THREE DISCRETE GROUPS WITH HOMOGENEOUS CHEMISTRY ALONG THE RED GIANT BRANCH IN THE GLOBULAR CLUSTER NGC 2808

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1. INTRODUCTION

For decades, the evidence of multiple stellar populations in globular clusters (GCs) has been hidden in plain sight in spectroscopic observations (Gratton et al. 2012). The large star-to-star abundance variations in light elements (depletion of C, O, Mg anticorrelated with enhancement of N, Na, and Al) were understood to be the simultaneous action of the NeNa and MgAl cycles in the same regions where the ON part of the CNO cycle is fully operative in H burning at high temperatures (Denisenkov & Denissenkova 1989; Langer et al. 1993). The pivotal study by Gratton et al. (2001) forever changed our perspective. Their finding of Na–O and Al–Mg anticorrelations among unevolved stars in NGC 6752 was the clearcut proof that these objects were formed by gas polluted by the ejecta of more massive stars from a past generation since the currently observed stars cannot synthesize the involved elements. Thus, whenever such anticorrelations are traced, we are witnessing the presence of multiple stellar generations.

The most outstanding signature, the Na–O anticorrelation discovered by the Lick–Texas group (see Kraft 1994), has been the subject of our ongoing FLAMES survey of 24 GCs (Carretta et al. 2006, 2009a, 2009b, 2010, 2014, and references therein). Well quantified by the interquartile range of the [O/Na] ratio (Carretta 2006, hereinafter Paper I), the homogeneous study of this feature shows that the phenomenon of multiple populations is primarily driven by the cluster total mass (Carretta et al. 2010) and it is tightly linked to the horizontal branch (HB) morphology (Carretta et al. 2007b; Gratton et al. 2010). However, the Na–O anticorrelation cannot provide useful enough information on the discrete or continuous nature of multiple populations due to the intrinsic difficulty in measuring oxygen abundances: often, only the broad division of stars in first and second generations with different compositions is revealed (e.g., Marino et al. 2008; Carretta et al. 2009b, 2014; Johnson & Pilachowski 2012; Cordero et al. 2014).

The increasing precision in photometric data can enable us to detect split sequences at all evolutionary phases, mainly due to the work by Milone and collaborators (see Milone et al. 2008, 2012, 2013). Discrete sequences mean interruptions in the injection of ejecta into the intracluster gas, and by calibrating the quiescent periods, we may hope to provide more stringent constraints on the still elusive nature of early generation polluters such as intermediate-mass asymptotic giant branch (AGB) stars (Ventura et al. 2001) or fast rotating massive stars (FRMSs; Decressin et al. 2007).

Very promising is the Mg–Al anticorrelation, which is only found in massive and/or metal-poor clusters (e.g., Carretta et al. 2009a; Yong et al. 2005). Recently, Carretta et al. (2012) found that in NGC 6752, red giant branch (RGB) stars are clearly clustered around three distinct values of Al, with groups nicely corresponding to the three photometric sequences revealed by Strömgren photometry on the RGB (Carretta et al. 2011). It seems that the [Al/Mg] ratio is very efficient in enhancing the signal of homogeneous subgroups, especially in GCs with [Fe/H] $\leq$ −1. We then applied the same approach to the GC NGC 2808.

NGC 2808 is the ideal target for exploring the connection between distinct photometric sequences and discrete populations with homogeneous chemistry. It is massive ($M_V = -9.39$ mag; Harris 1996) and moderately metal-poor, with three distinct main sequences (MSs; Piotto et al. 2007; Milone et al. 2012).
and a multimodal distribution of stars on the HB (see Bedin et al. 2000). This GC has been the target of extensive abundance analysis by our group. Carretta et al. (2004a) derived the Na–O anticorrelation in this cluster from 19 RGB stars, while other light elements (including Mg, Al, and Si) were studied for the same sample in Paper I. Na, O abundances for 120 giants and Al, Mg abundances for another limited sample of 12 RGB stars were obtained in Carretta et al. (2006) and Carretta et al. (2009a), respectively. Finally, Gratton et al. (2011) analyzed high resolution spectra of 42 stars on the HB of NGC 2808.

