



Publication Year	2016
Acceptance in OA	2020-06-26T12:25:57Z
Title	NGC 6362: The Least Massive Globular Cluster with Chemically Distinct Multiple Populations
Authors	Mucciarelli, Alessio, Dalessandro, Emanuele, MASSARI, DAVIDE, BELLAZZINI, Michele, Ferraro, Francesco R., Lanzoni, Barbara, Lardo, Carmela, Salaris, Maurizio, CASSISI, Santi
Publisher's version (DOI)	10.3847/0004-637X/824/2/73
Handle	http://hdl.handle.net/20.500.12386/26231
Journal	THE ASTROPHYSICAL JOURNAL
Volume	824



NGC 6362: THE LEAST MASSIVE GLOBULAR CLUSTER WITH CHEMICALLY DISTINCT MULTIPLE POPULATIONS*

ALESSIO MUCCIARELLI¹, EMANUELE DALESSANDRO¹, DAVIDE MASSARI^{2,3}, MICHELE BELLAZZINI², FRANCESCO R. FERRARO¹,
BARBARA LANZONI¹, CARMELA LARDO⁴, MAURIZIO SALARIS⁴, AND SANTI CASSISI⁵

¹ Dipartimento di Fisica & Astronomia, Università degli Studi di Bologna, Viale Bertini Pichat, 6/2, I-40127 Bologna, Italy

² INAF—Osservatorio Astronomico di Bologna, Via Ranzani 1, I-40127 Bologna, Italy

³ Kapteyn Astronomical Institute, University of Groningen, Landleven 12, 9747 AD Groningen, The Netherlands

⁴ Astrophysics Research Institute, Liverpool John Moores University, 146 Brownlow Hill, Liverpool L3 5RF, UK

⁵ INAF—Osservatorio Astronomico di Teramo, via Mentore Maggini, I-64100 Teramo, Italy

Received 2016 February 26; accepted 2016 April 13; published 2016 June 14

ABSTRACT

We present the first measure of Fe and Na abundances in NGC 6362, a low-mass globular cluster (GC) where first- and second-generation stars are fully spatially mixed. A total of 160 member stars (along the red giant branch (RGB) and the red horizontal branch (RHB)) were observed with the multi-object spectrograph FLAMES at the Very Large Telescope. We find that the cluster has an iron abundance of $[\text{Fe}/\text{H}] = -1.09 \pm 0.01$ dex, without evidence of intrinsic dispersion. On the other hand, the $[\text{Na}/\text{Fe}]$ distribution turns out to be intrinsically broad and bimodal. The Na-poor and Na-rich stars populate, respectively, the bluest and the reddest RGBs detected in the color–magnitude diagrams including the U filter. The RGB is composed of a mixture of first- and second-generation stars in a similar proportion, while almost all the RHB stars belong to the first cluster generation. To date, NGC 6362 is the least massive GC where both the photometric and spectroscopic signatures of multiple populations have been detected.

Key words: globular clusters: individual (NGC 6362) – stars: abundances – techniques: spectroscopic

Supporting material: machine-readable table

1. INTRODUCTION

Globular clusters (GCs) have long been considered the best example of a *simple stellar population*, i.e., stellar systems formed of stars with the same age and initial chemical composition (Renzini & Buzzoni 1986). This traditional paradigm remains still valid to a certain extent, although a wealth of recent photometric and spectroscopic results have shown that GCs are not as simple as previously thought, harboring multiple stellar populations (MPs) that differ in terms of chemical abundances.

Star-to-star differences in the C and N abundances have been known for decades in GCs (see, e.g., Osborn 1971; Norris 1981; Martell & Smith 2009; Pancino et al. 2010), with the detection of CN-weak and CN-strong stars. In recent years the use of high-resolution spectroscopy coupled with large samples of GC stars has established that old, massive GCs, both in our Galaxy (Carretta et al. 2009; Gratton et al. 2012) and in the Local Group satellites (Mucciarelli et al. 2009), show star-to-star variations in some light elements: intrinsic scatters of Na and O abundances have been observed in all the GCs, variations of Al abundances in most of them, while star-to-star scatters in Mg abundances have been found only in some peculiar clusters.

MPs in GCs manifest themselves also with different features in the color–magnitude diagrams (CMDs) when appropriate bands (or filter combinations) are used: main-sequence splittings, such as those observed in ω Centauri (Bedin et al. 2004), NGC 2808 (Piotto et al. 2007), and NGC 6752 (Milone et al. 2010), sub-giant branch (SGB) splittings (see, e.g., Milone et al. 2008; Piotto et al. 2012) and, in the majority

of cases, multimodal red giant branches (RGBs, see Piotto et al. 2015, for a recent review).

The most commonly accepted idea about MP formation is that secondary generations are formed from the ejecta of first-generation stars (polluters) along with *pristine material* (i.e., material with the same abundances as the first generation). Within this general framework, four main scenarios have been proposed, differing mainly in the nature of the polluters: (i) asymptotic giant branch stars (D’Ercole et al. 2008), (ii) fast-rotating massive stars (Decressin et al. 2007), (iii) interacting massive binary stars (De Mink et al. 2009), and (iv) supermassive stars (Denissenkov & Hartwick 2014; Denissenkov et al. 2015). An alternative scenario that does not require an age difference between first- and second-generation stars is the so-called *early disk accretion* scenario (Bastian et al. 2013). This model suggests that interacting massive stars and binaries can shed enriched material into the cluster, and low-mass pre-main-sequence stars (of the same generation), which are fully convective and have protoplanetary disks, are able to sweep up the enriched material and eventually accrete it. However, all the proposed scenarios present some shortcomings and they are not able to reproduce simultaneously all the observational pieces of evidence (see, e.g., Bastian 2015; Bastian & Lardo 2015; Kruijssen 2015).

By using a proper combination of archival *Hubble Space Telescope* (*HST*) and WFI@MPG/ESO data, Dalessandro et al. (2014, hereafter Paper I) found that in all CMDs involving the U band or the F336W *HST* filter, the RGB and SGB of the GC NGC 6362 split into two distinct sequences. In contrast, in the $(V, V-I)$ CMD the average color spread of RGB and SGB stars is fully compatible with the photometric errors. Theoretical models demonstrate (Sbordone et al. 2011) that this behavior is the photometric signature of the CNONa chemical anomalies.

* Based on data obtained at the Very Large Telescope under the programs 073.D-0211 and 093.D-0618.

The RGB and the SGB split in the $(U, U-V)$ CMD because of star-to-star variations in C and N abundances that are detectable in the U band (through the NH and CN bands present in this spectral range), while pure optical filters are insensitive to such variations. Nowadays, this behavior of the evolutionary sequences of GCs in U and optical filters is a common feature of GCs (see, e.g., Lardo et al. 2011).

