On the Star Formation Efficiencies and Evolution of Multiple Stellar Generations in Globular Clusters

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Abstract

By adopting empirical estimates of the helium enhancement ($\Delta Y$) between consecutive stellar generations for a sample of Galactic globular clusters (GGCs), we uniquely constraint the star formation efficiency ($\epsilon$) of each stellar generation in these stellar systems. In our approach, the star formation efficiency ($\epsilon$) is the central factor that links stellar generations as it defines both their stellar mass and the remaining mass available for further star formation, fixing also the amount of matter required to contaminate the next stellar generation. In this way, $\epsilon$ is here shown to be fully defined by the He enhancement between successive stellar generations in a GC. Our approach also has an impact on the evolution of clusters and thus considers the possible loss of stars through evaporation, tidal interactions and stellar evolution. We focus on the present mass ratio between consecutive stellar generations ($M_{(j-1)G}/M_{jG}$) and the present total mass of GGCs ($M_{GC}$). Such considerations suffice to determine the relative proportion of stars of consecutive generations that remain today in globular clusters ($\alpha_{(j-1)G}/\alpha_{jG}$). The latter is also shown to directly depend on the values of $\Delta Y$ and thus the He enhancement between consecutive stellar generations in GGC places major constraints on models of star formation and evolution of GC.

Key words: galaxies: star clusters – globular clusters: general – globular clusters: individual (NGC 6266, NGC 6397, NGC 6752, NGC 2808) – hydrodynamics

1. Introduction

Recent spectroscopic and photometric observations of Galactic globular clusters (GGCs) have led to the unexpected discovery of multiple stellar generations in these stellar systems. One can indeed find a stellar population, perhaps the first population, with chemical abundance ratios similar to those found in neighboring field halo stars, and within the same volume additional populations, characterized by their own specific abundances of He, C, N, O, Na, Mg, and Al, different to field halo stars. As stated by Cassisi et al. (2017): “these abundance patterns give origin, within individual clusters, to well defined anti-correlations between pairs of light elements, the most characteristic one being the Na–O anticorrelation, nowadays considered a prominent signature for the presence of multiple populations in a given GGC.” Similarly, multiple populations can be separated into distinct sequences in various color–magnitude diagrams (CMDs). Good examples of such photometric results, indicating discrete generations, have been derived for the two generations in NGC 6266 (Milone et al. 2015a) and in NGC 6397 (Milone et al. 2012a), as well as for the three generations of NGC 6752 (Milone et al. 2013) and the four generations of NGC 2808 (Marino et al. 2014; Milone et al. 2015b; D’Antona et al. 2016). For all of these clusters in our sample, definite results (He enhancement values, chemical composition, etc.) are given for each of the identified populations.

There is a general consent that the light element variations are produced by high-temperature proton captures in asymptotic giant branch (AGB) stars (e.g., D’Antona et al. 2002), in fast rotating massive stars (FRMSs; e.g., Prantzos & Charbonnel 2006), in massive interacting binaries (see de Mink et al. 2009; Schneider et al. 2014), in red supergiant stars (Szécsi & Wünsch 2019), in supermassive stars (e.g., Denissenkov & Hartwick 2014; Denissenkov et al. 2015), or in very massive stars (Vink 2018). The processed matter is then injected into the ambient gas by stellar winds, being able then to mix with either recently accreted primordial gas or with the matter left over from star formation.

All of the suggested scenarios for the formation of multiple stellar populations in GGCs, as well as the mentioned possible polluters, are affected by significant drawbacks (we refer the reader to the exhaustive reviews by Renzini et al. 2015 and Bastian & Lardo 2018). However, despite the existing limitations, here we explore how the distinct subpopulations formed in each individual cluster with their own chemical peculiarities.

Two very important constraints—obtained by an accurate analysis of suitable photometric data sets—are the helium abundance difference between distinct subpopulations and their present relative population ratios (Cassisi et al. 2017; Milone et al. 2018). This is because the various stellar candidate polluters predict different amounts of He enhancement in quite distinct evolutionary phases, and the analysis of present He ratios between the first stellar generation and the second or more poses a critical constraint on scenarios aimed to explain the origin of the multiple population phenomenon (see, e.g., Bastian et al. 2015; Tenorio-Tagle et al. 2016).

