The fraction of first and second generation stars in globular clusters. I The case of NGC 6752

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ABSTRACT

We present a new method to estimate the fraction of stars with chemical composition of first and second generation currently hosted in Galactic globular clusters (GCs). We compare cluster and field stars of similar metallicity in the [Fe/H]-[Na/H] plane. Since the phenomenon of multiple populations is only restricted to the cluster environment, the number of GC stars whose location coincides with that of field stars provides the fraction of first generation stars in that cluster. By exclusion, the fraction of second generation stars is derived. We assembled a dataset of 1891 field stars of the thin disk, thick disk, and halo of the Milky Way in the metallicity range $-3.15 \leq [\text{Fe/H}] \leq +0.48$ dex and with Na abundance from high resolution spectra. They are mostly dwarfs, but include also giants. Considering only the range in metallicity spanned by most GCs extensively studied for the Na-O anticorrelation ($-2.36 \leq [\text{Fe/H}] \leq -0.33$ dex), we have 804 stars. The total sample is homogenized by offsets in [Fe/H] and [Na/H] with respect to a reference sample using the same line list and NLTE correction for Na adopted in a recent extensive survey of GC stars. This fully accounts for offsets among analyses due to different temperature scales, line lists, adopted (or neglected) corrections for departures from LTE. We illustrate our method estimating the fraction of first and second generation stars in the well studied GC NGC 6752. As a by-product, the comparison of [Na/H] values in GC and field stars suggests that at least two classes of old stellar systems probably contributed to the halo assembly: one group with characteristics similar to the currently existing GCs, and the other more similar to the present-day dwarf satellite galaxies.

Key words. Stars: abundances – Stars: Population II – Galaxy: abundances – Galaxy: stellar content – Galaxy: globular clusters – Galaxy: globular clusters: individual: NGC 6752

1. Introduction

Once upon a time, the Galactic globular clusters (GCs) were considered the best example in nature of simple stellar populations (SSP, see e.g. the review by Renzini and Fusi Pecci 1988). The pioneering studies by Cohen (1978) and Peterson (1980) however showed that supposedly coeval stars in GCs were not of the same initial chemical composition, which is a requisite, by definition, of SSPs. In particular, Cohen (1978) concluded that “the primordial gas in M3 was not chemically homogeneous during the time interval when star formation of the currently observed M3 red giants took place.”

In both studies a scatter of Na abundances in cluster stars was noted, and Na is still one of the best tracers used to characterize the peculiar chemistry of stars in GCs. Different amounts of Na excess, anticorrelated with varying degrees of O depletion, were found in all GCs studied by the Lick-Texas group (see Kraft 1994 for a review). The discovery of the Na-O anticorrelation, coupled to the C-N anticorrelation already widely studied among cluster giants (e.g. Smith 1987), led to identify the nucleosynthesis source responsible for the observed changes in the network of proton-capture reactions in H-burning at high temperatures. The NeNa cycle was expected to operate, producing Na, in the same region where the ON part of the CNO cycle is fully active (Denisenkov and Denisenkova 1989, Langer et al. 1993), destroying O. The abundance variations were found only restricted to the dense environment of globular clusters, since Gratton et al. (2000) demonstrated that Na, O abundances are not modified in field stars from the typical levels established by supernovae (SNe) nucleosynthesis only.

However, at the time it was unclear where the hot H-burning was located, whether in the stars currently observed in GCs or outside. The finding of the Na-O anticorrelation (as well as star-to-star variations in Mg anticorrelated to those in Al) among unevolved stars in NGC 6752 (Gratton et al. 2001) unambiguously answered this question. These scarcely evolved stars do not reach temperatures high enough to efficiently produce Na or Al in their interiors; moreover, their convective envelope interest a negligible fraction of their mass. The milestone established by Gratton et al. (2001) was to show that the chemical pattern observed in dwarfs currently in GCs must have been necessarily imprinted in the gas from which they formed by the most massive stars of a previous stellar genera-
tion. Observing Na-O variations in cluster stars means that we are in presence of multiple stellar generations, no more and no less.

The new paradigm for GCs as examples of multiple stellar populations is currently well assessed, and much work was made in recent years (see the exhaustive reviews by Gratton et al. 2004, 2012): chemical tagging of different generations, identification of multiple photometric sequences in the color-magnitude diagrams (CMDs), impact of modified chemical composition on photometric bands (e.g. Carretta et al. 2011, Sbordone et al. 2011, Milone et al. 2012, Cassisi et al. 2013). However, much still remains to be done, in particular to better quantify the properties of different stellar generations such as the ratio between the fraction of first and second(s) generation(s) stars currently composing the cluster populations. This ratio is a fundamental parameter in several key issues related to the formation of GCs, their dynamical evolution and spatial mixing (Vesperini et al. 2013), and their connection to the formation of the Galactic halo (Carretta et al. 2010, Vesperini et al. 2010, Martell et al. 2011).

The first quantitative estimate was possible thanks to the extensive FLAMES survey of GCs (Carretta et al. 2006, Carretta et al. 2009a,b, and ongoing follow up). The homogeneous dataset of Na, O abundances for more than 1500 giant stars in about 20 GCs allowed Carretta et al. (2009a) to show that only one third of stars currently observed in GCs has a chemistry of first generation, primordial stars, the bulk (~ 70%) belongs to the second generation. Stars were assigned to the primordial (P) component if their O, and Na, content was similar to that of field stars of the same metallicity [Fe/H]. Stars deviating from the high-O, low-Na locus were considered second generation stars, of an intermediate (I) or extreme (E) component according to their [O/Na] ratio.

