.14 ±0.07	0.35 ±0.08	0.38 ±0.08	0.25 ±0.08	0.41 ±0.09	+0.34 ± 0.07	6.39	4
[Sc/Fe]	0.25 ±0.07	0.10 ±0.09	0.36 ±0.09	0.28 ±0.09	0.34 ±0.06	0.19 ±0.09	0.18 ±0.07	+0.24 ± 0.03	3.12	2
[Ti/Fe] ²	0.41 ±0.05	0.28 ±0.07	0.49 ±0.07	0.30 ±0.06	0.60 ±0.07	0.48 ±0.06	0.36 ±0.07	+0.42 ± 0.04	4.94	12
[Mn/Fe]	-0.08 ±0.08	-0.10 ±0.07	-0.12 ±0.08	-0.01 ±0.09	0.11 ±0.08	0.13 ±0.07	-0.01 ±0.10	-0.01 ± 0.04	5.37	1
[Fe/H]	-0.65 ±0.03	-0.41 ±0.02	-0.51 ±0.02	-0.51 ±0.03	-0.47 ±0.04	-0.45 ±0.03	-0.52 ±0.03	-0.50 ± 0.03	7.50	~100
[Co/Fe]	0.50 ±0.06	0.40 ±0.07	0.42 ±0.07	0.51 ±0.07	0.58 ±0.08	0.38 ±0.06	0.49 ±0.08	+0.42 ± 0.03	4.93	10
[Ni/Fe]	0.15 ±0.06	-0.08 ±0.08	-0.05 ±0.08	-0.07 ±0.07	0.19 ±0.08	-0.15 ±0.06	0.06 ±0.08	+0.01 ± 0.05	6.26	7
[Ba/Fe]	-0.21 ±0.07	-0.29 ±0.09	-0.12 ±0.06	-0.25 ±0.07	-0.01 ±0.07	-0.09 ±0.06	-0.19 ±0.07	-0.17 ± 0.05	2.34	1
[Eu/Fe]	0.45 ±0.06	0.39 ±0.05	0.38 ±0.06	0.52 ±0.05	0.51 ±0.06	0.50 ±0.05	0.40 ±0.06	+0.45 ± 0.02	0.52	1

Notes. Columns 2–8: abundances of the observed stars. Column 9: mean abundance for the cluster. Column 10: abundances adopted for the Sun in this paper. Abundances for the Sun are indicated as $\log\epsilon(\text{El.})$. Column 11: number of measured lines for each chemical element. The errors presented for each abundance were calculated by dividing the rms scatter by the square root of the number of the lines used for a given element and a given star. For elements whose abundance was obtained by spectrum-synthesis, the error is the output of the fitting procedure. ⁽¹⁾ The errors are the statistical errors obtained of the mean. ⁽²⁾ [Ti/Fe] is the average between Ti I and Ti II.

Table 4. Estimated errors on abundances, due to errors on atmospheric parameters and to spectral noise, compared with the observed errors.

ID	$\Delta T_{\text{eff}} = 40 \text{ K}$	$\Delta \log(g) = 0.24$	$\Delta v_t = 0.08$	$\Delta [\text{Fe}/\text{H}] = 0.03$	$\sigma_{S/N}$	σ_{tot}	σ_{obs}
$\Delta([\text{O}/\text{Fe}])$	-0.02	0.08	-0.01	0.00	0.05	0.10	0.12
$\Delta([\text{Na}/\text{Fe}])$	-0.05	0.04	-0.01	0.03	0.09	0.11	0.32
$\Delta([\text{Mg}/\text{Fe}])$	-0.01	-0.02	-0.01	0.01	0.05	0.06	0.08
$\Delta([\text{Al}/\text{Fe}])$	-0.01	-0.03	0.00	0.01	0.04	0.05	0.18
$\Delta([\text{Si}/\text{Fe}])$	0.03	-0.04	0.01	0.02	0.08	0.10	0.23
$\Delta([\text{Ca}/\text{Fe}])$	-0.04	-0.01	0.00	0.01	0.07	0.08	0.18
$\Delta([\text{Sc}/\text{Fe}])$	0.00	0.04	0.01	-0.01	0.09	0.10	0.09
$\Delta([\text{Ti}/\text{Fe}])$	-0.04	0.00	0.00	0.02	0.07	0.08	0.11
$\Delta([\text{Mn}/\text{Fe}])$	0.01	0.09	0.01	0.01	0.08	0.12	0.09
$\Delta([\text{Fe}/\text{H}])$	-0.01	0.03	0.03	0.02	0.02	0.05	0.08
$\Delta([\text{Co}/\text{Fe}])$	-0.02	0.05	0.00	0.02	0.07	0.09	0.07
$\Delta([\text{Ni}/\text{Fe}])$	-0.03	-0.04	0.05	0.03	0.08	0.11	0.13
$\Delta([\text{Ba}/\text{Fe}])$	-0.02	0.08	0.00	0.07	0.06	0.12	0.10
$\Delta([\text{Eu}/\text{Fe}])$	0.01	0.09	0.01	0.01	0.06	0.11	0.06

