

## STAR-TO-STAR Na AND O ABUNDANCE VARIATIONS ALONG THE RED GIANT BRANCH IN NGC 2808<sup>1</sup>

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### ABSTRACT

We report for the first time Na and O abundances from high-resolution, high signal-to-noise ratio echelle spectra of 20 red giants in NGC 2808, taken as part of the Science Verification program of the FLAMES multiobject spectrograph at the ESO VLT. In these stars, spanning about 3 mag from the red giant branch (RGB) tip, large variations are detected in the abundances of oxygen and sodium, anticorrelated with each other; this is well-known evidence of proton-capture reactions at high temperatures in the ON and NeNa cycles. One star appears super-O-poor; if the extension of the Na-O anticorrelation is confirmed, NGC 2808 might reach O-depletion levels as large as those of M13. This result confirms our previous findings based on lower resolution spectra (Carretta et al.) of a large star-to-star scatter in proton-capture elements at all positions along the RGB in NGC 2808, with no significant evolutionary contribution. Finally, the average metallicity for NGC 2808 is  $[\text{Fe}/\text{H}] = -1.14 \pm 0.01$  dex (rms = 0.06) from 19 stars.

*Subject headings:* globular clusters: general — globular clusters: individual (NGC 2808) — stars: abundances — stars: evolution

*Online material:* color figures

### 1. INTRODUCTION

Since the pioneering work of Osborn (1971), a large body of evidence has accumulated indicating that globular clusters (GCs) are *not* monometallic populations, as far as the light elements (C, N, O, Na, Mg, Al) are concerned. While early studies on the light elements C and N, as well as carbon isotopic ratios, showed that some kind of mixing was involved in red giant branch (RGB) stars (C abundances declining with increasing stellar luminosities, C and N abundances anticorrelated among stars of the same evolutionary phase; see Smith 1987 for a review), they could not explain why these variations were observed all the way down to unevolved stars where mixing is not supposed to play any role (see, e.g., the recent studies by Cannon et al. 1998, Harbeck et al. 2003, and references therein).

The Lick-Texas study of heavier elements (see Kraft 1994 and Snenen et al. 2004, hereafter S04, for complete references) in bright giants in several clusters showed that the  $[\text{Na}/\text{Fe}]$  and  $[\text{O}/\text{Fe}]$  ratios were anticorrelated: O depletion was always accompanied by Na enhancement, the stars in M13 displaying the most severe variations. Whenever C and N abundances were available, N was anticorrelated with O, whereas a clear correlation existed between O and C abundances. This points to a redistribution of C, N, and O in an H-burning CNO cycle. The theoretical background presented by Denisenkov & Denisenkova (1990) and Langer et al. (1993) clarified that proton-capture reactions at high temperatures in the ON and NeNa cycles are involved in building up the observed pattern.

While these anomalies are markedly confined to the dense cluster environment (e.g., Gratton et al. 2000), the true site where CNO and NeNa cycles concur to form the observed abundance pattern is still a matter of debate. In fact, the same chains of *p*-captures (on C, N, O, Ne, Mg) may occur both in the H-burning shell of low-mass ( $<1 M_{\odot}$ ) stars presently climbing up the RGB branch and in the so-called hot bottom burning (Blöcker & Schönberner 1991; Boothroyd & Sackmann 1992)

taking place in a prior generation of intermediate-mass ( $3\text{--}8 M_{\odot}$ ) stars in the asymptotic giant branch (IM-AGB) phase.

The first direct observations of O and Na abundances in dwarfs at the main-sequence turnoff in NGC 6752 (Gratton et al. 2001) and in 47 Tuc (Carretta et al. 2004) are clear-cut evidence that part of the observed Na-O anticorrelation must be primordially established, since these unevolved stars do not have either high enough temperatures in their cores for the required reactions or large enough convective envelopes to dredge up to the surface the products of *p*-capture reactions.

Here we present the results for Na and O obtained for 20 RGB stars in NGC 2808, observed during the FLAMES Science Verification. Carretta et al. (2003) exploited the MEDUSA mode of FLAMES at VLT-UT2 to uncover large star-to-star variations in Na abundances among 80 RGB stars in this cluster. In this Letter, we show that Na is anticorrelated with O, and we find preliminary evidence that in NGC 2808, the O depletion in some stars could be as extreme as in M13 super-O-poor stars.

