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THE UNIQUE Na:O ABUNDANCE DISTRIBUTION IN NGC 6791: THE FIRST OPEN(?) CLUSTER WITH MULTIPLE POPULATIONS

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ABSTRACT

Almost all globular clusters investigated exhibit a spread in their light element abundances, the most studied being an Na:O anticorrelation. In contrast, open clusters show a homogeneous composition and are still regarded as Simple Stellar Populations. The most probable reason for this difference is that globulars had an initial mass high enough to retain primordial gas and ejecta from the first stellar generation and thus formed a second generation with a distinct composition, an initial mass exceeding that of open clusters. NGC 6791 is a massive open cluster and warrants a detailed search for chemical inhomogeneities. We collected high-resolution, high signal-to-noise spectra of 21 members covering a wide range of evolutionary status and measured their Na, O, and Fe content. We found [Fe/H] $= +0.42 \pm 0.01$, in good agreement with previous values, and no evidence for a spread. However, the Na:O distribution is completely unprecedented. It becomes the first open cluster to show intrinsic abundance variations that cannot be explained by mixing, and thus the first discovered to host multiple populations. It is also the first star cluster to exhibit two subpopulations in the Na:O diagram with one being chemically homogeneous while the second has an intrinsic spread that follows the anticorrelation so far displayed only by globular clusters. NGC 6791 is unique in many aspects, displaying certain characteristics typical of open clusters, others more reminiscent of globulars, and yet others, in particular its Na:O behavior investigated here, that are totally unprecedented. It clearly had a complex and fascinating history.

Key words: open clusters and associations: individual (NGC 6791) – stars: abundances

Online-only material: color figures

1. INTRODUCTION

NGC 6791 is a truly unique object in the Galaxy. Since the first in-depth analysis by Kinman (1965), this cluster was recognized as being both very massive (for an open cluster, OC) as well as very old. Despite being perhaps the oldest OC, with an age of ∼8 Gyr (Carraro et al. 2006), its metallicity is among the highest of any cluster known. Indeed, the initial investigation of its metallicity yielded +0.75, far exceeding that of any other object and earning it the label of "super metal rich" (Spinrad & Taylor 1971). Subsequent investigations have settled on a somewhat lower but still extreme value of ∼ +0.4. The combination of large age and abundance places the cluster in a unique location in the age–metallicity relation for the disk. Carraro et al. (2006) even suggested a possibly extragalactic origin for NGC 6791, which would make it even more exceptional. Recently, Twarog et al. (2011) suggested it might have an age spread of a Gyr, another extraordinary quality if correct. It is one of only a very few OCs to show the infamous second parameter problem, with both a red clump (RC) as well as stars on the red and extended blue ends of a horizontal branch (Platais et al. 2011; Buzzoni et al. 2012).

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The entire field of globular cluster (GC) research has recently undergone a paradigm shift, driven by the discovery that GCs are surprisingly complex objects, formed by multiple instead of simple stellar populations, as previously believed. All of the GCs studied in detail so far show at least a spread in their light element content, the most evident being the spread in Na and O, which are anticorrelated (Carretta et al. 2009, 2010; Gratton et al. 2012). Carretta et al. (2010) have even argued for a new, chemical definition of a GC as any object that displays an Na:O anticorrelation.

The most natural explanation for chemical inhomogeneities is the self-pollution scenario, where a cluster experiences an extended star formation period, with the younger population born from an interstellar medium polluted by ejecta from stars of the older generation that have experienced hot H-burning via *p*-capture. The older generation's composition closely mimics that of similar metallicity halo field stars, while the younger generation is enhanced in He, N, Na, and Al and depleted in C, O, Ne, and Mg. The material required to form the second generation is retained due to the strong gravitational field (D'Ercole et al. 2008). However, there must be a minimum initial mass required to retain this material. Theoretical limits of the order of $10^5\ M_\odot$ (Vesperini et al. 2010) and observational values of $\sim 4 \times 10^4\ M_\odot$ (Carretta et al. 2009), within the extent of a typical cluster (a few pc), have been estimated for Galactic GCs, while Mucciarelli et al. (2009) find a limit more like $2 \times 10^5\ M_\odot$ for LMC clusters. Unfortunately, these mass estimates are often very uncertain and, more importantly, refer to the present-day mass. It is well-known theoretically that a cluster can lose much, most,

