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Reading the book: from "chemical anomalies" to "standard composition" of globular clusters

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Abstract. It is now commonly accepted that globular clusters (GCs) have undergone a complex formation and that they host at least two stellar generations. This is a recent paradigm and is founded on both photometric and spectroscopic evidence. We concentrate on results based on high-resolution spectroscopy and on how we moved from single to multiple stellar populations concept for GCs. We underline that the peculiar chemical composition of GC stars is fundamental in establishing the multiple populations scenario and briefly outline what can be learned from observations. Finally, recent observational results on large samples of stars in different evolutionary phases are discussed.

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

1. Introduction

We presently understand that globular clusters (GCs) are more complex than believed in the past. GCs do not host a single coeval, chemically homogeneous population but show clear evidence of at least two generations, slightly different in age but having (very) different chemical composition. This is manifest from the colour-magnitude diagrams if the photometry is very precise and/or obtained with filters able to enhance the differences (e.g., D'Antona et al. 2005; Piotto et al. 2007 for NGC 2808, Milone et al. 2008; Han et al. 2009 for NGC 1851) and more generally from the chemistry (e.g., Gratton et al. 2012). The topic is huge, so we will limit the discussion to the most recent results in the field of our main expertise, i.e., high-resolution spectroscopy. Thus, even if the first variations were noticed in the very light elements C and N, we will leave them aside (as we will do for Li and F) and concentrate here on other elements.

There are several chemical elements that present star-to-star variations in GCs (see

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Table 1. Which elements show variations and (anti-)correlations and where (see Gratton et al. 2012 for updated references).

Elements	Where	Notes
C, N	field stars and all GCs	C,N variations in GCs have primordial variation in addition to evolutionary one
O, Na	(almost) all GCs	see Fig. 1 for exceptions
Mg, Al	some GCs	metal-poor and/or massive GCs
Si	some GCs	metal-poor and/or massive GCs
Li, F	all (?) GCs	very few GCs studied
He	all (?) GCs	small variation in most GCs, large variation in a few (e.g., ω Cen, NGC 2808)
n-capture	in a few GCs	usually if also Fe varies?
Fe	in a few GCs	ω Cen, Ter 5, M22, M54, NGC 1851
K	NGC 2419	varies much less in other GCs, from a few data

Table 1). These variations are not random, rather some elements are found depleted in some stars when other are found enhanced in the same stars. Summarizing, in a typical GC we have **a)** stars with "normal" He, C, O, Mg, Na, and Al (first-generation stars) and **b)** stars with depleted C, O and enhanced He, N, Na (second-generation stars). Sometimes, **b1)** also depleted Mg and enhanced Al are seen, and/or **b2)** He may be strongly enhanced. **c)** Very rarely, Fe or heavier elements present significant variations.

1.1. The classical couples: Na and O, Al and Mg

Maybe the most famous relation is between Na and O. These elements vary in step, with O being depleted and Na enhanced, and this happens only in GC stars (see Gratton, Sneden, & Carretta 2004, where the work of the Lick-Texas group, who pioneered the field, is described). The finding of an Na-O anticorrelation also in non-evolved stars (Gratton et al. 2001; Ramírez & Cohen 2002 and more authors later) has been the final piece of evidence that these variations are not evolutionary, but have been imprinted in the stars at birth and are due to the contribution of a previous stellar generation. In fact low-mass, non-evolved stars are not able to sinthesise Na (their core does not reach the very high temperatures required to produce it through H-burning) and bring it to the surface.

Recent work on the Na-O anti-correlation has benefited from the high-multiplexing, high-sensitivity, high-resolution spectrographs on large telescopes. It has been possible to study the phenomenon in large samples of stars -of the order of 100 stars per cluster- in many GCs with very precise measurements, so that quantitative analyses and comparisons could be made. This has been done for stars on the red giant (RGB, see e.g., Marino et al. 2008; Carretta et al. 2009a,b; Johnson & Pilachowski 2012, for M4, 15 and 17 GCs, and M13, respectively), main sequence (MS, see e.g., Carretta et al. 2004; D'Orazi et al. 2010), and horizontal branch (HB, see e.g., Gratton et al. 2011, 2013; Marino et al. 2011c). It is very interesting to see that the Na-O anticorrelation, while always present, is different from cluster-to-cluster, having different extension and shape; these differences seem correlated with general clusters properties (see Carretta et al. 2010a).

At temperatures even higher than those at which Na is produced, Mg can be burned into Al. However, this appears to happen only in a subsample of clusters; Carretta et al. (2009b) studied 18 GCs, finding a significant Al enhancement in about one half of them. Studying the way this happens especially in the more metal-poor or more massive GCs, can give us insights on the nature of the stars that polluted the gas from which the second generation formed. We will come back to Al below.

1.2. As light as He

What produces the light elements variations is H-burning at high temperature, so it is simply natural that also He should vary. The influence of He abundance on the evolutionary sequences, especially the HB and MS, can be seen using photometry (e.g., Bedin et al. 2004; D'Antona et al. 2005; Piotto et al. 2007; Sbordone et al. 2011). However, in some "fortunate" cases, He abundance can be directly measured, not only inferred from the comparison to models. Generally, He lines are visible in hot stars, but Dupree et al. (2011) and especially Pasquini et al. (2011) were able to measure He in RGB stars (in ω Cen and NGC 2808, respectively). An easier task would seem to measure He in HB stars, and this has been done in a few cases (NGC 6752, M4, NGC 1851, M5: Villanova et al. 2009, 2012; Gratton et al. 2011, 2013) but it requires the right temperature, high resolution spectra, and very high S/N, so it is a difficult task. However, observations confirm that stars assigned to the second generation on the basis of their Na and O abundances have higher He content than first-generation stars.