As discussed in Paper I, NGC 6362 appears to be peculiar in many respects. With an estimated mass of $\sim 5 \times 10^4 M_{\odot}$, NGC 6362 is the least massive GC with detected photometric MPs. These observational findings put strong constraints on the mass threshold that enables the formation of MPs. In addition we have found that NGC 6362 is the first cluster where the radial distributions of its MPs show no significant radial difference up to its tidal radius. We interpreted such unexpected evidence as the result of a very advanced dynamical evolution and possibly of a significant mass-loss due to interactions with the Galactic disk and potential well (see Dalessandro et al. 2015).

However, while the presence of the RGB photometric split indicates the presence of MPs in this cluster, only a dedicated spectroscopic investigation can reveal the specific chemical patterns associated with each subpopulation that are needed for a proper comparison with other systems. Therefore, in order to fully characterize the MPs of NGC 6362, we have collected high-resolution spectra for a large number of member stars. In this paper we present the first derivation of the Fe and Na abundances ever obtained for this cluster, and we discuss these results in the light of those provided in Paper I.

The paper is structured as follows: the data set is presented in Section 2, we describe the details of the adopted data-analysis procedures in Section 3, in Section 4 we present the derived abundances of Na and Fe for the stars in our sample, in Section 5 we discuss these results, and in Section 6 we compare them with what is observed in M4, which shares a similar metallicity. The main results are then summarized in Section 7.

2. OBSERVATIONS

The observations have been performed with the multiplex facility FLAMES@ESO-VLT (Pasquini et al. 2000) in the UVES+GIRAFFE combined mode (Prop. ID: 093.D-0618, PI: Dalessandro). This mode allows the simultaneous allocation of eight UVES high-resolution fibers and 132 mid-resolution GIRAFFE-MEDUSA fibers. The employed gratings are the UVES Red Arm CD#3 580, which covers the spectral range between ~ 4800 and ~ 6800 Å with a spectral resolution of $\sim 45,000$, and the GIRAFFE setups HR11 (5597–5840 Å and $R \sim 24,000$) and HR13 (6120–6405 Å and $R \sim 22,000$). All the employed setups allow us to derive abundances of Fe (thanks to several available lines) and Na (sampling the two Na doublets at 5682–5688 Å and 6154–6160 Å). Unfortunately, oxygen abundances cannot be derived because of the close-to-zero radial velocity (RV) of the cluster, leading to a blending between the forbidden oxygen line at 6300.3 Å and the sky emission line at the same wavelength.

A total of two exposures of 45 minutes each for two different star configurations has been secured for the grating HR11 and two exposures of 32 minutes each have been performed with the grating HR13. The UVES targets have been kept fixed on the same targets in both star configurations in order to increase the signal-to-noise ratio (S/N). A total of 219 stars have been selected along the RGB and the red horizontal branch (RHB) from the ACS@HST and WFI@2.2 m ESO catalogs presented

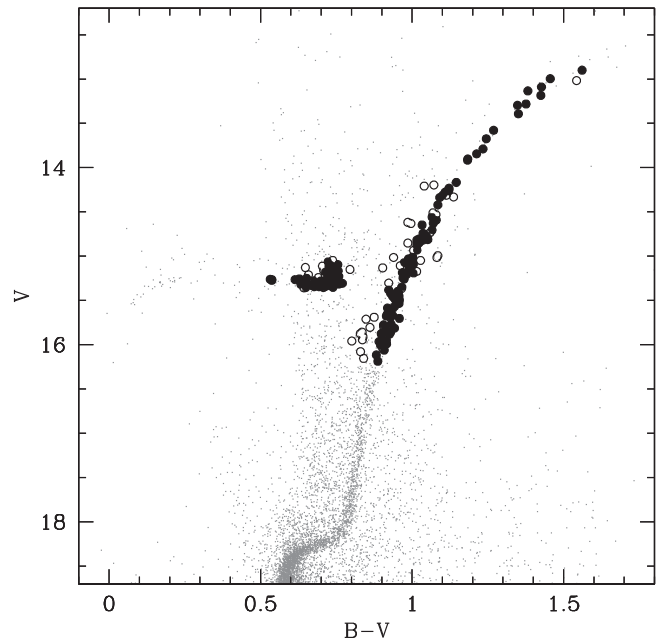


Figure 1. $(V, B - V)$ CMD of NGC 6362 (small gray circles) with the positions of the spectroscopic targets marked: filled circles are the cluster members, while the empty circles are the targets flagged as field stars. Photometry from Dalessandro et al. (2014).

in Paper I. These stars are (i) brighter than $V = 16.2$, thus reaching S/N of at least about 30 pixel^{-1} ; (ii) isolated, i.e., stars without a companion brighter than $V < V_{\text{star}} + 1.0$ within $2''$; and, for RGB targets only, (iii) along the two RGBs observed in the $(U, U - V)$ plane, thus properly sampling the two observed subpopulations detected in Paper I. The position of the spectroscopic targets in the $(V, B - V)$ CMD is shown in Figure 1. Table 1 lists the coordinates and the U, B, V magnitudes for all the member stars.

The spectra have been reduced with the dedicated ESO pipelines⁶, including bias subtraction, flat-fielding, wavelength calibration with a standard Th–Ar lamp, spectral extraction, and (only for the UVES spectra) order merging. The contribution of the sky has been subtracted from each spectrum by using a median sky spectrum obtained combining ~ 15 – 20 (for GIRAFFE) and two (for UVES) spectra of sky regions secured within each exposure.

3. ANALYSIS

The chemical abundances of Fe and Na have been derived with the package GALA (Mucciarelli et al. 2013b) by matching measured and theoretical equivalent widths (EWs) of a set of unblended lines. EWs and RVs have been measured with the code DAOSPEC (Stetson & Pancino 2008), automatically launched by using the package 4DAO (Mucciarelli 2013), which allows a visual inspection of all the performed Gaussian fits. We started by adopting as input value the nominal full width at half-maximum (FWHM) of the gratings, leaving DAOSPEC free to re-adjust the FWHM in order to minimize the median value of the distribution of residuals (see Stetson & Pancino 2008). For some RHB stars the final FWHM is larger than those found for the RGB stars, indicating the presence of a