However, a complete study of the Mg–Al pattern in NGC 2808 was hampered by the lack of large samples with homogeneous analysis since the adopted scales of atmospheric parameters were different in Paper I and in Carretta et al. (2009a). In the present Letter, we derive Mg and Al abundances for 31 red giants in NGC 2808. The high degree of homogeneity of the analysis coupled with small internal errors highlights that stars are clustered around three distinct levels of Al and Mg. The ratios of these subgroups are found to be in excellent correspondence with the numbers of stars in the three MSs.

2. DATA AND ANALYSIS

Here we present the abundances of Al and Mg for all the 31 stars observed with FLAMES/UVES. The UVES Red Arm fed by FLAMES fibers provides a wavelength coverage from 4800 to 6800 Å with a resolution of $R \simeq 45,000$, hence abundances of Al can be derived from the subordinate doublet at 6696–6698 Å (not available in the GIRAFFE setups used for the Na–O anticorrelation). The whole sample includes 19 stars from the FLAMES Science Verification (hereinafter sample SV; see Paper I) and 12 giants from the FLAMES survey (sample NAO; Carretta et al. 2006, 2009a; ESO Programme 072.D-0507), spanning the three brightest magnitudes along the RGB of NGC 2808 (see Figure 1). Details of the observations and data reduction can be found in the original papers.

The novelty of the present analysis is the use of our well tested procedure for the derivation of atmospheric parameters for the entire sample, in particular the effective temperature $T_{\text{eff}}$. First pass values are from $V-\text{K}$ colors and the calibrations of Alonso et al. (1999, 2001). These were the temperatures actually adopted in Paper I (sample SV). The final $T_{\text{eff}}$ values for all targets were, however, obtained using an average relation between the temperatures derived in this first step and the apparent magnitude of stars. This procedure was successfully used in our survey of 24 GCs to decrease the star-to-star errors in abundances due to uncertainties in temperatures since magnitudes of bright RGB stars can be measured with higher precision than colors. For NGC 2808, affected by relatively high differential (Bedin et al. 2000) reddening ($(E(B-V)) = 0.22$ mag; Harris 1996), the relation was derived as a function of the $K$ magnitudes from Two Micron All Sky Survey (Skrutskie et al. 2006), minimizing the impact of the differential reddening in the derived $T_{\text{eff}}$. Optical $V$ magnitudes are from Bedin et al. (2006). For the 12 giants of the NAO sample, the new temperatures differ on average by about 5 K from the previous values. The new temperatures are on average higher by 27 K, although with a large scatter (118 K), for the SV sample.

Surface gravities were obtained from the position in the color–magnitude diagram, using the derived $T_{\text{eff}}$, the distance modulus $(m-M)_V = 15.59$ mag from Harris (1996), bolometric corrections from Alonso et al. (1999), a mass of 0.85 $M_\odot$ for all stars, and $M_{\text{bol},\odot} = 4.75$ for the Sun, as in our previous studies of 23 other GCs. Values of the microturbulent velocity $v_t$ were obtained by eliminating trends in the relation between abundances from FeI lines and the expected line strength (Magain 1984).

Equivalent widths (EWs) of the two Al lines and of two to three high excitation Mg lines (5711, 6318, and 6319 Å) were measured with the ROSA package (Gratton 1998). The abundances were derived using the atmospheric parameters determined for each star, interpolating within the Kurucz (1993) solar-scaled grid, with the overshooting option switched off. The adopted line lists and atomic parameters are from Gratton et al. (2003).

Derived LTE abundances of Mg and Al are listed in Table 1 together with optical $B$, $V$, and $K$ magnitudes. For completeness, we also list the atmospheric parameters derived in the full abundance analysis (E. Carretta et al., in preparation). Adopted solar reference abundances are 7.43 dex for Mg and 6.23 dex for Al (Gratton et al. 2003; Carretta et al. 2004b).

Typical star-to-star errors in abundance ratios are 0.058 and 0.047 dex for [Al/Fe] and [Mg/Fe], respectively, due to internal errors in the adopted atmospheric parameters (5 K in $T_{\text{eff}}$, 0.04 dex in log $g$, 0.03 dex in [Fe/H], 0.05 km s$^{-1}$ in $v_t$) and EW measurements; all errors were estimated as described in detail in Carretta et al. (2007a, 2009a).