Recently, Milone et al. (2013) criticized as arbitrary the criteria used in Carretta et al. (2009a), because in the case of NGC 6752 the three discrete groups identified in Carretta et al. (2011, 2012) did not match the sub-divisions found by the abundances by Yong et al. (2003, 2005). However, the separation between first and second generation in Carretta et al. (2009a) is not arbitrary; the P component includes all stars with [Na/Fe] ratios in the range between [Na/Fe]_{min} and [Na/Fe]_{min} + 0.3, where 0.3 dex corresponds to ~ 4 times the star-to-star error on [Na/Fe] in each cluster, hence this group includes all stars with Na abundances similar to that of field stars. The method used in Carretta et al. (2009a) may suffer two possible shortcomings. First, it is based only on stars on the Na-O anticorrelation in each cluster, i.e. with measured abundances for both O and Na, even if the separation first/second generation is made using only Na abundances. Second, the minimum ratio [Na/Fe]_{min} is estimated by eye, assuming that the stars with lowest Na abundances along the anticorrelation (excluding possibly a few outliers) have the typical composition of normal halo stars, with no direct comparison with field stars.

Hence, in the present study we present a simple variation of that method, to overcome its possible uncertainties. We propose to compare in the [Na/H] vs [Fe/H] plane the location of Galactic field stars, fixing the level from SN ejecta nucleosynthesis only, to the position of giants in GCs. The excess of Na will clearly select second generation stars with modified composition. This approach does not rely directly on the Na-O anticorrelation, hence it may make use of all stars with measured Na abundances in a GC, usually a larger number than those with O abundances, more difficult to measure (O is depleted, whereas Na is enhanced in proton-capture reactions).

In the present paper we will present the assembling, over the metallicity range spanned by Galactic GCs, of the comparison sample of field stars (Section 2), using several literature studies, all shifted on a system defined by our reference sample (Gratton et al. 2003). The outliers in the [Na/H]-[Fe/H] distribution are discussed in Section 3, and the application of the present method is tested in Section 4 using NGC 6752, one of the closest and best studied GC, as a template. As a by-product of this comparison, some final considerations on the candidate building blocks that may have contributed to the formation of the Galactic halo are given in Section 4.

The abundances of Na in the reference sample by Gratton et al. (2003) are obtained with the same line lists, and include the same prescriptions for NLTE corrections to Na values, used in the FLAMES survey of GCs which at present is the largest survey of homogeneous abundances in globular cluster giants. Already 21 GCs (soon to become 24 with the addition of NGC 362, NGC 4833, and NGC 6093) are analyzed and this offers a unique opportunity. In a forthcoming paper we will apply the method developed here to derive homogeneous estimates of the fraction of first and second generation stars in all the globular clusters of this sample, to compare them with previously derived values from spectroscopy and/or photometry, and to study their relationship with global cluster properties.

2. The comparison sample of field stars
To assemble the comparison sample of field stars we searched the literature for the most recent studies based on high resolution spectroscopy providing Na abundances for a large number of stars of different metallicities. Our method to estimate the fraction of stars of different generations in GCs is based on comparing the location of cluster and field stars in the Fe-Na plane; hence, the main requisites are homogeneity of measurements and a good sampling in this plane to highlight possible outliers. In particular, our aim was to secure a good coverage in [Fe/H] over the range in metallicity spanned by the bulk of GCs.

2.1. Our approach: problems and methods
About twenty abundance analysis with these characteristics can be easily picked up in the past 15 years, with a number of
stars analyzed ranging from 23 metal-poor giants in Johnson (2002) to more than 1000 FGK dwarfs surveyed with HARPS in Adibekyan et al. (2012).

Obviously, independent studies designed to study different stellar populations to deal with different astrophysical problems involve a series of different methods and assumptions that in turn may affect the requirement of homogeneity. Among these we may include different temperature scales, based on photometry or derived from the spectra, differences in the adopted reference solar abundances, or in the scales of atomic parameters. The latter is less important for the Na I lines most used in abundance analysis, whose g-f values are very well known and homogeneously used, but may represent a source of discrepancy concerning Fe, especially when coupled to different temperature scales. Another potentially dangerous source of offset among different studies are the corrections for departures from the LTE assumptions, in particular for Na. This problem may become relevant especially when abundances derived for warm dwarfs are compared to those obtained in metal-poor, cool stars of low gravity, where the NLTE effects are stronger (see e.g. Baumüller et al. 1998, Gratton et al. 1999, Korotin and Mishenina 1999, Mashonkina et al. 2000, Takeda et al. 2003, Gieren et al. 2004, Andrievsky et al. 2007, Lind et al. 2011, and references therein). Moreover, different groups adopt different prescriptions for NLTE corrections.

Previous extensive compilations of literature data, namely those by Venn et al. (2004; 821 stars), and by Soubiran and Girard (2005; 743 stars), were designed to deal with specific problems (mainly related to the study of Galactic stellar populations) and are not very suitable to our purposes for various reasons. Venn et al. did not try to homogenise the abundance data apart from atomic data for a few neutron-capture elements (Y, Ba, and Eu). Moreover, in their sample they did not include the study by Gratton et al. (2003, hereinafter G), that we will adopt as our reference sample (see below, Section 2.2). Soubiran and Girard used stars in common among their 11 selected samples to operate an homogeneisation of the total sample. However, their study was focused on the interface between thick and thin disks, thus they restricted the metallicity range to stars more metal rich than [Fe/H] = −1.3 dex, also to avoid the larger scatter observed at low metallicities. Moreover, to further reduce the observed dispersion, they limited their sample to stars hotter than 4500 K. However, one of our aims is to provide a good sampling also in the low metal abundance regime; since our main purpose is to build a sample to be compared mainly to giant stars in rather metal-poor objects such as the GCs, the quoted existing compilations are unsuitable (apart from missing recent studies performed after 2005).