⁶ <http://www.eso.org/sci/software/pipelines/>

Table 1
Coordinates and Magnitudes for All of the Member Stars

Star	R.A. (J2000)	decl. (J2000)	U	B	V	T_{eff} (K)	$\log g$	v_{turb} (km s^{-1})	[Fe/H] (dex)	[Na/Fe] (dex)
201343	263.0750664	-66.8997455	17.220	16.048	15.074	4716	2.08	1.40	-1.11 ± 0.10	0.26 ± 0.08
500473	262.4560855	-67.0569192	17.383	16.451	15.494	4745	2.27	1.60	-1.13 ± 0.10	0.02 ± 0.16
600257	262.8930198	-66.9839966	17.059	15.817	14.768	4590	1.89	1.40	-1.05 ± 0.08	-0.02 ± 0.11
600352	262.8912788	-66.9723982	16.799	15.387	14.278	4495	1.64	1.50	-1.14 ± 0.08	0.19 ± 0.09
600496	262.8879197	-67.0502011	16.628	15.944	15.296	5587	2.55	1.50	-1.16 ± 0.10	0.02 ± 0.08
600530	262.8872475	-67.1038652	17.852	16.855	15.964	4863	2.51	1.40	-1.10 ± 0.10	0.58 ± 0.10
600607	262.8857838	-66.9837179	16.733	15.354	14.232	4475	1.61	1.40	-1.13 ± 0.09	0.06 ± 0.11
600850	262.8802788	-67.0446788	16.591	15.885	15.257	5655	2.56	1.50	-1.16 ± 0.12	0.37 ± 0.10
601019	262.8762369	-67.0575666	17.227	16.010	15.008	4668	2.03	1.40	-1.11 ± 0.09	0.32 ± 0.10
601528	262.8658176	-67.0464912	16.667	15.922	15.166	5254	2.37	1.50	-1.14 ± 0.15	-0.09 ± 0.07
601632	262.8636925	-66.9832167	17.418	16.418	15.476	4772	2.27	1.30	-1.10 ± 0.10	0.00 ± 0.11
601756	262.8604542	-67.0578518	16.781	15.411	14.309	4506	1.66	1.50	-1.15 ± 0.08	0.03 ± 0.09
602034	262.8537861	-67.0442901	16.525	15.793	15.261	6006	2.68	1.50	-1.11 ± 0.09	-0.04 ± 0.09
602223	262.8486807	-67.1455510	16.657	15.906	15.181	5345	2.41	1.50	-1.07 ± 0.12	-0.08 ± 0.12
602471	262.8423465	-67.0321127	16.755	16.025	15.306	5363	2.47	1.50	-1.07 ± 0.13	-0.05 ± 0.08
602685	262.8375124	-66.9349993	16.815	15.429	14.338	4523	1.68	1.40	-1.05 ± 0.08	0.06 ± 0.10
602803	262.8337385	-67.0625221	17.698	16.681	15.775	4836	2.42	1.40	-1.10 ± 0.10	0.29 ± 0.11

Note. Coordinates, magnitudes, atmospheric parameters, and [Fe/H] and [Na/Fe] abundance ratios for the target member stars. Identification numbers are from Paper I.

(This table is available in its entirety in machine-readable form.)

rotational broadening in addition to the instrumental profile. The projected rotational velocities ($v_e \sin i$) have been measured by comparing the line profiles of the RHB stars with grids of suitable synthetic spectra calculated with the code SYNTHE (Sbordone et al. 2004) and convolved with the nominal spectral resolution of the gratings used⁷ and with a rotational profile, varying the value of $v_e \sin i$. All the observed RHB stars have $v_e \sin i$ between 0 and 12 km s^{-1} . The observed distribution of rotational velocities is compatible with those measured for RHB stars in other GCs (Gratton et al. 2011, 2013). On the other hand, all the RGB stars are compatible with zero rotation. Figure 2 shows, as an example, the spectral region around the Ba II line at 6141 \AA for the RHB star #604095, with superimposed two synthetic spectra calculated with different rotation velocities. In the upper panel the observed spectrum is compared with a synthetic spectrum calculated with the best-fit rotational velocity ($v_e \sin i = 12 \text{ km s}^{-1}$), while the lower panel shows the comparison with a synthetic spectrum without rotation ($v_e \sin i = 0 \text{ km s}^{-1}$), which is not able to properly reproduce the line broadening.

First, we measured RV in each individual exposure. The spectra of each exposure have been corrected for their own heliocentric RV, then those corresponding to the same target have been co-added together. Finally the averaged spectra have been analyzed to obtain the EWs to be used for the chemical analysis.

Oscillator strengths for the Fe I lines used are from the critical compilation by Fuhr & Wiese (2006), while those for the two Na doublets are from the NIST database.⁸ Na abundances have been corrected for effects of nonlocal thermodynamic equilibrium (NLTE) by adopting the grid of corrections calculated by Gratton et al. (1999). Model atmospheres have been calculated with the last version of the

⁷ These values are confirmed also by the measure of the FWHM of bright unsaturated lines in the reference Th–Ar calibration lamp, following the method described by Behr et al. (2000).

⁸ http://physics.nist.gov/PhysRefData/ASD/lines_form.html

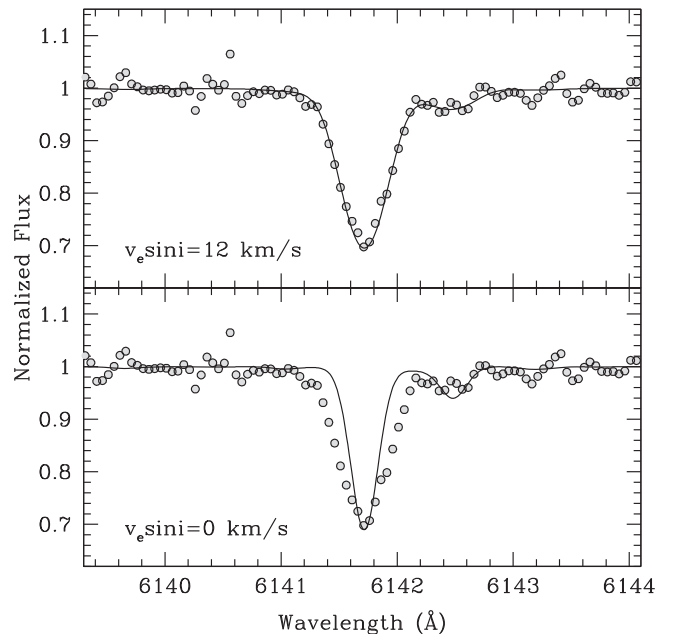


Figure 2. Spectral region around the Ba II line at 6141 \AA of the RHB star #604095 superimposed with the best-fit synthetic spectra calculated with $v_e \sin i = 12 \text{ km s}^{-1}$ (upper panel) and $= 0 \text{ km s}^{-1}$ (lower panel).

ATLAS9 code.⁹ Solar reference abundances are from Grevesse & Sauval (1998).

Possible values for the effective temperatures (T_{eff}) and surface gravities ($\log g$) have been derived from the photometry (Paper I). In particular, T_{eff} have been estimated by means of the $(B-V)_0 - T_{\text{eff}}$ relation by Alonso et al. (1999), adopting

⁹ <http://wwwuser.oats.inaf.it/castelli/sources/atlas9codes.html>

the extinction law by Cardelli et al. (1989) and a color excess $E(B - V) = 0.09$ mag (Harris 1996, 2010 edition). Gravities have been computed through the Stefan–Boltzmann equation, adopting the photometric T_{eff} , the bolometric corrections by Alonso et al. (1999), a distance modulus $(m - M)_V = 14.68$ mag (Harris 1996, 2010 edition), and an evolutive mass of $0.75M_{\odot}$, according to a 12 Gyr BaSTI isochrone with $Z = 0.004$ and α -enhanced chemical mixture (Pietrinferni et al. 2006).