3. THREE DISTINCT GROUPS ON THE RGB IN NGC 2808

The [Mg/Fe] and [Al/Fe] abundance ratios (and their sum) are plotted as a function of the temperature in Figure 2 (upper panel). No trend as a function of $T_{\text{eff}}$ (hence of the luminosity along the RGB) is discernible. Giants in NGC 2808 show from moderate to large star-to-star abundance variations in Mg content, with an average value [Mg/Fe] = 0.26 dex and an rms scatter of $\sigma = 0.16$ dex (31 stars). The Al abundance presents much larger variations, with a mean ratio of [Al/Fe] = +0.46 dex and a higher rms scatter ($\sigma = 0.47$ dex). On the other
hand, the sum of Al+Mg appears constant, with a very small dispersion ($\sigma = 0.05$ dex).

We recovered all stars with a subsolar Mg abundance found in the previous studies, three from the NAO sample (Carretta et al. 2009a) and one from the SV sample (Paper I). All of them are actual detections, not upper limits. The combined sample brings the number of stars with subsolar Mg abundance in NGC 2808 to four. Stars with such a low abundance are a notable exception among GCs, apart from NGC 2419 (Mucciarelli et al. 2012; Cohen & Kirby 2012) and M 13 (Sneden et al. 2004). The relatively high frequency of stars with strong depletion in Mg, coupled with the high temperature (~70 MK) required for the reactions of the Mg–Al cycle to occur, indicate that a fraction of stars in NGC 2808 was formed by matter extremely processed by hot H burning.

Even more interestingly, the better statistics from the present homogeneous analysis clearly reveals that the RGB stars of the merged sample are not continuously distributed along the Mg–Al anticorrelation, but are instead clustered into three distinct groups (Figure 3, upper panel). Using the distribution of stars along the Na–O anticorrelation in several GCs, Carretta et al. (2009b) divided the stellar population in each cluster in primordial (first generation) and intermediate and extreme components of second generation. By analogy, we associate the three groups along the Mg–Al anticorrelation in NGC 2808 with the same P, I, and E components in order of increasing Al abundance (and decreasing Mg content). The groups include 68% ± 15%, 19% ± 8%, and 13% ± 4% of stars in our sample, respectively, where the associated uncertainties are Poisson errors. Within the quoted statistical uncertainties, these fractions of stars derived from the Mg–Al anticorrelation are in excellent agreement with those estimated in Carretta et al. (2006) from the O-normal (61% ± 7%), O-poor (22% ± 4%), and super O-poor (17% ± 4%) RGB stars in NGC 2808 observed with GIRAFFE. A more accurate comparison must, however, await the reanalysis with the new, homogeneous temperature scale of all stars observed with both UVES and GIRAFFE.

No spurious effect due to the analysis can be responsible for the segregation of stars into these groups. Even corrections for departures from LTE can have only a negligible impact on this result, as shown in Figure 2 (lower panel) where we plot the [Al/Mg] ratios as a function of $T_{\text{eff}}$, indicating stars of different groups with different symbols. Giants with very similar atmospheric parameters that would be equally affected by possible NLTE corrections and uncertainties in atmospheric parameters are neatly segregated into the three groups P, I, and E.
Figure 2. Upper panel: \([\text{Mg/Fe}]\) (circles), \([\text{Al/Fe}]\) (squares), and \([\text{(Al+Mg)/Fe}]\) (triangles) abundance ratios as a function of the effective temperature. Lower panel: \([\text{Al/Mg}]\) ratios as a function of the temperature. Different symbols indicate stars in the three groups (see the text and Figure 3). (A color version of this figure is available in the online journal.)

Figure 3. Upper panel: Mg–Al anticorrelation in NGC 2808. Star to star error bars are indicated. Lower panel: the same plot, with two dilution models superimposed, starting at different primordial Mg levels. (A color version of this figure is available in the online journal.)