### 2. ATMOSPHERIC PARAMETERS AND ABUNDANCE ANALYSIS

Twenty RGB stars with  $V = 13.2\text{--}16.5$  were observed with the fiber-fed UV-Visual Echelle Spectrograph red arm ( $R = 47000$ , spectral coverage of 200 nm, centered at 580 nm). Full details of the observations and data reduction, magnitudes, and coordinates can be found in Cacciari et al. (2004, hereafter C04). The signal-to-noise ratio (S/N) varies a lot (the selection was optimized for studying mass loss, not for abundance analysis) and is shown in Figure 1 together with the target positions in the color-magnitude diagram (CMD).

Effective temperatures  $T_{\text{eff}}$  (from colors and the Alonso et al. 1999 calibration) are discussed in C04 and Carretta et al. (2003). Surface gravities  $\log g$  were obtained from temperatures and bolometric corrections, using the distance modulus  $(m - M)_V = 15.59$  (Harris 1996) and assuming that the stars have masses of  $0.85 M_{\odot}$ . The adopted bolometric magnitude of the Sun is  $M_{\text{bol}, \odot} = 4.75$ . Equivalent widths (EWs) for Fe I, Fe II, and Na lines were measured as described in Bragaglia et al. (2001). Details will be presented in a forthcoming

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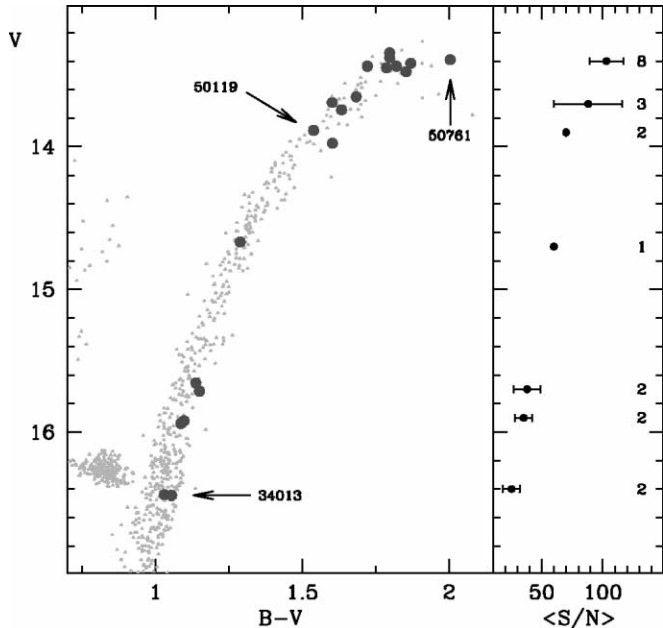


FIG. 1.—*Large filled circles*: Observed stars on the  $V, B - V$  CMD of NGC 2808 (Bedin et al. 2000). The right panel shows the average S/N at different magnitude levels, and numbers indicate how many stars were averaged each time. The coolest star is indicated as well as the ones with the lowest S/N (34013, dropped from discussion) and with the lowest O abundance (50119). [See the electronic edition of the Journal for a color version of this figure.]

paper. We derived the microturbulence velocity  $v_t$  by zeroing the slope of the abundances of Fe I versus EWs, and the overall model metallicity was chosen using the Kurucz (1993) grid of model atmospheres with the overshooting option set on. Abundances of Fe I, Fe II, and Na I were derived from the analysis of EWs (for Na from the doublets at 5682–5688 and 6154–6160 Å). O abundances were derived from spectral synthesis of the forbidden lines [O I]  $\lambda$ 6300.31, 6363.79, after cleaning the observed spectra for telluric line contamination. The contribution of the weak, high-excitation Ni line at 6300.34 Å, with the laboratory  $\log gf$  recently measured by Johansson et al. (2003), is negligible (about 0.5–1.2 mÅ) in the entire magnitude range. The reference solar abundances and atomic pa-

rameters for the lines are those of Gratton et al. (2003). Adopted parameters and derived abundances are listed in Table 1.

