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# The formation of globular clusters as a case of overcooling

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## ABSTRACT

Driven by recent observational findings, we select massive interactive binaries as the most suitable among the existing candidates for producing the chemical patterns typical of multiple populations of Galactic globular clusters. Still, to avoid supernova contamination, we are further driven to endorse the notion that above a critical mass stars fail to produce supernova events, but rather eventually sink into black holes without ejecting much energy and heavy metals. This assumption has the attractive implication of suppressing star formation feedback for some 5–10 million yr, in practice leading to runaway star formation, analog to *overcooling* that in absence of feedback would have turned most baryons into stars in the early Universe. Under such conditions, multiple episodes of star formation, incorporating binary star ejecta from previous episodes, appear to be unavoidable, thus accounting for the ubiquity of the multiple population phenomenon in globular clusters.

**Key words:** Galaxy: formation – globular clusters: general – galaxies: evolution; galaxies: formation.

## 1 INTRODUCTION

Chemical inhomogeneities among stars within Galactic globular clusters (GC) have been known to exist since a long time (e.g. Kraft 1979) but it was only with the discovery of highly helium enriched sub-populations (Bedin et al. 2004; Piotto et al. 2007) that the complexity of the phenomenon began to unfold, hence triggering a surge of photometric and spectroscopic studies, along with attempts at understanding how all this came about. *Hubble Space Telescope* (*HST*) multiband, deep imaging (Piotto et al. 2015), and *Very Large Telescope* (*VLT*) multi-object spectroscopy (Gratton, Carretta & Bragaglia 2012) then revealed an extremely rich phenomenology, more and more difficult to interpret, thus making the formation of GCs with their multiple populations a major unsolved problem in astrophysics. The common pattern exhibited by GCs is evidence for CNO- and *p*-capture-processed material dominating the surface composition of a major fraction of cluster stars, then called second generation (2G), whereas the remaining cluster stars, dubbed first generation (1G), show a surface composition similar to that of field stars of the same metallicity. This 1G/2G nomenclature implies that at least two distinct episodes of star formation took place, a point on which we shall return later. Moreover, what we see is a great deal of variance from cluster to cluster, in the number of stellar generations and in complexity of chemical patterns, having made more and more frustrating attempts at composing the puzzle.

In this paper, we let ourselves to be driven by recent observational progress in trying, in a bottom up approach, to sort out a GC formation scenario that should not violate the observational constraints. In Section 2, we summarize major advances gathered in the last few years, thanks to photometric and spectroscopic observations. In Section 3, we argue in favour of the idea according to which all

metal-poor GCs formed inside dwarf galaxies, well before the main body of the Galaxy was built, an epoch that instead coincided with the formation of the stellar halo. In Section 4, we argue that current observations dictate that the multiple population phenomenon is the result of multiple, successive episodes of star formation, leading to multiple stellar generations inside each GC progenitor. In Section 5, we discuss pros and cons of the various candidate polluters of CNO/*p*-capture processed material needed to form the 2G stars, as so far proposed. Among them, we single out massive interactive binaries as the most promising ones, an option that requires the additional assumption that massive stars above a critical mass do not explode as supernovae, failing to eject much energy and metals. In Section 6, we try to put together the pieces of the puzzle, as a sequence of plausible events, that culminate with the emphasis on the inevitability of multiple stellar generations in absence of supernova feedback. In Section 7, we acknowledge that metal-rich GCs cannot have formed inside dwarf galaxies, but rather did so inside the forming Galactic bulge, where conditions leading to GC formation were, however, much rarer there than in dwarf galaxies. Finally, in Section 8, we wrap up our scenario of GC formation and conclude.

## 2 MAIN OBSERVATIONAL PROGRESS IN THE LAST 5 YR

The ‘*HST*UV Legacy Survey of Galactic GCs’ (Piotto et al. 2015) has provided an exquisite, homogeneous documentation of the multiple population phenomenon for 57 GCs spanning a wide, representative range of masses, metallicities and 1G/2G phenomenology. It did so by combining four filters from the UV to the *I* band, namely F275W, F336W, F438W, and F814W. The three bluest passbands include the OH, NH, and CN + CH molecular bands, respectively, thus allowing to distinguish among stars with different degrees of CNO processing having taken place. A colour-pseudo-colour combination of these passbands has resulted in plots, dubbed Chromosome Maps

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(ChM) that most effectively allow us to identify 1G and 2G stars in each cluster, along with sub-populations within both the 1G and 2G ones (Milone et al. 2017). From this study, three main results are worth recalling here: (1) the fraction of 2G stars, i.e.  $2G/(1G + 2G)$ , increases with cluster mass from  $\sim 50$  per cent for  $\lesssim 10^5 M_\odot$  clusters to over 80 per cent in  $> 10^6 M_\odot$  clusters, i.e. that of 2G is the main GC formation phase; (2) in 10 out of the 57 GCs the ChM is split, with two nearly parallel sequences and therefore GCs were classified in two groups: Type I clusters showing single 1G and 2G sequences and Type II clusters with separate blue and red sequences; and (3) the 1G locus on the ChM of many clusters is appreciably spread in F275W-F814W colour, signalling that even the 1Gs are not fully chemically homogeneous.