Mauro et al. (2014) used the CaII triplet equivalent widths from Saviane et al. (2012) and corrected them by gravity and temperature effects using infrared magnitudes, instead of the traditional V magnitudes used by Saviane et al. (2012).

They found an average metallicity of $[\text{Fe}/\text{H}] = -0.38 \pm 0.14$ using the scale from Carretta et al. (2009a, see Table 2), which

becomes $[\text{Fe}/\text{H}] = -0.29 \pm 0.14$ if we adopt the new metallicity scale of Dias et al. (2016a,b). We do not confirm the possible metallicity spread suggested by Mauro et al. (2014).

Dias et al. (2015, 2016a) analyzed the low-resolution optical spectra of the same stars selected by Saviane et al. (2012, we refer to Table 2). They applied full-spectrum fitting against both a

synthetic and an empirical library. Their results agree with homogeneous high-resolution spectroscopic results within 0.08 dex and they defined a new metallicity scale based on their sample of 51 GGCs. They found an average metallicity for NGC 6440 of $[\text{Fe}/\text{H}] = -0.24 \pm 0.05$ dex, based on the same seven stars.

The three published results above from CaII triplet and optical spectra of the same stars agree very well. Nevertheless we analyzed the same stars with high-resolution spectroscopy and our result is about 0.2 dex more metal-poor. The typical error for the metallicity of a single star in the three analyses above is about 0.15 dex, therefore, the 0.2 dex difference may be explained by the error bars. We have added the metallicities for individual stars from the three analyses in Table 2 for reference.

Stellar parameters and abundances for Fe, O, Ca, Si, Mg, Al and C in NGC 6440 were derived by OR08 using high-resolution infrared spectra. Although we have no common star to make a direct comparison, the average of the sample from OR08 (10 RGB stars) for iron is $[\text{Fe}/\text{H}] = -0.54$ dex with a $\sigma = 0.06$, showing excellent agreement with our results.

The field of NGC 6440 is greatly affected by a large differential reddening (see Fig. 5). Valenti et al. (2004) used NIR photometry (J , H and K bands) and also found an iron abundance of $[\text{Fe}/\text{H}] = -0.49$ dex. Cohen et al. (2017) using a near-IR photometric metallicity calibration from VVV PSF photometry found an iron abundance of $[\text{Fe}/\text{H}] = -0.46$ dex. Both studies using photometry show good agreement with ours. Finally, the metallicity quoted by Harris (1996) of -0.36 dex is an average of the values above, mainly based on photometric results.

As it stands, there are some results showing an average metallicity of $[\text{Fe}/\text{H}] \sim -0.3$ for NGC 6440, and others showing $[\text{Fe}/\text{H}] \sim -0.5$ in agreement with our result. However, the two most reliable studies – based on high-resolution optical and near-IR spectra – are in very good agreement and strongly suggest that the metallicity is close to -0.5 . More bulge clusters need to be analyzed homogeneously in order to compare the metallicity scale.

4.2. Iron-peak elements

The abundance pattern of iron-peak elements may be of great help in identifying the ISM polluters from among the variety of possible sources. In particular, discriminating between SN and other polluters can provide information about the chemical evolution of the ISM from which the cluster has formed.