From our literature search, we eventually selected 14 studies, according to criteria defined below in Section 2.4. In Fig. 1 we show the ratio [Na/H] as a function of the metallicity [Fe/H] for all these samples, using the original values in each paper. The labels refer to the sample coding listed in Tab. 1. In each panel we indicate with dotted lines at [Fe/H] = −2.34 dex and −0.43 dex the metallicity range spanned by the large sample of GCs analysed by Carretta et al. (2009a,b) in the FLAMES survey of the Na-O anticorrelation in globular clusters. The middle value, at [Fe/H] = −1.56 dex, is the average metallicity (see Carretta et al. 2009c) of NGC 6752, that we will use as our test case.

In Tab. 1 we listed a one/two letter coding for each sample, together with a summary of a few properties of the samples. The original studies cover all the major Galactic stellar populations, thin and thick disks, and halo. Most objects are dwarf stars, but also subgiants and giants are represented in some samples. In column 7 we indicated whether the abundance analysis for Na was made under the LTE assumption or corrections for NLTE were applied (references in the latter case can be found in the original papers).

Aided by the reference lines at different metallicities, from Fig. 1 we first note that different samples occupy more or less the same position, indicating that offsets among different analyses are not severe. Second, there is some evidence of increased scatter in [Na/Fe] ratios at low metallicity, in particular between [Fe/H] = −2.3 dex and [Fe/H] = −1.5 dex. This occurrence, already noted in several studies, can be appreciated particularly well in a few samples (Gratton et al. 2003, Fulbright 2000, and Hanson et al. 1998).

In the following analysis, however, we chose to switch to the plane [Na/H] vs [Fe/H] for two main reasons. The first was simply to decouple Na and Fe, avoiding that errors in Fe reflect on both axis. The second is to fully exploit the different sites of nucleosynthesis for Na. The main production of Na is considered to be hydrostatic carbon burning in massive stars, a primary mechanism (see e.g. Woosley and Weaver 1995). Since Na is an odd-Z element, its production is a strong function of the neutron density, which is a function of the initial stellar metallicity (Truran and Arnett 1971, Woosley and Weaver 1995). A simple linear relation between [Na/H] and [Fe/H] is then expected. However, proton-captures on 22Ne in H-burning at high temperature result in the synthesis of Na able to explain the excess of Na observed in GC stars (Denisenkov and Denisenkova 1989). Moreover, Langer et al. (1993) proposed that synthesis of 23Na on the abundant isotope 20Ne may greatly contribute to the Na production via proton-capture. Hence, we can exploit these different production mechanisms for Na to our purposes.

Therefore, the [Na/H]-[Fe/H] plane could be considered one of the best diagnostics to separate the stars with chemical signature from plain supernova nucleosynthesis (both in the Galactic field populations and in globular clusters) from stars where the proton-capture reactions have acted to modify the original chemical imprinting. Any excess of [Na/H] in GC stars, with respect to the linear behaviour in field stars at any given metallicity, can be interpreted as a signature of second generation stars.

The run of the [Na/H] ratios as a function of metallicity is shown in Fig. 2 for all the 14 datasets used to build our total comparison sample of field stars. Possible systematics among them due to the different scales and methods adopted in the original studies were treated by mean of offsets computed using stars in common to bring all the [Na/H] and [Fe/H] values onto a homogeneous system defined by a reference sample, and corroborated by an extended reference sample, as discussed below.
2.2. The reference sample: Gratton et al. (2003)

Our privileged reference sample is the dataset of 150 field subdwarf and early subgiant stars with accurate parallaxes analysed by Gratton et al. (2003; hereinafter G, see Tab. 1 for details). That work was based on high resolution spectra for about 50 stars and on a collection of high quality equivalent widths (EWs) from the studies by Nissen and Schuster (1997), Prochaska et al. (2000), and Fulbright (2000).

There are several reasons to choose this set as reference sample:

- Adopted solar reference abundances for Na (6.21) and Fe (7.54) are the same as used in the FLAMES survey of Na,O abundances in GCs (including homogeneous abundances for almost 25 clusters);
- in like vein, the atomic parameters scale and line list are the same for field stars in G and cluster stars; as said above, this is not very relevant for Na, but it could be a plus concerning the iron abundances;
- the grid for corrections from NLTE effects used for Na (from Gratton et al. 1999) is the same also adopted for Na abundances in GC stars of the above extensive survey;
- the G sample homogeneously covers all the metallicity range relevant for GCs, going from [Fe/H] = −2.61 dex up to +0.07 dex.

Overall, taking into account the obvious differences due to dealing with nearby field stars rather than distant cluster stars, the G sample looks like the best reference sample to define a common system for our total comparison sample.

All the main stellar populations in the Galaxy are sampled in G: thin disk, thick disk, and halo. However, Gratton et al. (2003) did not adopt this classical classification. Using the orbital characteristics of the sample they distinguished stars belonging to a dissipative component (as proposed e.g. by Eggen et al. 1962, and including objects from the classical populations of halo and thick disk) and stars of an accretion component, as in the scenario proposed by Searle and Zinn (1978) for halo GCs. This classification scheme is becoming more and more used, thanks to large scale survey such as the SDSS that stimulated many observational and theoretical works (see e.g.
Carollo et al. 2013 and Zolotov et al. 2009 for the dual halo nature). The relevance of the accretion versus dissipative-collapse component will be clear when discussing the outliers in the field star total sample (see Section 3 below).

