FIRST EVIDENCE OF FULLY SPATIALLY MIXED FIRST AND SECOND GENERATIONS IN GLOBULAR CLUSTERS: THE CASE OF NGC 6362

EMANUELE DALESSANDRO1, DAVIDE MASSARI1, MICHELE BELLAZZINI2, PAOLO MIOCCHI1, ALESSIO MUCCIARELLI1, MAURIZIO SALARI1, AND BARBARA LANZONI1

1 Dipartimento di Fisica e Astronomia Università di Bologna, viale Berti Pichat 6/2, I-40127 Bologna, Italy
2 INAF-Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy
3 Astrophysics Research Institute, Liverpool John Moores University, IC2, Liverpool Science Park, 146 Brownlow Hill, Liverpool L3 5RF, UK
4 INAF-Osservatorio Astronomico di Collurania, via Mentore Maggini, I-64100 Teramo, Italy

Received 2014 May 28; accepted 2014 July 1; published 2014 July 23

ABSTRACT

We present the first evidence of multiple populations in the Galactic globular cluster NGC 6362. We used optical and near-UV Hubble Space Telescope and ground-based photometry, finding that both the sub-giant and red giant branches are split in two parallel sequences in all color–magnitude diagrams where the F336W filter (or U band) is used. This cluster is one of the least massive globulars (M_{tot} \sim 5 \times 10^4 M_{\odot}) where multiple populations have been detected so far. Even more interestingly and at odds with any previous finding, we observe that the two identified populations share the same radial distribution across the cluster extension. NGC 6362 is the first system where stars from different populations are found to be completely spatially mixed. Based on N-body and hydrodynamical simulations of multiple stellar generations, we argue that to reproduce these findings NGC 6362 should have lost up to 80% of its original mass.

Key words: globular clusters: individual (NGC 6362) – stars: Population II

Online-only material: color figures

1. INTRODUCTION

Globular clusters (GCs) have long been considered the best example of Single Stellar Populations, i.e., stellar systems formed by stars with the same age and initial chemical composition (Renzini & Buzzoni 1986). This traditional paradigm still remains valid to a certain extent, although a wealth of recent results showed that GCs are not as simple as previously thought, harboring multiple stellar populations (MPs). Indeed, star-to-star variations of light elements have been known for decades (see, for example, Cohen 1978), but this evidence was limited to a small number of stars in each cluster and was still compatible with a pure evolutionary effect (mixing). Over the last several years, intense and extended spectroscopic campaigns of large samples of stars in any evolutionary stage have established, with a high degree of confidence, that all GCs show primordial star-to-star variations in C, N, O, Na, Mg, and Al, and a strict homogeneity in the iron abundance (Gratton et al. 2004; Carretta et al. 2010b).

Such chemical inhomogeneities produce a variety of features in the color–magnitude diagrams (CMDs) as highlighted by high-quality photometry in the appropriate filters. For example, main-sequence splittings, as those observed in ω Centauri (Bedin et al. 2004), NGC 2808 (Piotto et al. 2007), and NGC 6752 (Milone et al. 2010), are thought to originate from large spreads in the He abundance, while Sub-Giant Branch (SGB) splittings can be driven by differences in the C+N+O abundances (e.g., Milone et al. 2008; Cassisi et al. 2008). However, the most ubiquitous photometric tracer of multiple populations is the color spread and/or the multi-modality in red giant branches (RGBs) with near-UV filters (NUV; see, for example, Marino et al. 2008; Lardo et al. 2011; Monelli et al. 2013). In these CMDs, stars enriched in C and N lie on the red side of the RGB, while stars with pristine abundances of these elements lie on the blue side. This effect is driven by the relative strength of deep CN and NH features in the range 3000 Å < \lambda < 4000 Å of the RGB spectra, as conclusively demonstrated by Sbordone et al. (2011). Due to this property, MPs have been identified in a good number of clusters so far, even using ground-based photometry (see, for example, Monelli et al. 2013).