Further progress in the characterization of the multiple population phenomenon included the following. Estimates of the maximum enhancement of the helium content  $\delta Y_{\max}$  of 2G stars with respect to 1G stars, found to range from just  $\sim 0.01$  for  $\lesssim 10^5 M_\odot$  GCs up to over  $\sim 0.08$  for  $> 10^6 M_\odot$  GCs (Milone et al. 2018). In this study, the effects on the ChMs were explored when the abundance of the elements C, N, O, Mg, and He are changed, one at a time. It turned out that the helium vector runs perfectly parallel to the 1G sequence, suggesting that even 1G stars in some GCs could exhibit a spread in helium abundance, an idea expanded by Lardo et al. (2018). Indeed, at first sight, 1G sequences appear dominated by helium variations without a concomitant CNO processing (as if due solely to *pp*-chain processing), whereas the 2G sequences result from a combination of both helium and nitrogen increases (as expected from CNO-cycle processing). However, Milone et al. (2018), having explored various possible scenarios, concluded that there appears to be no plausible stellar process that can produce sizable amount of helium without accompanying it with a large increase in nitrogen, and therefore the 1G colour spread had to be due to something else than helium. The 1G ChM sequence of the cluster NGC 3201 was then spectroscopically explored by Marino et al. (2019a) finding a  $\sim 0.1$  dex spread in [Fe/H] with a few extreme stars showing radial velocity variations, thus indicating that the 1G spread is due to a combination of modest iron variations with binary stars contributing to the colour spread. Binarity was further investigated in five GCs by Milone et al. (2020), quantifying the frequency of 1G+1G and 2G+2G, as well as 1G + 2G main-sequence binaries.

Another important piece of evidence was added by extending the search for multiple populations below the main sequence ‘knee’ produced by the formation of the  $H_2$  molecule, and well down into the fully convective M dwarf regime. This needed to add near-IR passbands, namely F110W and F160W (Milone et al. 2019 and references therein). Thus, in the GC NGC 6752, below the knee, the main sequence splits in at least three diverging sequences which are due to differences in water vapour blanketing in the F160W band. Thus, 2G stars, which are oxygen depleted, suffer less  $H_2O$  blanketing than 1G stars that have ‘normal’ oxygen abundance and therefore are bluer in the F110W-F160W colour compared to 1G stars. The same approach has been recently extended to ten GCs, confirming the split of the lower main sequence and demonstrating that (in the clusters with deeper data) the slope of the mass function is the same for all 1G and 2G populations and their proportions are consistent with those exhibited by 1G and 2G upper main-sequence and red giant stars (Dondoglio et al. 2022).

Finally, extensive chemical tagging of the ChMs of 29 GCs was accomplished by Marino et al. (2019b) using virtually all stars in the *HST* ChMs having chemical abundance analysis from own previous and literature studies. Besides, confirming a  $\sim 0.1$  dex spread in [Fe/H] among 1G stars, this study has shown that the split ChM

sequences in Type II clusters is due to a difference in [Fe/H] that can be as high as  $\sim 0.3$  dex in extreme cases. Interestingly, Marino et al. (2019b) have constructed a ‘universal’ ChM by stacking the ChM of individual clusters after rescaling them to virtually eliminate the effects of different metallicities. This universal ChM shows narrow, well-separated 1G and 2G sequences, with different clusters occupying different portions of these sequences. This demonstrates that the underlying physical processes of chemical processing and star formation ought to have an intrinsic underlying order, as opposed to once favoured mere stochasticity (Bastian 2015). Still, it remains to be understood how this order was established in nature.

### 3 WHERE DID GLOBULAR CLUSTERS FORM?

The GC with the most complex display of multiple populations is undoubtedly  $\omega$  Centauri, which hosts at least 15 distinct stellar populations (Bellini et al. 2017). Though at that time such complexity was not known yet, Bekki & Freeman (2003) proposed that  $\omega$  Cen was the remnant nuclear cluster of a now dissolved dwarf galaxy. We now wish to endorse an Ansatz such that not just  $\omega$  Cen, but virtually all GCs formed inside dwarf galaxies (as first proposed by Searle & Zinn 1978), perhaps with the exception of the more metal-rich ones. Indeed, the association of GCs with dwarf galaxies (as in the case of M54 and Sagittarius) and Gaia streams is now being widely pursued (e.g. Massari, Koppelman & Helmi 2019). On the other hand, even the most metal-poor GCs had to form in an environment in which the metallicity had reached about 1/100 solar, as expected for dwarf galaxies at over 12.5 Gyr lookback time, or  $z \gtrsim 3$ . In this picture, GCs did not hurry to separate themselves from the womb where they formed. This may have taken several Gyr to do so. While waiting for the Galaxy to grow, young GCs were still immersed in the dense gas of the host dwarf that worked as a tamper holding the stellar ejecta within the new born cluster and possibly feeding it with stellar ejecta from stars in the dwarf itself.