Only for the UVES targets can T_{eff} be derived spectroscopically, thanks to the large number of available iron lines distributed over a large range of excitation potentials, while this approach is not possible for the GIRAFFE targets because of the low number of Fe I lines with low excitation potential. For the UVES targets T_{eff} have been derived by imposing excitation equilibrium, i.e., the best T_{eff} is that which erases all trends between Fe I abundances and excitation potential. The photometric T_{eff} of the UVES targets are slightly higher than those derived spectroscopically, and they need to be lowered by ~ 80 K to match the spectroscopic ones. This offset has been applied to all the targets, including those belonging to the GIRAFFE sample, in order to use a self-consistent T_{eff} scale. Final values of $\log g$ have been computed with the new T_{eff} .

Microturbulent velocities (v_{turb}) for RGB stars have been derived spectroscopically by erasing all trends between abundances from Fe I lines and the measured EWs. For the RHB targets, the small number of available Fe I lines (less than 25) prevents a robust determination of v_{turb} . According to the analyses of RHB stars in GCs performed by Gratton et al. (2011, 2012, 2013), a unique value of v_{turb} can be used for all the RHB stars of a given cluster. Thus, we assumed $v_{\text{turb}} = 1.5 \text{ km s}^{-1}$ for all the RHB stars of the sample, since this value provides an average [Fe/H] abundance for the RHB stars that matches well that obtained for RGB stars.

The abundance uncertainties have been computed by adding in quadrature two main sources: (i) uncertainties arising from the EW measurements, which are estimated as the dispersion of the mean normalized to the root mean square of the number of lines used. They are of the order of ~ 0.01 – 0.03 dex for Fe and smaller than ~ 0.05 – 0.06 dex for Na; (ii) uncertainties arising from the atmospheric parameters. Errors in T_{eff} have been estimated taking into account the photometric uncertainties and the uncertainty in the color excess, and they are about 80–100 K. Those in $\log g$ have been estimated by taking into account the photometric errors and the uncertainties in T_{eff} , distance modulus, and mass; they are of the order of 0.05 dex. A conservative uncertainty of 0.2 km s^{-1} has been adopted for the microturbulent velocities.

4. Fe AND Na ABUNDANCE IN NGC 6362

Within the entire sample of observed stars, we identified a total of 160 bona fide cluster members (105 RGB and 55 RHB stars), according to their RV and metallicity. Figure 3 shows the distribution of the observed targets in the RV–[Fe/H] plane, together with the histograms of the RV and [Fe/H] distributions. Stars belonging to NGC 6362 are easily identified in this plane, since they cluster around $RV \sim -15 \text{ km s}^{-1}$ and $[Fe/H] \sim -1.1$ dex and they are easily distinguishable from field stars because the latter have metallicities peaked at $[Fe/H] \sim -0.6$ dex. We selected as cluster members the stars in the range $-25 < RV < -3 \text{ km s}^{-1}$ and $-1.3 < [Fe/H] < -0.9$ dex (filled circles in Figure 3), excluding, among them, three stars with significant RV variations among the

individual exposures, which are thus likely to be binary systems. The positions of the member stars in the CMD are shown in Figure 1 as filled circles, while the discarded stars are marked as empty circles. Table 1 lists the derived [Fe/H] and [Na/Fe] abundance ratios and the corresponding uncertainties for each cluster member.

Mean abundances, intrinsic scatters, and their uncertainties have been calculated with the maximum likelihood (ML) algorithm described in Mucciarelli et al. (2012). The average iron abundance is $[Fe/H] = -1.09 \pm 0.01$ dex with an observed scatter of 0.06 dex and an intrinsic scatter of 0.00 ± 0.01 dex, demonstrating the high degree of homogeneity of iron abundance in NGC 6362. This is the first determination of the iron content of NGC 6362 based on high-resolution spectra. Note that the only previous measurement of its metallicity has been provided by Geisler et al. (1997) by using Washington photometry, finding $[Fe/H] = -0.74 \pm 0.05$ dex.

The [Na/Fe] distribution of the sample of member stars is shown in panel (a) of Figure 4 as a generalized histogram. The ML algorithm provides an average value of $+0.13 \pm 0.01$ dex with an intrinsic dispersion of 0.16 ± 0.01 dex, indicating a significant star-to-star scatter. The [Na/Fe] distributions for the samples of RGB and RHB stars considered separately are shown in panels (b) and (c) of Figure 4, respectively. The two distributions appear quite different from each other: that of RGB stars is about 0.8 dex wide, with a main peak at $[Na/Fe] \sim 0.0$ dex, a secondary peak close to $[Na/Fe] \sim +0.3$ dex and an extended tail up to $[Na/Fe] \sim +0.6$ dex. On the other hand, the distribution of RHB stars is narrower, with a Gaussian shape and a peak at $[Na/Fe] \sim 0.0$ dex, nicely matching the main peak of the RGB distribution.

Figure 5 shows the behavior of [Fe/H] (upper panel) and [Na/Fe] (lower panel) as a function of T_{eff} for all the member stars of the cluster: no significant trend between abundance ratios and T_{eff} is found.

5. Na ABUNDANCE IN NGC 6362 AND MULTIPLE POPULATIONS

5.1. RGB Stars

The bimodality of the [Na/Fe] distribution of the RGB stars has been statistically analyzed by means of the algorithm for Gaussian mixture modeling described by Muratov & Gnedin (2010). We found that the hypothesis of a unimodal distribution can be rejected with a probability $>99.9\%$: the observed distribution can be reproduced with two Gaussian components, one peaked at $[Na/Fe] = +0.00$ dex and with $\sigma = 0.07$ dex, the other peaked at $[Na/Fe] = +0.33$ dex and with $\sigma = 0.13$ dex.

Usually, the Na abundance is used to discriminate between first-generation (FG) and second-generation (SG) stars, being Na-poor and Na-rich, respectively. According to the [Na/Fe] distribution shown in Figure 6(b), we therefore adopted $[Na/Fe] = +0.15$ dex as the boundary to separate FG and SG populations in NGC 6362. Following the approach already adopted in other works about multiple populations of GCs (see, e.g., Marino et al. 2008), we investigated the connection between the two Na-selected samples and the two RGBs observed in the CMD when the U filter is used. Such an RGB splitting is thought to be driven by variations in strength of the CN and NH molecular bands that dominate the 3000–4000 Å spectral region sampled by the U filter (Sbordone et al. 2011),