It is now commonly accepted that the CN-weak, Na-poor (hereafter, Na-poor) population is associated with a first generation (FG) of stars and the CN-strong, Na-rich (Na-rich) with a second generation (SG) of stars that formed during the first few ~100 Myr of the cluster life from an intra-cluster medium polluted by the FG stars (D’Ercole et al. 2008; Carretta et al. 2009; see, however, Bastian et al. 2013 for a model that does not require multiple episodes of star formation). Intermediate-mass asymptotic giant branch stars (IM-AGBs: Ventura & D’Antona 2008), fast rotating massive stars (Decressin et al. 2007), and massive binary stars (De Mink et al. 2009) have been proposed as the most likely polluters of the primordial intra-cluster medium, enhancing Na, Al, and He and depleting Mg and O, while leaving...
Figure 1. Zoomed view of the (a) \((m_{F606W} - m_{F814W}; m_{F606W})\) and (b) \((m_{F336W} - m_{F336W}; m_{F606W})\) CMDs obtained with the HST sample. Error bars as a function of magnitude are also shown. Red and blue dots are, respectively, FG and SG stars. In panels (c) and (d), theoretical models with different light-element mixture (Sbordone et al. 2011) and similar metallicity to NGC 6362 are shown for comparison. The blue isochrone has a standard light-element composition, while the red one is appropriate for a Na-rich population.

(A color version of this figure is available in the online journal.)

the iron abundance unaffected. However, all formation models face serious problems and we are still far from a full understanding of the processes responsible for the presence of MPs in GCs (see, e.g., Renzini 2008).

D’Ercole et al. (2008) performed hydrodynamical and N-body simulations to explore the formation of MPs in the scenario of IM-AGBs polluters. In their analysis, AGB ejecta form a cooling flow that rapidly collects in the innermost regions of the cluster, forming a concentrated SG stellar subsystem (see also Bekki 2011). Their models also predict that in the early evolutionary phases the cluster looses a significant fraction of its original mass. Indeed, the early explosions of SN II lead to a strong and preferential loss of FG stars, resulting in a cluster with a similar number of first and SG stars (D’Ercole et al. 2008). For comparison, we refer the reader to the constraints on the mass-loss budget of GCs in dwarf galaxies obtained by Larsen et al. (2014 and reference therein).

After the early loss of FG stars, the system eventually starts its long-term dynamical evolution driven by two-body relaxation.

Understanding the dynamics and the characteristic timescales over which MPs retain the memory of their primordial distribution is crucial to properly constrain the models and obtain new important insights on GC formation and evolution. In all cases where the radial distribution has been analyzed, the Na-rich population has invariably been found to be more concentrated than its Na-poor counterpart (see, e.g., Bellini et al. 2009; Carretta et al. 2010a; Kravtsov et al. 2011; Lardo et al. 2011; Johnson & Pilachowski 2012; Beccari et al. 2013).

In this work, we extend these kinds of studies to the low-mass GC NGC 6362. By means of a proper combination of high-resolution Hubble Space Telescope (HST) and ground-based optical and NUV data, we revealed the presence of multiple sequences along the SGB and RGB of this cluster. Surprisingly, we have found that the two populations do not show any difference in their relative radial distribution across the cluster extension. This result represents the first evidence of fully spatially mixed multiple populations ever collected in a GC.

2. OBSERVATIONS AND DATA ANALYSIS

The high-resolution HST database consists of images collected in two different observing runs. In the first run (HSTa; Prop: GO10775, PI: Sarajedini), Advanced Camera for Survey (ACS) Wide Field Channel (WFC) images were obtained with the F606W and F814W filters. The second set (HSTb; Prop: GO12008, PI: Kong) is a combination of ACS/WFC data secured with the F658N and F625W filters and Wide Field Camera 3 UVIS channel images obtained through the F336W filter. As in previous works (see Dalessandro et al. 2014), the data reduction has been performed independently for each data set using ALLSTAR and ALLFRAME (Stetson 1994). Instrumental magnitudes were converted to the VEGAMAG photometric system using the zeropoints and equations reported by Sirianni et al. (2005) and listed on the HST Web site. By combining HSTa and HSTb data, we also performed a relative proper motions analysis (Massari et al. 2013; Dalessandro et al. 2013). The results presented in Sections 3 and 4 are based on proper-motion decontaminated CMDs.