In this study we have measured the abundances of five iron peak elements: Fe, Sc, Mn, Co and Ni (see Table 3). We discussed Fe extensively in the previous section. Figure 6 shows the other iron-peak elements $[\text{Sc}/\text{Fe}]$, $[\text{Mn}/\text{Fe}]$, $[\text{Co}/\text{Fe}]$ and $[\text{Ni}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$ compared with abundances for halo and disk, and bulge field stars, including some bulge GCs. We have found super-solar values for Sc and Co.

Other authors have found super-solar abundances for iron-peak elements in bulge field stars: for example McWilliam & Rich (1994) found an average for $[\text{Co}/\text{Fe}] = 0.28$ dex and $[\text{Sc}/\text{Fe}] = 0.33$ dex, which are similar to our values after taking into account our errors (0.09 dex and 0.10 dex, respectively). Their solar value for nickel is also in agreement with our result. In a similar way, Johnson et al. (2014) found an enhanced value of the cobalt abundance of bulge field stars, although not as large as ours ($[\text{Co}/\text{Fe}] = 0.14$ dex). Although their absolute abundances are somewhat different from ours, Johnson et al. (2014) also found a larger enhancement of cobalt with respect to nickel (see Fig. 6 and Table 3).

Fig. 6. $[\text{Sc}/\text{Fe}]$, $[\text{Mn}/\text{Fe}]$, $[\text{Ni}/\text{Fe}]$, $[\text{Co}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$. Filled blue circles with error bars are our data for NGC 6440. Filled orange triangles represent bulge field stars (Barbuy et al. 2013; Johnson et al. 2014), filled gray triangles show halo and disk stars (Fulbright 2000; François et al. 2007; Reddy et al. 2003, 2006), and filled dark green triangles show NGC 6553 (Johnson et al. 2014).

Next we compare the iron-peak elements of NGC 6440 with NGC 6553, which is another bulge GCs, part of the same study of Johnson et al. (2014). We see similar patterns, although they do find for cobalt an average of $[\text{Co}/\text{Fe}] = 0.22$ dex and nickel an average of $[\text{Ni}/\text{Fe}] = 0.10$ dex, slightly low and slightly high compared to our values, respectively. However, if we take into account the difference in metallicity, the chemical patterns of iron-peak elements essentially follow a comparable pattern, where the enhancement of cobalt is larger with respect to nickel (see Fig. 6 and Table 3).

Some studies suggest that significant enhancements of Co and Sc, as observed in this study, can be due to a very light neutron exposure of the atmospheric materials (Smith & Lambert 1987; McWilliam & Rich 1994). Additionally, both elements Co and Sc could be produced by SN explosion.

Coming to manganese (Mn), Cescutti et al. (2008) have reproduced the behavior of Mn versus Fe for the bulge of the Milky Way taking into account the metallicity dependence of yields for SNeII and SNe Ia. Their models are in agreement with our results, indicating a strong contribution by SN explosion.

In summary, the high abundance of the iron-peak elements in NGC 6440, together with the fact that it does not show a significant iron spread, indicates that NGC 6440 formed in an environment with a high abundance of these elements, which are produced mainly by SNeIa and SNeII.

4.3. α elements

The chemical abundances for the α elements O, Mg, Si, Ca, and Ti listed in Table 3 are all significantly overabundant relative to solar scales. If we use Mg, Si, Ca, and Ti to estimate a mean

Fig. 7. $[\alpha/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$. Filled blue circles are our data for NGC 6440, filled red triangles are NGC 6441 (Gratton et al. 2006, 2007), filled yellow triangles are Terzan 5 (Origlia et al. 2011, 2013), filled cyan triangles are Terzan 4 (Origlia & Rich 2004), filled dark green triangles are NGC 6553 (Tang et al. 2017), filled magenta triangles are HP1 (Barbuy et al. 2016), filled orange triangles are bulge field stars (Gonzalez et al. 2012), filled green squares are GCs from Pritzl et al. (2005), and filled gray triangles are halo and disk fields stars (Venn et al. 2004).

Table 5. Mean abundance of elements for this work and OR08.

