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POTASSIUM: A NEW ACTOR ON THE GLOBULAR CLUSTER CHEMICAL EVOLUTION STAGE. THE CASE OF NGC 2808*

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ABSTRACT

We derive [K/Fe] abundance ratios for 119 stars in the globular cluster NGC 2808, all of them having O, Na, Mg, and Al abundances homogeneously measured in previous works. We detect an intrinsic star-to-star spread in the potassium abundance. Moreover [K/Fe] abundance ratios display statistically significant correlations with [Na/Fe] and [Al/Fe], and anti-correlations with [O/Fe] and [Mg/Fe]. All the four Mg deficient stars ([Mg/Fe] < 0.0) discovered so far in NGC 2808 are enriched in K by ∼0.3 dex with respect to those with normal [Mg/Fe]. NGC 2808 is the second globular cluster, after NGC 2419, where a clear Mg–K anti-correlation is detected, albeit of weaker amplitude. The simultaneous correlation/anti-correlation of [K/Fe] with all the light elements usually involved in the chemical anomalies observed in globular cluster stars strongly support the idea that these abundance patterns are due to the same self-enrichment mechanism that produces Na–O and Mg–Al anti-correlations. This finding suggests that detectable spreads in K abundances may be typical in the massive globular clusters where the self-enrichment processes are observed to produce their most extreme manifestations.

Key words: globular clusters: individual (NGC 2808) – stars: abundances – techniques: spectroscopic

1. INTRODUCTION

In the last decade, accurate photometric and spectroscopic investigations have changed our concept of globular clusters (GCs), which were considered for a long time as aggregates of coeval stars, born with the same initial chemical composition. This traditional paradigm is still valid in terms of the iron and iron-peak elements abundance, while large variations in light elements (O, Na, Mg, and Al) were revealed in all the GCs studied so far, in our Galaxy (see, e.g., Carretta et al. 2009; Gratton et al. 2012) and in the Local Group (Mucciarelli et al. 2009).

Chemical inhomogeneities are usually explained by invoking the existence of (at least) a second generation of stars formed within the first ∼100 Myr of the cluster life, from intra-cluster medium polluted by the first generation stars. Intermediate mass asymptotic giant branch (AGB) stars (D'Ercole et al. 2008), fast rotating massive stars (FRMS; Decressin et al. 2007) and binary stars (De Mink et al. 2009) were proposed as the most likely polluters that should significantly affect the abundance of light elements (e.g., enhancing Na, Al, and He and depleting Mg and O) while leaving the iron abundance unaffected. However, all these models face serious problems and we are still far from a full understanding of the processes underlying the presence of multiple populations in GCs (see, e.g., the alternative scenario proposed by Bastian et al. 2013).

Potassium is a *new entry* among the chemical anomalies in GCs. From the analysis of DEIMOS@Keck low-resolution spectra of 49 giant stars in the remote, massive GC NGC 2419, Mucciarelli et al. (2012, Mu12 hereafter) discovered that its stars span an unusually large range in K abundances, from solar values up to [K/Fe] ∼ +2 dex. Also, [K/Fe] anti-correlate with [Mg/Fe], which also covers a huge range, from values compatible with the α-enhancement observed in other ancient GCs down to [Mg/Fe] ∼ −1 dex. About 40% of the stars in NGC 2419 show sub-solar [Mg/Fe] abundance ratios and high K abundances. This were confirmed by Cohen & Kirby (2012) from the analysis of HIRES@Keck high-resolution spectra of 13 giant stars of NGC 2419. Note that most of the GC stars have [Mg/Fe] abundance ratios between +0.3 and +0.6 dex (thus, with variations generally smaller than those observed in the other light elements), and only a handful of GC stars with −0.3 < [Mg/Fe] < +0.3 are known (Carretta et al. 2009). NGC 2419 represents the only exception observed so far.

Currently, a solid interpretation of the origin of such a Mg–K anti-correlation is still lacking. Ventura et al. (2012, V12 hereafter) proposed a theoretical model where the Mg-poor/K-rich stellar population is *an extreme population directly formed from the AGB and super-AGB ejecta*, supporting the first claim by Mu12 that the spread in K is ascribable to the same self-enrichment process able to produce the other chemical anomalies. However, a proper modeling of the observed pattern requires a fine tuning in the reaction cross-sections and burning temperatures.