The wide-field database consists of images obtained with the Wide Field Imager (WFI) mounted at the MPG/ESO
2.2 m telescope (Prop: 71.D-0220(A), PI: Ortolani). Images were collected in three bands: $U50_{\text{ESO877}}$ (hereafter $U$), $B123_{\text{ESO878}}$ ($B$), and $V89_{\text{ESO843}}$ ($V$). The analysis has been performed following the same approach used for the $HST$ data. We reported the $U$ and $V$ instrumental magnitude to the VEGAMAG photometric system using the stars in common with HST$a$ and HST$b$. The $B$ magnitudes were reported instead to the standard Johnson photometric system using photometric standards.

Both the high-resolution and wide-field data sets have been put on the absolute astrometric system (Dalessandro et al. 2013). The final catalog is composed by stars detected in both HST$a$ and HST$b$ and in the complementary WFI field of view.

Details about the data-reduction procedures, proper-motion analysis and catalogs construction will be reported in forthcoming paper (E. Dalessandro et al. 2014, in preparation).

3. MULTIPLE POPULATIONS IN NGC 6362

In Figure 1(a), we show a zoom of the $(m_{F336W} - m_{F606W})$ CMD of NGC 6362. All the main evolutionary sequences (MS, SGB, and RGB) are well defined and their typical width is fully compatible with photometric errors. Conversely, in $(m_{F336W} - m_{F509W} , m_{F555W})$ CMD (Figure 1(b)), the SGB and the RGB broaden or clearly split. In particular, starting from the turnoff, it is possible to distinguish two sequences and follow them at different magnitude levels. We have verified that such behavior cannot be due to differential reddening (E. Dalessandro et al. 2014, in preparation). We determined a fiducial line following the approach described in Miocchi et al. (2013). Results and details obtained from this analysis will be shown in E. Dalessandro et al. (2014, in preparation).

According to combined spectro-photometric works (see, for example, Marino et al. 2008), the red sequence is expected to be populated by Na-rich stars, while the blue one is made of Na-poor stars, which should trace the primordial abundances of the clusters (hence, the FG). In Figures 1(c) and (d), we show two 12 Gyr isochrones of metallicity similar to that of NGC 6362 ([Fe/H] = −0.99; Harris 1996, 2010 edition) and with different light-element mixtures (Sbordone et al. 2011).

Clearly, the behavior observed for NGC 6362 at both the SGB and RGB levels in both the CMDs is qualitatively reproduced by theoretical models.

In the WFI sample the same behavior emerges: in the $(B-V, V)$ plane, stars define narrow sequences, whereas in the $(U-V, U)$ CMD both the SGB and RGB split or broaden more than expected from photometric errors (Figure 4). Of course, the poorer photometric accuracy and the Galactic field contamination make the distinction of the two populations less clear than in the high-resolution sample. Hence, in order to study the radial distribution of the FG and SG stars, in both the HST and the WFI samples, we considered only objects along the RGB in the magnitude interval $17.4 \leq U \leq 18.8$ in the $(U-V, U)$ CMD (Figure 4).

4. RADIAL DISTRIBUTION OF MULTIPLE POPULATIONS

In Figure 5 (upper panel), we show the cumulative radial distribution of FG and SG stars from the center to the tidal radius ($r_t = 841''$, corresponding to 30.9 pc at the adopted distance $d = 7.6$ Kpc; Harris 1996). Clearly, the radial distributions of the two populations do not show any significant difference. According to the K-S test, the probability that the two samples are not extracted from the same parent population is $P \sim 50\%$, well below the standard threshold of $P = 95\%$. The same behavior is confirmed also when the high-resolution and wide field samples are analyzed separately.