In a previous paper (Tenorio-Tagle et al. 2016, hereafter Paper I) by adopting the empirical estimates of He enhancement ($\Delta Y$), the present mass ratio between first and second stellar generations ($M_{1G}/M_{2G}$), and the actual mass of GGCs ($M_{GC}$), we constrained the star formation efficiency of Galactic GCs. The model was limited by considering only two stellar generations in each individual cluster, when at that time there were few clusters showing evidence of triple (or more) stellar subpopulations, such as the cases of NGC 2808 (Milone et al. 2015a) and NGC 6752 (Milone et al. 2013).
Nowadays, the number of GGCs that have been proven to host more than two stellar populations is largely increased mainly by the photometric data set collected in the framework of the Hubble Space Telescope UV Legacy Survey of Galactic GCs project (Milone et al. 2018). This project has also allowed for the homogeneous determination of ΔY for a large sample of clusters.

Here, we wish to extend the analysis performed in Paper I to a larger sample of clusters, hosting more than two stellar generations.

The plan of the paper is as follows: Section 2 describes all major assumptions in the model. Section 3 shows the direct dependence of ΔY on the efficiency of star formation for each stellar generation. Section 4 shows how the values of ΔY between consecutive generations impact the corresponding ratio of the number of stars that remain today as part of the cluster. Section 5 derives, under some assumptions, the total mass in stars formed in each generation as well as the mass of the clouds that originate them. Section 6 presents our main conclusions and an evaluation of our model.

2. Main Assumptions

Here we briefly outline the main assumptions at the basis of our considerations. We assume a massive pristine cloud that has been uniformly contaminated with the products of supernovae from the first stars in the galaxy, Population III stars, and thus presents a uniform Fe abundance. This is to be acquired by all stellar generations produced by the cloud, unless it manages to capture the products from subsequent supernovae enhancing then the Fe abundance of the remaining cloud and of further stellar generations. This is to cause the so-called “Fe spread,” as detected among the various stellar generations belonging to the most massive globular clusters.

The cloud with a total mass $M_{\text{tot}}$ collapses to form multiple stellar generations, each of these with a peculiar chemical pattern resulting from the contamination of the residual gas by H burning products cooked at high temperatures by the former stellar generation. It is assumed that the negative stellar feedback in dense compact clusters is drastically suppressed (see Silich & Tenorio-Tagle 2017, 2018) and leads to completely opposite results to those found in the adiabatic cluster wind model of Chevalier & Clegg (1985) in which all the gas left over from the star formation process is not considered as it is assumed to have been totally dispersed by the feedback caused by massive stars. Following Paper I, we assume that all stellar generations—at their formation—sample a full Kroupa (2001) initial mass function (IMF) with stars in the range 0.1–120 $M_\odot$ and, as expected from massive starbursts restricted to a small volume, a large fraction of their massive stars are to end up as interacting binaries (see de Mink et al. 2009; Schneider et al. 2014) contaminating the leftover gas. The contamination comes from the large fraction (about 70%) of massive stars that are in binaries and that will interact at some time during their evolution, consistent with observations of local high-mass star-forming regions (Sana et al. 2012; Bastian et al. 2013; Izzard et al. 2013).

As in Paper I, massive binaries are here held responsible for contaminating the leftover gas with H burning products while effectively holding the further collapse of the cloud. It is not until the end of the supernova (SN) II era (say ~40 Myr after the onset of the last episode of star formation) that gravity wins again and the collapse of the leftover cloud, now contaminated with the products of a former generation, leads to another episode of star formation (see also Kim & Lee 2018). With these assumptions in hand, one can envisage numerous episodes of star formation and further contamination of the residual gas until the latter is either exhausted (turned into stars) or dispersed by (feedback) the mechanical energy injected into the cluster volume by the last stellar generation. Indeed, SN have been declared responsible by several authors for dispersing the gas left over after star formation (see, for example, Calura et al. 2015). This inevitably leads to the assumption of a later accretion as in the model of D’Ercole et al. (2008) to ensure there is sufficient matter to form a second stellar generation and avoid a mass budget problem. Other scenarios, such as the dark remnant accretion scenario of Krause et al. (2012, 2013), find a limiting initial cloud mass of $10^3 M_\odot$ above which the gas may not be ejected and therefore form additional stars. In this respect Silich & Tenorio-Tagle (2017, 2018) defined the physical conditions that lead to the dispersion or retention of the parental cloud.

