Mem. S.A.It. Suppl. Vol. 19, 173


**Memorie** della
**Supplementi**

# Multiple stellar populations in the Globular Clusters NGC1851 and NGC6656 (M22).

A. P. Milone[1], G. Piotto[1], L. R. Bedin[2], A. F. Marino[3], Y. Momany[4], and S. Villanova[5]

[1] Dipartimento di Astronomia, Università di Padova, Vicolo dell'Osservatorio 3, Padova, I-35122, Italy
[2] Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
[3] Max Plank Institute for Astrophysics, Postfach 1317, 85741, Garching, Germany
[4] European Southern Observatory, Alonso de Cordova 3107, Vitacura, Santiago, Chile
[5] Grupo de Astronomia, Departamento de Fsica, Casilla 160, Universidad de Concepción, Chile

**Abstract.** In the last years, photometric and spectroscopic evidence has demonstrated that many, maybe all the Globular Clusters (GC) host multiple stellar populations. High-resolution spectroscopy has established that, while most GCs are mono-metallic with no significant abundance spread in *s*-elements, in all the globulars studied to date the presence of different stellar generation is inferred by the Na-O and the C-N anticorrelations.
In this context, NGC 1851 and NGC 6656 are among the most intriguing clusters. Contrary to the majority of GCs, they host two groups of stars with different s-elements abundance that are clearly associated to the two distinct sub-giant and red-giant branches detected in their color-magnitude diagrams (CMD). In the case of NGC 6656 s-rich stars are also enriched in iron and calcium. Each *s*-element group exhibits its own Na-O and C-N anticorrelations thus indicating the presence of sub-populations and suggesting that the parent clusters have experienced a very complex star-formation history. In this paper we summarize the properties of multiple populations in NGC 1851 and NGC 6656.

**Key words.** Stars: abundances – Stars: atmospheres – Stars: Population II – Galaxy: globular clusters

## 1. Introduction

In recent years, an increasing number of photometric and spectroscopic observational evidence have shattered the paradigm of globulars as the prototype of single, simple stellar populations (see Piotto 2009 for a recent review).

Spectroscopic studies have demonstrated that most GCs are mono-metallic with no detectable spread in their iron content and also *s*-process elements do not exhibit large star-to-star variations in the majority of globulars (e.g. Carretta et al. 2009a, D'Orazi et al. 2010 and references therein). On the contrary, in all the clusters studied to date with large stellar samples, have been detected star-to-star variations in the light elements C, N, O, Na, and

---

*Send offprint requests to*: A. P. Milone

Al (e.g. Carretta et al. 2009b, Pancino et al. 2010 and references therein). These variations are related to correlations and anticorrelations, which indicate the occurrence of high temperature hydrogen-burning processes which include CNO, NeNa, MgAl cycles and cannot occur in presently observed low mass GC stars.

Today it is widely accepted that the observed light-elements variations provide strong support to the presence of multiple stellar population in GCs with the second generations formed from the material polluted by a first generation of stars. On the contrary the debate on the nature of possible polluters is still open (e.g. D'Antona & Caloi al. 2004, Decressin et al. 2007).

While abundance variations are well known since the early sixties, it was only the recent spectacular discovery of multiple sequences in the CMD of several GCs that provide an un-controversial prove of the presence of multiple stellar populations in GCs and brought new interest and excitement in GCs research (e.g. Piotto et al. 2007). Photometric clues, often easy to detect simply by inspection of high-accuracy CMDs, arise in form of multiple main sequences (MS, Bedin et al. 2004, Piotto et al. 2007, Milone et al. 2010), split sub-giant branch (SGB, Milone et al. 2008, Anderson et al. 2009, Piotto 2009), and multiple red-giant branch (RGB, Marino et al. 2008, Yong et al. 2008, Lee et al. 2009).