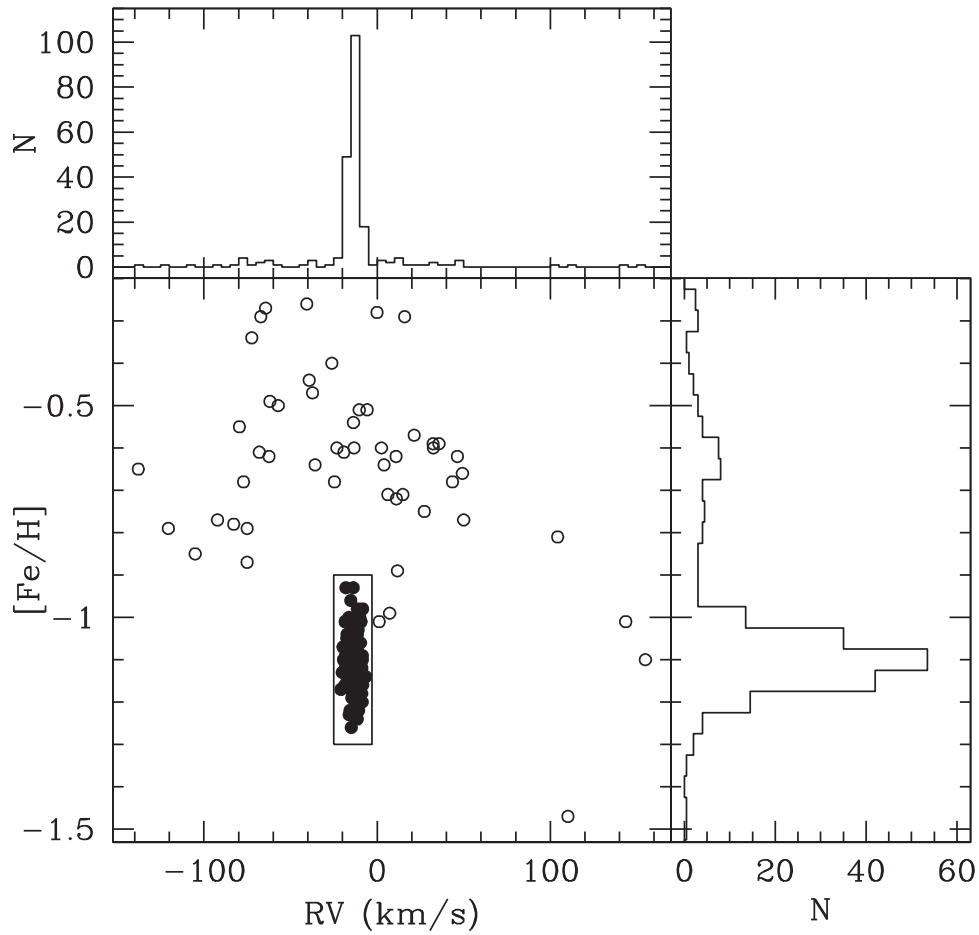


Figure 3. Position of the spectroscopic targets in the RV–[Fe/H] plane (same symbols as in Figure 1). The rectangle is the box used to select the bona fide cluster members. The histograms of [Fe/H] and RV distributions are also plotted.

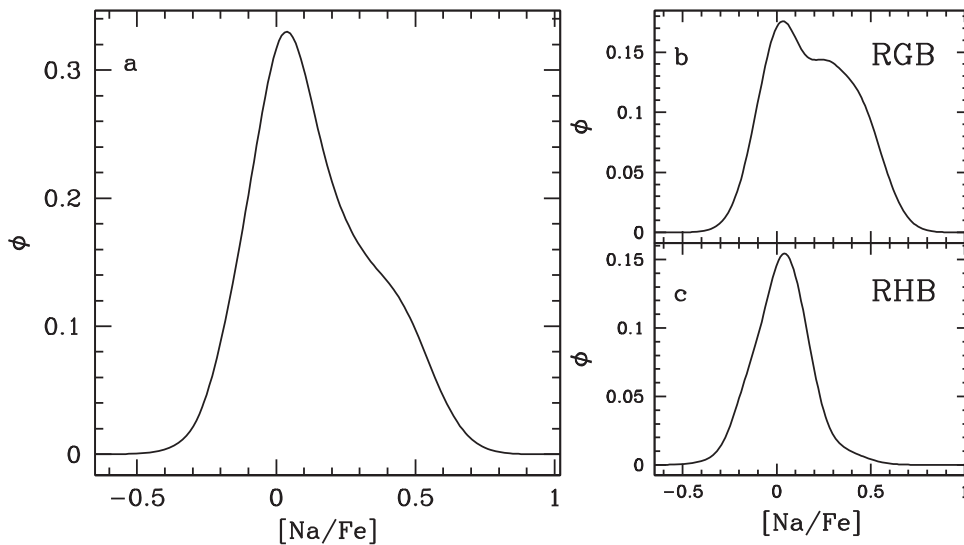


Figure 4. Generalized histograms of the [Na/Fe] abundances: (a) for the entire sample of member stars, (b) for only the RGB, and (c) for only the RHB.

and should therefore be directly ascribable to multiple populations.

As clearly shown in Figure 4(a), and as expected, the Na-poor stars reside on the bluest RGB, while the Na-rich stars populate the reddest RGB. The same result is found if we

consider the $(U, U - B)$ plane. We also found that the fractions of (Na-selected) FG and SG stars in NGC 6362 are basically the same ($\sim 47\%$ and $\sim 53\%$, respectively), corresponding to a ratio $N_{\text{SG}}/N_{\text{FG}} = 1.10 \pm 0.21$. This value agrees well with the ratio of second to first generation estimated photometrically

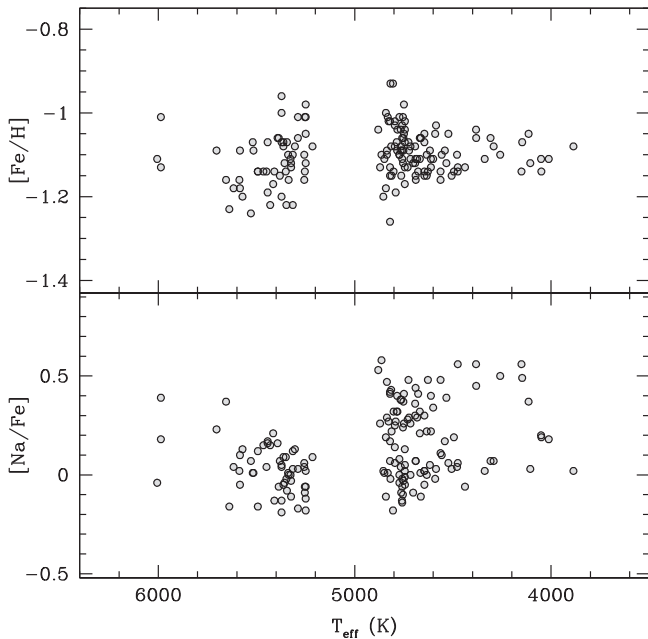


Figure 5. Behavior of [Fe/H] (upper panel) and [Na/Fe] (lower panel) as a function of T_{eff} for the member stars of NGC 6362.

in Paper I (~ 1.2) according to the star number counts along the two RGBs.¹⁰

5.2. HB Stars

As can be appreciated from Figures 4(c) and 6(c), the [Na/Fe] distribution of RHB stars appears to be quite different from that of RGB stars: about 82% of the RHB stars are Na-poor ([Na/Fe] < 0.15 dex), leading to a ratio of second to first generation $\frac{N_{\text{SG}}}{N_{\text{FG}}} = 0.22 \pm 0.08$. Hence, most of the stars populating the RHB of NGC 6362 belong to the first generation. This finding confirms previous analyses of HB stars in other GCs (see, e.g., Gratton et al. 2011, 2012, 2013; Marino et al. 2011), where the red part of the HB is preferentially populated by FG stars.