8 The tidal radius, as well the other structural parameters of NGC 6362, has been obtained by fitting the surface density profile with a single-mass King model following the approach described in Miocchi et al. (2013). Results and details obtained from this analysis will be shown in E. Dalessandro et al. (2014, in preparation).
We have also analyzed the radial trend of the ratio between the number of SG and FG stars \( \frac{N_{SG}}{N_{FG}} \) as a function of the distance from the cluster center. We divided the field of view covered by our database in five concentric annuli. As shown in Figure 5 (lower panel), a flat behavior around \( \frac{N_{SG}}{N_{FG}} = 1.2 \) across the cluster extension is observed. We have carefully checked that these results are robust to meaningful variations in the selection of the two populations.

This is the first evidence ever collected of two sub-populations in a GC sharing the same radial distribution across the cluster extension.\(^9\)

5. DISCUSSION

The observational evidence presented in this work demonstrates that the MPs in NGC 6362 are fully spatially mixed.

Recently, Vesperini et al. (2013) analyzed the long-term evolution of MPs in GCs as driven by two-body relaxation by means of N-body simulations. The initial conditions of their simulations are clusters with almost the same number of FG and SG stars, with the latter being more centrally concentrated than the former from their birth (D’Ercole et al. 2008). These systems have already experienced intra-cluster enrichment (D’Ercole et al. 2008) and have already lost mass (preferentially in the form of FG stars) as a result of the expansion triggered by SN II explosions. Following the dynamical evolution of all their simulations, the authors find that the difference in the radial distribution of the two populations is progressively eliminated starting from the cluster center and enclosing larger and larger portions of the cluster as dynamical evolution proceeds and the mass loss budget, due to dynamical effects, becomes significant. In particular, the simulations by Vesperini et al. (2013) show that complete mixing is expected in advanced dynamical evolutionary stages, after \( \sim 10 t_h \) (the actual timescale depending on the initial conditions and in particular on the initial concentration of SG stars), for clusters that lost at least 60%-70% of their masses during the long-term dynamical evolution, regardless of the assumed MP formation scenario.\(^10\)

To this amount of mass lost, in the context in which MPs form through multiple star formation episodes (Decressin et al. 2007; Ventura & D’Antona 2008; D’Ercole et al. 2008), the expected \( \sim 50\% \) of primordial mass loss during the early and somehow violent evolution \( (t < 1 \text{ Gyr}) \), mainly driven by SN II explosions (D’Ercole et al. 2008) should be added. Therefore, we can argue that in this framework the present mass of NGC 6362 should be \( \sim 20\% \) of its original value.

From the collected data, we estimated the half-mass radius \( r_h \sim 150'' \) (\( \sim 5.6 \text{ pc} \)) of NGC 6362. We also derived its present relaxation time at \( r_h \) to be \( t_h \sim 1.7 \text{ Gyr} \) corresponding to about one-seventh of the cluster age \( (t_{\text{age}} = 12.5 - 13 \text{ Gyr}; \text{Dotter et al. 2010}) \). These values are not peculiar in any respects, being fully comparable with those found in other Galactic GCs (see, for example, Harris 1996, 2010 edition) still showing clear radial trends among MPs. \( t_h \) is actually slightly larger than the average for Galactic GCs. This would suggest that NGC 6362 had a dynamical history significantly different from other GGCs with similar present-day properties, leading to a larger amount of mass loss.