In any event, GCs are not pristine, though at least the metal poor largely predate the Galaxy. Often GCs are thought as having been accreted by the Galaxy, as if the Galaxy was already in place and the GCs arrived later, whereas it may well be that the actual late-comer is the bulk of the Galaxy itself, which was slowly built up by inflowing gas streams, as currently understood (Dekel et al. 2009). Thus, as the Galaxy grew up, most dwarfs, but not all, have been tidally destroyed, then releasing their GCs.

GCs are extremely compact objects, with density of the order of  $\sim 10^7$  particles  $\text{cm}^{-3}$  (now all in stars), i.e. many thousand times that of typical molecular clouds in today’s Milky Way. Runaway gas cooling and gravitational collapse must have occurred to form them, but it is less clear how gas was squeezed to such high densities *before* forming stars. On the other hand, besides being very dense, GCs are also extremely slow rotators (Sollima, Baumgardt & Hilker 2019). It is possible that GCs can only form in deep local minima of the potential well created by the collapse of giant molecular clouds and in minima of the interstellar medium (ISM) vorticity, which may explain why (thin) disc GCs do not exist. Otherwise, a mechanism should be invented as to remove angular momentum with extremely high efficiency from giant molecular clouds.

Tantalizing direct evidence for a GC forming inside a dwarf at  $z \sim 6$  was recently obtained from a highly lensed dwarf galaxy with a size of  $\sim 400$  pc and a stellar mass of  $\sim 2 \times 10^7 M_\odot$  which hosts a compact, unresolved nucleus with  $R_e < 13$  pc and a stellar mass of  $\sim 10^6 M_\odot$  (Vanzella et al. 2019). The extent to which this phenomenon may be ubiquitous at high redshift could soon be explored with JWST (e.g. Pozzetti, Maraston & Renzini 2019).

In any event, if forming GCs and their parent dwarfs were tightly interconnected, then a fraction of the dwarf itself may have contributed CNO/ $p$ -capture processed materials for the production of multiple stellar generations in the clusters. This may help solving the infamous ‘mass budget problem’ affecting all scenarios for the origin of multiple populations, i.e. the fact that, in each cluster, the present 1G stars fall short by about a factor of  $\sim 10$  from having produced all the stuff needed to make the 2G ones (e.g. Renzini et al. 2015). Thus, for this to happen, the part of a dwarf producing the 1G stars feeding the nascent GC should have a mass roughly 10 times that of a present-day GC, i.e. a few per cent of the dwarf mass. Indeed, GC masses are typically in the range  $10^5 - 10^6 M_{\odot}$ , whereas dwarf masses reach up to several  $10^8 M_{\odot}$ . This dwarf galaxy picture of a progenitor GC is radically different from one in which progenitors are seen as just more massive, compact clusters, i.e. as a naked, massive GC. Objects of this later kind are hard to destroy, whereas most dwarfs hosting GCs can survive only as long as the main body of the Galaxy has not been assembled yet, and therefore tidal forces are still relatively weak. Thus, as the dwarf stars are tidally stripped, so are most of the stars of the 1G generation that provided the material to form the 2G stars.

One additional option offered by the dwarf precursor scenario is that two or more clusters may have formed within the dwarf, at slightly different times, hence with different metallicities, and that later in-spiralled to merge. For example, such cluster merging was invoked for the Type II cluster NGC 1851 (Tautvaisiene et al. 2022).

#### 4 WHY MULTIPLE EPISODES OF STAR FORMATION?

At early times, in the ‘70s and 80s’, there was some reluctance to abandon a paradigm that was looking at GCs as prototypical ‘simple stellar populations’, or SSPs. The origin of the chemical inhomogeneities was hopefully sought in internal processes within individual stars, or appealing to accretion from a contaminated ISM (e.g. Kraft 1979; D’Antona, Gratton & Chieffi 1983; Renzini 1983; Iben & Renzini 1984). Yet, several arguments support the notion that it is inescapable to have distinct, successive episodes of star formation within forming GCs. First came the discovery that ‘chemical anomalies’ (as they were called) are not confined to red giants but extend down to the main sequence (Hesser & Bell 1980). This excluded the possibility that the chemical anomalies could be established in red giants via some sort of unconventional mixing. As we argue next, modern data further emphasize the case for multiple generations inside individual GCs.

