1. INTRODUCTION

The complex, multi-population nature of globular clusters (GCs) is presently well assessed (see Gratton et al. 2004 for an extensive review): there is evidence of multiple sequences from photometry in some GCs and more universally from spectroscopy (see, e.g., Piotto 2009). Our survey of 19 GCs (Carretta et al. 2009b, 2009d) confirmed that star-to-star variations in light elements, inferred He enhancement, multiple sequences and subgiant branches, horizontal branches (HBs); elements, occurring in the core of giants clouds/associations or even in the core of dwarf galaxies (Bekki et al. 2007; Böker 2008).

Combining information coming from the chemistry and the color–magnitude diagrams (CMDs) (anticorrelations between elements, inferred He enhancement, multiple/main sequences and subgiant branches, horizontal branches (HBs); see Bragaglia 2010 for a recent review), we may be able to put together several pieces of the puzzle and reach a more in-depth understanding of star formation in dense environments. This will offer a circumstantiated answer to fundamental questions such as how the GCs formed and whether they were able to build at least part of their metals.

In this context, M54 (NGC 6715) appears as a key object. It is an old, metal-poor (e.g., Layden & Sarajedini 1997), massive GC immersed in the nucleus of the Sagittarius dwarf spheroidal (Sgr dSph) galaxy, presently disrupting within our Galaxy (Ibata et al. 1994; B08, and references therein). M54 is the most massive of the four GCs associated with the Sgr dSph, and it has a very extended HB with a population of “blue hook” stars, found only in a few of the most massive GCs (Rosenberg et al. 2004). Therefore, it is at the same time the nearest bona fide extragalactic cluster and the second most massive GC in the Milky Way, after ω Cen (Harris 1996).

M54 and ω Cen represent the high-mass tail of the GC mass distribution, and show many similarities, worthy of deeper insight: (1) both have intrinsic dispersion in metallicity [Fe/H], even if of different amplitude; (2) they are either associated with an adequate sampling of the Na–O anticorrelation to shed light on the complex scene of the initial cluster evolution, likely occurring in the core of giants clouds/associations or even in the core of dwarf galaxies (Bekki et al. 2007; Böker 2008).

We derive homogeneous abundances of Fe, O, Na, and α-elements from high-resolution FLAMES spectra for 76 red giant stars in NGC 6715 (M54) and for 25 red giants in the surrounding nucleus of the Sagittarius (Sgr) dwarf galaxy. Our main findings are the following. (1) We confirm that M54 shows intrinsic metallicity dispersion, ~0.19 dex rms. (2) When the stars of the Sgr nucleus are included, the metallicity distribution strongly resembles that in ω Cen; the relative contribution of the most metal-rich stars is, however, different in these two objects. (3) In both globular clusters (GCs) there is a very extended Na–O anticorrelation, which is a signature of different stellar generations born within the cluster. (4) The metal-poor and metal-rich components in M54 (and ω Cen) show clearly distinct extension of the Na–O anticorrelation, the most heavily polluted stars being those of the metal-rich component. We propose a tentative scenario for cluster formation that could explain these features. Finally, similarities and differences found in the two most massive GCs in our Galaxy can be easily explained if they are similar objects (nuclear clusters in dwarf galaxies) observed at different stages of their dynamical evolution.

Key words: globular clusters: general – globular clusters: individual (NGC 6715, NGC 5139) – stars: abundances – stars: evolution – stars: Population II

Online-only material: color figures

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Received 2009 December 18; accepted 2010 February 8; published 2010 April 1