The ionization equilibrium Fe II/Fe I is good: on average,  $[\text{Fe}/\text{H}]_{\text{II}} - [\text{Fe}/\text{H}]_{\text{I}} = 0.00 \pm 0.03$ , rms = 0.15 dex (19 stars: for star 34013, with S/N  $\sim 20$ , measurements of EWs were unreliable, and so this star was dropped from further discussion). Excluding the coolest star (50761), there seems to be a slight trend for increasing the Fe II – Fe I difference with decreasing  $T_{\text{eff}}$ . While this could hint at possible departures from LTE (overionization), the good agreement of Fe I abundances all over the sampled range in  $T_{\text{eff}}$  argues against an underestimate of [Fe/H] abundances. Another possibility is that the structure of the atmospheres for the coolest giants is not well reproduced by models of the Kurucz grid (see Dalle Ore 1993). No noticeable trend of derived abundances as a function of the excitation potential is discernible. This supports the adoption of the Alonso et al. (1999) temperature scale, as found also by Ivans et al. (2001). Estimates of typical errors in  $T_{\text{eff}}$ ,  $\log g$ , [A/H], and  $v_t$  are 70 K, 0.1 dex, 0.1 dex, and 0.1 km s $^{-1}$ , respectively. When combined with errors in the measurement of EWs, they translate into a total (internal) error of about 0.08 dex in [Fe/H] and [Na/Fe] and 0.13 dex in [O/Fe].

Average values for NGC 2808 are  $[\text{Fe}/\text{H}]_{\text{I}} = -1.14 \pm 0.01$ , rms = 0.06 dex and  $[\text{Fe}/\text{H}]_{\text{II}} = -1.14 \pm 0.03$ , rms = 0.13 dex. This is the first determination of the iron abundance based on modern high-resolution spectra for this cluster.

### 3. RESULTS AND DISCUSSION

Derived abundances of Na and O are plotted in Figure 2. [O/Fe] ratios were referred to Fe II; [Na/Fe] ratios are corrected for departures from LTE as in Gratton et al. (1999) and are referred to Fe I abundances. This is the first study to unveil the existence of the Na-O anticorrelation in this cluster. In Carretta et al. (2003), we pointed out the large spread observed in Na abundances at all luminosities along the RGB; however, the MEDUSA spectra (acquired to study the mass loss) were centered on the Na D or H $\alpha$  features, and they did not contain O lines.

Here we also show that O abundances are very different among stars at the same position along the RGB. We show in

TABLE 1  
ADOPTED PARAMETERS AND DERIVED ABUNDANCES

Star ID	S/N	$T_{\text{eff}}$ (K)	$\log g$ (dex)	$v_t$ (km s $^{-1}$ )	$n$	$[\text{Fe}/\text{H}]_{\text{I}}$ (dex)	$\sigma$ (dex)	$n$	$[\text{Fe}/\text{H}]_{\text{II}}$ (dex)	$\sigma$ (dex)	$n$	[Na/Fe] (dex)	$\sigma$ (dex)	[O/Fe] (dex)
10201	45	4717	2.02	1.20	51	-1.06	0.13	8	-1.21	0.05	3	+0.23	0.06	-0.05
13983	40	4826	2.17	0.60	33	-1.08	0.08	5	-1.09	0.13	2	+0.45	0.12	-0.54
32685	30	4788	2.03	0.83	34	-1.15	0.09	5	-1.41	0.07	2	+0.48	0.10	<-0.24
34013	20	5110	2.51	0.80	29	-0.89:	0.21	...	...	...	...	...	...	...
37872	120	4015	0.71	1.68	96	-1.10	0.11	14	-1.06	0.08	4	+0.44	0.07	-0.34
42886	30	4791	2.14	0.85	47	-1.16	0.14	4	-1.38	0.10	2	-0.17	0.13	<+0.47
43217	30	4916	2.41	0.80	33	-1.00	0.12	7	-1.17	0.13	1	-0.31	...	<+0.37
46099	80	4032	0.76	1.72	60	-1.18	0.12	10	-1.19	0.12	2	+0.17	0.03	+0.25
46422	100	3943	0.52	1.85	95	-1.17	0.12	14	-1.08	0.09	3	+0.12	0.11	+0.23
46580	65	4051	0.74	1.68	89	-1.15	0.11	15	-1.03	0.13	4	+0.33	0.05	+0.10
47606	110	3839	0.44	1.66	85	-1.12	0.14	14	-1.14	0.16	4	+0.09	0.05	+0.20
48609	110	3846	0.44	1.78	58	-1.22	0.12	8	-1.11	0.13	3	+0.07	0.09	+0.20
48889	85	3943	0.52	1.80	99	-1.15	0.15	13	-1.22	0.12	4	+0.64	0.13	-0.07
50119	70	4166	0.93	1.73	119	-1.08	0.15	18	-1.21	0.13	4	+0.53	0.03	<-1.00
50761	120	3756	0.31	1.75	81	-1.22	0.12	10	-0.81	0.07	4	+0.15	0.12	-0.29
51454	120	3893	0.51	1.65	90	-1.26	0.11	14	-1.11	0.13	4	+0.21	0.07	+0.13
51499	85	3960	0.57	1.70	104	-1.25	0.10	18	-1.24	0.12	4	+0.17	0.10	+0.29
51983	95	3855	0.47	1.77	71	-1.15	0.11	13	-1.16	0.12	4	+0.53	0.09	-0.17
53390	60	4426	1.43	1.30	106	-1.12	0.10	19	-1.14	0.13	4	+0.00	0.09	+0.40
56032	70	4045	0.87	1.70	103	-1.10	0.10	17	-0.99	0.12	4	+0.06	0.09	+0.19

