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A timeline explains the variety of multiple populations in globular clusters

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Abstract. In the first instance, the reliability of models proposed to explain the formation of multiple populations in Globular Clusters depends on their capability to achieve the nuclear reactions products displayed by the abundances variation of light elements. All these reactions can take place in the framework of the Asymptotic Giant Branch scenario, but not all of them are possible in the other proposed models. In addition, this scenario provides a 'timeline' for the nucleosynthesis, which can be matched with the variety of abundance anomalies displayed by different GCs, providing a coherent framework of interpretation.

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

1. Introduction

Two papers recently examined the problems posed by the presence of multiple populations in Globular Clusters (GC), to discern which formation models could comply with such problems taken one by one. Interestingly, Renzini et al. (2015) "saved" —with lot of reservation— the Asymptotic Giant Branch (AGB) model (Ventura et al. 2001; D'Ercole et al. 2008), the first one to be proposed (Norris et al. 1981; D'Antona et al. 1983). On the contrary, Bastian et al. (2015) analysis did not save any model. In spite of this analysis, *all* models proposed so far are listed in the recent literature at the same level of reliability/unreliability.

D'Antona et al. (2016) discussed that the main requirement for a model is that it must be able to deal, at least qualitatively, with *all* the chemical constraints imposed by the abundances displayed in GCs second generation (SG) stars. Here I summarize why all models proposed so far, apart from the AGB one, face insurmountable difficulties to deal with some important chemical patterns of multiple populations. In fact, the AGB model also provides a framework in which the variety of abundance patterns can be explained within a scheme of "nature and nurture" evolution.

2. The helium content

One of the most interesting signatures in SG stars is that their helium abundance is moderately larger, and sometimes much larger than the standard value expected in old metal poor stars, close or equal to the Big Bang abundance. The "extreme" populations (largely oxygen depleted, and, where measured, also magnesium depleted) hosted in a few massive clusters may show a large helium enhancement (by a mass fraction increase $\Delta Y \gtrsim 0.1$), generally well distinguished by the rest of the clusters' stars, a signature of "discreteness" which may be one of the most important constraints to any models (Renzini et al. 2015). In most models the helium yield is directly related to the relevance of the p-captures which characterize the chemical anomalies, but *none* of these models is able to account either for the discreteness or for the amplitude of the helium enhancement in the extreme populations, apart from the AGB model in the version suggested by D'Ercole et al. (2008). In particular, the early disk accretion (EDA) model proposed by Bastian et al. (2013) does not meet the required high helium content of the extreme population not its discreteness (Cassisi & Salaris 2014; D'Antona et al. 2014), while the fast rotating massive stars (FRMS, e.g. Decressin et al. 2007) model predicts the formation of SG stars with even much larger helium abundances, up to Y$\sim$0.8. According to observations, stars with Y$\gtrsim$0.4 are totally absent in GCs, so that this latter model is forced to invoke the additional hypothesis that star formation is not possible above a limiting Y value, as suggested by Wang et al. (2016). The discreteness is also impossible in the FRMS model, unless other contriving rules are devised.

The AGB model in its most popular form (D'Ercole et al. 2008) attributes the extreme populations, with their high and quite uniform Y, to star formation in the undiluted ejecta of the most massive AGB and super–AGB stars, which have Y abundances of ∼0.36–0.38, according to modeling (Doherty et al. 2014, and references therein). Finding an extreme population with larger Y would then be in contrast with this model.

I remark most measurement of Y are indirect, so that they should never be taken at face value. For example, the value of the extreme Y may be a result of the analysis of the $T_{\rm eff}$ distribution and extent of the horizontal branch (D'Antona et al. 2002) but this kind of determination depends on at least two more input parameters: 1) the mass lost on the red giant branch, before the remnant settles in the He–core burning phase, and 2) the precise metallicity and alpha–enhancement of the cluster stars. di Criscienzo et al. (2011) derived a value Y=0.42 for the extreme blue HB stars in NGC 2419, but Di Criscienzo et al. (2015) revised the value down to Y=0.36, when they adopted an updated, larger metallicity for the cluster stars[1]. Y=0.42 was formally incompatible with the AGB model, while Y=0.36 is not. The first determinations of Y from the blue main sequence of NGC 2808 gave Y$\sim$0.4 (D'Antona et al. 2005; Piotto et al. 2007), but the recent re-analysis by Milone et al. (2015) limits ΔY$\sim$0.1 between the red main sequence (their group B) and the blue main sequence (group E), while identifying a further, redder sequence (group A) which, interpreted in terms of helium, would add a ΔY=–0.03 with respect to group B. In any case, the maximum Y value for sequence E is between Y=0.35 and Y=0.38.

A direct understanding of the discreteness of the high-Y group is provided by the D'Ercole et al. (2008) dynamical model including pristine gas re-accretion onto the cluster. When re-accretion occurs, star formation shifts suddenly from the composition of the pure AGB ejecta to the composition of the ejecta mixed with the standard–Y re-accreted gas.