Gas accretion onto pre-existing stars cannot work for several reasons. There is indeed a clear 1G-2G separation in most GCs and it is hard to understand why some 1G stars would have escaped completely from accreting material while others would have accreted a lot and be turned into 2G ones. Moreover, discreteness is not confined to 1G versus 2G, but the ChM of many GCs shows that the 2G sequence is made of several disjoint clumps, again hard to understand how such clumps would have been generated by an accretion process. Moreover, in several GCs, the most extreme 2G population is made of stars that are extremely oxygen depleted, by up a factor of  $\sim 10$  with respect to 1G stars in the same cluster. These stars are also strongly helium enhanced, hence have higher molecular weight compared to 1G stars. Accretion on to pre-existing 1G stars of oxygen-depleted/helium-enriched material cannot account for these stars, because the Rayleigh–Taylor instability would quickly lead to mixing of the accreted, higher molecular weight material with the rest of the star, then washing away the oxygen depletion. Hence, highly oxygen-depleted stars ought to have formed out of almost

pure 1G stellar ejecta. Finally, the identity of the mass functions of 1G and 2G lower main sequences (Dondoglio et al. 2022) is hard to accommodate in an accretion scenario, where accretion is expected to favour more massive stars. All these issues are instead quite naturally accounted if GCs formed through a series of star formation events (bursts), from two to several. Problems exist but are elsewhere for this scenario, whereas the accretion hypothesis has never been confronted with the actual complexity of the data.

#### 5 WHAT STARS HAVE PRODUCED THE 2G RAW MATERIAL?

Type I GCs are quite homogeneous as far as the iron abundance is concerned, with the exception of the mentioned  $\sim 0.1$  dex spread in  $[\text{Fe}/\text{H}]$  among the 1G stars. The presence of a  $\sim 0.3$  dex difference in  $[\text{Fe}/\text{H}]$  between the parallel blue and red ChM sequences of Type II GCs testifies that some supernova contamination took place after the formation of the blue 2G sequence of these clusters and before/during the formation of their iron-enriched, red sequences. Yet, in both cases, the amount of extra iron involved, in bulk solar masses, is relatively tiny: at most just a few per cent of the total iron released by core collapse supernovae (CCSNe) from the 1G (Renzini 2013; Marino et al. 2019b). This means that both kinds of 2G stars had to form either before or well after the explosion of the bulk of CCSNe produced by the 1G. This is known as the supernova avoidance problem (Renzini et al. 2015). Alternatively, supernova ejecta may have preferentially escaped from the forming GC, see later in this section, but we consider less attractive this option as it would possibly exacerbate the mass budget problem if entraining other gas.

Supernova avoidance can be realized in two distinct ways, depending on the nature of the polluters, i.e. the kind of stars that produced the CNO/ $p$ -capture processed material. If those were massive or supermassive stars (SMS), then the whole GC formation, with all 1G and 2G stars, had to be a very fast process, lasting just a few to several million years, so that only a few massive stars had the time to turn into CCSNe. So, this time-scale is dictated by the supernova avoidance constraint.

Alternatively, if the polluters were intermediate mass AGB stars, one had to wait of order of a few  $10^8$  yr, so to accumulate enough processed material, before starting to form the 2G stars. Almost all the metals produced by the 1G CCSNe had to disappear completely for Type I clusters, while some 2 per cent being retained by Type II clusters as needed to form their ChM red sequence.

In all evidence, both scenarios are highly contrived. In the case of massive star polluters, binaries should play the main role (de Mink et al. 2009) as some 70 per cent of OB-Type stars are interacting binaries (Sana, de Mink & de Koter 2012). Close binaries offer the additional advantage of quite naturally promoting fast rotation and deep envelope mixing during the core hydrogen burning phase of their components. Then, prompt common-envelope phases of the binaries can release their whole envelopes, fully processed by CNO-cycle and  $p$ -capture processes, well before experiencing their core collapse. Moreover, the mass lost during common envelope phases is shed at low velocity, hence with minimal energy injection into the ISM, an aspect that may turn relevant, as we shall see later. For these reasons, in our opinion, close binaries offer a more attractive option over the single fast rotating massive stars (FRMS) alternative (Krause et al. 2013), which can violate the GC-specific constraint<sup>1</sup>

<sup>1</sup>GC specificity indicates that the multiple population phenomenon is typical of GCs but rare in the field.

(Renzini et al. 2015) while an extruding disc does not appear to be an obvious place for star formation to occur.