The natural explanation is that most of the RHB stars that we observe are the progeny of stars previously located along the bluest RGB detected in the CMDs including the U filter. In this view, the Na-rich RGB stars populating the bluest RGB of Figure 6 (and accounting for $\sim 50\%$ of the total RGB stars) will populate the blue part of the HB of the cluster. Note that HB stars bluer than the instability strip have not been observed in this program.

Both the number counts of the two RGBs (Paper I) and the ratio between Na-poor and Na-rich RGB stars indicate a similar population of FG and SG stars, while the RHB stars are mainly FG stars. We calculated the number of Na-rich stars expected to populate the blue HB in order to obtain a ratio of second to first generation of 1.10 along the entire HB. The stars have been selected from the WFI catalog within $850''$ from the cluster center (corresponding to the FLAMES field of view) and

¹⁰ We checked that the use of different prescriptions for the NLTE corrections for Na abundances does not change these results. [Na/Fe] abundance ratios have been recalculated by adopting the NLTE corrections by Lind et al. (2011) that provide abundances lower than about 0.15–0.2 dex, while the overall [Na/Fe] distribution, the $N_{\text{SG}}/N_{\text{FG}}$ ratio, and the photometric distribution of Na-rich and Na-poor stars remain the same.

adopting $(B - V) = 0.4$ mag as the boundary between red and blue HB stars. A total of 130 and 80 red and blue HB stars, respectively, have been counted. The RHB is located in a region of the CMD contaminated by main-sequence field stars (see Figure 1), at variance with the blue portion of the HB. For this reason the number counts of the RHB have been corrected for the field-star contamination by considering the proportion of field stars to be 19% (according to the fraction of field stars detected among the RHB spectroscopic targets). Finally, we expect to find 79 (out 80) Na-rich blue HB stars. Hence, in order to have the same ratio of second to first generation that we observe among the RGB stars, the blue HB should be populated only by Na-rich stars, in agreement with the analysis of blue HB stars in GCs performed by Gratton et al. (2011, 2012, 2013).

6. COMPARISON WITH M4

Among all the other Galactic GCs with secure evidence of multiple stellar populations, M4 is the least massive one with a metallicity comparable to that of NGC 6362 (Harris 1996, 2010 edition; Marino et al. 2008; Carretta et al. 2009; Villanova & Geisler 2011). Hence, a comparison between these two clusters could yield particularly interesting information, and, by following the approach described in Mucciarelli et al. (2013a), we therefore adopted the same technique described above to perform the chemical analysis of a sample of stars in M4. In this way, the derived [Fe/H] and [Na/Fe] abundance ratios for the two GCs are free from any possible systematics arising from the adopted model atmospheres, line lists, method to measure EWs, code to derive the abundances, solar reference abundances, and NLTE corrections. This kind of comparative analysis is much more robust than a simple comparison with literature abundances.

We retrieved, from the ESO Archive¹¹, UVES and GIRAFFE spectra of 93 stars along the RGB of M4, acquired with the same setups used for NGC 6362 and with comparable spectral quality (Prop. ID: 072.D-0570, PI: Carretta). The atmospheric parameters have been computed following the same procedure described above. T_{eff} have been derived from B and V photometry (taken from Carretta et al. 2009), adopting $E(B - V) = 0.35$ mag (Harris 1996, 2010 edition) and applying suitable corrections for differential reddening computed according to the procedure described in Massari et al. (2012). Surface gravities have been computed assuming a distance modulus of $(m - M)_V = 12.82$ mag (Harris 1996, 2010 edition). We restrict the analysis only to the stars considered as cluster members by Carretta et al. (2009). The average [Fe/H] of the sample is $[\text{Fe}/\text{H}] = -1.14 \pm 0.01$ dex with an observed scatter $\sigma_{\text{obs}} = 0.06$ dex and an intrinsic scatter $\sigma_{\text{int}} = 0.00 \pm 0.02$ dex, in nice agreement with the previous determinations (see, e.g., Marino et al. 2008; Carretta et al. 2009; Mucciarelli et al. 2011) and confirming that M4 and NGC 6362 have very similar metallicities.

The distribution of [Na/Fe] of M4 stars spans about 0.7 dex, with an average value of $+0.27 \pm 0.01$ and an intrinsic spread of 0.16 ± 0.01 . The comparison between the [Na/Fe] distributions of NGC 6362 and M4 is shown in Figure 7. The two distributions are similar in terms of the covered abundance range and the position of the two main peaks at $[\text{Na}/\text{Fe}] \sim 0.0$ and $+0.3$ dex. However, we note that they show a remarkably different number ratio of the two populations,

¹¹ <http://archive.eso.org/cms/eso-data.html>

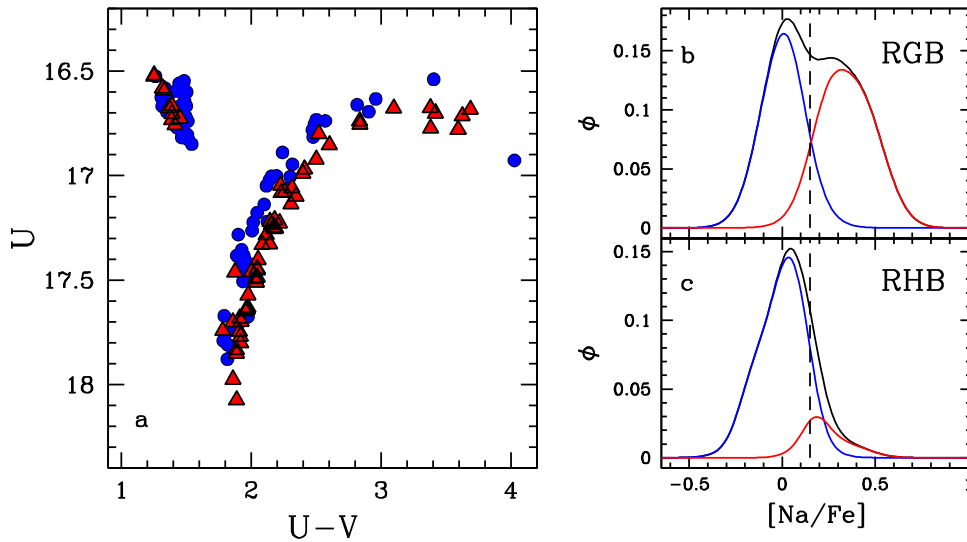


Figure 6. Panel (a): $(U, U - V)$ CMD of the spectroscopic targets (only member stars). The stars are divided according to the $[\text{Na}/\text{Fe}]$ abundance ratio, assuming $[\text{Na}/\text{Fe}] = 0.15$ dex as a boundary to distinguish between FG and SG stars. Red triangles are Na-rich stars, blue circles the Na-poor stars. Panels (b) and (c) show the $[\text{Na}/\text{Fe}]$ distribution of the RGB and RHB stars, respectively, with the generalized histograms of the Na-poor and Na-rich stars (blue and red, respectively).