Carretta et al. (2013) analyzed small samples of stars in different evolutionary stages (turnoff, sub-giant, and giant stars) in seven GCs, finding no evidence of intrinsic scatter in their K content. All the studied stars have Mg and K abundances that well match the values of the *normal* stellar population of NGC 2419.

In order to unveil the possible role played by K in the framework of the GC self-enrichment process, and to understand whether the Mg–K anti-correlation in NGC 2419 is a singular

* Based on data obtained at the ESO Very Large Telescope under the programs 072.D-0507 and 091.D-0329.

event among the chemical anomalies of the GCs, we started a project aimed at deriving the K abundance in different GCs. This paper is focused on the massive GC NGC 2808, one of the clusters with the most extended Na–O anti-correlation (see, e.g., Carretta et al. 2006) and harboring four Mg-poor stars (Carretta et al. 2009; Carretta 2014), making it an ideal cluster where K abundance spreads can be searched for.

2. OBSERVATIONS

The observations were performed with the spectroscopic facility FLAMES (Pasquini et al. 2000) in the UVES+MEDUSA combined mode. We adopted the 860 Red Arm CD4 UVES set-up, with a spectral coverage of 6600–10600 Å and a resolution of ∼45,000, and the HR18 GIRAFFE grating, covering from 7648 to 7889 Å and with a spectral resolution of 18,400. These set-ups were chosen in order to sample the K i resonance line at 7699 Å.

We used two fiber allocation configurations to observe our targets, which are 119 red giant branch (RGB) stars whose membership to NGC 2808 was already established, and whose Fe, O, Na, Mg, and Al abundances were homogeneously estimated by Carretta et al. (2006, 2009, C06 and C09 hereafter, respectively). The goal of our project is to build on their analysis by adding the abundance of potassium. In the following all the adopted abundance ratios are from these works, except for [K/Fe].

For each fiber configuration two exposures of 1300 s each were secured, in order to reach a S/N ratio per pixel around the K line of ∼100 for the faintest targets ($V \sim 15.4$) and of ∼200 for the brightest ones ($V \sim 13.8$). All the spectra were reduced with the UVES-FLAMES and GIRAFFE ESO pipelines, including bias subtraction, flat-fielding, wavelength calibration, spectral extraction, and order merging (only for UVES spectra).

3. K ABUNDANCES

The K abundances of the targets were derived from the measure of the K i line at 7699 Å with the package GALA (Mucciarelli et al. 2013). The line EWs were measured with the code DAOSPEC (Stetson & Pancino 2008), through the wrapper 4DAO (Mucciarelli 2013). Eleven stars were observed both with UVES and GIRAFFE spectra: we found an average difference between their K line EWs of $EW_{UVES} - EW_{GIR} = 2.5 \pm 1.2$ mÅ ($\sigma = 4.0$ mÅ), corresponding to a typical variation smaller than 2% in EW (∼0.03–0.04 dex in K abundance).

Effective temperatures ($T_{\rm eff}$) and surface gravities ($\log g$) are from C06. The analysis of the entire FLAMES sample of four GCs secured within this project (A. Mucciarelli et al., in preparation) has revealed that the use of the micro-turbulent velocities ($v_{\rm turb}$) derived by C06 leads to an unexpected trend between K abundances and $v_{\rm turb}$, probably due to the small number of Fe i lines used to infer $v_{\rm turb}$. In order to use a homogeneous scale of $v_{\rm turb}$, we adopted the calibration by Kirby et al. (2009) which provides $v_{\rm turb}$ as a function of log g. No trend between $v_{\rm turb}$ and the K abundances is detected when the relation by Kirby et al. (2009) is used. The K abundances are corrected for the departures from LTE by applying non-LTE abundance corrections computed with the non-LTE (NLTE) radiative transfer code MULTI (modified version 2.3; Carlsson 1986), MARCS model atmospheres (Gustafsson et al. 2008), and a new model atom of neutral potassium (T. Merle et al., in preparation). NLTE EWs are larger than in LTE, leading to NLTE K abundances lower by about −0.3 dex.