SMS ( $\sim 10^4 - 10^5 M_{\odot}$ ; Denissenkov & Hartwick 2014) very well satisfy the GC-specificity constraint but encounter another serious difficulty. The mass of these SMS models cannot exceed this limit, otherwise their interior would be too hot for producing  $p$ -process elements in the observed mix. Thus, a few times  $10^4 M_{\odot}$  SMS cannot physically produce the  $\sim 10^5 M_{\odot}$  of excess helium now stored in the 2G stars of  $\omega$  Cen (Renzini et al. 2015). To overwhelm this difficulty, Gieles et al. (2018) have proposed a scenario in which the SMS, once formed, keeps accreting stars at a rate similar to its wind mass loss, so there would be virtually no limit to the amount of material that the SMS could process. However, for this mechanism to work, several conditions should be verified, including: (a) central temperature and density must be high enough to timely produce  $p$ -processed material in the desired amount; (b) the SMS must be fully convective<sup>2</sup>, in such a way that this material is continuously brought to the surface and shed to the ISM; and (c) the radius of SMS should be very large, so that stars are captured at the required rate. These conditions can be mutually exclusive. For example, in their scenario, the authors assume the radius of a  $10^5 M_{\odot}$  SMS to be  $30\,000 R_{\odot}$ , which implies a mean density of only  $\sim 6 \times 10^{-9} \text{ g cm}^{-3}$  or a central density of  $\sim 3 \times 10^{-7} \text{ g cm}^{-3}$  for a polytrope of index 3 (Cox & Giuli 1968). For comparison, the central density of the Sun is  $\sim 9$  orders of magnitude higher. It remains to be seen whether an SMS with these properties (mass, size, convection, and  $p$ -process production) could really exist, but we consider it unlikely. For certain, SMS stellar models satisfying all three constraints do not currently exist and, as it stands, the proposed SMS scenario unfortunately does not appear viable.

AGB stars were soon and for a long time regarded as the natural polluters for the production of multiple populations. Candidates would be stars in the mass range  $\sim 3 - 8 M_{\odot}$ , hence with lifetimes of  $\sim 30 - 300$  Myr. Some apparent mismatch concerning the detailed abundances, such as a predicted Na-O correlation in front of the observed anticorrelation, could be alleviated by either appealing to modification within current uncertainties of some nuclear reaction rate (Renzini et al. 2015), or by tuning AGB models and their mass loss in order to have most of the fresh sodium to be ejected before being destroyed. So, chemistry may not be fatal for the AGB scenario. More difficult is to understand how to avoid that 1G supernova products be incorporated into 2G stars, given that at most  $\sim 2$  per cent of them are so in Type II clusters and almost none in Type I clusters. If GCs form inside dwarfs, this would require to eject from the dwarf itself most ( $\sim 98$  per cent) of the CCSNe products while still retaining the AGB products and at least part of the initial ISM of the dwarf, a very contrived scenario. In principle, given the shallow potential well of the dwarfs, the supernova shock heated *bubbles* could manage to carve windows in the ISM and outgas from them with minor ISM entrainment. Existing simulation offer a contradictory panorama, with the supernova ejecta being either fully retained by the protocluster (Krause et al. 2013), or selectively fully ejected (Tenorio-Tagle et al. 2016) or fully ejected along with the original ISM of the precursor (D’Ercole et al. 2010). All supernova ejecta should instead be replaced by the materials lost by the AGB stars plus some original material having somehow escaped the supernova contamination. It appears quite unlikely that virtually all forming GCs would have followed this very specific sequence of events. This makes the weakness of the AGB option.

<sup>2</sup>Hence the SMS structure would be a polytrope of index  $n = 3$ .

However, also the massive binary star alternative has to face the supernova avoidance problem, an aspect that was not addressed in de Mink et al. (2009). Massive binaries filling their Roche lobes and shedding CNO/ $p$ -capture processed materials are indeed both co-spatial and time concomitant with massive stars, single and double alike, finally undergoing core collapse. Hard to imagine how nature could separate the precious CNO/ $p$ -capture processed matter from the unwanted metals ejected by supernova explosions, given that both occupy the same space at the same time. The only escape, it seems to us, is to assume that above a certain stellar mass ( $M_{\text{noSN}}$ ), core collapse is not accompanied by supernova explosion and metal ejection, but the core ‘silently’ sinks into a black hole. This was postulated by Krause et al. (2013) precisely to ensure supernova avoidance in their FRMS scenario. Though independent arguments exist supporting this possibility (e.g. Sukhbold et al. 2016; Adams et al. 2017; Sander et al. 2019; Eldridge & Stanway 2022 and references therein), it remains somewhat perplexing that a very massive star of several 10 solar masses could *quietly* sink into a black hole without much energy release and ejection of processed materials.