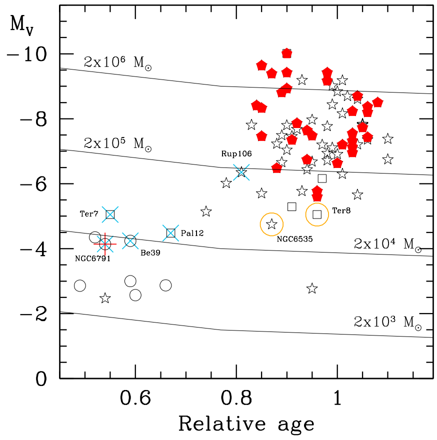

Fig. 1. Relative age parameter vs. absolute magnitude for globular and old open clusters (for a detailed description, see Bragaglia et al. 2012, from which the figure is taken). Red filled symbols are GCs where the Na-O anti-correlation has been observed; open symbols stand for GCs not observed or old open clusters. Light blue crosses indicate clusters that do not show evidence of Na-O anti-correlation: two GC members of Sagittarius dSph, Rup 106, and the two massive, old OCs, Be 39 and NGC 6791 (the latter indicated also in red, since its situation is still not completely assessed). Two orange, large circles indicate GCs with work on-going.

1.3. Heavier elements

Apart from ω Cen and Terzan 5 (Ferraro et al. 2009), there are a few more GCs for which also iron and heavier elements vary from star-to-star, probable indication of a formation mechanism even more complex than for normal GCs. One classical example is M22, for which a demonstration of true Fe dispersion has only recently been produced (see e.g., Marino et al. 2009, 2011b, who showed the presence of two groups, with neutron-capture elements correlated with Fe abundance). Another case is M54, for which we (Carretta et al. 2010b,c) showed that the Fe-poor and Fe-rich components have both an Na-O anti-correlation and that they are different, similar to what is found in ω Cen (Johnson & Pilachowski 2010; Marino et al. 2011a); the two clusters could have formed in a similar way and be in a different evolutionary stage. Finally, NGC 1851 has been the target of many recent studies, since it shows many interesting features, like a split subgiant branch (Milone et al. 2008), possibly tied to variations in CNO content and/or to age difference (e.g., Cassisi et al. 2008; Ventura et al. 2009), dispersion in Fe and the possibility that it originated from a merger (Carretta et al. 2010d, 2011), the presence of enhanced n-capture elements correlated with the light elements (e.g., Yong & Grundahl 2008; Yong et al. 2009; Carretta et al. 2011), etc. It is clearly a cluster that merits further attention.

2. The "universality" of the Na-O anti-correlation in GCs

We have seen that the Na-O anti-correlation seems a general feature of GCs, so that we have proposed (Carretta et al. 2010a) that it could be used as a sort of definition, indicating those clusters that are massive enough and were born in an environment that favoured gas accumulation and production of a second generation. This universality is shown in Fig. 1, where the separation between old, massive GCs, hosting multiple populations and younger, less massive open clusters (OCs), home of a single population, seems natural. However, the region in-between still needs to be studied and we have begun to investigate which is the lower mass at which multiple populations can manifest (recalling, however, the distinction between present-day and original cluster mass). Results are still not univocal for the old OC NGC6791, where Geisler et al. (2012) find an Na-O anti-correlation while our work, still ongoing, does not. They are instead very clear for Be 39, which we find very homogeneous and composed by a single population (Bragaglia et al. 2012). Further clusters are under exam by our group or by others (e.g., Ter 8, in which the Na-O anti-correlation, if present, seems to be less extended than in more massive clusters, or Rup 106, which does not show any) but the complete analyses are not published yet.

3. Recent results and old questions

An important diagnostic to understand what went on at the GC formation and during the early evolution is the continuous or discrete behaviour of properties. Photometrically, it has been demonstrated that there are discrete distribution of He in MS or on the HB (e.g., D'Antona et al. 2005; Piotto et al. 2007, 2005, for NGC 2808 and ω Cen), and discrete components show up along other evolutionary sequences, especially when the right filter combinations are used (e.g., Milone et al. 2012).

Spectroscopically, we need to obtain both large samples and precise measures to check if distinct groups can be isolated by their chemical properties. This has been possible for instance in M4, where Marino et al. (2008) separated two distinct groups in the Na and O distribution, and in NGC 2808, where we see three groups, reminiscent of the tripartition of the HB and of the MS (Carretta et al. 2006). A good element to study seems to be Al. For instance, in NGC 6752 we were able to see three groups in the ratio [Al/Mg]; they can be traced on the RGB using the Strömgren index c_y, defined by Yong et al. (2008) to measure N. So we can tie the CNO, NeNa, and MgAl cycles together. For this cluster, the intermediate population cannot be obtained diluting the two extremes, so it seems to require two episodes of formation and two different first-generation polluters.

Finally, we only briefly mention the recent finding of an anti-correlation between Mg and K in NGC 2419 (Cohen & Kirby 2012; Mucciarelli et al. 2012), a very enigmatic cluster. The extreme values found both for Mg and K seem to be an unicum, at least based on the scanty data available at the moment (Carretta et al., in prep.). Maybe this is an extreme manifestation of the usual Mg depletion (Ventura et al. 2012), but it is certainly worth further investigation, to understand what makes this cluster so peculiar.

We are learning every day more on the clusters' formation mechanism(s), but still many fundamental questions, all tied together, remain to be answered: a) do we have continuous star formation or separate episodes, b) are all Milky Way GCs formed in the same way, c) and do they differ from those in dwarf galaxies, d) can we find very young GC-analogs to study the early stages directly, e) is one class of polluters enough to explain all GC properties, f) what are the best diagnostic on which to focus?

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