Figure 4. Upper panel: distribution of \([\text{Al/Mg}]\) ratios for the entire sample of giants in NGC 2808. Lower panel: cumulative distributions of \([\text{Al/Mg}]\) ratios in the P (solid line), I (dotted line), and E (dashed line) groups. The probabilities of the Kolmogorov–Smirnov test are also indicated. (A color version of this figure is available in the online journal.)

We show in the upper panel of Figure 4 the distribution of the \([\text{Al/Mg}]\) ratios, which actually maximize the signal along the anticorrelation and allow us to nicely trace the three distinct clumps of stars separated by gaps at \([\text{Al/Mg}] \sim 0.5\) dex and \([\text{Al/Mg}] \sim 1.15\) dex. The three components are characterized by very different average values of the \([\text{Al/Mg}]\) ratio: \(-0.191 \pm 0.035\) dex (\(\sigma = 0.160\) dex, 21 P stars), \(+0.818 \pm 0.065\) dex (\(\sigma = 0.158\) dex, 6 I stars), and \(+1.310 \pm 0.050\) dex (\(\sigma = 0.100\) dex, 4 E stars).

To evaluate how sound this division is, in the lower panel of Figure 4 we plot the cumulative distribution of \([\text{Al/Mg}]\) ratios for each of the P, I, and E groups. A Kolmogorov–Smirnov test always allows one to reject the null hypothesis that the three components are extracted from the same parent population with >99.999% confidence.

There is also a hint that the average metallicity slightly increases with the \([\text{Al/Mg}]\) ratio, from \([\text{Fe/H}] = -1.136\) dex (\(\sigma = 0.032\) dex) for the P group to \([\text{Fe/H}] = -1.120\) dex (\(\sigma = 0.020\) dex) and \([\text{Fe/H}] = -1.110\) dex (\(\sigma = 0.006\) dex) for the I and E components, respectively. Although these values cannot be considered formally different with a high level of confidence, this finding is in qualitative agreement with the prediction that...
more He enrichment in more polluted stars (e.g., D’Antona et al. 2002) would also increase the strength of metallic lines in stars with the same original metal abundance (Böhm-Vitense 1979), confirming the result obtained from a larger sample by Bragaglia et al. (2010) in NGC 2808.

4. DISCUSSION AND CONCLUSIONS

In the present study, we were able to provide a chemical tagging of three distinct groups of stars along the Mg–Al anticorrelation on the RGB in NGC 2808, using the largest homogeneous set of Mg and Al abundances for giants in this cluster. The separation among the three groups on the RGB is much clearer in NGC 2808 than in NGC 6752 (Carretta et al. 2012; Milone et al. 2013). On the other hand, the three MSs in NGC 6752 seem to stand out less clearly than in the benchmark of multiple MSs represented by NGC 2808 (see Milone et al. 2012, 2013). This is not unexpected, because NGC 2808 is much more massive than NGC 6752 and it is currently well assessed that the cluster total mass is the main parameter driving the phenomenon of multiple populations in GCs (Carretta et al. 2010).

The fractions of stars in each of the P, I, and E components we found on the RGB are in very close agreement with the number ratios found for single MS stars in NGC 2808 by Milone et al. (2012): 62% ± 2%, 24% ± 2%, and 14% ± 3% for the red, middle, and blue MSs, respectively.

Having found three discrete populations of RGB stars, each characterized by a different chemical composition, we may ask what the impact of this result on the formation scenario and the elusive nature of first generation polluters is. Two commonly adopted scenarios (where the polluters are either rotating massive stars, Decressin et al. 2007; or intermediate-mass AGB stars, Ventura et al. 2001) share a need for dilution of the nuclearly processed matter with unprocessed, pristine gas (Prantzos et al. 2007; D’Ercole et al. 2011). We then plot in the lower panel of Figure 3 two simple dilution models, as in Carretta et al. (2009a). The first, adopting as polluted and original abundance ratios the extremes observed in NGC 2808, is able to reproduce the E and P groups: however, the I component is clearly left out. To be matched by this model, [Mg/Fe] and [Al/Fe] should be lowered, on average, by about 0.10 and 0.20 dex, respectively: the last value is about 4σ different from the plausible range. On the other hand, if we arbitrarily change the starting values of Mg and Al to fit simultaneously the I and E components, the primordial level of Mg and Al would be inconsistent with what is actually observed. To summarize, there is no way to reproduce the intermediate component by mixing primordial and extremely polluted gas. As in the previous case of NGC 6752, we must conclude again that different polluters acted to produce the chemical composition observed in the I and E groups.