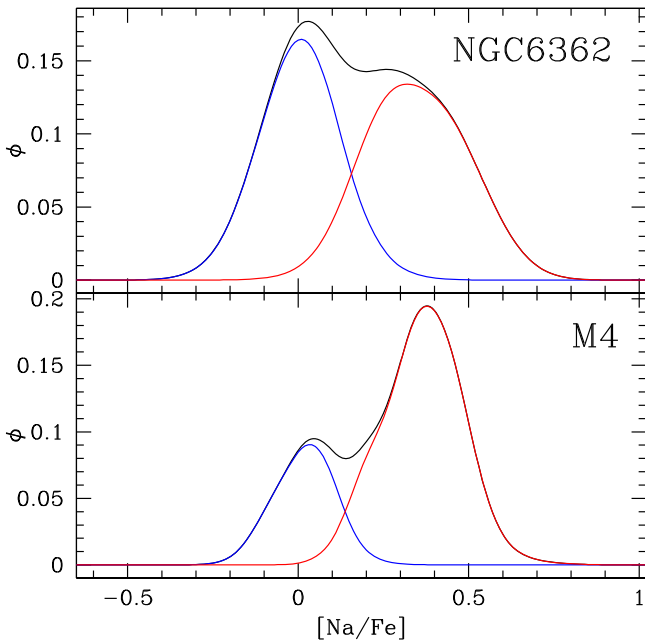


Figure 7. $[\text{Na}/\text{Fe}]$ distribution in the RGB stars of NGC 6362 (upper panel) and M4 (lower panel). In both panels, blue and red histograms are the distributions of Na-poor and Na-rich stars, respectively, assuming $[\text{Na}/\text{Fe}] = 0.2$ dex as the boundary.

with the Na-rich population dominating in the case of M4. In fact, assuming the same boundary adopted for NGC 6362, the ratio between Na-rich and Na-poor stars in M4 is $\frac{N_{\text{SG}}}{N_{\text{FG}}} = 2.76 \pm 0.70$, corresponding to a fraction of FG stars of $\sim 27\%$. This is in agreement with what was found by Marino et al. (2008) and Carretta et al. (2009) for M4, and with that usually found in all GCs (Bastian & Lardo 2015 estimated an average ratio between Na-rich and Na-poor stars of $(0.68 \pm 0.07)\%$).

7. SUMMARY AND CONCLUSIONS

The main results obtained from the spectroscopic analysis presented in this paper are:

- i. the iron content of NGC 6362 is $[\text{Fe}/\text{H}] = -1.09 \pm 0.01$, without evidence of intrinsic spread. This is the first determination of its iron abundance based on high-resolution spectra;
- ii. the $[\text{Na}/\text{Fe}]$ distribution of the cluster shows a clearly bimodal distribution, revealing the presence of two quite distinct stellar populations. We find a clear-cut correspondence between the Na abundances and the two RGBs detected in the CMDs including the U or the F336W *HST* filters (Paper I), with the Na-poor stars populating the bluest RGB and the Na-rich stars the reddest RGB, as theoretically expected;
- iii. among the RGB stars, the two populations, selected according to their $[\text{Na}/\text{Fe}]$ abundance, are equally populated, which is at variance with the other GCs where the stellar content is dominated by the Na-rich population.

The results of this paper confirm that NGC 6362 is the least massive cluster where MPs have been observed, as discussed in Paper I on a purely photometric basis. The other two GCs with comparable masses and evidence of chemical anomalies, namely NGC 288 and M4, are two and three times more massive than NGC 6362, respectively, when masses are estimated in a homogeneous way (see Paper I), by using the best-fit King model that reproduces their density profiles and the velocity dispersion data by Pryor & Meylan (1993). On the other hand, old open clusters slightly less massive (by a factor of 3–5) than NGC 6362 do not exhibit intrinsic scatters in the light elements—see the cases of Berkeley 39 (Bragaglia et al. 2012) and NGC 6791, though this latter case is still a matter of debate since different groups find opposite results (Geisler et al. 2012; Bragaglia et al. 2014; Cunha et al. 2015). Whatever the true nature of the polluters is, this finding about NGC 6362 can provide crucial constraints on the minimum cluster mass necessary to retain the low-energy ejecta and to undergo self-enrichment processes.

The differential comparison with M4 clearly reveals that these two clusters share the same chemical patterns, with broad and bimodal $[\text{Na}/\text{Fe}]$ distributions. However, we observe that

FG and SG are equally populated in NGC 6362, at variance with what is observed in M4, where SG stars represent 73% of the total. Indeed, the analysis of 19 GCs discussed by Carretta et al. (2009) provides typical fractions of $\sim 30\%$ for the first generation and $\sim 70\%$ for the polluted stars. The only GC in the sample of Carretta et al. (2009) with a comparable first-generation fraction is NGC 2808 (50%). NGC 2808, however, is very different from NGC 6362 and most GCs, in terms of extent of anticorrelation (Carretta et al. 2009), the fraction of the extreme generation ($[O/Na] < -0.9$ dex), horizontal branch morphology (Dalessandro et al. 2011), and mass (NGC 2808 is more massive by a factor of 8, according to McLaughlin & van der Marel 2005).

The fact that SG stars typically outnumber FG stars is usually explained by invoking a relevant and preferential loss of FG stars during the early stages of the GC's life. In fact, it is expected (Bekki 2011; D'Ercole et al. 2011) that FG stars are initially less segregated than SG stars. As a consequence, they reach the conditions to escape the cluster during the early expansion of the system that takes place during the first ~ 1 Gyr of the cluster, which is dominated by stellar evolution and explosions of supernovae.

In the case of NGC 6362, the present-day number ratio between FG stars and SG stars is representative of that shown by the cluster at the time when FG and SG stars have reached full spatial mixing, as shown by Vesperini et al. (2013) and Miholics et al. (2015). In fact, after mixing is achieved, different subpopulations are expected to lose stars at similar rates. How the present-day ratio is related to the primordial one depends on the fraction of mass lost. Both Vesperini et al. (2013) and Miholics et al. (2015) find that in order to reach a completely spatially mixed configuration, NGC 6362 should have lost a significant fraction of mass during its long-term dynamical evolution. Indeed Miholics et al. (2015) have estimated that, given its orbit, NGC 6362 has been tidally filled for most of its life, independently of its initial conditions, and therefore it likely lost a large fraction of stars because of tidal stripping. If this is the case, it is expected that NGC 6362 was born with a very small and highly concentrated SG subpopulation.

We can conclude that, putting together the number of peculiar properties observed in this cluster, NGC 6362 turns out to be a unique case among the Galactic GCs. Any theory aimed at explaining the formation and evolution of GCs (from initial, more massive clusters to those that we currently observe) must account also for the peculiar case of NGC 6362.

We warmly thank the anonymous referee for suggestions that helped to improve the paper. This research is part of the project COSMIC-LAB (<http://www.cosmic-lab.eu>) funded by the European Research Council (under contract ERC-2010-AdG-267675).