ABSTRACT

We derive homogeneous abundances of Fe, O, Na, and α-elements from high-resolution FLAMES spectra for 76 red giant stars in NGC 6715 (M54) and for 25 red giants in the surrounding nucleus of the Sagittarius (Sgr) dwarf galaxy. Our main findings are the following. (1) We confirm that M54 shows intrinsic metallicity dispersion, ~0.19 dex rms. (2) When the stars of the Sgr nucleus are included, the metallicity distribution strongly resembles that in ω Cen; the relative contribution of the most metal-rich stars is, however, different in these two objects. (3) In both globular clusters (GCs) there is a very extended Na–O anticorrelation, which is a signature of different stellar generations born within the cluster. (4) The metal-poor and metal-rich components in M54 (and ω Cen) show clearly distinct extension of the Na–O anticorrelation, the most heavily polluted stars being those of the metal-rich component. We propose a tentative scenario for cluster formation that could explain these features. Finally, similarities and differences found in the two most massive GCs in our Galaxy can be easily explained if they are similar objects (nuclear clusters in dwarf galaxies) observed at different stages of their dynamical evolution.

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* Based on data collected at the ESO telescopes under program 081.D-286.
(M54) or suspected to be born in (ω Cen) a dwarf galaxy; (3) both lie in the intermediate region (in the $M_V$ versus half mass radius) between ultra compact dwarfs (UCDs) and GCs, very close to the low-mass limit of the UCDs (see Figure 1 in Tolstoy et al. 2009; Mackey & van den Bergh 2005; Federici et al. 2007). All these similarities may led to the legitimate suspicion that M54 and ω Cen could be siblings, or at least next of kin. In particular, B08 speculated that the residual of the (future) complete dissolution of the Sgr galaxy will leave a long-living compact remnant composed of a bulk of metal-poor stars (the original M54 cluster) plus a lesser population of metal-rich stars from the original nucleus of Sgr (Sgr, N). This would be very similar to the current status of ω Cen (see Pancino et al. 2000, and references therein), suggesting that this puzzling system may have formed through an analogous process.

In this Letter, we investigate this scenario in further detail, comparing newly obtained abundance analysis from high dispersion spectra of M54 (and Sgr, N) stars with similar data for ω Cen taken from the literature.

2. SPECTROSCOPIC DATA

2.1. M54

The only previous study of M54 based on high-resolution spectroscopy was that of Brown et al. (1999, hereinafter BW99) who analyzed five giant stars. They found an average $[\text{Fe/H}] = -1.55$ dex and evidence of proton-capture reactions (low O, enhanced Na and Al) in the abundance ratios of one (perhaps two) stars.

Our study is based on the FLAMES (GIRAFFE and UVES) spectra of 76 stars on the red giant branch (RGB) of M54, and of 25 stars belonging to the Sgr dwarf spheroidal (dSph) nucleus; the two samples are selected from the RGBs of the two populations that are well separated in the CMD (B08). A full description of the analysis and results will be presented elsewhere (E. Carretta et al. 2010, in preparation). In this Letter, we only show results concerning Fe, Na, O, and the two α-elements Mg and Si. However, our abundance analysis traces as closely as possible the homogeneous procedures adopted for other GCs (see Carretta et al. 2009b, 2009d, and references therein).8

2.2. ω Cen

ω Cen has been extensively studied at high spectral resolution. We consider here the following data sets:

1. Metallicity distribution. We used data from Stanford et al. (2007), which is the most recent large sample (about 380 stars) with metallicity publicly available in the literature, plus about 20 stars in Origlia et al. (2003, O03), the only spectroscopic study including the metal-rich branch RGB-a.

2. Na–O anticorrelation. To date, the only analysis of ω Cen comparable to the present one for M54 is the extensive data set from NDC95, who obtained homogeneous abundances from high-resolution spectra for 40 RGB stars.9

8 For instance, the temperature is derived from a relation between $T_{\text{eff}}$ (from $V-K$ and the Alonso et al. 1990 calibration) and $K$ magnitudes, much more reliably measured than colors. This leads to very small internal errors in the atmospheric parameters, and hence in the derived abundances. This approach is not valid for the Sgr dSph stars: in this case, the adopted temperatures are simply those from $V-K$ colors.

9 A similar, but more extensive analysis is currently under way, and preliminary results seem to support the findings of the present Letter (A. F. Marino 2009, private communication).