Element	This work	OR08
$[\text{Fe}/\text{H}]$	-0.51 ± 0.03	-0.54 ± 0.02
$[\text{O}/\text{Fe}]$	0.52 ± 0.05	0.33 ± 0.02
$[\text{Mg}/\text{Fe}]$	0.37 ± 0.03	0.33 ± 0.01
$[\text{Al}/\text{Fe}]$	0.56 ± 0.07	0.46 ± 0.02
$[\text{Si}/\text{Fe}]$	0.20 ± 0.09	0.32 ± 0.02
$[\text{Ca}/\text{Fe}]$	0.34 ± 0.07	0.37 ± 0.01
$[\text{Ti}/\text{Fe}]$	0.42 ± 0.04	0.33 ± 0.03

Notes. The errors listed here, for this work and for OR08, are the standard errors of the mean ($\sigma_{\text{obs}}/\sqrt{N^{\circ}\text{stars}}$).

α -element value (O will be treated separately) we obtain:

$$[\alpha/\text{Fe}] = 0.35 \pm 0.06.$$

OR08 also measured alpha elements for NGC 6440. These are, in general, in good agreement with our values (see Table 5 and Fig. 9). The most significant discrepancies are for oxygen and aluminum. These elements will be discussed separately below in the subsection on O-Na and Mg-Al, respectively.

In Figs. 7 and 8, we note that NGC 6440 follows the trend of bulge field stars for the alpha elements, in accordance also with other bulge GCs that follow the same trend (NGC 6441, Terzan 5, Terzan 4, HP1, NGC 6553).

Analyzing the total observational error and the actual dispersion (Table 4), which tell us whether for some elements there might be an internal spread, we note that for the alpha elements: O, Mg and Ti, there is a good agreement between total and observed dispersion, however for both Si and Ca the actual spread is significantly larger than expected due to errors. Unlike the light elements, we do not expect Si and Ca to show an intrinsic

variation. We note that oxygen doesn't show significant scatter (see Sects. 1, 4.4 and 4.5). It is necessary, therefore, to corroborate this behavior using a large sample of stars.

When comparing these results for NGC 6440 with other bulge GCs, we noticed that NGC 6441, NGC 6553, Terzan 5 and HP1 also show some spread in their α -elements. On the other hand the scatter in the alpha element abundances for bulge field stars is evident.

Many authors agree that the bulge formation was rapid, as shown by the enhanced alpha plateau against $[\text{Fe}/\text{H}]$ in bulge field stars (e.g., Ballero et al. 2007; Cescutti & Matteucci 2011). This enhancement in alpha elements is produced by massive stars exploding as SNe II at early epochs, producing super-solar alpha abundances. Then, this plateau eventually turns down as metallicity increases due to the onset of SN Ia yielding mainly iron-peak elements without alphas.

For higher SF rates, more iron is produced before SNe Ia start changing the composition of the ISM, and the knee occurs at higher metallicities. The location of the knee for stars in the bulge shows that its evolution was faster than that of the halo and the disk.

In this context, we note that all alpha elements in NGC 6440 are overabundant, and especially oxygen, indicating an early enrichment by SNe II. This is in good agreement with the alpha enhancement that is shown by bulge stars. The other bulge GCs, such as HP1, NGC 6441, NGC 6553, and Terzan 5 also follow the trend of the bulge.

Analyzing the $[\text{O}/\text{Fe}]$ versus $[\text{Fe}/\text{H}]$, we note that the bulge GC NGC 6441 shows an oxygen abundance generally lower than bulge field stars (with scatter), indicating a depletion of oxygen, in accordance with the model of self enrichment in GCs. In contrast, NGC 6440 follows very well the trend of the bulge with low spread.

4.4. Na-O anticorrelation

Many Galactic GCs so far studied show an anticorrelation between Na and O abundances, which is the most recognized as evidence for the existence of MP in GCs (Carretta et al. 2009b,c; Gratton et al. 2012). The only old GC that apparently does not show this anticorrelation is Ruprecht 106 (Villanova et al. 2013), but the origin (galactic or extragalactic) of this object is in doubt.