REFERENCES

- Alonso, A., Arribas, S., & Martinez-Roger, C. 1999, *A&AS*, 140, 261
- Bastian, N. 2015, arXiv:1510.01330.
- Bastian, N., Lamers, H. J. G. L. M., de Mink, S. E., et al. 2013, *MNRAS*, 436, 2398
- Bastian, N., & Lardo, C. 2015, *MNRAS*, 453, 357
- Beccari, G., Bellazzini, M., Lardo, C., et al. 2013, *MNRAS*, 431, 1995
- Bedin, L. R., Piotto, G., Anderson, J., et al. 2004, *ApJ*, 605L, 125
- Behr, B. B., Cohen, J. G., & McCarthy, J. K. 2000, *ApJ*, 531L, 37
- Bekki, K. 2011, *MNRAS*, 413, 2241
- Bragaglia, A., Gratton, R. G., Carretta, E., et al. 2012, *A&A*, 548, 122
- Bragaglia, A., Sneden, C., Carretta, E., et al. 2014, *ApJ*, 796, 68
- Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245
- Carretta, E., Bragaglia, A., Gratton, R. G., D'Orazi, V., & Lucatello, S. 2009, *A&A*, 508, 695
- Cunha, K., Smith, V. V., Johnson, J. A., et al. 2015, *ApJ*, 798L, 41
- Dalessandro, E., Massari, D., Bellazzini, M., et al. 2014, *ApJL*, 791L, 4
- Dalessandro, E., Miocchi, P., Carraro, G., Jilková, L., & Moitinho, A. 2015, *MNRAS*, 449, 1811
- Dalessandro, E., Salaris, M., Ferraro, F. R., et al. 2011, *MNRAS*, 410, 694
- Decressin, T., Meynet, G., Charbonell, C., Prantzos, N., & Ekstrom, S. 2007, *A&A*, 464, 1029
- De Mink, S. E., Pols, O. R., Langer, N., & Izzard, R. G. 2009, *A&A*, 507L, 1
- Denissenkov, P. A., & Hartwick, F. D. A. 2014, *MNRAS*, 437, 21
- Denissenkov, P. A., VandenBerg, D. A., Hartwick, F. D. A., et al. 2015, *MNRAS*, 448, 3314
- D'Ercole, A., D'Antona, F., & Vesperini, E. 2011, *MNRAS*, 415, 1304
- D'Ercole, A., Vesperini, E., D'Antona, F., McMillan, S. L. W., & Recchi, S. 2008, *MNRAS*, 391, 825
- Fuhr, J. R., & Wiese, W. L. 2006, *JPCRD*, 35, 1669
- Geisler, D., Claria, J. J., & Minniti, D. 1997, *PASP*, 109, 799
- Geisler, D., Villanova, S., Carraro, G., et al. 2012, *ApJL*, 756L, 40
- Gratton, R. G., Carretta, E., & Bragaglia, A. 2012, *A&ARv*, 20, 50
- Gratton, R. G., Carretta, E., Eriksson, K., & Gustafsson, B. 1999, *A&A*, 350, 955
- Gratton, R. G., Lucatello, S., Carretta, E., et al. 2011, *A&A*, 534, 123
- Gratton, R. G., Lucatello, S., Carretta, E., et al. 2012, *A&A*, 539, 19
- Gratton, R. G., Lucatello, S., Sollima, A., et al. 2013, *A&A*, 549, 41
- Grevesse, N., & Sauval, A. J. 1998, *SSRv*, 85, 161
- Harris, W. E. 1996, *AJ*, 112, 1487
- Kruijssen, J. M. D. 2015, *MNRAS*, 454, 1658
- Lardo, C., Bellazzini, M., Pancino, E., et al. 2011, *A&A*, 525, 114
- Lind, K., Asplund, M., Barklem, P. S., & Belyaev, A. K. 2011, *A&A*, 528, 103
- Marino, A. F., Villanova, S., Milone, A. P., et al. 2011, *ApJ*, 730L, 16
- Marino, A. F., Villanova, S., Piotto, G., et al. 2008, *A&A*, 490, 625
- Martell, S. L., & Smith, G. H. 2009, *PASP*, 121, 577
- Massari, D., Mucciarelli, A., Dalessandro, E., et al. 2012, *ApJ*, 755L, 32
- McLaughlin, D. E., & van der Marel, R. P. 2005, *ApJS*, 161, 304
- Miholics, M., Webb, J. J., & Sills, A. 2015, *MNRAS*, 454, 2166
- Milone, A. P., Piotto, G., King, I. R., et al. 2010, *ApJ*, 709, 1183
- Milone, A. P., Bedin, L. R., Piotto, G., et al. 2008, *ApJ*, 673, 241
- Mucciarelli, A. 2013, arXiv:1311.1403
- Mucciarelli, A., Bellazzini, M., Catelan, M., et al. 2013a, *MNRAS*, 435, 3667
- Mucciarelli, A., Bellazzini, M., Ibata, R., et al. 2012, *MNRAS*, 426, 2889
- Mucciarelli, A., Origlia, L., Ferraro, F. R., & Pancino, E. 2009, *ApJL*, 695, L134
- Mucciarelli, A., Pancino, E., Lovisi, L., Ferraro, F. R., & Lapenna, E. 2013b, *ApJ*, 766, 78
- Mucciarelli, A., Salaris, M., Lovisi, L., et al. 2011, *MNRAS*, 412, 81
- Muratov, A. L., & Gnedin, O. Y. 2010, *ApJ*, 718, 1266
- Norris 1981, *ApJ*, 248, 177
- Osborn, W. 1971, *Obs*, 91, 223
- Pancino, E., Rejkuba, M., Zoccali, M., & Carrera, R. 2010, *A&A*, 524, 44
- Pasquini, L., Avila, G., Allaert, E., et al. 2000, *Proc. SPIE*, 4008, 129
- Pietrinferni, A., Cassisi, S., Salaris, M., & Castellì, F. 2006, *ApJ*, 642, 797
- Piotto, G., Bedin, L. R., Anderson, J., et al. 2007, *ApJ*, 661L, 53
- Piotto, G., Milone, A. P., Anderson, J., et al. 2012, *ApJ*, 760, 39
- Piotto, G., Milone, A. P., Bedin, L. R., et al. 2015, *AJ*, 149, 91
- Pryor, C., & Meylan, G. 1993, *ASPC*, 50, 357
- Renzini, A., & Buzzoni, A. 1986, *Spectral Evolution of Galaxies*, ed. C. Chiosi & A. Renzini, *ASSL*, 122, 195
- Sbordone, L., Bonifacio, P., Castelli, F., & Kurucz, R. L. 2004, *MmSAI*, 75, 396
- Sbordone, L., Salaris, M., Weiss, A., & Cassisi, S. 2011, *A&A*, 534, A9
- Stetson, P., & Pancino, E. 2008, *PASP*, 120, 1332
- Vesperini, E., McMillan, S. L. W., D'Antona, F., & D'Ercole, A. 2013, *MNRAS*, 429, 1913
- Villanova, S., & Geisler, D. 2011, *A&A*, 535, 31