NOTE.— $n$  is the number of measured lines.

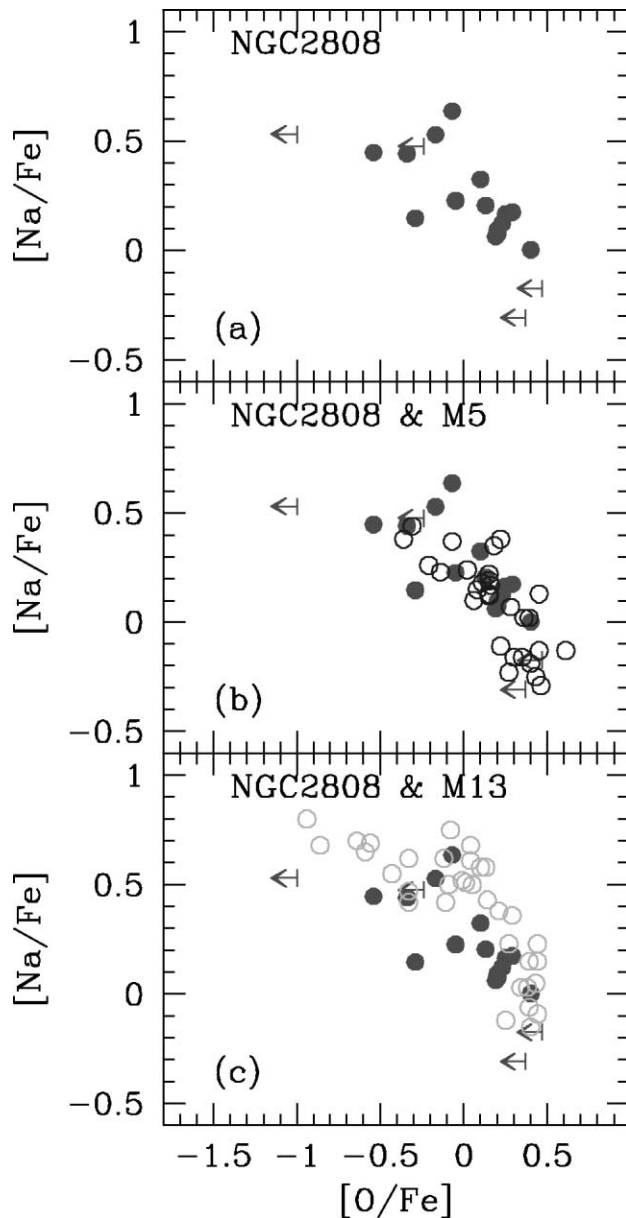


FIG. 2.—[Na/Fe] vs. [O/Fe] ratios in red giants of NGC 2808 (*upper panel*). Filled circles are effective detections. Upper limits in O are indicated by arrows. *Middle panel*: Same as upper panel, but with RGB stars in M5 superposed (Ivans et al. 2001; *open circles*). *Lower panel*: Same as upper panels, but with RGB stars in M13 superposed (S04; *open circles*). [See the electronic edition of the Journal for a color version of this figure.]