Yet, as of today, the massive binary star option, with the *ad hoc* assumption that stars above a certain mass limits fail to produce a supernova event, appears to be more promising than other scenarios. It is based on the presumption that in an environment with extremely high gas densities ( $\gtrsim 10^7 \text{ cm}^{-3}$ ) multiple bursts of star formation are inevitable, the problem actually being how to stop it rather than how to go on and on with an extremely high efficiency of gas conversion into stars. Given the ubiquity of multiple generations among GCs, multiple bursts ought to be an inevitable outcome, rather than the result of a fortuitous conspiracy. This is further explored next.

## 6 WHAT WAS THE SEQUENCE OF EVENTS?

Here, we explore further the scenario of GC formation based on three assumptions: (1) GCs (or at least the metal poor ones) formed inside dwarf galaxies; (2) 1G massive binaries produce the CNO/ $p$ -capture materials that are ejected during their common envelope events and then incorporated into 2G stars; and (3) massive stars above a certain limit (e.g.  $20 - 40 M_{\odot}$  [?]), no matter whether single or binary) do not end up with a metal producing supernova, but sink directly into a black hole.

The first assumption has already been justified in Section 2. Thus, in this view, progenitors of GCs are not just bigger GCs, but the host dwarfs themselves that can be much more massive than the hosted GC(s). Therefore, binary star polluters to make 2G stars are not only those in the 1G inside the just formed GC, but also those in a suitable portion of the dwarf itself. This would solve the mass budget problem. The very high gas density inside the the forming GC and its surrounding regions within the dwarf galaxy should ensure rapid energy dissipation, such as that from the fast winds of massive stars, favouring further collapse of binary ejecta down into the GC. This process may not be continuous, but rather going through ups and downs in a series of bursts thus making the discrete multiple populations exhibited by many ChMs. In some case, the very first 2G stars may form from almost pure 1G ejecta, thus making the highly oxygen depleted 2G stars that are present in some cluster.

The duration of star formation depends on the assumed stellar mass above which no metal producing supernovae take place. This would be  $\sim 10$  Myr for  $M_{\text{noSN}} = 20 M_{\odot}$  or  $\sim 5$  Myr for  $M_{\text{noSN}} = 40 M_{\odot}$ . Notice that  $M_{\text{noSN}}$  cannot be too small, otherwise the global metal yield would become insufficient to account for the metal enrichment of galaxies (Krause et al. 2013). Nevertheless, 5–10 Myr appear to be

a sufficient time to accommodate multiple stellar generations from an ISM whose chemical composition is evolving rapidly in response to the input from 1G stars of the young GC and the host dwarf. Most importantly, the absence of supernova explosions during this time, i.e. of feedback, can only help turning more gas into 2G stars. Indeed, in absence of feedback, an *overcooling* radial flow appears to be inevitable, with virtually all gas being turned into stars, as long ago recognized it would have been so in the early Universe (White & Rees 1978). Therefore, the postulate of having no supernovae above  $M_{\text{noSN}}$  so to avoid metal pollution also has the additional, beneficial effect of suppressing most of feedback for  $\sim 5\text{--}10$  Myr, hence facilitating the growth of young GCs with more and more 2G populations. Of course, suppressing supernova feedback does not eliminate feedback completely, because the effect of fast winds from hot, massive stars remains. This lesser feedback may introduce modulations in star formation rate during the 2G built up, then resulting in secondary bursts leading to the multiple 2G populations present in several GCs. Notice that in such an overcooling phase most, if not all, binary ejecta are converted/incorporated into 2G stars, thus leading to a major step towards solving the mass budget problem.

However, as no supernovae explode during this time there remains to explain why a  $\sim 0.1$  dex spread in  $[\text{Fe}/\text{H}]$  exists among 1G stars (Marino et al. 2019a). The only option seems to be that the ISM out of which 1G stars formed was not perfectly mixed, which is possible but hard to prove independently. Different is the case of the iron enrichment in Type II clusters (Marino et al. 2019b). Indeed, it is conceivable that after the no supernova phase came to an end and the ISM started to be enriched in metals, then another burst of star formation could have taken place, then leading to the formation of both the 1G and 2G stars of the metal-rich (red) sequences in the ChM of these clusters. As mentioned earlier, it is also conceivable that in some cases more than one GC formed within a given dwarf, with slightly different  $[\text{Fe}/\text{H}]$ , and that they later merged to form a single GC (Tautvaisiene et al. 2022). Indeed, the extreme complexity of the ChM of  $\omega$  Cen (Milone et al. 2017; Marino et al. 2019b) argues for multiple, separate star-forming protocusters that eventually merged together after forming their 1G and 2G stars and even while being enriched in iron.