A possible shortcoming of this reference sample is that it does not include giant stars, that are the vast majority of stars usually observed in distant GCs. We will see that this is not a source of concern because we can tie together the worlds of giants and dwarfs by using the sample of unevolved stars observed in globular clusters, in particular in our test case NGC 6752.

However, to ensure the reliability of the comparison sample of field stars, we defined an extended reference sample that (i) provides a larger number of stars for the cross-match with other studies for the homogeneity of the different datasets, and (ii) includes a number of giants to check that in the [Na/H]-[Fe/H] plane they occupy the same region of dwarfs, despite e.g. the different amounts of correction for NLTE on Na.

### 2.3. The extended reference sample

To build up our extended reference sample we considered the study of about 300 field stars by Carretta et al. (2000; hereinafter code CA), in the metallicity range from [Fe/H]$\approx -2.8$ dex to [Fe/H]$\approx +0.3$ dex (see Tab.II) encompassing the metal abundance distribution of GCs. CA analysed or reanalysed stars using $EW$ from high resolution spectra using homogeneous methods. The main advantages of adding this study are that both giants and dwarfs are included in the sample, the corrections for NLTE effects on Na are from the same grid as for metallicities, and the sample includes the reanalysis of the extensive set of disk stars by Edvardsson et al. (1993); present in both the large compilations by Venn et al. (2004) and Sobiraj and Girard (2005), we preferred to use the sample as reference.

Adopting the CA sample we may check for possible systematic differences between dwarfs and giants due e.g. to the corrections for NLTE effects on Na. Owing to large ionising corrections for NLTE effects on Na.

### Table 1. Mean properties of the samples

| nr. stars with Na | max. [Fe/H] | max. [Na/H] | evol. stage | LTE or NLTE | pop. 1 | pop. 2 | pop. 3 | comm. stars | mean off. [Fe/H] | mean off. [Na/H] | ref. |
|------------------|-------------|-------------|-------------|-------------|--------|--------|--------|-------------|----------------|----------------|------|
| G 150            | 147         | -2.61      | +0.07      | dwarfs, SGB | accret. comp. | thick disk | thin disk | -0.10 dex | $\sigma = 0.07$ | $\sigma = 0.07$ | Gratton et al. (2003) |
| CA 286           | 237         | -2.84      | +0.29      | dwarfs, giants | halo | thick disk | thin disk | 41 | +0.01 dex | $\sigma = 0.08$ | Carretta et al. (2000) |
| GR 58            | 49          | -2.31      | -0.63      | dwarfs, giants | halo | thick disk | thin disk | 14 | -0.02 dex | $\sigma = 0.09$ | Gratton et al. (2000) |
| N 94             | 94          | -1.60      | -0.63      | dwarfs | LTE | halo | thick disk | 35 | -0.06 dex | $\sigma = 0.04$ | Nissen & Schuster (2010) |
| F 178            | 174         | -3.01      | -0.05      | dwarfs, giants | LTE | halo | thick disk | 110 | +0.06 dex | $\sigma = 0.05$ | Fulbright (2000) |
| H 59             | 59          | -2.93      | -0.91      | giants | LTE | halo | thick disk | 32 | +0.27 dex | $\sigma = 0.16$ | Hanson et al. (1998) |
| GE 55            | 55          | -3.12      | -0.14      | dwarfs | LTE | halo | thick disk | 23 | -0.00 dex | $\sigma = 0.07$ | Gehren et al. (2006) |
| J 43             | 42          | -2.99      | -0.45      | turnoff, SGB | LTE | halo | thick disk | 18 | +0.06 dex | $\sigma = 0.08$ | Jonsell et al. (2005) |
| M3 100           | 100         | -2.66      | +0.25      | dwarfs, giants | NLTE | halo | thick disk | 34 | -0.11 dex | $\sigma = 0.17$ | Mishenina et al. (2003) |
| A 1111           | 1110        | -1.39      | +0.55      | dwarfs | LTE | halo | thick disk | 24 | -0.08 dex | $\sigma = 0.11$ | Adibekyan et al. (2012) |
| R 176            | 164         | -1.98      | +0.37      | dwarfs | LTE | halo | thick disk | 43 | -0.05 dex | $\sigma = 0.08$ | Reddy et al. (2006) |
| M1 142           | 142         | -0.96      | +0.32      | dwarfs | LTE | thick disk | Thin disk | 10 | +0.04 dex | $\sigma = 0.06$ | Mishenina et al. (2011) |
| B 102            | 102         | -0.91      | +0.37      | dwarfs | LTE | thick disk | Thin disk | 8 | -0.05 dex | $\sigma = 0.07$ | Bensby et al. (2005) |
| C 90             | 81          | -1.04      | +0.08      | dwarfs | LTE | thin disk | Thin disk | 5 | +0.06 dex | $\sigma = 0.05$ | Chen et al. (2000) |
fluxes and high densities, the corrections are usually less im-
portant for unevolved stars than for giants.

In Fig. 2 (left panels) we show the temperature-gravity di-
gram for stars in the CA sample (open red squares), divided
into two subsamples of different metallicity at [Fe/H] = −1 dex.
While the higher metallicity subsample contains only dwarfs
(being mostly based on the reanalysis of the Egdardson et al.
dataset), at low metallicity both giants and unevolved stars are
present. The values of [Na/H], including corrections for NLTE
effects from Gratton et al. (1999), are plotted in the right panels
as a function of the gravity. No offset in Na abundances can be
seen between low and high gravity stars.