Uncertainties in the derived abundances were computed by taking into account two different sources of errors: (1) the uncertainty arising from the EW measurement, as estimated by DAOSPEC, typically of the order of ∼0.02–0.03 dex for GIRAFFE targets and ∼0.04–0.05 dex for UVES targets, and (2) the uncertainties arising from the atmospheric parameters. For the latter source of error, we take into account the correlation among the parameters: we adopted 40 K as a typical uncertainty in $T_{\rm eff}$, as quoted by C06. A $T_{\rm eff}$ variation of ±40 K changes the K abundance by ±0.06–0.07 dex and leads to a variation of $\log g$ smaller than ±0.1 (with a null impact on the K abundance). This $\log g$ variation leads to a change in $v_{\rm turb}$ of ∓ 0.04 km s^{-1}, corresponding to a K variation of ±0.02–0.03 dex. Hence, we estimated a total uncertainty of about 0.09–0.11 dex.

4. RESULTS

The mean difference between our radial velocity estimates and those by C06 is $\langle \Delta V_r \rangle = -0.1$ km s^{-1} with a standard deviation of $\sigma_\Delta = 0.8$ km s^{-1}. Of the 119 targets, 3 have $|\Delta V_r| > 3.0$ km s^{-1}, i.e., much larger than $3\sigma_\Delta$, hence they were flagged as possible binary stars and excluded from the following discussion (but shown in the plots as empty symbols). It is interesting to note that some of the candidate unresolved binary systems identified here stand out as extreme outliers in the chemical abundance plots shown in Figure 1. This suggests that some stars observed to lie out of the general trends between abundance ratio in GCs or other stellar systems may not have a genuine anomalous composition but, instead, may have their abundances altered by their unrecognized binary nature. The abundance distribution of the remaining 116 stars spans a sizeable range, from [K/Fe] = −0.16 up to [K/Fe] = +0.33. We used the Maximum Likelihood algorithm described in Mu12, which provides the mean and intrinsic spread of a given abundance ratio by taking into account the uncertainties of each individual star. We found that the sample displays a statistically significant *intrinsic* star-to-star scatter in [K/Fe], $\sigma_{\rm int}^{\rm [K/Fe]} = 0.05 \pm 0.01$.

Additional support for this conclusion comes from the behavior of [K/Fe] as a function of [O/Fe], [Na/Fe], [Mg/Fe], and [Al/Fe] shown in Figures 1 and 2. The GIRAFFE targets (for which only O and Na abundances are available) are shown as red circles and the UVES targets (for which O, Na, Mg, and Al were measured) as green squares. Recently, Carretta (2014) re-analyzed the stars already discussed in C09 and derived new Mg and Al abundances for the stars originally discussed in Carretta et al. (2004) but not planned in our observations. However, two of these new stars are in common with our GIRAFFE sample and we included their Mg and Al abundances (marked as filled triangles in Figure 2), even if formally their analysis is based on a slightly different $T_{\rm eff}$ scale (with $T_{\rm eff}$ differences of 71 K and −18 K with respect to C06).

All the four abundance ratios show clear and statistically significant correlations with the K abundance. In particular, [Na/Fe] and [Al/Fe] correlate with [K/Fe], and [O/Fe] and [Mg/Fe] anti-correlate with [K/Fe]. The Spearman correlation test gives probabilities that the variables are non-correlated of $P(K–O) = 1.5 \times 10^{-4}$, $P(K–Na) = 3.9 \times 10^{-4}$, $P(K–Mg) = 0.0665$, and $P(K–Al) = 0.0024$. To better assess the significance of the correlations of K with Mg and Al, we test the hypotheses that stars with [Mg/Fe]([Al/Fe]) $\leqslant$ 0.0(+0.5) and those with [Mg/Fe]([Al/Fe]) > 0.0(+0.5) (1) are extracted from the same parent distribution in [K/Fe], with a Kolmogorov–Smirnov test,