Figure 3 the strengths of the forbidden [O I] line at 6300 Å in three pairs of stars with similar atmospheric parameters, yet quite large differences in the Na and O content, from just above the RGB bump (where only upper limits could be derived for O; nevertheless, stars 42886 and 32685 differ by 0.5 dex in Na abundances) to the upper RGB and RGB tip. From this figure, it is clear that large star-to-star scatter in *both* O and Na abundances does exist among red giants in NGC 2808.

In Figure 2, we also compare our data in NGC 2808 to similar ones for M5 (Ivans et al. 2001) and for M13 (S04), after an adjustment for the offset in the adopted solar O abundance (0.14 dex). The comparison with M5 (a cluster with almost the same mean [Fe/H] as NGC 2808; see, e.g., Carretta & Gratton 1997) shows that the Na-O distributions are grossly similar. In the high-O, low-Na regime, stars observed by Ivans et al.

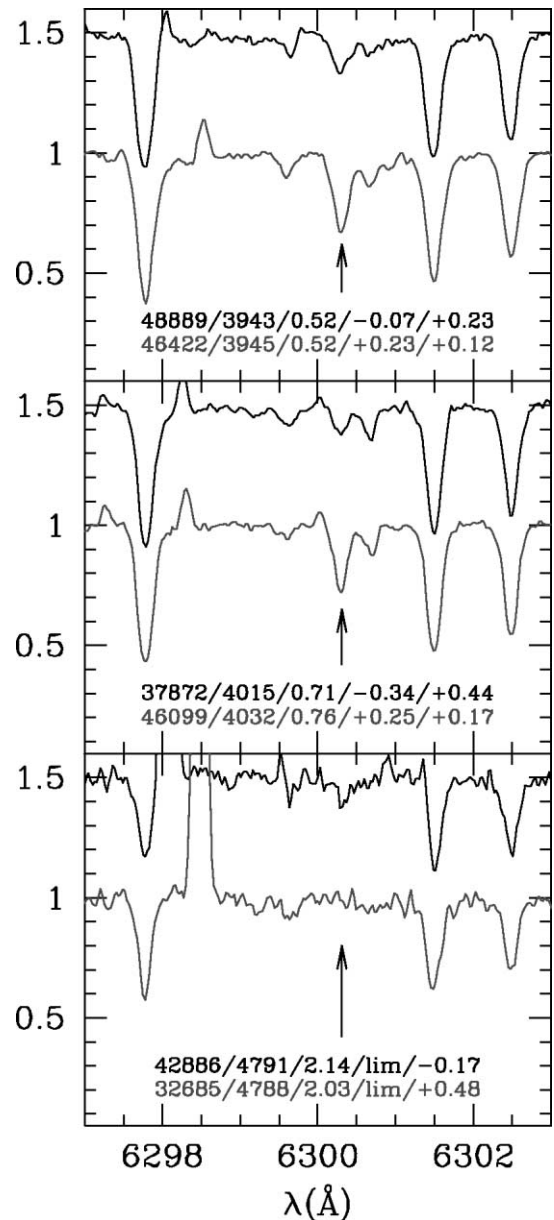


FIG. 3.—Comparison of observed spectra of three pairs of RGB stars in NGC 2808. Arrows indicate the [O I]  $\lambda$ 6300.31 forbidden line. Each pair has similar atmospheric parameters, as indicated by the labels, that give star ID,  $T_{\text{eff}}$ ,  $\log g$ , [O/Fe], and [Na/Fe]. [See the electronic edition of the Journal for a color version of this figure.]

(2001) have mostly spectra with  $S/N > 60$ , whereas only an  $S/N \sim 30$  could be reached for our two stars of NGC 2808, giving only upper limits for O abundances. However, the impression is that in the O-poor, Na-rich part of this diagram, the two distributions might be somewhat different, with NGC 2808 reaching larger O depletions. For the most O-poor star (50119), even with  $S/N \approx 70$ , the [O I] line at 6300.31 Å is vanishingly small, and only an upper limit could be assigned. The comparison with M13, the archetype for extremely O-depleted stars, seems to show that a similar degree of O depletion is also possibly reached in NGC 2808. Admittedly, this is based on only one star. Higher quality spectra, purportedly acquired, should be taken to verify this issue.