In our scenario the blowout of individual SN and the fragmentation of their shells of swept-up matter are also central to our considerations. SN explosions lead to a highly supersonic shock wave that sweeps into an expanding shell all the matter that it encounters, all of it, whether it is the nearby wind of the secondary or the normal interstellar medium (ISM) or the gas left over from star formation. As this happens the kinetic energy of the ejected matter is being converted into thermal energy, after crossing the inner or reverse shock. The remnant structure presents then an outer expanding shell that contains all the swept-up matter and that continuously acquires the new material overtaken by the leading shock. The back of the shell is bound by a contact discontinuity that encloses all of the thermalized ejecta. As both the hot ejecta and the outer shell expand with the same speed, there is no mixing at all between the swept-up gas and the SN products.

Sooner or later, however, the supernova remnant (SNR) will find the edge of the cloud and this will lead to its blowout. As a section of the leading shock finds the density gradient it will speed up radially and away from the cloud center. The same will happen to the corresponding section of the shell behind the accelerated shock. However, its sudden acceleration will drive the shell Rayleigh–Taylor to be unstable and this will lead to its fragmentation. The hot thermalized ejecta will then rapidly move between the shell fragments and follow the leading shock out of the cluster, while the remains of the shell, with most of the swept-up matter, no longer having a driving pressure cease to expand and easily mix with the leftover cloud (see Tenorio-Tagle et al. 2015, 2016).

If one demands a full IMF, we believe the blowout of an SN is the key to understand why most GGCs show the same Fe metallicity in their stellar generations. Otherwise, the retention of SN products should cause a metallicity spread between generations, which only seems to have occurred in very small amounts (less than 5%) in the most massive GCs, which clearly were able to capture an SNR.

Blowout of an SN is also expected if the SN shell is able to overtake several of the neighboring wind sources, as this enhances the thermal energy content causing its acceleration and sudden fragmentation even if evolving into a constant density medium (see Silich & Tenorio-Tagle 2017). In this way the ejecta from an SN is eventually expelled out of the cluster without changing the metallicity of the leftover gas. Only an
SN exploding in the central and denser regions of the most massive and compact clouds is expected to become pressure confined and then be able to eventually cause an Fe contamination of the residual gas.

As in Paper I, we base our analysis on the measured helium abundance enhancement (ΔY), and the present mass ratio between consecutive stellar generations, but no attempt was made to correlate these empirical constraints with other observed peculiarities such as, for instance, the light element abundance, which are out of the scope of our analysis. Note, however, that to determine the empirical values of ΔY that best reproduce the observations, a fine grid of synthetic spectra, based on the average abundance of at least 22 different elements in each of the detected stellar generations is used. The absolute value of the synthetic color distance between two stellar generations at each of the observed filters minus the corresponding observed color distance between the two stellar generations leads to the best ΔY value (Sbordone et al. 2011; Milone et al. 2012b, 2012c, 2013). Note also that the synthetic spectra used for each of the stellar generations warrants without knowledge of the possible contaminant(s) the “correct” elemental abundance of the gas out of which further stellar generations were formed.

3. ΔY Constraints on the Star Formation Efficiency of Subsequent Stellar Generations

After the gravitational collapse of the pristine cloud, the mass in stars of the first stellar generation is

\[ M_{1G} = \epsilon_{1G} M_{\text{tot}}. \]  

(1)

where \( \epsilon_{1G} \) is the efficiency of star formation and \( M_{\text{tot}} \) is the mass of the pristine cloud. Here interacting massive binary (IMB) stars are considered to be polluters, and therefore we used the output from the Binary Population and Spectral Synthesis (BPASS) code (Version 2.1; Eldridge et al. 2017; see Figure 1(a)) to obtain the cumulative masses of the ejected hydrogen and helium:

\[ M_{H}(t) = \int_{0}^{t} M_{H} \, dt, \]  

(2)

\[ M_{\text{He}}(t) = \int_{0}^{t} M_{\text{He}} \, dt. \]  

(3)