Apparently the main properties of stellar generations, like the relative fraction of stars, their location in the CMD, the spatial distribution, and the chemical behavior differ from cluster to cluster. However, it is clear that some groups of clusters share all similar properties:

1. Na-O anticorrelation and C-N correlations are presents in all the GCs studied to date. When stars with available Na and O abundances have been identified in the $U$ vs. ($U$-$B$) CMD, it was found that the group of Na-poor (O-rich) stars are spread on the blue side of the RGB, while the Na-rich (O-poor) population define a narrow sequence on the red RGB (e.g. Marino et al. 2008).
2. In few cases the MS morphology supports the presence of stellar populations with different helium. NGC 2808 has three distinct MSs (Piotto et al. 2007) possibly associated to three stellar population with primordial helium and with Y$\sim$0.33 and Y$\sim$0.40 (D'Antona et al. 2005). A spread MS have been detected in NGC 104 (47 Tuc, Anderson et al. 2009) and NGC 6752 (Milone et al. 2010) where there is also some hint of a MS split.
3. In some GCs, like NGC 104, NGC 1851, NGC 5286, NGC 6388, and NGC 6656 there is a double SGB (Milone et al. 2008, Piotto 2008, Anderson et al. 2009) associated to two stellar groups with either a difference in age by $\sim$1 Gyr or with almost the same age but a significant difference in their overall C+N+O content (Cassisi et al. 2008, Ventura et al. 2009, Di Criscienzo et al. 2010).
4. Finally there is the 'extreme' case of $\omega$ Centauri with either multiple MSs (e.g. Anderson 1997, Bedin et al. 2004), multiple SGBs (e.g. Sollima et al. 2005, Villanova et al. 2007), multiple RGBs (Lee et al. 1999, Pancino et al. 2000) and large star-to-star variation in iron and $s$-elements (e.g. Johnson & Pilachowski 2010, Marino et al. 2010). Interestingly multiple populations have been detected also in the Sgr dwarf galaxy central cluster NGC 6715 (e. g. Siegel et al. 2007, Piotto 2009 and reference therein) and in Terzan 5 that is considered the surviving remnant of one of the primordial building blocks that are thought to merge and form galaxy bulges (Ferraro et al. 2009).

NGC 1851 and NGC 6656 are among the most studied clusters of the third group and are the main subject of this paper. In the following we will compare the observed CMDs of these GCs and the abundance of the critical elements Fe, O, Na, and s-elements.

## 2. The color-magnitude diagram

High-accuracy photometry obtained with the WFPC2 and WFC/ACS camera on board of the Hubble Space Telescope (*HST*) has revealed that the SGB of NGC 1851 is clearly split into

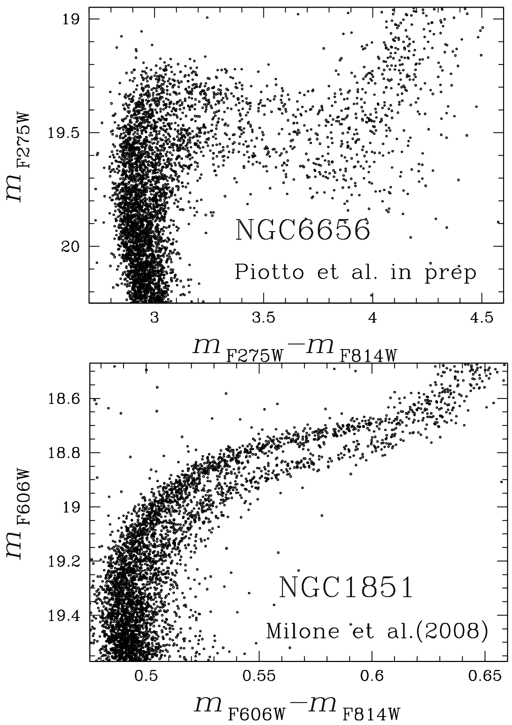


**Fig. 1.** Zoom of the CMD around the SGB for NGC 6656 (*upper panel*) and NGC 1851 (*lower panel*) from WFC3/UVIS and ACS/WFC data (GO10775, P. I. Sarajedini and GO12311, P. I. Piotto).