To further reinforce our reference sample, we also added
another study from the group of Gratton and collaborators, in-
cluding in our extended reference sample the about 60 stars
analysed by Gratton et al. (2000; hereinafter code GR, see
Tab. I for further details). This is a set of stars mostly in the
metallicity range −2 ≤ [Fe/H] ≤ −1 dex, with well determined
evolutionary phases from the main sequence up to the upper red
giant branch. Again, as in CA, temperature scale and linelist are
different from those adopted by G, but the NLTE corrections
applied to Na are from the same grid used by G and CA.

In Fig. 3 stars of the GR sample are plotted as filled blue
squares. At low metallicity the sequence in the $T_{\text{eff}}$ − log $g$ plane
is well defined, and a good sampling of all the evolutionary
phases is evident. No difference in the locus occupied by stars
in the different phases is visible in the right panels, even among
the much more limited metal-rich subset.

Thus, we adopted the G sample as our favourite reference
sample, that, in combination with the CA and GR datasets,
constitutes our extended reference sample. These three sets are
separated in Tab. I from the other samples.

### 2.4. The final comparison sample

From our literature search we retained only the studies with at
least five analysed stars in common with our reference sample
G or more than 10 objects in common with the total extended
sample. Apart from the three already quoted samples, the stud-
ies we used were: Hanson et al. (1998, hereinafter code H),
Fulbright (2000; F), Chen et al. (2000; C), Mishenina et al.
(2003; M3), Jonsell et al. (2005; J), Bensby et al. (2005; B),
Gehren et al. (2006; GE), Reddy et al. (2006; R), Nissen and
Schuster (2010; N), Mishenina et al. (2011; M1), Adibekyan
et al. (2012; A). The code labels, the total number of stars and
those with Na abundances, the metallicity range, the main evo-
lutionary stage, whether the Na abundance analysis was or was
not in LTE, and the main Galactic populations sampled in each
In absolute value, the mean offsets in temperature and gravity for the 13 samples are $|T_{\text{eff}}| = 49$, $\sigma = 30$ K and $|\log g| = 0.09$, $\sigma = 0.06$ dex. Using the sensitivities of Na and Fe to variations in the atmospheric parameters listed in the original papers, we verified that the measured offsets with respect to the G scale translate into uncertainties not exceeding $\pm 0.05$ dex in [Na/H] (and similar amounts in [Fe/H]).

The final sample was obtained by eliminating all objects without Na abundance and applying the proper offsets in [Na/H] and [Fe/H] to all stars in each dataset. Stars with multiple determinations were treated according to the following criteria: (i) all stars in the G dataset were retained; (ii) for multiple measurements with no star from G, those in CA or GR samples were retained, if present, averaging their values if a star was measured in both sample; (iii) stars measured in more than one of the other samples were averaged.

The total final sample consists of 1891 individual, unique stars on the scale defined by the G sample. Among these objects, 147 are from G, 200 from CA, 32 from GR, 39 from N, 30 from F, 26 from H, 14 from GE, 9 from J, 21 from M3, 1014 from A, 88 from R, 80 from M1, 40 from B, 49 from C, and 102 are averaged values from different studies. The assembled dataset covers the metallicity range from [Fe/H]= $-3.15$ dex up to [Fe/H]= +0.48 dex. Restricting the range to the interval $-2.36 \leq [\text{Fe/H}] \leq -0.33$ dex where are located the GCs studied in the FLAMES survey by Carretta et al. (2009a,b), and the bulk of GCs in general, the field star sample includes 804 stars. A good fraction of stars, especially at high metallicity, is from the sample A, devoted to the chemical analysis of dwarf stars from the HARPS GTO planet search program. Objects outside the metallicity range most relevant for GCs could well be rejected, but we retained all the same in our final sample because it could be used in future to study the Galactic chemical evolution of Na using a large and homogeneous dataset.

In Tab. 2 we list an increasing order number, the star name, gravity and temperature, the [Fe/H] and [Na/H] values corrected to the G scale, the original sample code (AV means that the Fe and Na values from different samples were averaged), the Hipparcos name (when available; else 000000 is listed), the right ascension and declination, referred to the 2000 equinox, as listed in SINBAD. This table will be available only in electronic form at the CDS database. Here we only present a few lines as an indication of its content.

The [Na/H] values of this final sample are plotted as a function of metallicity in Fig. 4. Stars of the G sample are evidenced in this figure to show how the reference sample well covers all the range in [Fe/H] of interest for GCs.

3. Outliers in the field comparison sample

There are stars in Fig. 4 that clearly deviate from the almost linear relation between Na and Fe. This occurrence is already seen in Fig. 1 (as an increased scatter at low metallicity) and in Fig. 2 in the original samples, in particular in G, F, and H. As a consequence, this behaviour cannot be a spurious effect due, e.g., to the corrections applied to the original [Na/H] and [Fe/H] values to bring them onto the G system.
Table 2. Final sample

| n   | HD/B/H/G | log g | T_eff | [Fe/H] | [Na/H] sample | HIP  | R.A.(2000)   | DEC.(2000)   |
|-----|----------|-------|-------|--------|---------------|------|--------------|--------------|
| 0001| HD 224930| 4.32  | 5357  | −0.90  | −0.67         | G    | 171          | +27 04 16.1304|
| 0002| HD 3567  | 4.16  | 6087  | −1.22  | −1.50         | G    | 3026         | −08 18 33.3052|
| 0003| HD 3628  | 4.01  | 5704  | −0.21  | −0.10         | G    | 3806         | +03 08 13.2646|
| 0004| CD-35 0360| 4.53  | 5048  | −1.15  | −1.19         | G    | 5004         | −34 40 28.9509|
| 0005| HD 6582  | 4.46  | 5322  | −0.87  | −0.79         | G    | 5336         | +55 55 13.2264|

1- the code AV in the sample column means that the star was observed in more than one sample and the listed values of [Fe/H] and [Na/H] are averages.