According to the models, GCs show this anticorrelation due to the fact that the material of some of the stars we observe has been processed through proton-capture nucleosynthesis by the CNO cycle, which depletes oxygen, while the NeNa chain enriches Na (Ventura & D'Antona 2006). It is therefore postulated that a first generation of stars is followed by a second generation that is much more Na-rich and O-poor. The Na-O anticorrelation in NGC 6440 is partly seen in our data, but it is not so extended as commonly seen in most galactic GCs.

Comparing the measurement dispersion of Na ($\sigma_{\text{tot}} = 0.11$ dex) with the observed one ($\sigma_{\text{obs}} = 0.32$ dex), there is clearly a significant intrinsic spread, while the opposite is true for oxygen. The observed spread ($\sigma_{\text{obs}} = 0.12$ dex) is consistent with measurement errors ($\sigma_{\text{tot}} = 0.10$ dex), at odds with most galactic GCs.

A low intrinsic oxygen dispersion is also found for most of the other bulge clusters. For example, OR08 measured oxygen abundances in ten stars of NGC 6440. Although our mean values differ by 0.19 dex, as shown in Table 5 and Fig. 9, they also found no significant spread in oxygen, in agreement with our findings. HP1 is another bulge cluster showing no clear O-Na anticorrelation (Fig. 10) according to Barbuy et al. (2016). On

Fig. 8. [O/Fe], [Mg/Fe], [Si/Fe], [Ca/Fe], [Ti/Fe] vs. [Fe/H]. Filled blue circles are our data for NGC 6440, filled red triangles are NGC 6441 (Gratton et al. 2006, 2007), filled yellow triangles are Terzan 5 (Origlia et al. 2011, 2013), filled cyan triangles are Terzan 4 (Origlia & Rich 2004), filled dark green triangles are NGC 6553 (Tang et al. 2017), filled magenta triangles are HP1 (Barbuy et al. 2016), filled orange triangles are bulge field stars (Gonzalez et al. 2012; Johnson et al. 2014; Lecureur et al. 2007), filled green squares are GCs from Pritzl et al. (2005), and filled gray triangles are halo and disk fields stars (Venn et al. 2004).

the other hand, HP1 has a relatively low mass, therefore it is likely to not show this anticorrelation (Barbuy et al. 2016). A low spread in oxygen was also found in NGC 6553 (Tang et al. 2017) in a sample of ten stars. Terzan 4 shows a similar behavior, with a low spread in oxygen (Origlia & Rich 2004); although their sample is only four stars. The only exception to this picture is NGC 6441, which possesses an extended O-Na anticorrelation. It should be noted that the mass of this cluster is the largest among bulge GCs compared in this study (Fig. 10), which makes the possibility of self-enhancement more likely.

4.5. Mg-Al and Na-Al

A Mg-Al anticorrelation has been found in several galactic GCs by different authors, particularly by Carretta et al. (2009b) in a

large sample. Aluminum has shown a particularly high spread in almost all the galactic GCs, especially those with a metallicity lower than $[\text{Fe}/\text{H}] = -1.1$ dex (Mészáros et al. 2015).

We have found no Mg-Al anticorrelation in NGC 6440. Although Al shows a significant spread ($\sigma_{\text{obs}} = 0.18$), Mg does not ($\sigma_{\text{obs}} = 0.08$). In this respect, NGC 6440 follows the trend of bulge field stars and galactic GCs of similar metallicity. The spread in abundance of Mg and Al found by OR08 ($\sigma_{\text{Mg}} = 0.03$ and $\sigma_{\text{Al}} = 0.05$) is small compared with ours. However it should be noted that the individual errors on the Al abundance in the study of OR08 are in the order of 0.14 dex.

With respect to other bulge GCs, we noticed that Terzan 5 follows the trend of bulge field stars, but not that of Galactic GCs. And NGC 6553 and HP1 do not agree with either bulge field stars or galactic GCs.

Fig. 9. Comparison between this study (blue filled circles) and OR08 (red filled squares) for NGC 6440.