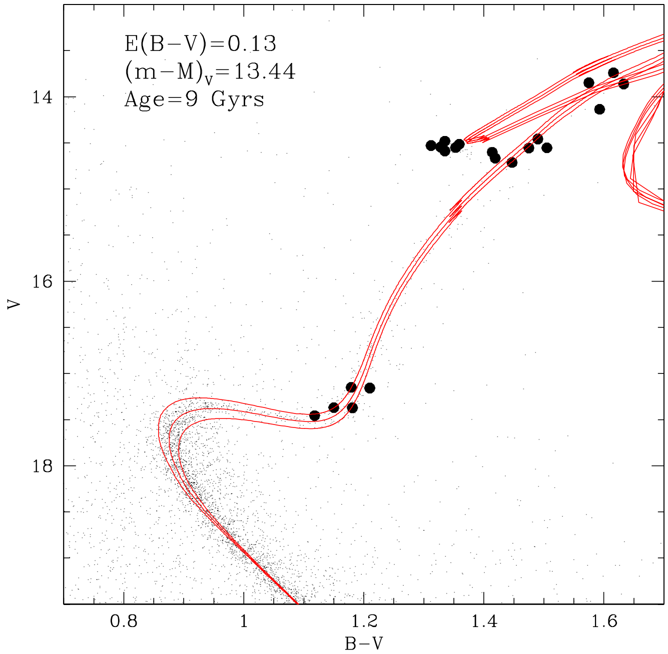

Figure 1. CMD of NGC 6791 from Stetson et al. (2003) with the observed RGB/RC stars indicated as filled circles, together with isochrones of 8, 9, and 10 Gyr from Pietrinferni et al. (2004).

(A color version of this figure is available in the online journal.)

or even all of its initial mass during its subsequent evolution due to both internal and external factors (Lamers et al. 2010).

On the other hand, OCs so far do not show any spread in chemical abundances that cannot be attributed to simple, in situ mixing processes (De Silva et al. 2009). This can be explained in the self-pollution scenario because they formed with an initial mass lower than any GC and below the above minimum, so they could not retain primordial gas or ejecta to form a second generation.

Given its uniqueness, NGC 6791 has been the subject of many observational studies. A number of high-resolution spectroscopic investigations have firmly established the metallicity and many details of its chemical composition (Gratton et al. 2006; Carraro et al. 2006; Origlia et al. 2006; Carretta et al. 2007). However, no data on both Na and O for more than a few stars are published. Given the importance of Na and O for examining the formation and chemical evolution of clusters, a study of these elements in a large sample of stars will fill this gap and constrain the nature of this intriguing cluster, which is the aim of this Letter.

2. OBSERVATIONS AND DATA REDUCTION

We employ two independent observations to compile a comprehensive data set and to study as wide a range of evolutionary stages as possible. One data set consists of spectra collected with HIRES at the Keck I telescope. We observed five stars located in the lower part of the red giant branch (RGB) (see Figure 1). Spectra cover the range 3500–10000 Å with a resolution of 45,000. These data are discussed in more detail in S. Villanova et al. (2012, in preparation). Our second data set consists of lower resolution (R ∼15,000) spectra obtained with the multifiber Hydra spectrograph at the WIYN telescope. We observed 19 stars located in the upper part of the RGB, the red clump, and the asymptotic giant branch (AGB; Figure 1). Spectra cover the range 6050–6375 Å. Targets were selected on the basis of extensive B, V, I photometry (Stetson et al. 2003).