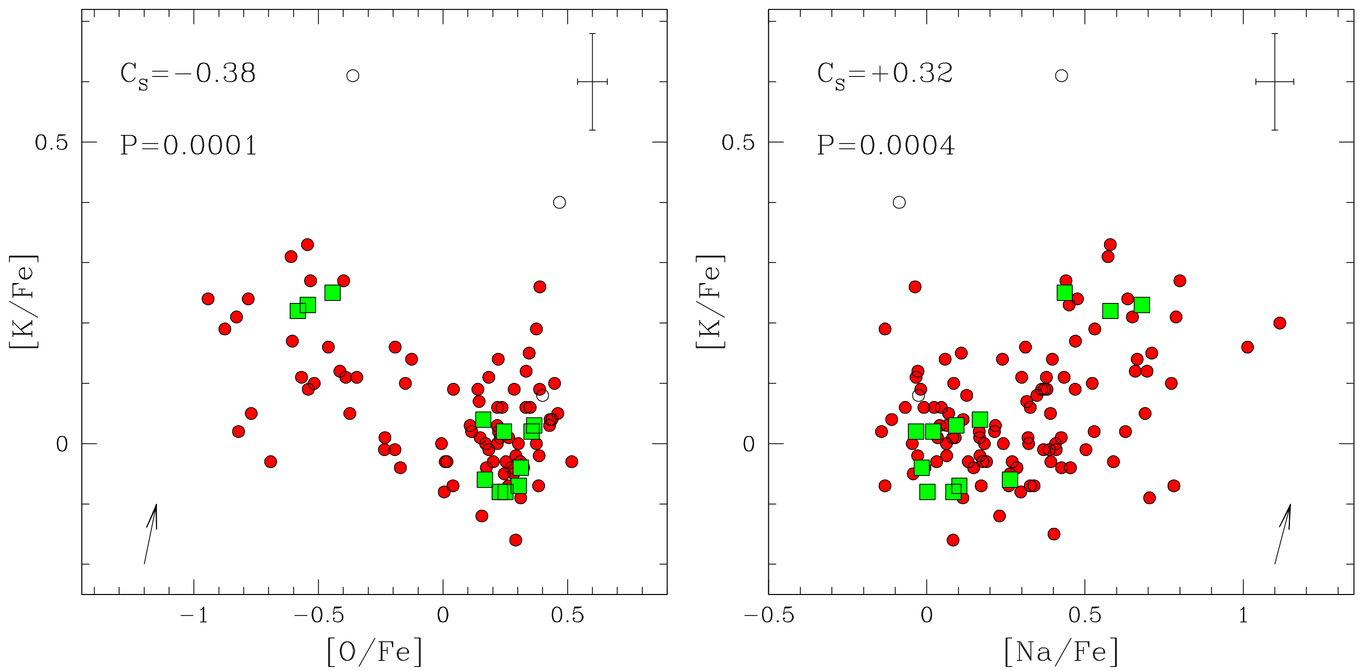

Figure 1. [K/Fe] as a function of [O/Fe] (left panel) and [Na/Fe] (right panel). Red circles are the GIRAFFE targets and green squares the UVES targets. Empty circles are stars excluded from the analysis for their variable V_r (likely binary stars). The arrows show the effects of a change by 40 K in $T_{\rm eff}$ and the corresponding variations in log g and $v_{\rm turb}$.