two branches with the bright SGB component containing about the 60% of the total number of SGB stars and the remaining 40% of stars belonging to the faint SGB (Milone et al. 2008). Similarly to the case of NGC 1851, after a careful correction for differential reddening, the SGB of NGC 6656 also revealed a bimodality with a fraction of bright over faint-SGB stars similar to the one measured in NGC 1851 (Piotto 2009, Marino et al. 2009). A comparison of the SGBs of NGC 1851 and NGC 6656 is given in Fig. 1 where we show a zoom of the WFC3/UVIS CMDs around the SGB. The spread SGB has been explained in terms of two stellar generations, only slightly differing in age, the younger one having an increased C+N+O abundance (Cassisi et al. 2008, Ventura et al. 2009). As an alternative possibility, we note that observations are consistent with two stellar populations with constant CNO but differing in age by ∼1 Gyr (Milone et al. 2008). Significant star-to-star variations in the overall CNO abundance have been detected among NGC 6656 RGB stars by Marino et al. (2010) and in two out four NGC 1851 giants by Yong et al. (2009). The letter results is not confirmed by the recent analysis by Villanova et al. (2010) who did not find significant CNO abundance variation in 15 RGB stars of NGC 1851.

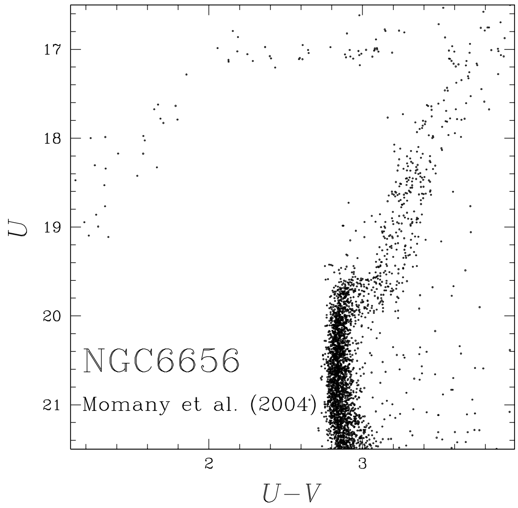


**Fig. 2.** CMD of NGC 6656 from ground-based photometry corrected for differential reddening.

Neither the MS nor the RGB of these clusters shows any hint of bimodality or spread in the $m_{F606W} - m_{F814W}$ color. Ritcher et al. (1999) found that NGC 6566 exhibits a bimodal distribution in the $m_1$ index among RGB stars and a similar bimodality was detected by Calamida et al. (2007) for the case of NGC 1851. A similar split among RGB stars of both clusters has been observed in the *hk* index by Lee et al. (2009) and in the *U* vs. *(U−I)* and *U* vs. *(U−V)* CMD by Han et al. (2009) and Momany et al. (2004, Fig. 2 ). In these cases the RGB components are clearly associated to the two SGBs.

## 3. Chemical abundances

In this section we investigate the behavior of proton-capture elements, iron, sodium and oxygen abundances as they provide crucial

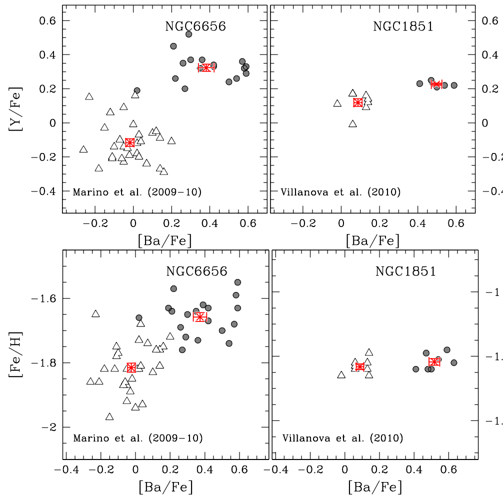


**Fig. 3.** [Y/Fe] (*upper panels*) and [Fe/H] (*lower panels*) as a function of [Ba/Fe]. Filled circles and empty triangles represent the $s$-rich and the $s$-poor stars. The red crosses with error bars indicate the average abundance of stars in each group.