3. THE COMPARISON BETWEEN M54 AND ω Cen

3.1. Metallicity Dispersion

The average metallicity for M54 derived from neutral Fe lines is $[\text{Fe/H}] = -1.559 \pm 0.021$ dex ($\sigma = 0.189$ dex, 76 stars), which is almost coincident with the value obtained by BW99. We obtained an average $[\text{Fe/H}]$ value of $-0.622 \pm 0.068$ dex, $\sigma = 0.353$ dex for the 25 stars of the Sgr dSph nucleus. Since internal errors in $[\text{Fe/H}]$ in our analysis are $\sim 0.02$ dex, we confirm (at more than 8$\sigma$) the existence of a metallicity dispersion in M54, as proposed by Sarajedini & Layden (1995) and B08.

In Figure 1, we compare metallicity distribution functions (MDF) in M54+Sgr dSph nucleus (our data) and ω Cen (Stanford et al. 2007, O03). MDFs are formally different; however, similarities may be traced in the global appearance. In both cases: (1) the bulk of stars is metal-poor, with a major peak at $[\text{Fe/H}] \sim -1.6 \div -1.5$ dex, (2) this peak is followed by a gradual decrease toward increasing metallicity up to $[\text{Fe/H}] = -1.0$ with more or less evident secondary peaks, and (3) a long tail up to solar metallicities is observed.

The same conclusions are also evident for ω Cen in Figure 9 of Norris et al. (1996). While the exact relative fraction of the various component is obviously affected by different selection effects acting in the different samples, the similarity of the overall shape is well established and intriguing.

3.2. The Na–O Anticorrelation

The Na–O anticorrelations obtained for M54 (our data) and for ω Cen (NDC95) are shown in Figure 2. They are the two most pronounced known examples of O-depletions anticorrelated with Na-enhancements among RGB stars in GCs. The interquartile range of the distribution of $[\text{O/Na}]$ ratios, assumed as a quantitative measure of the extension of the anticorrelation...
Na–O anticorrelation is given in Carretta et al. (2009c): in a bona fide GC the This provides an indirect support to the very same definition of MV.

(see Carretta 2006), are interquartile range (IQR)[O/Na] = 1.169 and 1.310 for M54 and ω Cen, respectively. While the primordial component fractions (26% ± 6% and 31% ± 9%, respectively: see the definition in Carretta et al. 2009d) are very similar to the average fraction of first generation stars in other GCs (about 33%), M54 has the highest fractions of second generation stars with extreme composition found up to date: $E_{M54} = 28% ± 6%$. The values of IQR easily exceeding the previous record detainted by NGC 2808 (Carretta et al. 2009d), M54 and ω Cen nicely extend to the most massive clusters in the Galaxy the tight correlation between the extension of the Na–O anticorrelation and the total cluster mass (Carretta et al. 2009c). This provides an indirect support to the very same definition of GC as given in Carretta et al. (2009c): in a bona fide GC the Na–O anticorrelation is always observed, whether its luminosity is faint like that of NGC 6838 (M71, $M_V = -5.60$; Harris 1996) or comparable to that of the faintest dwarf galaxies, like the cases of M54 ($M_V = -10.01$; Harris 1996) and ω Cen ($M_V = -10.29$; Harris 1996).

However, our most striking finding is that in both M54 and ω Cen this pattern has a clearly different extent if we regard separately the metal-poor and metal-rich components (separated at [Fe/H] $= -1.56$ dex, as shown in the middle and right panels of Figure 2—this is of course a simplification): the metal-rich component reaches higher degrees of processing by proton-capture reaction in H-burning at high temperature. This difference is exactly mirrored also in the outcome of the Mg–Al cycle (E. Carretta et al. 2010, in preparation) using our data for M54 and using the data from NDC95 and from intermediate-resolution spectroscopy of a quite large sample of giants with Na and Al abundances recently derived by Johnson et al. (2009)

in ω Cen. A metallicity dependence of the distributions of Na and Al was already noted by the latter authors.