The hypothesis of re-accretion has been criticized by (Bastian et al. 2014), who showed that the very young massive cluster (YMC) number 23 in ESO 338-IG04 is placed in a gas–deprived hole of radius ∼100–200pc. The inference is that, at such distances, the gas dynamics will be dominated by the gravitational potential of the host galaxy, and re-accretion is unprobable. D'Ercole et al. (2016, submitted) show that re-accretion is possible if the cluster formed in the dense disks of high redshift galaxies (Kravtsov & Gnedin 2005). Thus the YMCs will not follow the same evolution as the ancient GCs and may not be able to develop a dominant SG component. Old GCs may have formed in an environment so different from the present one that the YMCs *are not* early snapshots of old GCs, and this is one reason why all efforts to find signatures of the formation of the SG stars have been unfruitful (e.g. Bastian

[1] In fact di Criscienzo et al. (2011) had warned that "The value Y = 0.42 is not mandatory, as a different, larger choice of the initial [Fe/H] may allow a fit with a smaller (but in any case very high) helium."

et al. 2013; Cabrera-Ziri et al. 2014; Longmore 2015).

The AGB model for helium has been further questioned by the analysis by Bastian et al. (2015), based on a discrepancy between the contemporary predictions of the model concerning both Y and the O–Na patterns, interpreted as dilution curves. No other model is in agreement with the data the Bastian' analysis, but a discrepancy by $\Delta Y \sim 0.02$–0.03 can be due to the uncertainties in the O and Na yields of AGB stars (see also D'Antona et al. 2016) .

3. Advanced p–capture elements: the case of Mg and Si

Some clusters show the signature of p–capture which occur at temperatures larger than those available in the interiors of stars during the H–burning lifetime, in particular, anticorrelations Mg–Al and Mg–Si is present NGC 2808 (Carretta 2015). The p–processing which depletes ^{24}Mg and that forming ^{28}Si from ^{27}Al occur at T$\sim$75MK, while the limiting temperature inside the cores of massive stars is $\sim$65MK, and it is only reached in the core of the most massive model computed (120$M_{\odot}$) during its final stages of burning (Decressin et al. 2007). It is fundamental to realize that not much can be done to increase the temperature during the core–H burning stage of massive stars, due to its very shallow dependence on the total mass. We have to conclude that the Mg depletions found in the SG of some clusters (Sneden et al. 2004; Carretta et al. 2009; Carretta 2015) can not be due to nuclear processing in the interior of massive main sequence stars. For the same reason, silicon production is also excluded.

This inability to deal with some chemical processing signatures present in GC stars is sufficient to reject the whole list of models based on nuclear processing inside massive stars: the FRMS model (Decressin et al. 2007), the massive interacting binaries (MIB, de Mink et al. 2009), and the already quoted EDA model, in which anomalies are produced by accretion of the processed gas lost by MIBs. The "supermassive stars" model by Denissenkov & Hartwick (2014) resorts to supermassive stars precisely to reach internal temperatures at which magnesium can be burned. Criticism to this latter model comes from different considerations (Renzini et al. 2015).

AGBs 'hot bottom burning envelopes are the only place where the required p–captures may occur (Prantzos et al. 2007), for the largest AGB masses, and for low metallicities. The *qualitative* picture is in favour of this model, as the trends of observations are correctly modeled (D'Antona et al. 2016), even if the abundances obtained in the most favorable computations of yields of massive AGBs show some *quantitative* discrepancies with respect to the observed anomalies.

4. The increase in C+N+O and s–process abundances

A number of clusters show SG populations including C+N+O and s–process enrichment. Only in a few clusters the CNO enhancement is determined —NGC 1851 (Yong et al. 2015) and M 22 (Marino et al. 2012), plus ω Cen (Marino et al. 2012)— but in several other clusters having s–process bimodality or spread, a C+N+O increase is strongly suggested by the presence of a double sub-giant branch (Piotto et al. 2012). This feature may be due to the shift of same–age isochrones in the presence of a larger CNO content (Cassisi et al. 2008; Ventura et al. 2009). Although some models for massive star evolution may be compatible with the s-process increase (e.g. non-standard models for their production may occur in rotating massive stars Pignatari et al. 2008), H–burning does not change the C+N+O. On the contrary, in AGB stars the CNO is altered by the third Dredge Up (3DU), which becomes relevant when smaller masses evolve. In some cases, the SG star formation may be efficient at times in which masses suffering 3DU are evolving. This hypothesis has been applied to the data of NGC 2808, and helps to explain the population labelled "C" in Milone et al. (2015), which is Nitrogen rich, but almost normal in the other elements abundance.

5. A timeline for the variety of SG

The different chemical anomalies present in GCs can be explained by a 'timeline' of SG star formation from the ejecta of AGBs with different masses: the early and most massive ones producing the extreme stars with Si increase and Mg depletion, the late and smaller ones producing the populations showing C+N+O and s–process elements increase. The 'timeline' is set by events which, at different epochs, may prevent star formation for lapses of time which may differ from cluster to cluster. These events may include late type II SN explosions, but also low mass X–ray binaries and the first type Ia SN explosions. Occam' razor rule encourages to prefer a single model to comply with all the abundance variation. The alternative is that different pollutors, not yet identified, may be responsible the different anomalies.

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