information on multiple stellar populations. A peculiar property of the cluster pair NGC 1851-NGC 6656 is the large scatter in the abundance of those $n$-capture elements that are associated to $s$-processes. This result comes from Marino et al. (2009, 2010) for NGC 6656 and Hesser et al. (1982), Yong et al. (2008), and Villanova et al. (2010) for NGC 1851. As an example, Fig. 3 shows the abundance of [Ba/Fe] as a function of [Y/Fe] for NGC 6656 (*Left Panel*) and NGC 1851 (*Right Panel*). In both clusters $n$-capture elements are clearly segregated around two distinct values of barium and yttrium in sharp contrast from what found in most GCs where the abundance of these elements does not exhibit significant star-to-star variations.

Since the solar-system abundances of barium and yttrium are mainly due to $s$-process, in the following we will call stars with high and low [Ba/Fe] ([Y/Fe]) as '$s$-rich' and '$s$-poor'. Following Marino et al. (2009), we will also use different symbols in Fig. 3 and in the subsequent figures to separate these two groups of stars.

When we compare the iron abundance for NGC 6656 with the $s$-elements abundance, we find a strong correlation, with $s$-rich stars having systematically higher [Fe/H] as shown in the lower-left panel of Fig. 3. The $s$-rich and $s$-poor groups have average $[Fe/H]_{rich} = -1.68 \pm 0.02$ and $[Fe/H]_{poor} = -1.82 \pm 0.02$, respectively ($\delta$[Fe/H] = 0.14 ± 0.03, Marino et al. 2009). This result demonstrated that, at odds with 'normal' monometallic GCs the different stellar populations of NGC 6656 have significant difference in their iron content.

The presence of intrinsic spread in iron in NGC 1851 has been widely discussed in literature. Yong et al. (2008) analyzed UVES spectra for eight RGB stars and detected a dispersion in [Fe/H] of ~0.10 dex suggesting a possible intrinsic spread in iron. A small but detectable metallicity spread, compatible with the presence of two groups of stars with a metallicity difference of ~0.07 dex has been claimed also by Carretta et al. 2010 on the basis of their abundance analysis of more than 120 RGB stars. These results are not confirmed by Villanova et al. (2010) who studied high S/N MIKE/Magellan spectra for 15 RGB and found a smaller [Fe/H] spread compatible with observational errors. Villanova et al. (2010) detected no significant difference in iron between the $s$-rich and $s$-poor as shown in the lower-left panel of Fig. 3.

In the light of these results we matched spectroscopic data on NGC 6656 from Marino et al. (2009, 2010) with the Strömgren photometry by Richter et al. (1999). Results are shown in Fig. 4 where we plotted the $m_1$ versus $(b-y)$ diagram for NGC 6656. At odds with what observed by using the $V$ vs *(V-I)* diagram, where the stars belonging to the two groups appear to populate an unique RGB sequence, it is evident that $s$-rich and $s$-poor stars define two distinct RGBs. As the $m_1$ index is strongly dependent by the CN bands strength, we expect this bimodality as due to the overabundance in both C and N measured by Marino et al. (2010) in $s$-rich stars.