Table 1
Optical Photometry, Atmospheric Parameters, and Abundances for the Observed Stars

ID	B (mag)	V (mag)	I (mag)	$T_{\rm eff}$ (K)	log (g)	v_t (km s^{-1})	[Fe/H]	[O/Fe]	[Na/Fe]
T01	15.817	14.482	13.146	4447	2.30	1.22	0.40	0.06	−0.09
T03	15.923	14.588	13.264	4429	2.33	1.17	0.49	−0.10	−0.11
T04	16.084	14.665	13.182	4195	2.21	1.00	0.37	0.24	0.31
T05	15.874	14.546	13.235	4465	2.34	1.21	0.41	0.18	0.34
T06	15.841	14.529	13.168	4400	2.29	1.18	0.41	0.12	0.35
T07	15.357	13.741	11.962	3951	1.57	1.29	0.39	0.09	0.30
T09	16.160	14.713	13.230	4226	2.26	1.00	0.47	0.14	0.49
T10	15.424	13.849	12.191	4033	1.70	1.27	0.37	0.11	0.42
T11	15.949	14.459	12.890	4163	2.10	1.06	0.39	0.17	0.28
T12	16.032	14.557	13.027	4184	2.16	1.04	0.47	0.04	0.45
T13	16.016	14.602	13.274	4439	2.35	1.17	0.49	0.16	0.24
T14	15.904	14.551	13.217	4427	2.32	1.18	0.38	0.25	0.26
T15	15.729	14.136	12.373	3942	1.75	1.12	0.36	0.08	0.48
T17	16.059	14.554	12.988	4119	2.10	1.01	0.46	0.01	0.46
T18	15.874	14.515	13.176	4468	2.33	1.22	0.40	0.01	−0.13
T19	15.495	13.862	11.892	3822	1.48	1.22	0.53	−0.07	0.46
T31	18.329	17.150	15.954	4699	3.56	0.39	0.40	0.00	−0.19
T32	18.368	17.158	15.923	4672	3.55	0.37	0.45	0.06	−0.15
T33	18.575	17.457	16.330	4894	3.79	0.42	0.38	−0.01	−0.13
T34	18.553	17.372	16.164	4727	3.67	0.33	0.40	–	−0.07
T35	18.520	17.370	16.210	4800	3.70	0.38	0.41	−0.01	−0.13
Sun	···	···	···	5777	4.44	0.80	7.50	8.80[a]	6.32[b]

Notes.
[a] log(O/H)+12.
[b] log(Na/H)+12.

We cross-correlated Stetson's catalog with the Two Micron All Sky Survey to obtain J, H, K_s magnitudes. Table 1 gives optical photometry of the members.

Data were reduced using IRAF,[8] including bias subtraction, flat-field correction, wavelength calibration, sky subtraction, spectral rectification, and combination. Cosmic rays were removed using the program from van Dokkum (2001). HIRES spectra have a typical signal-to-noise ratio (S/N) of ∼50 at 6300 Å, while Hydra spectra have an S/N of ∼70 at this wavelength.

Radial velocities were measured by the *fxcor* package in IRAF, using a synthetic spectrum as a template. The mean heliocentric value is -44.6 ± 0.5 km s^{-1}, while the dispersion is 2.3 ± 0.4 km s^{-1}, in good agreement with published values, e.g., Geisler (1988), Carraro et al. (2006), and Gao & Chen (2012). Three stars in our sample have very different velocities from the mean and were rejected as non-members. On the basis of radial velocity and metallicity, we conclude that all of the other targets are definite cluster members.

3. ABUNDANCE ANALYSIS

The Fe abundances were obtained from the equivalent widths. The main problem was the continuum determination, due to the very high metallicity. We solved this by comparing our spectra with a synthetic one having the mean atmospheric parameters of the targets and using as a continuum only those portions of the observed spectra where the corresponding synthetic spectrum was $\leqslant$1% below the theoretical continuum. For O and Na, whose lines are affected by blending, including that by

[8] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with National Science Foundation.

molecules like CN in cool stars, we used the spectrum-synthesis method, calculating five spectra having different abundances and adopting the one that minimizes the rms. The O content was obtained from the forbidden line at 6300 Å and Na from the 6154 Å line (and also the 6160 Å line for warmer stars). The O line was decontaminated from telluric lines using an O-type star. We were unable to measure O for one lower RGB star due to cosmic ray contamination.