The strongly Mg-depleted stars observed in NGC 2808 represent a difficult problem for the aforementioned formation scenarios. Discrete distribution of He values has been invoked as a likely way to explain both the three distinct MSs and the multimodal distribution of stars on the HB of NGC 2808 (D’Antona et al. 2005). The bluest MS is reproduced using a model with a helium mass fraction of $Y \sim 0.38$, and this should then be the He content of stars in the Mg-poor group, the E component. However, in one of the latest formulations of the AGB-based formation scenario (D’Ercole et al. 2012) the largest Mg depletions are not from the super AGBs, but come from AGB stars of 5–6 $M_\odot$. The He content of these stars is $Y \lesssim 0.34$ (see Table 1 in D’Ercole et al. 2012), which is the threshold above which the authors adopt a deep-mixing scheme able to decrease the O abundance in second generation He-rich stars down to very low values $[O/Fe] \sim -0.8 \div -1.0$ observed in GCs such as NGC 2808 (Paper I) or M 13 (Johnson & Pilachowski 2012). Unfortunately, the very Mg-poor stars of the E component are also the most O-poor stars in NGC 2808 (E. Carretta et al., in preparation). Hence, as advanced by D’Ercole et al. (2012), this extreme population constitutes a problem for any pollution model and for the deep mixing scenario. On the other hand, efficient destruction of Mg and enhancement of Al are apparently produced by FRMSs only at the end of the MS, and with simultaneous strong Na destruction (Decressin et al. 2007), which is again not well matched by observations.

In summary:

1. We provided a better statistical base for the known Mg–Al anticorrelation observed in NGC 2808 (Carretta et al. 2009a), more than doubling the size of the sample of stars with homogeneous Mg and Al abundances. The anticorrelation is very extended, reaching a regime where very Mg-poor giants are found, a rare occurrence among GC stars.

2. For the first time, we found clear evidence of three discrete populations, each with distinctly homogeneous chemical composition on the RGB of NGC 2808. The first group, P, has a primordial composition of field stars of similar metallicity and the I and E components show signatures of increasing matter processing in hot H burning.

3. The fractions of P, I, and E stars along the Mg–Al anticorrelation are in excellent agreement with the number ratios found by Milone et al. (2012) for the three MSs in NGC 2808. We conclude that P, I, and E stars represent the progeny of the red, intermediate, and blue MSs, with increasing He content.

4. No simple dilution model appears to be able to simultaneously reproduce the chemistry of the three discrete components in NGC 2808, suggesting again that in this cluster, two different classes of first generation polluters were at work. This is also seen in NGC 6752, another GC with three discrete stellar populations spectroscopically detected on the RGB.

Future steps include enlarging the set of Al abundances in this GC using a program to measure the [Al/Fe] ratios of more than 100 giants in NGC 2808 with the HR21 setup of GIRAFFE and observation of the strong Al doublet at 8772–74 Å for which observing time was just granted at the ESO/VLT. Moreover, the homogeneous reanalysis of other elements, in particular, the proton-capture species O, Na, and Si, with the proper temperature scale, is in progress to provide the full network of correlations and anticorrelations in this peculiar GC.