### 3.1. Na-O anticorrelation

Sodium versus oxygen is plotted in Fig. 5 for the pair NGC 1851-NGC 6656. The most important result is that in these clusters both the

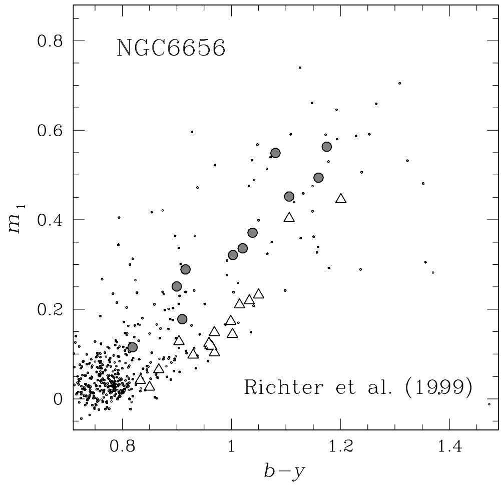


**Fig. 4.** the $m_1$, *(b-y)* diagram for NGC 6656 corrected for differential reddening. *s*-rich and *s*-poor stars are represented with full circles and open triangles.

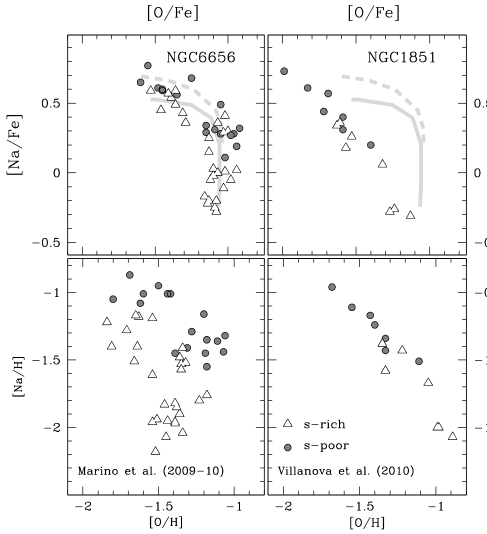


**Fig. 5.** Na-O anticorrelation for NGC 6656 (*upper-left panels*) and NGC 1851 (*upper-right panel*) RGB stars. *s*-rich and *s*-poor stars are represented as full circles and open triangles. In the upper panels the fiducial lines of the Na-O anticorrelations for the *s*-rich and the *s*-poor stars of NGC 6656 are as continuous and dashed gray lines respectively. In the lower panels we plotted [Na/H] as a function of [O/H].

*s*-rich and the *s*-poor group have its own Na-O anticorrelation. In the case of NGC 6656 also the C-N anticorrelation has been detected in both the *s*-groups by Marino et al. (2010).

In both clusters *s*-rich stars have, on average, higher sodium but while in the NGC 6656 both *s*-poor and *s*-rich stars span almost the same [O/Fe] range, in NGC 1851 *s*-rich stars are extended toward lower oxygen suggesting that in this case the interstellar medium could have been polluted by more massive stars.

## 4. Conclusions

We have summarized some spectroscopic and photometric findings on multiple stellar populations in the GCs NGC 1851 and NGC 6656.

From spectroscopic and photometric observations, it comes out that the SGB and RGB split is related to the presence of two groups of stars with different *s*-element contents and a possible difference in CNO abundance. According to this interpretation, *s*-poor stars would constitute the first population. The second stellar generation should have been formed after the AGB winds of this first stellar generation had polluted the protocluster interstellar medium with *s*-elements. In the case of NGC 6656, this second generation may have formed from material that was also enriched by core-collapse supernovae ejecta, as indicated by their higher iron, magnesium, and silicon content, and the lack of correlation of the iron content with a pure r-process element (Eu).

This scenario is seriously challenged by the recent findings on light elements Na, O, C, and N. As already mentioned in Sect. 1, the Na-O and the C-N anticorrelations can be considered the signature of multiple star-formation episodes. This implies that both clusters are composed by two groups of stars with distinct *s*-element content that define double SGB and RGB observed in the CMD but each group is made by multiple sub-populations of stars with different Na and O abundance. NGC 1851 and NGC 6656 do not host only two stellar populations but have experienced a much more complex star-formation history with similarities to the 'extreme' cases of $\omega$ Centauri (Da Costa et al. 2009, Da Costa & Marino, 2010) and the Sgr dwarf galaxy central cluster NGC 6715. A detailed comparison of the abundance patterns in $\omega$ Centauri and NGC 6715 with those of NGC 1851 and NGC 6656 is strongly needed to resolve this problem.