This yields for a cluster formed with its full IMF in a cloud with a metallicity \( Z = 0.001 \), after 40 Myr of evolution, a fraction of the stellar mass shed by massive stars, including binaries, equal to \( M_{c} = 0.083 M_{1G} = 0.083 \epsilon_{1G} M_{\text{tot}} \). This is assumed to mix thoroughly with the mass of pristine gas left over after the 1G has formed: \( M_{p} = (1 - \epsilon_{1G}) M_{\text{tot}} \). In this way the helium mass fraction of the mixed gas, \( Y \), is

\[ Y = \frac{(1 - \epsilon_{1G}) Y_{p} + 0.083 \epsilon_{1G} Y_{c}}{1 - 0.917 \epsilon_{1G}}, \]  

(4)

where the cumulative He mass fraction \( Y_{c} \) (see Figure 1(b)) is

\[ Y_{c}(t) = \frac{M_{\text{He}}(t)}{M_{H}(t) + M_{\text{He}}(t)}. \]  

(5)

After 40 Myr of evolution the He mass fraction for our low-metallicity cluster is \( Y_{c} = 0.459 \), while the primordial value \( Y_{p} = 0.245 \). The corresponding value of the helium enhancement (ΔY) in the leftover gas then is

\[ \Delta Y = Y - Y_{p} = \frac{0.083 \epsilon_{1G} (Y_{c} - Y_{p})}{1 - 0.917 \epsilon_{1G}}. \]  

(6)

Following the above assumptions one can derive the values of the helium enhancements \( \Delta Y_{j-1,j} \) for subsequent stellar generations:

\[ \Delta Y_{j-1,j} = Y_{j} - Y_{j-1} = \frac{0.083 \epsilon_{j-1,j} (Y_{c} - Y_{j-1})}{1 - 0.917 \epsilon_{j-1,j}}. \]  

(7)

Thus, as claimed in Paper I, the efficiency of star formation of the previous stellar generation (\( \epsilon_{j-1,j} \)) also defines both the total amount of gas left over from star formation as well as the mass of the contaminated gas (0.083\( M_{j-1,j} \)), which leads,
presents the results from Equation \( Y \) for \( j \). The solid line presents the results from Equation (6) assuming \( Y_{(j-1)} = Y_\ast \). The dashed line is for \( Y_{(j-1)} = 0.30 \) and shows the largest expected change in the location of the solid line (see the text).

Figure 2. \( \log \Delta Y_{(j-1),\ast} \) vs. the star formation efficiency (\( \epsilon \)). The solid line presents the results from Equation (6) assuming \( Y_{(j-1)} = Y_\ast \). The dashed line is for \( Y_{(j-1)} = 0.30 \) and shows the largest expected change in the location of the solid line (see the text).

upon a thorough mixing, to a contaminated cloud ready to trigger another stellar generation with its own He abundance \( Y_j = Y_{(j-1)} + \Delta Y_{(j-1),\ast} \). Thus, if \( \Delta Y \) is measured between generation \( j \) and \( j-1 \), such a quantity (\( \epsilon_{(j-1),G} \)) is then fully defined by the observations, by the values of \( \Delta Y_{(j-1),\ast} \):

\[
\epsilon_{(j-1),G} = \frac{\Delta Y_{(j-1),\ast}}{0.083(Y_\ast - Y_{(j-1)}) + 0.917\Delta Y_{(j-1),\ast}}.
\] (8)

According to Equation (8), the \( \Delta Y_{(j-1),\ast} \) values between subsequent generations lead to the efficiency of star formation of all but the last stellar generation (see Figure 2). Note that the factor 0.083 \((Y_\ast - Y_{(j-1)})\) shifts the location of this line. However, even if one uses an extremely large value of \( Y_{(j-1)} \sim 0.30 \), as found for the blue main sequence (MS) in \( \omega \) Centauri, which represents the largest "super-helium-rich" population ever found in a GGC (Bedin et al. 2004; Salaris et al. 2004), the changes in the resultant location of Equation (8) are marginal (see Figure 2). And thus, within this framework, cases with small values of \( \Delta Y \) lead to small values of \( \epsilon_{(j-1),G} \) and, conversely, large \( \epsilon_{(j-1),G} \) result from large \( \Delta Y \) values (see Figure 2).

Equation (8) provides then a way to derive the star formation efficiencies of multiple generations in globular clusters. This method is completely different than the traditional one in which the star formation efficiency \( \epsilon = \) mass in stars/mass of the progenitor cloud. This is unapplicable to globular clusters, as their stellar mass is largely modified by many Gyr of stellar and dynamical evolution, and the mass of the progenitor cloud is completely unknown.