The recent finding of a clear Na-O anticorrelation among unevolved stars in NGC 6752 (Gratton et al. 2001) and in 47 Tuc (Carretta et al. 2004) strongly points out that variations in

these elements must be due to H burning at high temperature in stars able to dredge up and then eject their O-poor, Na-rich matter. In fact, because dwarf stars are unable to manage either of these requirements, an external origin for the Na and O abundance pattern must necessarily be accepted. IM-AGB stars are found to be good candidates (see, e.g., Ventura et al. 2002).

A certain amount of further modifications as the star climbs up the RGB was postulated since the lightest elements, like carbon, show a decrease as a function of stellar luminosity. For Na and O, the only clear evidence was found for M13, where a shift in the average abundances was noted for the brightest red giants (Pilachowski et al. 1996; Kraft et al. 1997), above  $\log g \sim 1.0$ . However, recently S04 found that the anticorrelation between O and Mg isotopic ratios in M13 is very similar to that in NGC 6752 (Yong et al. 2003), where the primordial pattern of chemical anomalies is well established. On this basis, S04 concluded that in M13 the extreme O depletions are also likely originated in IM-AGB stars. Apparently, the observed Na-O pattern in NGC 2808 is not very different from the marked anticorrelation in M13. The implication is that in NGC 2808, we are also seeing the results of a pattern of abundances already established by a first generation of IM-AGB stars (see, e.g., Parmentier 2004 and D'Antona & Caloi 2004). An evolutionary contribution, if any, is nevertheless very small in this cluster (Carretta et al. 2003).

Is there any link between chemical inhomogeneities and global properties in GCs? This remains presently an unsolved issue, but this study in NGC 2808 may allow us to add another piece to the puzzle. In fact, NGC 2808 and M13 have rather different horizontal-branch (HB) morphologies, in spite of their similar [Fe/H]. NGC 2808 is the most famous example of a bimodal HB: almost one-fourth of its HB stars lie in the blue part of the CMD, while presenting a well populated, stubby red HB. Yet, our findings seem to show O depletions as large as in M13, where only a long blue HB is seen. On the other hand, NGC 6752 (whose blue HB is very similar to the one of M13) does not show (Yong et al. 2003) super-O-poor stars as observed in M13 and as are likely to be observed in NGC 2808.

Clusters like M5 and M3 are, in this respect, more similar to NGC 6752. The Na-O anticorrelation in these clusters does not reach the extreme values of M13 (S04; Ivans et al. 2001). Moreover, NGC 6752 is a post-core-collapse system (Harris 1996), whereas the other quoted GCs have different, but not *extremely* different, concentration parameters. Still, variations in Na and O are also observed in the much less massive and loose cluster Pal 5 (Smith et al. 2002), presently leaving a trail of its stars into the Galactic field because of disruptive processes like tidal shocking.

In summary, abundance inhomogeneities in elements produced by *p*-capture fusions at high temperature are observed in GCs independently of (1) total mass and concentration, (2) Galactic (disk or halo) population, (3) overall metallicity, and (4) HB morphological type. At face value, the Na-O anticorrelation is found in every cluster surveyed so far, despite the large differences in global properties. Following Occam's razor, this might imply that we are seeing the outcome of a process intimately related to dense aggregates, maybe intrinsically connected to their own formation process. This is supported by the lack of such a behavior in field stars (see Gratton et al. 2000).

What to do next? We are quite confident about the *shape* and meaning of the Na-O anticorrelation in terms of products of *p*-capture reactions in the ON and NeNa cycles. A step forward would now be to study the *distribution function* of the anticorrelation, using high-quality spectra of large samples ( $\sim 100$ ) of stars along the RGB in several clusters spanning a variety of parameters (age, metallicity, HB morphology, etc.), to look for any possible connection unnoticed until now because of the paucity of samples. This is a project we are currently working on using the FLAMES multiobject spectrograph at ESO VLT.

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