Atmospheric parameters were obtained as follows. First, $T_{\rm eff}$ was derived from the $B-V$, $V-I$, $V-J$, $V-H$, $V-K$, $J-H$, and $J-K$ colors using the relations by Alonso et al. (1999) and Ramirez & Melendez (2005) and taking the mean. Surface gravities (log(g)) were obtained from the canonical equation:

$$\log\left(\frac{g}{g_\odot}\right) = \log\left(\frac{M}{M_\odot}\right) + 4\cdot\log\left(\frac{T_{\rm eff}}{T_\odot}\right) - \log\left(\frac{L}{L_\odot}\right).$$

The bolometric correction was derived from the relations of Alonso et al. (1999) and Flower (1996). The reddening $E(B-V)$, distance modulus $(m-M)_{\rm V}$, and mass were obtained from isochrone fitting of the V versus $B-V$ color–magnitude diagram (CMD) using BaSTI (Pietrinferni et al. 2004) isochrones (Figure 1). We obtained $E(B-V) = 0.13$, $(m-M)_{\rm V} = 13.44$, 9 Gyr and a mass of 1.13 $M_\odot$ for RGB stars, and 1.05 $M_\odot$ for RC and AGB stars. All of these are in good agreement with previous values, e.g., Carraro et al. (2006). In particular, the mass agrees well with the value of 1.087 ± 0.004 $M_\odot$ derived by Brogaard et al. (2011) for the turnoff mass from detailed observations of a binary. Microturbulent velocity ($v_{\rm t}$) was obtained from the relation of Gratton et al. (1996) which utilizes both temperature and gravity:

$$v_{\rm t} = 0.00119\cdot T_{\rm eff} - 0.90\cdot\log(g) - 2.$$

The input metallicity was [Fe/H] = +0.40. The LTE program MOOG (Sneden 1973) was used for the abundance analysis coupled with atmosphere models by Kurucz (1992). We adopted the same line list used in our previous papers (e.g., Villanova et al. 2010). Atmospheric parameters and final derived abundances are reported in Table 1, together with adopted solar values.

We performed a check on our atmospheric parameters by plotting our targets and all cluster stars in log(g) and log($L/L_\odot$) versus $T_{\rm eff}$ diagrams in Figure 2. The RGB is well defined in both diagrams, indicating that if any differential reddening is present (Platais et al. 2011), it does not affect our parameters significantly. The AGB and RGB are well separated, allowing us to confidently assign the proper mass to each target. We compare our parameters with an appropriate BaSTI model of 9 Gyr and find no difference in luminosity but a systematic difference in temperature of 120 K. Otherwise, all our stars are located on or very close to the theoretical model, confirming the reliability of our procedure.

NLTE effects can influence Na abundance determinations. The lines we used are the least affected, and the influence is minimal at this high metallicity (Lind et al. 2011). More importantly, differential effects are very small over the range of parameters of our sample. Lind et al. (2011) show the maximum difference expected is only 0.05 dex. Thus, we did not make any correction.

A sample of our stars exhibited an anticorrelation between our initial Na abundance and $T_{\rm eff}$. Following the referee's suggestion, we investigated if this could be due to blends with species such as CN not properly accounted for in the line list. We estimated the N abundance from the strength of the CN