Though still very contrived, this scenario seems able to qualitatively account for all the major observed properties of GC multiple populations. For example, the increase of the 2G fraction with cluster mass (Milone et al. 2017) can be the natural result of the deeper potential well in which they resided, favouring the accumulation of more 1G ejecta from the dwarf 1G population and promoting a higher number of multiple bursts.

Finally, most dwarfs were stripped away by tidal interactions as the main body of the Galaxy grew in mass. In this respect, one last constraint is set by the fact that in the field stars, with 2G chemical patterns are very rare (Martell et al. 2011), dictating that most of the 2G stars formed inside the GC itself and were retained by it. This means that the various bursts of star formation had to take place well inside the already formed, young GC. Support to this possibility comes from the fact that 2G stars appear to be more centrally concentrated compared to 1G stars (e.g. Milone et al. 2012).

This overall scenario for GC formation is quite similar to the one advocated by Elmegreen (2017), with the main difference being the extension of the time interval without supernova explosions, from  $\sim 3$  up to  $\sim 10$  Myr. Suppressing supernova feedback for several million years has the effect of boosting the overall star formation efficiency (fraction of the gas turned into GC stars), allowing more 1G-processed material to become available for the formation of 2G stars. With only 3 Myr duration for the star formation phase,

only binary components more massive than  $\sim 100 M_{\odot}$  would have had time to evolve off the main sequence (Yusof et al. 2022), fill their Roche lobe, and deliver their processed envelopes. This would probably fall short of accounting for the required mass budget, whereas extending to a 10 Myr interval would allow stars down to  $\sim 20 M_{\odot}$  to contribute. A longer duration of this phase has also the effect of allowing a  $\sim 30$  times wider volume inside the dwarf to contribute to the inflowing stream feeding the forming GC, again busting further the mass budget. This assumes that the starburst is not confined to the nascent GC, but at the same time extends over a suitable region around it. The  $\sim 100$  pc wide 30 Doradus star-bursting region in the LMC, with its central R136 cluster, is highly reminiscent of the proposed process of GC formation. Indeed, it has been seen as a nearby analog to GC formation at high redshift, with the formation of the central cluster taking place within an extended region that has been actively star forming over the last  $\sim 10$  Myr (Schneider et al. 2018 and references therein). In summary, in this proposed scenario, GCs form over a  $\sim 10$  Myr time interval, as the central peak of a star-bursting region encompassing a mass some 10 times larger than the mass of the final GC, corresponding to a few per cent of the total mass of the hosting dwarf galaxy.

## 7 DO METAL-RICH GLOBULAR CLUSTERS FIT IN THIS SCENARIO?

Metal-rich GCs do not quite fit in this scenario. The most metal-rich ones (NGC 6528 and NGC 6553) are  $\sim 10\text{--}12$  Gyr old, almost solar in iron and slightly enhanced in  $[\alpha/\text{Fe}]$  (Ortolani et al. 1995; Montecinos et al. 2021). Given the mass–metallicity relation of high redshift galaxies (e.g. Erb et al. 2006; Kashino et al. 2017), clearly they did not form inside a dwarf. Rather, they must have formed while the Galaxy had already grown to some  $10^{10} M_{\odot}$ . Yet, clusters such as NGC 6388 and NGC 6441 ( $[\text{Fe}/\text{H}] = -0.5$ ) exhibit prominent 2G sequences in their ChM (Bellini et al. 2013; Milone et al. 2017; Tailo et al. 2017), whereas this is less obvious for NGC 6553 (Montecinos et al. 2021), which has near solar metallicity. Therefore, sites other than high redshift dwarf galaxies have been able to form GCs with their multiple generations. Giant star-forming clumps in  $z \sim 2$  galaxies have been proposed as such possible sites (Shapiro, Genzel & Förster Schreiber 2010), with clumps possibly migrating inward to build the bulge, where indeed metal-rich GCs reside. Still, for this to happen along with multiple stellar generations, conditions similar to those prevailing in high-redshift dwarfs should have been present also in early discs/bulges of more massive galaxies. This includes very high gas fraction and relatively low-specific angular momentum of gas-rich clumps, so to make possible a collapse to very high gas and stellar mass densities.

In this respect, it is worth noting that the vast majority of the  $\sim 150$  Galactic GCs reside in the galactic halo, which has a mass of  $\sim 10^9 M_{\odot}$ , whereas only  $\sim 15$  of them belong to the bulge (Barbuy, Bica & Ortolani 1998), which has a mass of  $\sim 2 \times 10^{10} M_{\odot}$  (Valenti et al. 2016). Thus, the metal-rich bulge was some 100 times less efficient in forming GCs than the metal-poor stellar halo, a known effect also common among giant elliptical galaxies (Harris & Harris 2002; Lamers et al. 2017). Thus, it appears that conditions leading to GC formation were present also during the built up of the Galactic bulge, but such conditions were very much rarer in the bulge than in pre-galactic dwarfs.