We plot in Fig. 11 Na versus Al, because these two light elements have the highest spread in this GC, allowing us to distinguish more clearly to which generation each star from our sample belongs. In this plot we can see a clear difference in the trends of disk and halo stars with respect to bulge stars, highlighting again their difference in chemical evolution history. In addition, we note a good agreement between bulge stars and Galactic GCs including NGC 6440. However, NGC 6553, NGC 6441, and especially HP1, do not show such a good agreement with bulge or galactic GCs.

4.6. Heavy elements

The heavy elements are produced by successive capture of neutrons through two processes, slow and rapid. In the first process (*s*-process), the neutron capture time is longer than the beta decay lifetime, for example during the AGB phase. On the other hand, the *r*-process occurs when the neutron capture time is much shorter than the beta-decay lifetime, for example during the SNeII. Therefore, the analysis of these elements undoubtedly helps to better understand the processes involved in the formation of the MP in the GCs, because they are very good tracers of stellar nucleosynthesis.

The production of *s*-elements is associated mainly with low-mass AGB stars (Gallino et al. 1998; Straniero et al. 2006), which can produce heavy elements like Ba. The *r*-process is associated mainly with SNe II explosions, with an important contribution of alpha elements and to a less extent iron-peak elements.

We measure two heavy elements in NGC 6440: Ba and Eu. Analyzing the abundance of Ba for NGC 6440 we find that the mean is slightly sub-solar ($[Ba/Fe] = -0.17$ dex), although there is consistency with some bulge field stars with very low $[Ba/Fe]$ (see Fig. 12). The bulge GCs NGC 6441 and HP1 show

Fig. 10. $[O/Fe]$ vs. $[Na/Fe]$. Filled blue circles are our data for NGC 6440, filled red triangles are NGC 6441 (Gratton et al. 2006, 2007), filled dark green triangles are NGC 6553 (Tang et al. 2017), filled magenta triangles are HP1 (Barbuy et al. 2016), and filled green squares are Galactic GCs from Carretta et al. (2009c).

significant differences with respect to NGC 6440, both GCs being super-solar in their content of Ba and following the trend of the bulge field stars. $[Ba/Fe]$ in NGC 6440 is a bit lower than this trend for its metallicity, indicating a low production of *s*-elements, which is associated with a low early pollution by AGB stars in NGC 6440.

In the case of $[Eu/Fe]$, there is a marked decrease with $[Fe/H]$ for bulge stars. The decrease is due to the production of iron by SN Ia after a time delay of 100 Myr to 1 Gyr (Ballero et al. 2007). The abundance of $[Eu/Fe]$ in NGC 6440 shows values more in line with the trend of the bulge and in very good agreement with NGC 6441.

As explained above, the trend of $[Ba/Eu]$ versus $[Fe/H]$ is very sensitive to the relative importance of *s*-process versus *r*-process. In the case of NGC 6440, we have found a value of $[Ba/Eu]$, which is very under-solar and close to pure *r*-process (see Fig. 13). Thus, in NGC 6440, heavy elements appear to have been mainly produced by explosive events, such as core collapse SNe.

5. Origin of NGC 6440

NGC 6440 shows a good agreement with the bulge chemical pattern, indicating a common origin. Only some iron-peak elements (Co and Mn) are slightly higher and $[Ba/Eu]$ slightly lower with respect to the bulge field stars. This could indicate that the place of formation of NGC 6440 suffered a more extended SN pre-enrichment compared with the bulk of the field stars and that it was born at the very beginning of the bulge history when the contamination by AGB stars had not yet started. This may also help to explain its relatively high alpha abundances compared to bulge objects of similar metallicity.

NGC 6440 joins the other bulge GCs in the trend of alpha-element enrichment patterns for bulge stars, although with some dispersion. In particular, NGC 6440 seems to not present a spread in oxygen. Apparently bulge GCs have different ratios of first- and second-generation stars, possibly due to the harsh

Fig. 11. $[\text{Mg}/\text{Fe}]$, $[\text{Na}/\text{Fe}]$ vs. $[\text{Al}/\text{Fe}]$. Filled blue circles are our data for NGC 6440, filled red triangles are NGC 6441 (Gratton et al. 2006), filled yellow triangles are Terzan 5 (Origlia et al. 2011), filled dark green triangles are NGC 6553 (Tang et al. 2017), filled magenta triangles are HP1 (Barbuy et al. 2016), filled orange triangles are bulge field stars (Lecureur et al. 2007), filled green square are GCs from (Carretta et al. 2009c), and filled gray triangles are halo and disk field stars (Fulbright 2000; Reddy et al. 2003, 2006; Barklem et al. 2005; Cayrel et al. 2004).