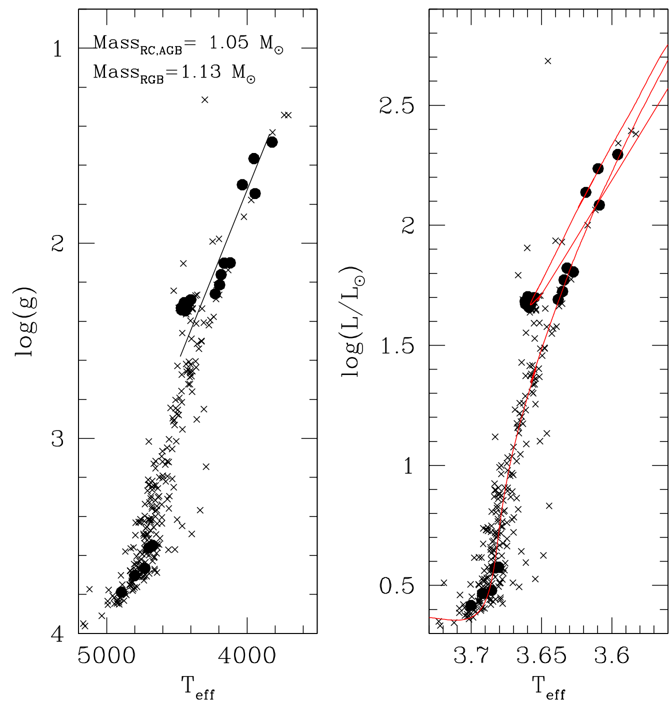

Figure 2. Left: log(g) vs. $T_{\rm eff}$ for evolved stars in NGC 6791 (crosses) and for our targets (circles). The adopted line separates RGB from RC/AGB stars. Masses adopted for RGB and RC/AGB stars are indicated. Right: log($L/L_\odot$) vs. $T_{\rm eff}$ for the same stars. The red curve is the BaSTI isochrone for 9 Gyr.

(A color version of this figure is available in the online journal.)

feature at 6195–6198 Å in four stars covering the range of Na abundance and $T_{\rm eff}$, finding [N/Fe] = +0.2. We then obtained final Na abundances for all stars, using this N abundance. The Na content was lowered by ∼0.1 dex in all stars, with two of our coolest stars being most affected. Figure 3 includes a portion of the spectrum around the Na lines for our coolest star together with the best-fit synthetic spectrum. Although some residual absorption may be present, it minimally affects the abundance derived from the 6154 Å line, the only one used for these cool stars.

An internal error analysis was performed by varying $T_{\rm eff}$, log(g), [Fe/H], and $v_{\rm t}$ by an amount equal to the estimated internal error and redetermining abundances of star T05, assumed to represent the entire sample. Parameters were varied by $\Delta T_{\rm eff} = +10$ K, $\Delta\log(g) = +0.05$, Δ[Fe/H] = +0.05 dex, and $\Delta v_{\rm t} = +0.04$ km s^{-1}. The temperature error was obtained by comparing the individual color-based determinations for each star, while the errors in gravity and microturbulence were obtained applying error propagation to the previous equations assuming an internal uncertainty of 0.05 $M_\odot$. The [Fe/H] error was taken as the rms of our results. Other error sources such as uncertainties in the distance modulus and reddening affect our results systematically and can be neglected here. We stress the fact that these are only internal errors. Systematic errors are certainly larger but not of major concern. Total internal abundance errors ($\sigma_{\rm tot}$), including spectral noise, are 0.07, 0.05, and 0.05 dex for [O/Fe], [Na/Fe], and [Fe/H], respectively.

4. RESULTS

4.1. Fe

We found a mean [Fe/H] of $+0.42 \pm 0.01$, in the middle of the literature values. Carraro et al. (2006) find [Fe/H] = +0.39,