On the other hand, multiple generations are not exclusive to ancient GCs formed at high redshift. Evidence for chemical patterns similar to those exhibited by Galactic GCs have indeed been reported for Magellanic Cloud GCs as young as  $\sim 2$  Gyr, whereas so far no sign for

them have been found in younger clusters (Martocchia et al. 2018). However, note that the filter combinations needed to construct the ChMs are generally unavailable for such clusters.

## 8 SUMMARY AND CONCLUSIONS

The ubiquity of the multiple population phenomenon in GCs indicates that the processes leading to them must be virtually unavoidable during the formation of massive GCs, as opposed to a combination of fortuitous conditions. In search for such processes, we have proceeded bottom up, starting from the observational evidences, especially those accumulated in recent years. We started endorsing the notion that GCs, at least the metal-poor ones, formed at a very early stage inside dwarf galaxies pre-existing the main body of the Galaxy itself. We then argued that the multiple population phenomenon is more readily understandable as a sequence of star formation events, leading to multiple stellar generations, as opposed to alternatives such as accretion on to pre-existing stars, as this latter scenario appears to be incapable of complying with major observational constraints.

We then briefly considered, one by one, the various stellar candidates for the production of the chemical material needed for the production of multiple populations. This included AGB stars, FRMSs, SMS, and massive interactive binaries. These latter ones, the binaries, have been singled out as those offering the most promising option. However, an additional assumption became necessary to avoid major supernova contamination of the CNO/ $p$ -capture processed material gently shed by the binaries during their common-envelope events. We then came to adopt also the notion that, above a critical mass, stars would fail to explode as supernovae ejecting lots of energy and metals, but rather sink into black holes without much display.

The lack of supernova explosions for a period of some 5–10 million yr has the important consequence of suppressing most of the star formation feedback shortly after the formation of the 1G of GC stars. Under such conditions, nothing prevents the residual gas, together with the binary star ejecta, to keep flowing into the nascent GC while forming stars in a series of bursts, until supernovae finally begin. This physical situation is analog to that leading to overcooling, that in absence of feedback would have turned all the baryons into stars in the early Universe. The attractive aspect of this scenario is that multiple stellar generation become unavoidable once the first GC generation has formed, thus accounting for the ubiquity of the multiple stellar population phenomenon. If this is the way GCs formed, then such a *delayed feedback* is likely to play a role in star formation in general. In particular, it would boost the star formation efficiency in dense regions, perhaps helping the formation of nuclear clusters and more, all possibilities whose exploration is beyond the scope of the present paper.

Yet, not all GCs may have formed inside a dwarf. Certainly not those in the Galactic bulge which are metal rich. We take this as evidence that conditions conducive to GC formation existed also during the major epoch of star formation in the bulge, some 10 Gyr ago (Renzini et al. 2018), such as extremely high gas density coupled with low vorticity. However, given the specific frequency of bulge and halo GCs (i.e. their number per unit halo/bulge mass), it appears that such conditions were  $\sim 100$  times more rare in the bulge than they were in dwarfs that once dissolved left free their GCs and made the stellar halo of the Galaxy.

In this proposed scenario, a few observational facts still remain unaccounted. This is the case for the presence of lithium and/or some heavy s-process elements (such as barium) in a few 2G stars,

especially among the red-sequence stars of Type II clusters (Marino et al. 2019b). Lithium and s-process elements have been traditionally taken as the smoking gun for the intervention of AGB stars (e.g. D’Antona et al. 2019 and references therein). As red-sequence stars in Type II GCs experienced iron enrichment from supernovae, over  $\sim 10$  Myr after the formation of the 1G, they may as well have included ejecta from massive AGB stars that started to enrich the ISM another  $\sim 20$  Myr after the beginning of supernova explosions. Admittedly, this tentative solution is a bit contrived, but so complex is the overall multiple population phenomenon that some apparently minor detail may need a specific fix.

In conclusion, after having defended the AGB options for many years, given the observational evidences we and others have recently gathered, we came to consider massive interactive binaries as the most promising factories for the production of the CNO/ $p$ -capture processed material used to make 2G stars. We further advocate the *ad hoc* assumption that massive stars (either single or binary) above a critical mass fail to explode as supernovae, hence for some 5–10 Myr failing to provide feedback to regulate and stop further star formation. We argue that during this period, in absence of supernova feedback, *overcooling* leading to repeated burst of star formation was inevitable, thus producing the multiple stellar generations, we observe today in Galactic GCs. All the pieces of the puzzle have been on the table for quite some time. This is our attempt at putting them together.

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## DATA AVAILABILITY

No new data were generated or analysed in support of this research.

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