Fig. 4. [Na/H] ratios as a function of the metallicity in our final sample, after correcting for the offsets in Na and Fe with respect to G. Stars in the G sample are evidenced as blue symbols.

Since our method to derive the fraction of second generation stars is based on the excess of Na with respect to a baseline provided by field stars, it is important to better understand the nature of these outliers, especially because the deviation from linearity seems to become more and more relevant just at the metal abundance of our test case NGC 6752 ([Fe/H] ≃ −1.5).

We selected in Fig. 5 those stars that seems to deviate in Na at a given metallicity from the bulk of the distribution, to understand if there is some common feature that may explain the lower than average Na abundances.

The selection of these outliers was made by eye, but is far from subjective and was checked by a linear fit in the [Na/H]-[Fe/H] plane of all the 1891 stars in the final sample. The dispersion in [Na/H] around this fit is 0.123 dex, and we checked that all candidate outliers have a sodium abundance from ∼ 2 up to 5.8σ lower than that derived from the fit at any given metallicity.

Fig. 5. Upper panel: [Na/Fe] ratios as a function of metallicity for stars in the final homogenized sample (grey triangles for dwarfs and blue triangles for giants). Larger filled circles represent stars individuated as outliers with respect to the bulk of the distribution (with no distinction between dwarfs and the few giants). Dotted line have the same meaning as in previous figures. Bottom panel: the same, but for the ratios [Na/H].

Among the 30 stars selected in Fig. 5 a good fraction (10 stars, 30%) is from the G sample. The majority belongs to the accretion component defined by G (8 stars out of 10), 6 of them being found on retrograde orbits, as does the single star from GR included among the 30 selected stars. Six stars from N (including 3 objects in common with G and another star in common with A) are all of the low-α group defined in N (see also Schuster et al. 2012).

Another third of stars in the selected set is from F (8 stars were also in common with H, and 2 are average values with H.
and M3). Most of them (7 out of 10) are on retrograde orbits. Three other stars are unique objects from H, and two of them were also found on retrograde orbits. All stars in this group from F are among the highest velocity stars in Fulbright (2002), who found for them a different pattern of abundances with respect to lower velocity stars. In particular, the mean values for the [Na/Fe] and [Mg/Fe] were about 0.2 dex lower for the high velocity group (see Figure 6 in Fulbright 2002).

One of the three low-α stars studied by Ivans et al. (2003; BD +80 245 = HIP 40068) is included in this low-Na subset, as is the common proper motion pair HD 134439/40 whose formation was associated by King (1997) to the environment typical of dwarf spheroidals on the basis of the observed underabundances in α-elements. All three stars have large apogalactic distances (about 20 kpc for HIP 40068, Fulbright 2002; more than 40 for the pair HD 134439/40, King 1997).

It is clear that the sequence of stars selected with low Na abundances in Fig. 4 is predominantly composed by objects whose origin is attributed to accretion in the dichotomy of the Galactic halo studied by several groups (e.g. Hanson et al. 1998, Fulbright 2000, 2002, Stephens and Boesgaard 2002, Gratton et al. 2003, Nissen and Schuster 2010, Schuster et al. 2012 and references therein). It is convenient to adopt for these stars the terminology used by Nissen and Schuster (1997): these objects are better seen as iron-enriched than as α− or Na-poor. They formed in regions where the usual nucleosynthesis by type II SNe produced the known amount of α−elements and Na; however, the original fragments were probably small, not much dense and with a slow star formation rate. Hence, the low-α (Na) component received chemical enrichment from both SNe II and SNeIa owing to the slower chemical evolution timescales. The increased iron yields acted to dilute the overabundance of some products from the SNe II down to the observed level.

By contrast, the bulk of stars with higher Na (the high-α group in Nissen and Schuster 1997, 2010, 2011, Schuster et al. 2012; the dissipative component in G) was generated from gas which experienced much more rapid chemical evolution, preserving the abundances of Na and α−elements. This component may have been formed in more massive primordial fragments or participated to the early collapse of the proto-Galactic cloud. In the [Na/H]-[Fe/H] plane, the latter component represents the bulk of our sample, 89% of stars in the metallicity range −2.3 < [Fe/H] < −0.8 dex is Na-normal.

4. Application of the method: the case of NGC 6752

After setting the stage, it is time to introduce our main players, the multiple populations of globular clusters. We selected NGC 6752 to test the method. This is one of the closest GC, often its stars are observed as calibrators in many spectroscopic studies, and it has been the target of several accurate abundance analyses and photometric studies as well. Among many others, nitrogen abundances were studied by Yong et al. (2008), whereas a detailed study of the Mg isotopes was performed by Yong et al. (2003). Recently, three discrete stellar populations on the RGB were recognized first by Carretta et al. (2011) by using Grundahl’s Strömgren photometry from Calamida et al. (2007); afterward, their different chemical composition was studied by Carretta et al. (2012). The discreteness of the photometric sequences was confirmed by Milone et al. (2013) with a larger set of photometric observations.