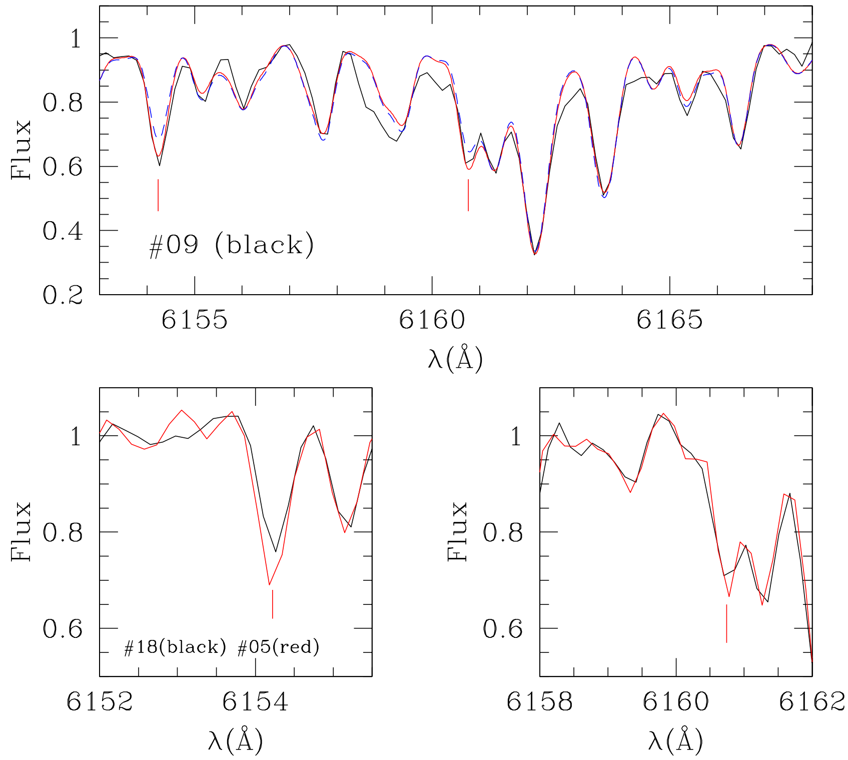

Figure 3. Top: spectrum around the Na I 6154 and 6160 Å lines (marked) for the coolest star, together with a synthetic spectrum for [Na/Fe] = 0 (blue) and +0.5 (red). Bottom: spectra of two RC stars in the same region. The stars (T05 and T18) have almost identical atmospheric parameters but a wide range in Na absorption strength is evident, confirming the large difference in Na abundance. The 6160 Å line is strongly blended and was not used in the abundance analysis but still shows the differential absorption.

(A color version of this figure is available in the online journal.)

Origlia et al. (2006) +0.35, while Carretta et al. (2007) give +0.46. We have an independent confirmation of our value. The HIRES spectra are analyzed in more detail in S. Villanova et al. (2012, in preparation), where the atmospheric parameters are derived purely spectroscopically. Nevertheless, S. Villanova et al. (2012, in preparation) also obtain [Fe/H] = +0.42 ± 0.02. The perfect agreement between the observed dispersion, 0.05 dex, and that from error analysis demonstrates that NGC 6791 lacks any measurable intrinsic metallicity dispersion, in accord with all other studies and as expected for an OC.

4.2. O and Na

However, our O and Na analysis yields several completely surprising results. First, [Na/Fe] has an observed dispersion of 0.26 dex, >5 times larger than that expected from error analysis, while that of [O/Fe], 0.10 dex, is 1.5 times larger. Figure 3 compares the spectra of two different stars at the Na lines. Both are RC stars and have virtually identical atmospheric parameters, but exhibit a large variation in Na absorption and thus must have a large Na abundance difference. To further investigate this point, Figure 4 (left) displays a histogram of the Na distribution. Two well-separated populations appear. A KMM mixture-modeling test (Ashman et al. 1994) strongly supports a bimodal Gaussian over a single-Gaussian distribution, at a confidence level of >99%. The two-Gaussian fit to the distribution finds one population with a mean and dispersion of [Na/Fe] = −0.14 ± 0.02, $\sigma_{[\mathrm{Na/Fe}]} = 0.04 \pm 0.01$, while the second has [Na/Fe] = +0.36 ± 0.03, $\sigma_{[\mathrm{Na/Fe}]} = 0.12 \pm 0.02$. Thus, while the dispersion of the first peak is small, within the observational errors, the dispersion of the second is >2 times larger than expected and appears quite significant. The implication is that the second subpopulation has an intrinsic Na dispersion, while the first is homogeneous. The Na-poor population includes all of the lower RGB stars as well as three RC stars, while the other population is composed of RC stars as well as upper RGB and AGB stars. Thus, while evolutionary effects may be involved, they cannot fully explain the observed behavior. In any case, Na and O are not predicted to be affected by evolutionary mixing in a significant way at this mass and metallicity (Gratton et al. 2000).