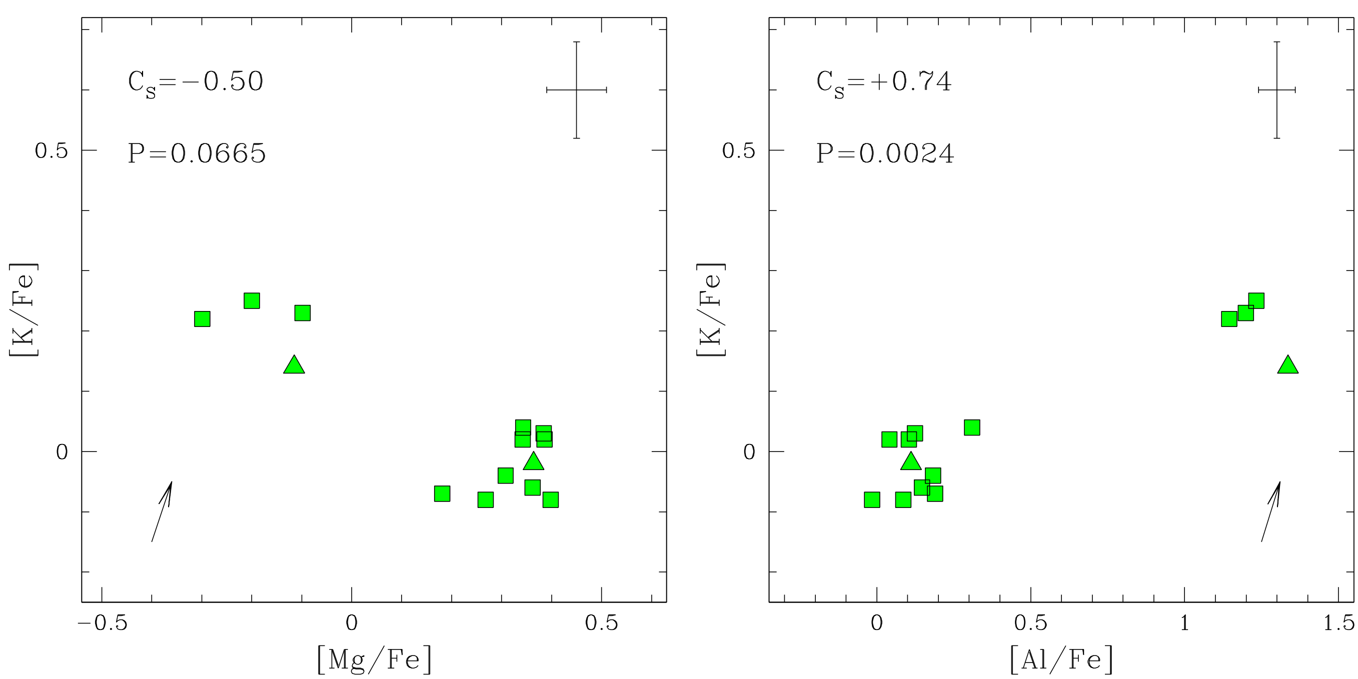

Figure 2. [K/Fe] as a function of [Mg/Fe] (left panel) and [Al/Fe] (right panel). Green squares are the UVES targets, while the triangles are the additionally two stars in common with Carretta (2014).

and (2) are extracted from distribution of [K/Fe] having the same mean, with Student's and Welch's tests. The hypothesis (1) is rejected with $P = 1.8 \times 10^{-3}$ and hypothesis (2) with $P < 5.0 \times 10^{-5}$.

At the core of the Mg–K anti-correlation is the fact that the four Mg-deficient stars ([Mg/Fe] < 0.0) identified in NGC 2808 are also found to be K-enhanced with respect to Mg-normal stars. While the amplitude of the enhancement is relatively weak (≃+0.3 dex) the trend is analogous to that found in NGC 2419 by Mu12. Following the classification scheme set up by Carretta (2014), Mg-deficient and K-rich stars should correspond to the *Extreme* population and Mg-normal and K-poor stars to the *Primordial* population.

5. SANITY CHECKS

We performed several sanity checks to assess the robustness to systematics of the results described above.

Correlations with atmospheric parameters. Atmospheric parameters of stars along the RGB of a globular cluster are

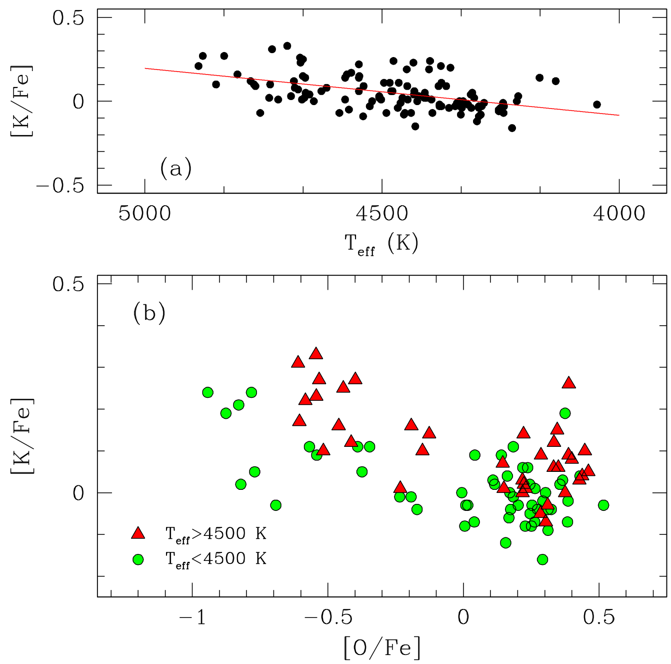

Figure 3. (a) Trend of [K/Fe] abundance ratio with $T_{\rm eff}$. The red line is a linear fit to the data. (b) [K/Fe] as a function of [O/Fe]. Stars hotter and cooler than 4500 K are plotted with different symbols (red triangles and green circles, respectively) to highlight the effect of the trend between K abundance and $T_{\rm eff}$ on the [K/Fe]–[O/Fe] correlation.

correlated. An increase of $T_{\rm eff}$, coupled with the corresponding variations in log g and $v_{\rm turb}$, produces an increase in all the abundance ratios. The effect of these changes on the abundance ratios is shown by the arrows in Figure 1 and 2. The directions of the plotted vectors show that while a systematic in one of the atmospheric parameter can (in principle) play a role in the K–Na correlation (and, perhaps, also in the K–Al one), they are almost perpendicular to the directions of the K–Mg and K–O anti-correlations (see also the discussion in Mu12).