In summary, we found that the two most massive GCs in the Galaxy have a very similar pattern of anticorrelations and correlations for proton-capture elements. We suggest that this is not due to a mere chance, but it is rather a consequence of the way these large GCs are formed.

3.3. The Metal-rich Nuclear Component(s)

What about the stars of the Sgr dSph nucleus? The large spread in O and Na abundances (anticorrelated with each other) is confined only to stars in M54. Those in the Sgr dSph nucleus present a run of these elements as a function of the metallicity typical of Galactic field stars, apart from the well-known offsets already observed for stars in Sgr dSph (e.g., Smecker-Hane & McWilliam 2002; T. A. Smecker-Hane & A. McWilliam 2010 in preparation; Sbordone et al. 2007). This suggests that these stars did not participate in the episode of formation of M54, as also proposed on different grounds by B08.

There is not a dwarf galaxy around ω Cen (any longer?). However, in Section 3.1, by comparing the MDFs, we anticipated the idea that the two most massive GCs observed in our Galaxy might have followed a very similar evolutionary path, with M54 being seen still “frozen” in an earlier phase with respect to ω Cen. In the case of M54, the population belonging to the Sgr dSph is prominent at high metallicity. For ω Cen only few studies insofar were focused on the most metal-rich population, apart from O03 that analyzed a few stars of the so-called anomalous RGB (RGB-a) using infrared low-resolution spectroscopy.

In Figure 3, we compare our results for M54 plus Sgr dSph (details will be presented in E. Carretta et al. 2010, in preparation) with those for ω Cen (NDC95) including stars on the RGB-a (O03). While offsets between infrared and optical spectroscopy might well be present, it is quite evident that stars on the most metal-rich RGB in ω Cen show the same lack of anticorrelation between p-capture elements observed for stars in the Sgr dSph nucleus. Again, the similarity of the trends is striking and suggests that in the case of ω Cen the most visible residual of the ancestral galaxy once surrounding this cluster is probably represented by the so-called RGB-a.12

Searches for likely debris of ω Cen proto-galaxy are actively ongoing (e.g., Wylie-de Boer et al. 2010; Meza et al. 2005; Mizutani et al. 2003; D. Romano 2009, private communication), but a residual is almost certainly under our eyes since many years, still linked to the cluster itself, as a witness of the same process of nucleation still at work in the case of M54 (B08).

4. DISCUSSION AND CONCLUSIONS

We found intriguing analogies between the chemical composition of stars in M54 and in ω Cen. This supports the idea that these two objects (the most massive GCs of the Milky Way) may have formed in a very similar way, and represents just two subsequent snapshots of the same basic evolution of dwarf (nucleated?) galaxies, taken at different times. The more advanced stage reached by ω Cen (completely dissolved parent galaxy) is expected, as the peri-Galactic of its orbit is much closer to 11 Or re-analyzed stars from Pancino et al. (2003).

12 There are also indications, though debated, of different proper motions and ages, for stars on the different branches of the CMD of ω Cen; see Gratton et al. (2004) for references.
Concerning the dominant cluster populations, the truly intriguing fact is that the anticorrelation is more extended at higher metallicities, where we observe a large incidence of extremely O-poor, and likely very He-rich stars. In fact, we expect the extension of the Na–O anticorrelation to be determined by the range of masses of the polluters. Taking the AGB case, larger mass polluters (6–8 $M_\odot$, lifetimes $\sim$40–70 Myr, using the isochrones by Marigo et al. 2008) produce an extended anticorrelation, with very low O abundances, and large production of He, while smaller mass polluters (5–6 $M_\odot$, lifetime $\sim$70–100 Myr) produce a much less extended anticorrelation, with minimal effects on He.