We are aware of a similar, unpublished study of Na and O abundances in NGC 6791. Briefly, these authors use WIYN + Hydra to investigate a similar number of RC and RGB stars and find no evidence for any abundance spread. However, their mean S/N is only 23 and thus their errors are much larger than ours. While they interpret their result as a homogeneous composition with a spread due only to errors, our more precise results allow us to disentangle the two subpopulations and reveal the intrinsic variation.

The real nature of the two populations is revealed when we plot [Na/Fe] versus [O/Fe] (Figure 4, right panel). Our data are compared with the database on GCs by Carretta et al. (2009) and metal-rich ([Fe/H] > −0.2) field stars from Reddy et al. (2003, 2006). The Na-poor population is well separated from the GC trend, with a mean O content and dispersion of [O/Fe] = +0.00 ± 0.02, $\sigma_{[\mathrm{O/Fe}]} = 0.05 \pm 0.01$, while the Na-rich population has [O/Fe] = +0.13 ± 0.02, $\sigma_{[\mathrm{O/Fe}]} = 0.07 \pm 0.01$. The mean O and Na contents with their errors are shown. The significance of the difference between the two [Na/Fe] subpopulations is 16σ and 5σ for [O/Fe]. Thus, it appears that there is a real spread (perhaps bimodality) in O as well as Na. The Na-poor population shows a homogeneous Na and O content, similar to field stars, and no trend appears. The distribution of

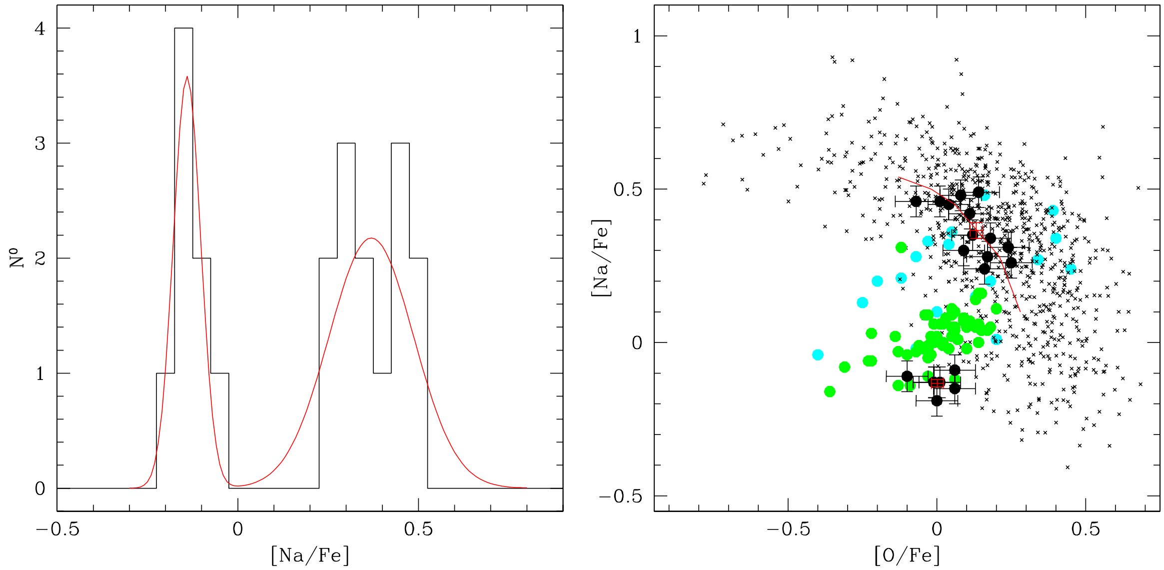

Figure 4. Left: histogram of the [Na/Fe] abundance ratio distribution (lines) with a two-Gaussian fit (curves). Right: [Na/Fe] vs. [O/Fe] for stars in NGC 6791 (filled circles with error bars), GC stars (crosses), metal-rich ([Fe/H] > −0.2) field stars (green filled circles), and the means for OCs from De Silva et al. (2009) (blue filled circles). The mean GC anticorrelation is shown by the red curve.

