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Anomalous globular clusters: insights from neutron capture elements abundances

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Abstract. Thanks to the large amount of spectroscopic and photometric data assembled in the last couple of decades, the assumption that all globular clusters (GCs) contain a simple mono-metallic stellar population has been modified. Besides the common variations in the elements created/destroyed in the H-burning processes, spreads and/or multi-modalities in heavier elements have been detected in a few objects. Among the most remarkable chemical inhomogeneity in these *anomalous* objects is the internal variation in the neutron-capture (*n*-capture) elements, that can provide some information about the material from which stars were born. I report a summary of the chemical pattern observed in GCs where variations in *n*-capture have been detected, and the connection between these chemical features and the distribution of stars along the color-magnitude diagrams in the context of the lively debate on multiple stellar populations.

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

1. Introduction

In recent years, observational evidence, both from high resolution spectroscopy and from photometry, has established that GCs can host more than one stellar population. Nearly all the GCs studied with a good statistics show internal variations in the elements involved in the H-burning reactions, e.g. C, N, O, Na, Mg, and Al (Carretta et al. 2009). In these clusters, that we may call *normal* GCs, stellar abundances of elements heavier than those affected by H-burning resemble the halo field compositions at similar metallicities, and show internal consistency within observational errors.

Recent spectroscopic studies have revealed some chemical anomalies, i.e. some GCs have variations not only in light elements, but also in the bulk heavy element content, and significant metallicity dispersions. In some cases, these chemical anomalies are connected to peculiar distribution of stars along color-magnitude diagram (CMD), e. g. split/broad sub-giant branches (SGBs)

GCs proven to be *anomalous* include NGC 6656 (M22, Marino et al. (2009), Da Costa et al. (2009); NGC 2419, Cohen et al. (2010); Terzan 5, Ferraro et al. (2009); NGC 1851, Yong & Grundahl (2008); Carretta et al.

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(2011)), and the Sagittarius dwarf galaxy central cluster M54 (Sarajedini & Layden 1995; Carretta et al. 2010). All these objects share superficial similarities with the most massive and peculiar GC ω Cen (e.g. Da Costa & Marino 2011), whose huge metallicity variations have been known since the 1970s (e.g. Dickens & Woolley (1967), Freeman & Rodgers (1975), Norris & Da Costa (1995), Suntzeff & Kraft (1996); and more recently Johnson & Pilachowski (2010); Marino et al. (2011b)). In addition, some of these *anomalous* clusters show intriguing chemical star-to-star variations in the abundance of the n-capture elements relative to Fe.

In the following I discuss the observational scenario for *anomalous* GCs, focusing on the two cases of M22 and ω Cen, with connections between the chemical abundances of the stars and their position along the CMD. Preliminar results for the case of 47 Tuc, where a split SGB has been recently detected, have been also discussed in the context of the chemistry-multiple SGBs connections.

2. n-capture element variations in GCs

The study of the star-to-star n-capture elements variations provides fundamental knowledge about the history and nature of nucleosynthesis in *anomalous* GCs. Indeed, n-capture elements can be synthesized from the rapid (r) and slow (s) n-capture processes, expected to occur in different stellar environments, i.e. in explosive environments the former (e.g. Wasserburg & Qian 2000), and in long-lived low and intermediate-mass stars the latter (e.g. Busso et al. 1999; Karakas et al. 2012). In particular, abundance variation in elements predicted to be almost entirely produced in r (e.g. Eu 97% r, Simmerer et al. 2004) or s processes can give potential insights about the chemical enrichment in *anomalous* GCs.

In the multi-variegate zoo of *anomalous* GCs, there are objects representative of both r and s-capture element enrichment. Sneden et al. (1997) have shown that the GC M15 shows a Ba-Eu correlation, with evidence for a bimodal distribution on the [Ba/Eu] vs. [Eu/Fe]

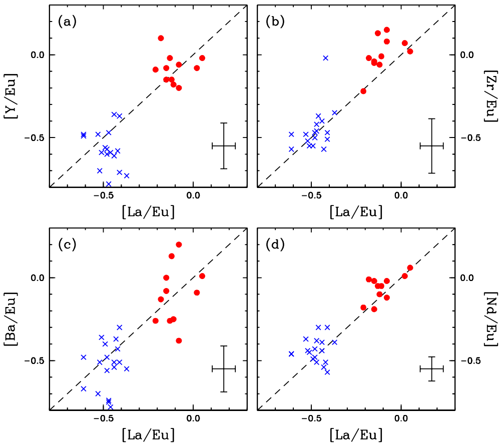

Fig. 1. Y, Zr, Ba, and La abundances relative to Eu as a function of [La/Eu] in M22 from Marino et al. (2011a). In each panel, the dashed line represents equality of the displayed abundance ratios. Filled circles are used for stars with s-process enhancements and $\times$ symbols are for stars without such enhancements.