The explanation we propose for our observations requires appropriate geometry and timing: the metal-poor second generation needs to be formed by the ejecta of $\sim$5–6 $M_\odot$ AGB stars, and the metal-rich one only by the ejecta of $\sim$6–8 $M_\odot$ AGBs. If we want to avoid the contribution by the most massive polluters to the metal-poor second generation, we need a delay of the cooling flow (or gas replenishing) from this population by $\sim$10–30 Myr. This can be obtained if we assume that the metal-rich component formed $\sim$10–30 Myr later than the metal-poor one from material further enriched in metals (a reasonable but not demonstrated assumption). The easiest way to get this is to have two (or more) close but distinct regions (this may be expected if the region of star formation is very large). Let us call these regions A and B. With this small time offset, while the $\sim$6–8 $M_\odot$ stars of the metal-poor component (A region) are in their AGB phase, massive stars of the metal-rich component (B region) are still exploding as core-collapse SNe. The large kinetic energy injected into both A and B regions prevents the gathering of gas from both metal-poor and metal-rich populations. In this phase, there is not any cooling flow yet. When the rate of SN explosions in region B becomes low enough, a quiet phase follows, lasting some tens Myr. In this phase, cooling flow formation is possible for both the metal-poor component (region A, with AGB polluters of $\sim$5–6 $M_\odot$) and for the metal-rich one (region B, AGB polluters of $\sim$6–8 $M_\odot$). In this scenario, the second generation stars form nearly simultaneously in the metal-poor (region A) and metal-rich (region B) cooling flows. Finally, the SN explosions of stars formed in these cooling flows (or the onset of type Ia SNe) stop this later phase of star formation. The initially binary (or multiple) protocluster has then ample time to merge for dynamical friction, and to appear as a single system, but with complex chemical composition. Of course, in the case of $\omega$ Cen, we may have more than two regions.

In this tentative hypothesis, the main difference between typical and massive GCs is that in the latter the star formation continues at a high rate for a more prolonged period (although shifting toward other regions of the global star-forming area) than in the case of the small mass clusters. Of course, this scenario needs verifications, and it is for the moment quite speculative. However, we think it represents a reasonable extension to larger masses of what we have considered insofar for more typical GCs. In any case, the case presented here offers further support to the connection between GCs and dwarf galaxies (see also Freeman 2002 on a model for $\omega$ Cen similar to the one proposed here).

We warmly thank Andy McWilliam for sending us his manuscript and data on Sagittarius in advance of publication. E.C. thanks Lucia Ballo for useful comments and suggestions. Partial funding come from the PRIN MIUR 2007 CRA
1.06.07.05, PRIN INAF 2007 CRA 1.06.10.04, the DFG cluster of excellence “Origin and Structure of the Universe.”