Using the best-fit King model reproducing the density profile and the velocity dispersion data by Pryor & Meylan (1993), we have estimated that the present-day total mass of NGC 6362 is \( M_{\text{tot}} = (5.3 \pm 1.5) \times 10^5 M_\odot \). This is about two to three times smaller than what we estimated, using the same approach, for two other small GCs, NGC 288 and M 4, for which spectroscopic and photometric evidence of MPs have been obtained (for comparison, see also the estimates by McLaughlin & van der Marel 2005 and Sollima et al. 2012). NGC 6362 might be the least massive cluster where MPs have been found so far. This is an important result, which needs to be confirmed with a more accurate velocity dispersion measure, which is indeed the main source of uncertainties at this stage. This finding would help to constrain the conditions for the onset of light-element self-enrichment in star clusters (Carretta et al. 2010b). The original mass of NGC 6362 should be fixed around some \( 2 \times 10^5 M_\odot \) in the MP formation scenarios proposed by D’Ercole et al. (2008) and Decressin et al. (2007), or \( \sim 10^5 M_\odot \) in the framework suggested by de Mink et al. (2009) and Bastian et al. (2013). These quantities are, in any case, smaller than the expected average primordial mass of Galactic GCs. In this context, it

\(^9\) In the case of NGC 6752, Milone et al. (2013) found the same radial distribution of SG and FG stars in the innermost region \( r < 2 r_h \). However, SG stars appear significantly more centrally concentrated than FG ones when the analysis is extended to larger distances (Kravtsov et al. 2011). On the other hand, Lardo et al. (2011) were unable to find differences in the radial distribution of the various populations in the two most distant clusters of their sample because the quality of the available data were clearly insufficient for this purpose (see Beccari et al. 2013).

\(^10\) Note that the simulations by Vesperini et al. (2013) have been performed assuming that all stars have the same mass. With a realistic mass function, the relaxation toward the populations spatial mixing would presumably be faster.
is also worth noting that the original mass of NGC 6362 is comparable to, or even smaller than, what is estimated for many young clusters in nearby galaxies, where no observational evidence compatible with multiple star formation episodes has been revealed (see, for example, Cabrera-Ziri et al. 2014).

Another possibility is that the two populations had similar tidal disturbances (E. Dalessandro et al. 2014, in preparation).

### REFERENCES

Allen, C., Moreno, E., & Pichardo, B. 2006, ApJ, 652, 1150
Bastian, N., Lammers, H. J. G. L. M., de Mink, S. E., et al. 2013, MNRAS, 436, 2398
Becchi, K. 2011, MNRAS, 412, 2241
Cabrera-Ziri, I., Bastian, N., Davies, B., et al. 2014, MNRAS, 441, 2754
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2009, A&A, 505, 117
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2010a, ApJL, 714, L7
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2010b, A&A, 516, A55
Carretta, E., Bragaglia, A., Gratton, R. G., et al. 2014, A&A, 561, A87
Cassisi, S., Salaris, M., Pietrinferni, A., et al. 2008, ApJL, 672, L115
Cohen, J. G. 1978, ApJ, 223, 487
Dalessandro, E., Ferraro, F. R., Massari, D., et al. 2013, ApJ, 778, 135
Dalessandro, E., Pallanca, C., Ferraro, F. R., et al. 2014, ApJL, 784, L29
Decressin, T., Meynet, G., Charbonnel, C., Prantzos, N., & Ekström, S. 2007, A&A, 464, 1029
de Mink, S. E., Pols, O. R., Langer, N., & Izzard, R. G. 2009, A&A, 507, L1
D’Ercole, A., Vesperini, E., D’Antona, F., McMillan, S. L. W., & Hurley, J. R. 2010-2011, project “The Chemical and Dynamical Evolution of the Milky Way and Local Group Galaxies”, prot. 2010LYSN2T (PI: F. Matteucci).

We warmly thank the referee Nate Bastian for his suggestions and comments that helped us to improve the presentation of our results. We also thank Enrico Vesperini for useful discussions. This research is part of the project COSMIC-LAB funded by the European Research Council (under contract ERC-2010-AdG-267675). S.C. acknowledges financial support from PRIN-INAF 2011 “Multiple Populations in Globular Clusters: their role in the Galaxy assembly” (PI: E. Carretta), and from PRIN MIUR 2010-2011, project “The Chemical and Dynamical Evolution of the Milky Way and Local Group Galaxies”, prot. 2010LYSN2T (PI: F. Matteucci).