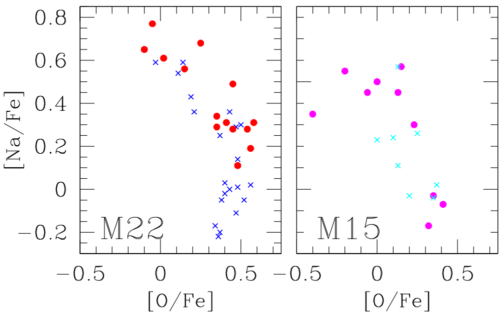

Fig. 2. Na-O anticorrelation for M22 s-rich and s-poor stars from Marino et al. (2011a) (symbols are as in Fig. 1), and for stars in M15 (from Sneden et al. 1997). For the M15 Sneden et al. sample, cyan points represent stars with [Eu/Fe]<0.50 dex, and magenta points stars with [Eu/Fe]>0.50 dex.

plane (see their Fig. 6). Although in principle, r processes can contribute to the Ba production, the correlation with Eu points towards a main contribution from r-processes.

Omega Cen, NGC 1851, and M22 show different degrees of variations in n-capture elements, but, at odds with M15, the [Eu/Fe]

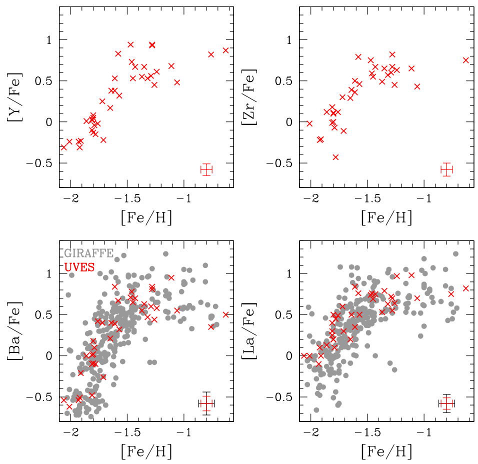

Fig. 3. Y, Zr, Ba, and La abundances relative to Fe as a function of [Fe/H] in ω Cen. Gray points are GIRAFFE data (from Marino et al. 2011a), red points are UVES data (from Marino et al. (2013a), in prep.).

abundance does not vary within errors. In fact, successive stellar generations in these objects may have formed from material processed in low-mass stars asymptotic-giant branch (AGB) stars. A summary of the chemical pattern of ω Cen and M22 is the subject of next sections.

2.1. M22

For a long time ω Cen was considered the unique GC with internal overall metallicity variations. Thus the recent discovery (Marino et al. 2009) of an intrinsic Fe variation in M22 confirmed from high-resolution spectroscopy was surprising. The most striking chemical feature of M22 is the bimodality in the content of elements mainly produced in the *s* elements (Marino et al. 2009, 2011a; Roederer et al. 2011).

As shown in Fig. 1 (from Marino et al. 2011a) there is a bimodality in the distribution of *s*-process elements in M22, while the *r*-process Eu is constant within our observational errors. A stellar group is enriched in *s*-process abundances (*s*-rich) with respect to the other *s*-poor stars (see Marino et al. (2011a) for a definition). This bimodality corresponds to a different C+N+O content (Marino et al. 2011a; Alves-Brito et al. 2012). Interestingly, each *s*-group individually defines a Na-O anticorrelation (left panel in Fig. 2), suggesting that both have suffered from the same enrichment occurred in normal GCs. A spread in O and Na is also present in each stellar group in M15, that, at odds with M22, shows evidence for an enrichment due to *r*-processed material (Sneden et al. (1997); right panel of Fig. 2).

2.2. Omega Centauri

The complex multiple stellar population phenomenon in ω Cen manifests in an intricate chemical pattern. The understanding of the chemical enrichment history of this object is challenging and requires the knowledge of the chemical composition of its hosted (maybe discrete) stellar populations.

The large spread in Fe in this cluster is known since a long time. However, in recent years, thanks to the spectroscopic homogenous analysis of large samples of stars in this GC, at mid and high resolution, it has been possible to study in more details the chemical patterns of stars at different metallicities (e.g. Johnson & Pilachowski 2010; Marino et al. 2011b).

The run of the *n*-capture elements Ba and La as a function of metallicity from the Marino et al. (2011b) GIRAFFE dataset is shown in Fig. 3 (lower panels). Super-imposed to this dataset is a sample of stars studied at higher resolution with UVES. For this sample the abundances of Y and Zr have also been measured (Marino et al. 2013a). All these elements show a range larger than 1 dex, and a clear growth with metallicity up to [Fe/H]~ -1.5; for higher metallicities the distribution is flat (see also Norris & Da Costa 1995; Smith et al. 2000; Johnson & Pilachowski 2010).