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REFERENCES

Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261
Alonso, A., Arribas, S., & Martinez-Roger, C. 2001, A&A, 376, 1039
Bedin, L. R., Piotto, G., Zoccali, M., et al. 2000, A&A, 363, 159
Böhm-Vitense, E. 1979, ApJ, 234, 521
Bragaglia, A., Carretta, E., Gratton, R. G., et al. 2010, A&A, 519, 60
Carretta, E. 2006, AJ, 131, 1766, (Paper I)
Carretta, E., Bragaglia, A., & Cacciari, C. 2004a, ApJL, 610, L25
Carretta, E., Bragaglia, A., Gratton, R. G., D’Orazi, V., & Lucatello, S. 2011, A&A, 535, 121
Carretta, E., Bragaglia, A., Gratton, R. G., & Lucatello, S. 2009a, A&A, 505, 139
Carretta, E., Bragaglia, A., Gratton, R. G., Lucatello, S., & D’Orazi, V. 2012, ApJL, 750, L14
Carretta, E., Bragaglia, A., Gratton, R. G., Lucatello, S., & D’Orazi, V. 2011, A&A, 534, 123
Carretta, E., Piotto, G., Anderson, J., et al. 2007a, ApJL, 661, L53
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2006, A&A, 450, 523
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2009b, A&A, 505, 117
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2010, A&A, 516, 55
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2014, A&A, 564, A60
Carretta, E., Gratton, R. G., Bragaglia, A., Bonifacio, P., & Pasquini, L. 2004b, A&A, 416, 925
Carretta, E., Recio-Blanco, A., Gratton, R. G., Piotto, G., & Bragaglia, A. 2007b, ApJL, 760, 86
Cohen, J. G., & Kirby, E. N. 2012, ApJ, 760, 86
Cordero, M. J., Pilachowski, C. A., Johnson, C. I., et al. 2014, ApJ, 780, 94
D’Antona, F., Bellazzini, M., Caloi, V., et al. 2005, ApJ, 631, 868
D’Antona, F., Caloi, V., Montalbán, J., Ventura, P., & Gratton, R. 2002, A&A, 395, 69
Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., & Ekstrom, S. 2007, A&A, 464, 1029
Denisenkov, P. A., & Denisenkova, S. N. 1989, ATsir, 158, 11
D’Ercole, A., D’Antona, F., Carini, R., Vesperini, E., & Ventura, P. 2012, MNRAS, 423, 1521
D’Ercole, A., D’Antona, F., & Vesperini, E. 2011, MNRAS, 415, 1304
Gratton, R. G. 1988, Rome Obs. Preprint Ser., 29
Gratton, R. G., Bonifacio, P., Bragaglia, A., et al. 2001, A&A, 369, 87
Gratton, R. G., Carretta, E., & Bragaglia, A. 2012, A&ARv, 20, 50
Gratton, R. G., Carretta, E., Bragaglia, A., Lucatello, S., & D’Orazi, V. 2010, A&A, 517, 81
Gratton, R. G., Carretta, E., Claudii, R., Lucatello, S., & Barbieri, M. 2003, A&A, 404, 187
Gratton, R. G., Lucatello, S., Carretta, E., et al. 2011, A&A, 534, 123
Harris, W. E. 1996, AJ, 112, 1487
Johnson, C. I., & Pilachowski, C. A. 2012, ApJL, 754, L38
Kraft, R. P. 1994, PASP, 106, 553
Kurucz, R. L. 1993, CD-ROM 13 (Cambridge, MA: Smithsonian Astrophysical Observatory)
Langer, G. E., Hoffman, R., & Sneden, C. 1993, PASP, 105, 301
Magain, P. 1984, A&A, 134, 189
Marino, A. F., Villanova, S., Piotto, G., et al. 2008, A&A, 490, 625
Milone, A. P., Bedin, L., Piotto, G., et al. 2008, ApJ, 673, 241
Milone, A. P., Marino, A. F., Piotto, G., et al. 2013, ApJ, 765, 120
Milone, A. P., Piotto, G., Bedin, L., et al. 2012, A&A, 537, A77
Mucciarelli, A., Bellazzini, M., Ibata, R., et al. 2012, MNRAS, 426, 2889
Piotto, G., Bedin, L., Anderson, J., et al. 2007, ApJL, 661, L53
Prantzos, N., Charbonnel, C., &Biadis, C. 2007, A&A, 470, 179
Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163
Sneden, C., Kraft, R. P., Guhathakurta, P., Peterson, R. C., & Fulbright, J. P. 2004, AJ, 127, 2162
Ventura, P., D’Antona, F., Mazzitelli, I., & Gratton, R. 2001, ApJL, 550, L65
Yong, D., Grundahl, F., Nissen, P. E., Jensen, H. R., & Lambert, D. L. 2005, A&A, 438, 875