*Acknowledgements.* We gratefully acknowledge M. Hilker, R. Kraft, C. Sneden, and G. Wallerstein for sending us their data.

## References

Anderson, J. 1997, PhD thesis, Univ. of California, Berkley
Anderson, J., et al. 2009, ApJ, 697, L62
Bedin, L. R., et al., 2004, ApJ, 605, L125
Calamida, A., et al. 2007, ApJ, 670, 400
Carretta, E., et al. 2009a, A&A 505, 117
Carretta, E., et al. 2009b, A&A 508, 695
Carretta, E., et al. 2010, ApJ, 722, L1
Cassisi, et al. 2008, ApJ, 672, L115
Da Costa, G., Held, E. V., Saviane, I. & Gullieuszik, M. 2009, ApJ705, 1481
Da Costa, G. & Marino, A. F. 2010, in press (arXiv1009.1955)
D'Antona, F., & Caloi, V. 2004, ApJ, 611, 871
D'Antona, F., et al. 2005, ApJ, 631, 868
D'Orazi, V., et al. 2010, ApJ, 719, 213
Decressin, T., et al. 2007, A&A, 464, 1029
Di Criscienzo, M., Ventura, P., D'Antona, F., & Piotto, G., 2010, MNRAS, 408, 999
Ferraro F. R., et al., 2009, Nature, 462, 483
Han, S.-I., et al. 2010, ApJ, 707, L190
Hesser, J. E., Bell, R. A., Harris, G. L. H. & Cannon, R., D. 1982, AJ, 87, 1470
Johnson, C. I., & Pilachowski, C. A., 2010 ApJ, 722, 1373
Lee, Y.-W., et al., 1999, Nature, 402, 55
Lee, J.-W., Kang, Y.-W., Lee, J., & Lee, Y.-W. 2009, Nature, 462, 480
Marino, A. F., et al. 2008, A&A 490, 625
Marino, A. F., et al. 2009, A&A 505, 1099
Marino, A. F., et al., in preparation
Marino, A. F., et al. 2010, in IAU Symp. 268, Light Elements in the Universe, ed. C. Charbonnel et al. (Cambridge: Cambridge Univ. Press), 183
Milone, A. P., et al. 2008, ApJ, 673, 241
Milone, A. P., et al. 2010, ApJ, 709, 1183
Momany, Y., et al. 2004 A&A, 420, 605
Pancino, E., et al. 2000, ApJ, 534, L83
Pancino, E., Rejkuba, M., Zoccali, M., Carrera, R. 2010, in press (arXiv1009.1589)
Piotto, G., et al. 2007, ApJ, 661, L53
Piotto, G., et al. in preparation
Piotto, G. 2009, in IAU Symposium No. 258, the Ages of Stars, (arXiv0902.1422)
Richter, P., Hilker, M., & Richtler, T. A&A, 1999, 350, 476
Siegel, M., et al. 2007, ApJ, 667, L57
Sollima, A., Ferraro, F. R., Pancino, E., & Bellazzini, M. 2005, MNRAS, 357, 265
Yong, D., & Grundahal, F. 2008, ApJ, 672, L39
Yong, D., Grundahal, F., Johnson, A., & Asplund, M. 2008, ApJ, 684, 1159
Yong, D., et al., 2009 ApJ, 695, L62
Ventura, P., et al., 2009 MNRAS, 399, 934
Villanova, S., et al. 2007, ApJ, 663, 296
Villanova, S., Geisler, D., & Piotto, G. 2010, ApJ, 722, L18