Indeed, we noted that a weak residual trend between [K/Fe] and $T_{\rm eff}$ is present in our data (see panel (a) of Figure 3). However, this trend with $T_{\rm eff}$ is clearly not at the origin of the K–O and K–Mg correlation, as it can be appreciated from Figure 3, where we plotted with different symbols stars hotter and cooler than $T_{\rm eff}$ = 4500 K. Both groups display the K–O correlation, with a small offset in K abundances fully consistent with the vector shown in Figure 1. The application of a rigid offset of +0.08 dex in [K/Fe] to the stars of one group would lead to a full overlap of the two parallel sequences in the [K/Fe] versus [O/Fe] plane. Note that such an offset corresponds to a variation of ∼50 K, compatible with 1σ uncertainty in $T_{\rm eff}$, but with a negligible impact on the abundances of other elements. A similar behavior occurs in the [K/Fe] versus [Mg/Fe] plane, though the small sample prevents an interpretation as clean as that emerging from Figure 3. The same effect is observed in the [K/Fe] versus [Na/Fe] plane, explaining (at least partially) the large K abundance scatter measured at different values of [Na/Fe]. It is especially relevant to note that the removal of this small systematic would make the observed correlations of K with other light elements even tighter than that shown in Figures 1 and 2. Note that the three K-rich stars observed with UVES have a [K/Fe] scatter smaller than that measured among the GIRAFFE targets with similar [O/Fe] or [Na/Fe]. This can be explained with the fact that these stars have similar $T_{\rm eff}$, covering a range of about 100 K, while the entire sample of GIRAFFE targets covers about 800 K.

NLTE corrections. [K/Fe] abundance ratios were re-derived using the NLTE corrections by Takeda et al. (2002),[6] leading to a decrease of [K/Fe] of ∼0.2 dex. The use of these NLTE corrections does not erase the observed correlations between [K/Fe] and the other light elements, and the difference in K abundance between Mg-normal and Mg-deficient stars remains the same. The correlations are preserved also when a constant NLTE correction of −0.3 dex is adopted, as done by Mu12 in the case of NGC 2419.

An alternative set of spectroscopic parameters. We derived spectroscopically the atmospheric parameters of the stars of NGC 2808 observed with UVES, thus repeating the analysis with a set of parameters fully independent of those by C09 that we used before. We combined the UVES spectra taken within our program, with those by C09 from the Red Arm 580 set-up, thus providing a total spectral coverage of about 4000 Å. The atmospheric parameters were derived imposing (1) no trend between Fe I abundances and excitation potential (to constrain $T_{\rm eff}$), (2) no trend between Fe I abundances and EWs (to constrain $v_{\rm turb}$), (3) the same abundance, within the uncertainties, from Fe I and Fe II lines (to constrain log g). This new analysis, based on ∼250 Fe I lines and ∼20–25 Fe II lines, provides atmospheric parameters that match well those used above, with differences smaller than 50–60 K in $T_{\rm eff}$, ∼0.1 in log g, and 0.2–0.3 km s^{-1} in v_t. Consequently, the newly derived abundances are in good agreement with those presented above and the relevant trends with [K/Fe] remain essentially untouched.

6. DISCUSSION

The present analysis provides two main results: (1) the K abundance is not uniform among the stars of NGC 2808 but it exhibits a small but significant intrinsic spread; (2) K abundances are correlated with the abundances of the light elements involved in the chemical anomalies ubiquitously detected in globular clusters (namely O, Na, Mg, and Al). In particular, the four Mg-deficient cluster stars detected so far are all K-enhanced, implying the existence of a tight Mg–K anti-correlation similar to that observed in NGC 2419, albeit with a much smaller amplitude. *This is the second case of a GC where a Mg–K anti-correlation is detected.*

As for other light elements in NGC 2808 (Carretta 2014) the distribution of K is not unimodal, thus suggesting that the enrichment occurred in discrete events. The bi-modality of the K distribution is evident in the UVES sample. The GIRAFFE sample satisfies all the criteria established by Muratov & Gnedin (2010) for a non-unimodal distribution (the so-called Gaussian mixture modeling, GMM, test). In particular, the GMM test rejects the hypothesis of unimodal distribution at the 99.5% confidence level.