In the present context, we are interested in abundances of proton-capture elements, in particular Na. One of the largest sample was analyzed in Carretta et al. (2007), where Fe, Na, O abundances were derived for about 150 giants using the multi-fiber FLAMES spectrograph. These data were complemented by Al, Mg, and Si abundances in Carretta et al. (2012). Smaller samples, but generally based on higher resolution and high S/N spectra, are from Yong et al. (2005, 2008) and Grundahl et al. (2002). We will mainly employ the samples from Carretta et al. to better exploit the homogeneity of data.

The stars in NGC 6752 from Carretta et al. (2007) are compared to field stars in the present final sample in Fig. 5 to illustrate our method. Different symbols indicate the P, I, and E components as defined in Carretta et al. (2009a) by using stars with both Na and O abundances. Cluster stars with only Na measured are also indicated (open star symbols).

Even from this large scale figure it is evident that about 2/3 of stars in NGC 6752 stand clearly off the distribution of field stars, implying that these are actually stars with chemical composition modified by processes involving proton-capture reactions and only restricted to the cluster environment.

The sample of cluster and field stars ultimately rest on the same scale concerning the line lists and NLTE corrections.
Fig. 7. [Na/H] ratios as a function of effective temperature to test the concordance between field and cluster stars with nucleosynthesis from SNe. Filled symbols are stars in NGC 6752 from Carretta et al. (2005, 2007). Empty symbols are field stars in the present final sample. Circles indicate giants and squares represent dwarf/subgiant stars.

for Na. However, the effective temperature scales adopted in Carretta et al. (2007) and in the reference sample G are different, and the presence of the low-Na field stars mainly from the accretion component may generate a doubt on the vertical normalization. To check this issue and nail down the samples we used stars with pure nucleosynthesis from SNe, both in field and in NGC 6752, as follows.

We selected a range of ±0.2 dex in [Fe/H] centered on the average metallicity of NGC 6752 ([Fe/H] = −1.56 dex, Carretta et al. 2009c). We then plotted in Fig. 7 as a function of the effective temperature the [Na/H] ratios of all stars from Carretta et al. (2007) with [Na/Fe] < +0.05 dex and the four most Na-poor scarcely evolved stars from Carretta et al. (2005), three turn off stars and one subgiant. This set of cluster stars is then chosen purposely to represent the primordial stellar population in GCs, the one reflecting only nucleosynthesis from SNe.

From the present final sample we then selected stars in the same metallicity range, and matching the temperature and gravity ranges of cluster stars. These field stars are plotted in Fig. 7 and blend in with cluster stars very nicely. There is no systematic difference in the [Na/H] content. Furthermore, the sensitivity of [Na/H] to a change of 50 K in $T_{\text{eff}}$ is only 0.04 dex (Carretta et al. 2007), and to bring the average [Na/H] = −1.6 dex down to about −2.3 (to match the sequence of low-Na stars at the metallicity of NGC 6752) would require a change/error of 875 K in temperature, frankly unrealistic.

These are stars studied in Gratton et al. (2001) and simply reanalyzed in Carretta et al. (2005) by using updated line list and damping parameters, used afterward for GC giants.

We could then safely proceed to the comparison between the distributions in [Na/H] of field and cluster stars. An enlargement of Fig. 6 is shown in Fig. 8. From this Figure it is evident that the division in components as defined in Carretta et al. (2009a) using both Na and O abundances is approximately still valid.

A few outliers field stars can be seen superimposed to the stars in NGC 6752: HD 93529, BD+54 1323, and BD+52 1601 (Fig. 9). It is however dubious that they could represent new
cases of second generation GC stars lost to the field. The first is from the H sample, is found on a retrograde orbit and could be originated into a fragment accreted in the Galaxy, maybe experiencing a peculiar chemical evolution. Travaglio et al. (2004) reported BD+54 1323 among the stars suspected of AGB contamination, likely by mass transfer from a past companion, since for this star Burris et al. (2000) measured high values of light $s$-process elements. Finally, BD+52 1601 is listed in the Fourth Catalog of Interferometric Measurements of Binary Stars with a period of 9 hours.

Excluding these three outliers, we estimated that the upper envelope of the field star distribution can be put at $[\text{Na}/\text{H}] \sim -1.3$ dex (Fig. 10 dashed line), by comparing the distribution of field and cluster stars in the metallicity range $-1.7 <[\text{Fe}/\text{H}]< -1.4$ dex. This value corresponds well to the 3-$\sigma$ upper deviation ($[\text{Na}/\text{H}]=-1.33$ dex) from the field star relation obtained by eliminating iteratively all the outliers around the fit $[\text{Na}/\text{H}]$ vs $[\text{Fe}/\text{H}]$ in the metallicity range $-2.4 <[\text{Fe}/\text{H}]< -0.3$ dex, as suggested by the referee.

Adopting the limit in $[\text{Na}/\text{H}]$ at -1.3 dex as the boundary between first and second generation stars in NGC 6752, we counted 36 and 97 stars in the two groups, respectively. On a total of 133 stars with Na abundances, we then derived fractions of $27 \pm 5\%$ and $73 \pm 7\%$ for the first and second generation components in NGC 6752, where the associated errors are from the Poisson statistics. These values are in perfect agreement with the fractions $27 \pm 5\%$ (P) and $73 \pm 9\%$ (I+E) obtained in Carretta et al. (2009a) by using only the 98 stars with both Na and O abundances.