REFERENCES

Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, A&AS, 140, 261
Bellazzini, M., et al. 2008, AJ, 136, 1147 (B08)
Bekki, K., Campbell, S. W., Lattanzio, J. C., & Norris, J. E. 2007, MNRAS, 377, 335
Böker, T. 2008, ApJ, 672, L111
Bragaglia, A. 2010, in IAU Symp. 268, Light Elements in the Universe, ed. C. Charbonnel et al. (Cambridge: Cambridge Univ. Press)
Brown, J. A., Wallerstein, G., & Gonzalez, G. 1999, AJ, 118, 1245
Butler, D., Dickens, R. J., & Epps, E. 1978, ApJ, 225, 148
Carretta, E. 2006, AJ, 131, 1766
Carretta, E., Bragaglia, A., Gratton, R. G., D’Orazi, V., & Lucatello, S. 2009a, A&A, 508, 695
Carretta, E., Bragaglia, A., Gratton, R. G., & Lucatello, S. 2009b, A&A, 505, 139
Carretta, E., Bragaglia, A., Gratton, R. G., Recio-Blanco, A., Lucatello, S., D’Orazi, V., & Cassisi, S. 2009c, A&A, submitted
Carretta, E., et al. 2009d, A&A, 505, 117
Cohen, J. G., & Bell, R. A. 1986, ApJ, 305, 698
Denisenkov, P. A., & Denisenkova, S. N. 1989, Astron. Tsir., 1538, 11
Federici, L., Bellazzini, M., Galletti, S., Fusi Pecci, F., Buzzoni, A., & Parmegiani, G. 2007, A&A, 473, 429
Ferraro, F. R., et al. 2009, Nature, 462, 483
Freeman, K. C. 2002, in ASP Conf. Ser. 265, ω Cen: A Unique Window Into Astrophysics, ed. F. van Leeuwen & J. D. Hughes (San Francisco, CA: ASP), 423
Freeman, K. C., & Rodgers, A. W. 1975, ApJ, 201, L71
Georgiev, I. Y., Hilker, M., Puzia, T. H., Goudfrooij, P., & Baumgardt, H. 2009, MNRAS, 396, 1075
Gratton, R. G., Sneden, C., & Carretta, E. 2004, ARA&A, 42, 385
Gratton, R. G., et al. 2001, A&A, 369, 87
Harris, W. E. 1996, AJ, 112, 1487
Ibata, R. A., Irwin, M. J., & Gilmore, G. 1994, Nature, 370, 194
Johnson, C. I., Pilachowski, C. A., Rich, M. R., & Fulbright, J. P. 2009, ApJ, 698, 2048
Langer, G. E., Hoffman, R., & Sneden, C. 1993, PASP, 105, 301
Layden, A. C., & Sarajedini, A. 1997, ApJ, 486, L107
Mackey, A. D., & van den Bergh, S. 2005, MNRAS, 360, 631
Marigo, P., Girardi, L., Bressan, A., Groenewegen, M. A. T., Silva, L., & Granato, G. L. 2008, A&A, 482, 883
Marino, A. F., Milone, A. P., Piotto, G., Villanova, S., Bedin, L., Bellini, A., & Renzini, A. 2009, A&A, 505, 1099
Meza, A., Navarro, J. F., Abadi, M. G., & Steinmetz, M. 2005, MNRAS, 359, 93
Mizutani, A., Chiba, M., & Sakamoto, T. 2003, ApJ, 589, L89
Norris, J. E., & Da Costa, G. S. 1995, ApJ, 447, 680 (NDC95)
Norris, J. E., Freeman, K. C., & Mighell, K. J. 1996, ApJ, 462, 241
Origlia, L., Ferraro, F. R., Bellazzini, M., & Pancino, E. 2003, ApJ, 591, 916 (O03)
Paltoglou, G., & Norris, J. E. 1989, ApJ, 336, 185
Pancino, E., Ferraro, F. R., Bellazzini, M., Piotto, G., & Zoccali, M. 2000, ApJ, 534, L83
Pancino, E., Origlia, L., Ferraro, F. R., Bellazzini, M., Hill, V., & Pasquini, L. 2003, in ASP Conf. Proc. 296, New Horizons in Globular Cluster Astronomy, ed. G. Piotto et al. (San Francisco, CA: ASP), 226
Piotto, G. 2009, in IAU Symp. 258, The Ages of Stars, ed. E. E. Mamajek, D. R. Soderblom, & R. F. G. Wyse (Cambridge: Cambridge Univ. Press), 233
Rosenberg, A., Recio-Blanco, A., & Garcia-Marín, M. 2004, ApJ, 603, 135
Sarajedini, A., & Layden, A. C. 1995, AJ, 109, 1086
Sbordone, L., Bonifacio, P., Buonanno, R., Marconi, G., Monaco, L., & Zaggia, S. 2007, A&A, 465, 815
Stanford, L. M., Da Costa, G. S., Norris, J. E., & Cannon, R. D. 2007, ApJ, 667, 911
Tolstoy, E., Hill, V., & Tosi, M. 2009, ARA&A, 47, 371
Wylie-de Boer, E. C., Freeman, K. C., & Williams, M. 2010, AJ, 139, 636