3.1. The Total Efficiency of Star Formation (\( \epsilon_{\text{tot}} \))

In our approach the total mass available for stellar generation \( (j)G \) is

\[
M_{(j)} = (1 - \epsilon_{(j-1),G})M_{(j-1)} + 0.083\epsilon_{(j-1),G}M_{(j-1)} = (1 - 0.917\epsilon_{(j-1),G})M_{(j-1)},
\] (9)

where the first term accounts for the fraction of the gas left over after the formation of the \( (j-1) \) stellar generation \((1 - \epsilon_{(j-1),G})M_{(j-1)} \) and the second term for the reinserted mass that contaminates the leftover gas. The only exception is the first stellar generation for which there is no previous injection of matter and thus the total available mass for star formation is \( M_{\text{tot}} \). One can express \( M_{(j-1)} \) also as a function of the mass left from all previous generations. In such a case \( M_{(j)} \) is

\[
M_{(j)} = (1 - 0.917\epsilon_{(j-1),G})\times (1 - 0.917\epsilon_{(j-2),G})\times \ldots \times (1 - 0.917\epsilon_{(j-1),G})M_{\text{tot}},
\] (10)

As in Equation (1), this equation multiplied by a star formation efficiency factor \( \epsilon_{(j),G} \) leads to the mass of the next stellar generation.

To calculate the total efficiency of star formation \( \epsilon_{\text{tot}} \) in our scheme requires us to take into consideration the amount of matter returned by massive stars to cause the contamination of the leftover gas and then be used again in further episodes of star formation. In such a case,

\[
M_\ast = M_{\text{tot}}\epsilon_{1G} + \epsilon_{2G}(1 - 0.917\epsilon_{1G}) + \epsilon_{3G}(1 - 0.917\epsilon_{1G})(1 - 0.917\epsilon_{2G}) + \ldots + \epsilon_{nG}(1 - 0.917\epsilon_{1G})(1 - 0.917\epsilon_{2G})\ldots(1 - 0.917\epsilon_{(n-1)G}) = \epsilon_{\text{tot}}M_{\text{tot}},
\] (11)

and thus \( \epsilon_{\text{tot}} \) is equal to the sum of the efficiencies of all stellar generations, taking into consideration, however, the fraction of the remaining gas available for each of them:

\[
\epsilon_{\text{tot}} = \epsilon_{1G} + \epsilon_{2G}(1 - 0.917\epsilon_{1G}) + \epsilon_{3G}(1 - 0.917\epsilon_{1G})(1 - 0.917\epsilon_{2G}) + \ldots + \epsilon_{nG}(1 - 0.917\epsilon_{1G})(1 - 0.917\epsilon_{2G})\ldots(1 - 0.917\epsilon_{(n-1)G}).
\] (12)

Values of \( \epsilon_{\text{tot}} \) for the clusters considered here are given in Table 1.

4. \( \Delta Y \) Constraints on the Dynamical Evolution of Globular Clusters

One can also consider the evolution of stellar clusters, accounting for the possible loss of stars through evaporation, tidal interactions, or stellar evolution. In such a case, Equations (1) and (10), once multiplied by \( \epsilon_{(j),G} \), should also be multiplied by the fraction of newly formed stars that have remained until now gravitationally trapped within the cluster \( \alpha_{(j),G} \leq 1 \) and contribute to its present mass while remaining in the cluster, \( \alpha_{(j),G}M_{(j),G} \). In this way one can derive the mass ratio between consecutive generations and compare it with the mass ratio inferred from the observations.
In Table 1 we list the observed and derived parameters for some well-studied GGCs. The table first indicates the NGC identification number, followed by the observed total mass and the derived total efficiency ($e_{\text{tot}}$) and the calculated range of $M_{\text{tot}}$ (see Section 5). The following lines provide data and derived parameters for different stellar generations in each cluster. Columns 2–4 give the observed mass in each generation, the value of $Y_{\text{tot}}$, and the observed He enhancement $\Delta Y$ between generations. The last two columns list the efficiency of star formation, as derived from Equation (8), and the assumed or derived values of the $\alpha$ ratios for each set of consecutive generations.