Similarly to M22, variations in C+N+O abundances have been detected (Marino et al. 2012) in ω Cen. The a Na-O anticorrelation is present along almost the entire metallicity range with the exception of the most metal

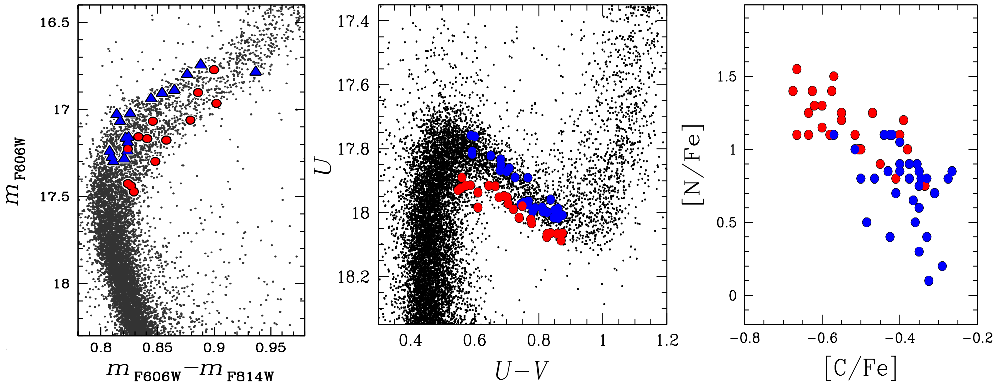

Fig. 4. *Left panel*: M22 double SGB in the $m_{F606W} - m_{F606W}$-m_{F814W} CMD (from Marino et al. 2012); *Right panels*: U-($U - V$) CMD for 47 Tuc zoomed on the SGB. Stars in red and blue are our spectroscopically analysed stars on the faint and bright SGB, respectively. The C and N abundances of these stars has been reported on the N-C plane from Marino et al. (2013b).

poor and most metal rich stars (Marino et al. 2011b; Johnson & Pilachowski 2010).

To explain the intricate chemical pattern observed in ω Cen, D'Antona et al. (2011) suggested that successive generations of increasing metallicity could form from massive AGB ejecta diluted with the infalling iron-enriched pristine matter. This is predicted to occur until the diluting material is exhausted. Later on, the most metal rich stars in the cluster may have been formed directly from the massive AGB ejecta, and shows a direct Na-O correlation (as suggested by the data sample presented in Marino et al. 2011b; Johnson & Pilachowski 2010). However, as D'Antona et al. (2011) pointed out the large growth in the abundances of s-process elements observed in this peculiar cluster remains difficult to be understood within a chemical evolution model.

3. Connections with the CMD

The *anomalous* GCs have been extensively photometrically investigated. Photometry from *Hubble Space Telescope* has revealed that M22 and NGC 1851, that are chemically similar (Marino et al. 2009; Yong & Grundahl 2008; Carretta et al. 2011; Lardo et al. 2012), show a split SGB (Milone et al. 2008; Piotto et al. 2012).

The analysis of GIRAFFE spectra of M22 SGB stars presented in Marino et al. (2012) has demonstrated that the two SGBs are populated by the two s stellar groups (see Sect. 2.1), and the split can be ascribed to the different CNO content observed on the RGB (Marino et al. 2011a), as predicted by Cassisi et al. (2008) and Ventura et al. (2009).

When appropriate colours, e.g $U - V$, are used to construct the CMD, the two SGBs in M22 evolve in a double red-giant branch, associated with metallicity+CNO variations (Marino et al. 2011a, 2012). A CMD showing the position of the M22 stars with different s content on the SGB has been shown in Fig. 4 (left panel). The fact that an *anomalously* multi-modal SGB has been observed in the clusters with s element variations, suggets that the two phenomena may be strictly connected, as higher s abundances are correlated with C+N+O abundances.

A split SGB has been recently observed in the massive GC 47 Tuc (Anderson et al. (2009), Milone et al. (2012), di Criscienzo et al. (2010), right panel in Fig 4). In this case there are no measurements of n-capture on SGB stars. Preliminar results for chemical abundances in the light elements C and N of SGB stars in 47 Tuc reveal that the fainter SGB hosts stars with higher N content (Fig 4 from Marino et al. 2013b).

4. Conclusions

We are discovering the presence of peculiarities in GCs, e.g. heavy element internal variations, complex (anti)correlations among light elements. Some GCs show variations in the chemical abundance of *n*-capture elements due to enrichment from *s*-processes, in some cases, or *r*-processes in other cases. The variation in *s*-elements appears to be linked to peculiarities in the CMDs, such as the SGB splits that have been associated with C+N+O variations. The *r*-process enrichment in GCs seems to not be linked to such peculiarities along the CMD.

Many issues are still contrived in depicting a picture for the formation of multiple stellar populations, in particular for the *anomalous* GCs, e.g.: *(i)* the nature of the polluters for the *n*-capture enrichment; *(ii)* if an unique scenario can explain the heterogeneity of the multiple population zoo; *(iii)* the possible extragalactic origin for *anomalous* GCs.

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