Fig. 12. $[\text{Eu}]$, $[\text{Ba}/\text{Fe}]$ vs. $[\text{Fe}/\text{H}]$. Filled blue circles are our data for NGC 6440, filled red triangles are NGC 6441 (Gratton et al. 2006), filled magenta triangles are HP1 (Barbuy et al. 2016), filled orange triangles are bulge field stars (Van der Swaelmen et al. 2016), filled green square are GCs from Pritzl et al. (2005), and filled gray triangles are halo and disk stars (Fulbright 2000; François et al. 2007; Reddy et al. 2006; Barklem et al. 2005; Venn et al. 2004).

Fig. 13. $[\text{Ba}/\text{Eu}]$ vs. $[\text{Fe}/\text{H}]$. Filled blue circles are our data for NGC 6440, filled red triangles are NGC 6441 (Gratton et al. 2006), filled magenta triangles are HP1 (Barbuy et al. 2016), filled orange triangles are bulge field stars (Van der Swaelmen et al. 2016), filled green square are GCs from Pritzl et al. (2005), and filled gray triangles are halo and disk stars (Fulbright 2000; François et al. 2007; Reddy et al. 2006; Barklem et al. 2005; Venn et al. 2004).

environment of the bulge to which these clusters have been exposed for a large period of their lives. More stars are needed to confirm this hypothesis.

There are no detailed studies on the dynamics of NGC 6440. Proper motions are needed to complement our radial velocities and derive the orbit of this cluster to check that it is actually confined to the bulge as the chemical analysis seems to indicate.

6. Conclusions

In this paper we present a detailed chemical analysis of NGC 6440 for seven of its RGB stars with an S/N between 25–30 at 650 nm. We measured abundances of 14 chemical elements using high-resolution spectra and performed an accurate error analysis. This has allowed us to make a detailed comparison with several important components of the Milky Way (bulge

field stars, disk field stars, halo field stars, galactic GCs), from a chemical point of view. The main findings are the followings.

- We find a mean iron abundance of $[\text{Fe}/\text{H}] = -0.50 \pm 0.03$ dex, in agreement with OR08. Like OR08, we do not find a significant spread in iron, although our sample is small.
- Oxygen measurements for NGC 6440 show a mean $[\text{O}/\text{Fe}] = 0.52 \pm 0.10$ dex; one of the highest among Galactic GCs. The other alpha elements are also generally relatively enriched.
- Although Na shows an intrinsic spread, there is not a clear Na-O anticorrelation, since oxygen does not show a significant spread, in contrast with most Galactic GCs.
- We find no Mg-Al anticorrelation but do detect an intrinsic spread in Al.
- We find MP in this cluster associated with the spread in Na and Al.
- $[\text{Ba}/\text{Eu}]$ suggests a low contribution by AGB stars to the gas from which NGC 6440 formed.
- Analysis of alpha-, iron-peak-, and heavy elements indicates a strong and early contamination by SNe II.
- In general, the chemical abundances of stars in NGC 6440 show good agreement with those of bulge field stars in most of the elements analyzed in this paper, indicating a common formation and evolution process.

It is interesting to note that the comparison performed with other bulge GCs such as NGC 6441, HP1, NGC 6553, Terzan 5 and Terzan 4 shows both concordances and discrepancies. For α -elements we notice that all bulge GCs follow very nicely the trend with metallicity of bulge field stars. Conversely, the O-Na, Mg-Al and Na-Al plots, where we should see the typical inhomogeneities that characterize other galactic GCs, show only a spread in Na but not a clear O-Na anticorrelation like in the case of HP1. This could suggest that bulge GCs have undergone different chemical evolution histories, but we need a larger sample of bulge GCs with detailed chemical measurements to reach a firm conclusion.

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