(A color version of this figure is available in the online journal.)

Na–O abundances for the Na-rich population nicely follows part of the mean GC Na:O anticorrelation.

The above behavior is extraordinary in several ways. First, NGC 6791 becomes the first OC to display an intrinsic dispersion in any element that is unlikely to be explained by mixing effects, and therefore the first (presumed) OC discovered with multiple populations. Na shows a clear spread, while the spread in O is not as strong but still likely. Second, Na exhibits bimodality. Third, the Na-rich population also appears to have an internal spread. Finally, this population follows the almost ubiquitous Na:O anticorrelation seen in GC giants. As such, the Carretta et al. (2009) GC definition implies that at least this population of NGC 6791 stars constitutes a GC. If one believes the minimum mass limits so far derived in order to form multiple populations, then NGC 6791 must have lost at least 90% of its original mass. This is in agreement with expectations for "normal" GCs (D'Ercole et al. 2008). We also find more "second generation" or Na-enhanced stars than Na-poor stars, which is also expected from GC formation models and seen in other GCs (Carretta et al. 2010).

The above raises the fundamental questions: what is NGC 6791 and what was its origin? Is it an OC, as always considered, a GC, as suggested by its Na:O anticorrelation, a hybrid, or some other type of unique object? It is so far the only supposed OC to show multiple populations. Note that the Na-poor population overlaps reasonably well with disk field stars but not with other OCs, while the Na-rich population falls along the mean OC trend. Clearly, the formation of such a peculiar object was complex and requires new ideas. NGC 6791's present-day mass ($\sim 5 \times 10^3\ M_\odot$; Kinman 1965; Origlia et al. 2006; Platais et al. 2011) is far below the predicted minimum mass needed to retain gas and form a second generation, but its initial mass could have been much larger.

Perhaps, as proposed by Carraro et al. (2006) and Buzzoni et al. (2012), NGC 6791 is the remnant of a dwarf galaxy captured and tidally disrupted by the Milky Way. In this case the two subpopulations might have formed as independent clusters, one presumably much more massive and GC-like, and then merged in the core of the host galaxy and survived disruption. Twarog et al. (2011) find evidence for a radial age spread of ∼1 Gyr, further substantiating the suggestion of multiple star formation epochs. However, we see no significant difference in the radial distribution, mean velocity, or its dispersion of the two Na subpopulations. As Carraro et al. (2006) point out, we are also left with the major problem of explaining the formation of extremely metal-rich stars, which would normally require a very massive environment, many orders of magnitude larger than the current mass. What is clear is that NGC 6791 is neither a traditional OC nor GC but an extraordinary object with much left to explore and reveal to us. Similar observations of other massive OCs and low mass GCs would be of great interest.

5. CONCLUSION

We analyzed high-resolution, high S/N spectra from two independent data sets for 21 member stars covering a wide range of evolutionary states in the traditional OC NGC 6791. We obtained O, Na, and Fe abundances with small internal errors. We found a homogeneous $[Fe/H] = +0.42 \pm 0.01$. Surprisingly, stars are divided into two subpopulations with different mean O and especially Na contents. The significance of these differences are many σ. Thus, NGC 6791 becomes the first OC to display an intrinsic dispersion in any element and the first presumed OC discovered with multiple populations. It is also the first cluster of any kind to show Na-poor stars with a homogeneous Na content, along with an Na-rich group showing an intrinsic Na spread. The Na-poor group falls near the field star O/Na content, while the Na-rich population follows the Na–O anticorrelation typical of GCs. NGC 6791 defies the traditional definition of either an OC or GC. How such a complex and highly enriched object was formed is unknown.

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