This new method is conceptually similar to that employed in Carretta et al. (2009a), but the present variation allow us to make use of all stars with a measured Na abundances, decreasing the statistical errors because it is usually easier to measure abundances of elements that are enhanced (and not depleted) in the proton-capture reactions and have much stronger line strengths. Obviously, the present method is blind to the separation between the intermediate and extreme components of second generation stars.

For a further consistency check we used also the smaller sample of 37 stars along the RGB in NGC 6752 presented in Yong et al. (2005). Na and Fe abundances were derived from spectra generally of higher-resolution and S/N than most stars in Carretta et al. (2007); these abundances were obtained using different scales of atmospheric parameters and line lists. However, there are 14 stars in common between the two samples: the differences in $[\text{Fe}/\text{H}]$ and $[\text{Na}/\text{H}]$ (in the sense Carretta minus Yong) are shown in Fig. 11.

On average, the offset in $[\text{Fe}/\text{H}]$ is not significant (0.046 dex, with an r.m.s. scatter of 0.041 dex, 14 stars). However, a clear trend as a function of temperature does exist, probably due almost entirely to the NLTE corrections for Na (adopted from Gratton et al. 1999 in Carretta et al., neglected in Yong...
et al.). They are relevant as both samples cover a large interval in luminosity and temperature along the RGB in this nearby cluster. We then fitted a linear regression through the data in the lower panel of Fig. 11 and derived the correction as a function of the effective temperatures by Yong et al. required to shift their abundances on the system used in the present work.

The separation between first and second generation at $[\text{Na}/\text{H}]=-1.3$ dex also in the case of the corrected data by Yong et al. (Fig. 12) returns values in good agreement with our previous findings: we found that 11 stars out of 37 (30 ± 9%) have a primordial composition consistent with that of field stars, whereas 26 stars (70 ± 14% of the sample) belong to the second generation in NGC 6752.

5. Final thoughts on the formation of the Galactic halo

In the present work we discussed how second generation stars in globular clusters may be selected from their excess in Na above the level established in field stars. However, there are also a few field stars with chemical signatures that indicate a very likely origin in GCs. Some begin to be serendipitously individuated thanks to their Na excesses (Carretta et al. 2010; Ramírez et al. 2012); in other cases focused studies purposely search for second generation GC stars lost to the field by looking at excess in the CN band strength (Martell et al. 2011).

Stars with typical chemistry of second generation stars in GCs are thus rather easy to be recognized in the Galactic field. However, we have indirect evidence that the bulk of the contribution of GCs to the halo must be in form of stars bearing the primordial composition of first generation stars. This conclusion stems (i) from the observed proportion of the stellar generations in GCs (~ 30% primordial, ~ 70% polluted), (ii) from the evidence that the second generation stars are formed from gas polluted by a fraction only of first generation stars (the most massive), and (iii) from consequent theoretical considerations and modeling (see e.g. Bekki et al. 2007, D’Ercole et al. 2008, Vesperini et al. 2010, Schaerer and Charbonnel 2011 and references therein). All these studies invoke a massive loss of almost all the primordial stellar generation in early GCs (that were likely several times more massive than present-day GCs), to correctly reproduce the currently observed ratio of multiple populations without the need of ad hoc initial mass functions (IMFs). These stars would be not distinguished from normal halo field stars from their chemical composition alone (this is just the foundation of the present approach), but, if present, they would be intermingled with the bulk of the field stellar distribution.

However, we also signaled the presence of outliers, field stars with low Na abundances, that are claimed by several studies to come from small fragments accreted in the halo. A not exhaustive comparison of this component with the chemical pattern of a few dwarf spheroidals (dSphs) is given in Fig. 13. Most of the giants studied in dSphs have a tendency to lie below the main distribution of Galactic field stars in the $[\text{Na}/\text{H}]-[\text{Fe}/\text{H}]$ plane (see also Fig. 12 in Tolstoy et al. 2009, with the more classical $[\text{Na}/\text{Fe}]$ ratios). These stars well agree with the accretion component of the Galaxy. Unfortunately, we have no stars in common with the analyses in dSphs to bring them on our common system. However, the same line of reasoning as above suggest that different studies should be anyway consistent within a few hundredths of dex, else the temperatures

**Fig. 12.** As in Fig. 8 but using for NGC 6752 the 37 stars from Yong et al. (2005; red circles), corrected to the system of Na and Fe abundances of the present work.

**Fig. 13.** Comparison of our final sample of field stars with stars in four dwarf spheroidals: Draco (Cohen and Huang 2009; Shetrone et al. 2001), Sculptor (Kirby and Cohen 2012, Shetrone et al. 2003, Geisler et al. 2005), Carina (Shetrone et al. 2003, Venn et al. 2012, Koch et al. 2008), and Leo I (Shetrone et al. 2003).
would be wrong by several hundreds of kelvin, an unpalatable option.

Hence, the results of this triple comparison (Galactic field stars, GCs, dSphs) seem to suggest/hint that at least two classes of objects contributed to the building up of the Galactic halo. On one hand, some fragments were similar to the present-day dwarf spheroidal still orbiting our Galaxy, in particular in the low metallicity regime (see also Tolstoy et al. 2009). On the other hand, a more important fraction of the halo seems to have formed in larger fragments, whose higher mass allowed to reach quickly the same metallicity level of the component of the Galaxy undergoing dissipative collapse at the same epoch. The ensuing location of first generation stars lost at early epochs in GCs and of the field stars of the dissipative component is then undistinguishable, at present, and corroborate this dual channel for the origin of part of the halo.

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