Stars with sub-solar [Mg/Fe] abundance ratios are quite rare in Galactic GCs: among the 19 GCs investigated by Carretta et al. (2009) only NGC 2808 is found to harbor four stars with [Mg/Fe] < 0; two were detected in M54 (Carretta et al. 2010) and four in Omega Centauri (Norris & Da Costa 1995). All these clusters (plus NGC 2419) are among the most massive of the entire GC system of the Milky Way and present the most extreme manifestations of the light element self-enrichment process typical of globulars. They display extended (anti-)

[6] http://optik2.mtk.nao.ac.jp/~takeda/potassium_nonlte/

correlations between abundances of light elements, complex Horizontal Branch morphologies with extended blue tails, and are observed (or suspected) to host populations with extreme He abundances ($Y > 0.3$; see, e.g., D'Antona et al. 2005; Dalessandro et al. 2008, 2011; Gratton et al. 2011; King et al. 2012; Beccari et al. 2013; and references therein). Our results for NGC 2419 and NGC 2808 strongly suggest that, at least in these massive and metal-poor clusters, Mg-deficiency is associated with K-enhancement. Other clusters, where self-enrichment did not reach the stage leading to the production of Mg-deficient stars, probably were not able to synthesize enough potassium to display a detectable spread in [K/Fe] (Carretta et al. 2013).

The evidence that [K/Fe] correlates also with O, Na, and Al supports the hypothesis that the spread in K is ascribable to the same self-enrichment process that produces the observed abundance variations (and correlations) for these elements. Still, placing NGC 2419 in this scenario is not straightforward. In fact, while its K–Mg anti-correlation is consistent with being an extended version of that observed in NGC 2808, this is not the case for the K–Na and K–Al correlations, since, according to Cohen & Kirby (2012), at any given [Na/Fe] and [Al/Fe] there is a large spread of [K/Fe] (see also Carretta et al. 2013 for a thorough discussion). Perhaps this is somehow related to the different metallicity regime of the two clusters, whose [K/H] ratio for first-generation stars differ by $\sim$1.0 dex (see also V12).

Within the scenario where self-enrichment is driven by AGB stars, K production is expected to occur in the same hot bottom burning environment where the other chemical anomalies are produced (V12). In these models, the stars of the extreme populations of both NGC 2419 and NGC 2808 are thought to have formed directly from the pure ejecta of AGB/super-AGB stars, without dilution with pristine gas (see, e.g., D'Antona et al. 2005; Di Criscienzo et al. 2011). Potassium can be produced by proton capture on argon nuclei, through the thermonuclear chain $^{36}\mathrm{Ar}(p,\gamma)^{37}\mathrm{K}(e^{+},\nu)^{37}\mathrm{Cl}(p,\gamma)^{38}\mathrm{Ar}(p,\gamma)^{39}\mathrm{K}$, occurring at temperatures of about 10^8 K. Even if the chain able to produce K is known, several uncertainties affect our knowledge of this reaction. In particular, V12 had to increase the cross section of the reaction $^{38}\mathrm{Ar}(p,\gamma)^{39}\mathrm{K}$ by a factor of 100 to reproduce the K abundances measured in the Mg-deficient stars of NGC 2419. We refer the reader to V12 for a complete discussion about the uncertainties in these reactions.

Note that no explicit predictions about K abundance anomalies are available for other models of self-enrichment (based on FRMS or binary stars) and we cannot use the observed scatter in the K content of NGC 2808 to discriminate among different scenarios. However, strong Mg-depletion can be currently predicted only by AGB/super-AGB models, with adequate mass loss rates and/or convection efficiency. It is also interesting to note that V12, in their basic model for a cluster as metal-poor as NGC 2419, predict that Mg-depleted stars should also have their oxygen abundance depleted by as much as $\simeq -1.7$ dex, not much different from the maximum oxygen depletion we observe in NGC 2808 stars ($\simeq -1.3$ dex).

In conclusion, the present analysis supports the idea that K enrichment is among the outcomes of the process of self-enrichment occurring in globular clusters and, in particular, significant K-enhancement is present in extremely Mg-depleted stars. Hence, at least for the Mg–K anti-correlation, NGC 2419 is not a *unicum*. The future extension of this survey to other clusters will establish if the homogeneous analysis of large samples may reveal the presence of small spreads of K abundances also in other GCs.

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