Please note that in NGC 6266 $M_{1G}$ is larger than $M_{2G}$ (Milone et al. 2015a) and the opposite is true for NGC 6397 (Milone et al. 2012a). In fact, the fraction of 1G stars ranges from about 8% to 67%, as shown by Milone et al. (2017). Marino et al. (2014) found for a sample of 50 clusters, that the fraction of 1G stars anticorrelates with the present mass of the cluster.

NGC 6752 seems to have had very low abundances in the first and second generation (Milone et al. 2013).

In NGC 2808 the total efficiency of star formation is not larger but is close to 1 (see Equation (12); Milone et al. 2015b; D’Antona et al. 2016). According to the last reference there are five stellar generations A, B, C, D, and E. However, there is no $\Delta Y$ enhancement between generations B and C, and thus we have taken these B + C as one single generation. This was also justified by the less evident observed separation between the MSs of B and C.
5. Estimates of the Original Mass of the Cloud ($M_{\text{tot}}$) and of the Stellar Generations

Assuming a certain value of the retained stars for the last generation, ($\alpha_{\text{(tot)}}$) and of the star formation efficiency of the last generation ($\epsilon_{\text{(tot)}}$) one can calculate from fractions $\alpha_{(j-1)G}/\alpha_{(j)G}$ (Equations (15) and (16)) absolute values of $\alpha_{(j)G}$ for all previous generations. For example, in the case of clusters with only two stellar generations the values of $\alpha_{(1)G}$ for the first stellar generation are functions of the selected efficiency of the last stellar generation $\epsilon_{(2)G}$ and the value selected for $\alpha_{(2)G}$. Similarly, for clusters with more than two stellar generations one can derive values of $\alpha_{(a-1)G}$ for selected values of $\epsilon_{(a)G}$ and $\alpha_{(a)G}$ and in a similar way use these results to obtain values of $\alpha_{(a-2)G}$ and so on, until one obtains values of $\alpha_{(1)G}$. In all cases one should only keep the resultant $\alpha$ values that are ≤1. Note then that values of $\alpha_{(1)G}$ for the first stellar generation depend directly on the selected values for the efficiency of the last stellar generation ($\epsilon_{(tot)}$) as well as on $\alpha_{(tot)}$ (see Figure 3).

The derived values of $\alpha_{(j)G}$ can be further used to convert present-day generation masses, $M_{(j)G}$, into the total original stellar mass of each generation ($M_{(j)\ast}$), accounting for their full IMF:

$$M_{(j)\ast} = M_{(j)G}/(\alpha_{(j)G}f_{\text{low}}),$$

(17)

where $f_{\text{low}}$ is a fraction of low-mass stars that survive until the present in the stellar IMF. For a standard IMF and a mass limit 0.8 $M_\odot$ it is $f_{\text{low}} \approx 0.38$ (e.g., de Mink et al. 2009).

Additionally, it is possible to use the star formation efficiencies, $\epsilon_{(j)G}$, to convert the total stellar generation masses ($M_{(j)\ast}$) to the mass of the gas cloud out of which they were formed, $M_{(j)}$:

$$M_{(j)} = M_{(j)\ast}/\epsilon_{(j)G},$$

(18)

where $\epsilon_{(j)G}$ is given by Equation (8). Note that $M_{(j)} \equiv M_{\text{tot}}$ is the mass of the original gaseous cloud out of which the whole
cluster was formed. Figure 4 displays the calculated range of $M_{\text{tot}}$ for the considered clusters (see also Table 1). This is shown as a function of the star formation efficiency of the last generation and for the wide range of values used for $\alpha_{(n)G}$. The procedure uses Equations (15) and (16) to derive the $\alpha_{(n)G}$ values of each generation and Equations (17) and (18) to derive the total mass in stars for each generation and the mass of the cloud out of which they formed to finally obtain $M_{\text{tot}}$. Note that in all cases, the lower limit to $M_{\text{tot}}$ is the same for all allowed values of $\alpha_{(n)G}$, while the upper limit is in all cases given by the lowest considered $\epsilon_{(n)G}$ and $\alpha_{(n)G}$ values. The upper limits for the mass of the primordial gas cloud result from demanding that the last generation of star formation, in each of the considered clusters, has been mostly lost ($\alpha_{(n)G} = 0.1$), and thus the stars from the last generation that we see today represent only a small fraction of the stars initially formed. A small $\alpha_{(n)G}$ immediately implies a large $M_{\text{tot}}$, which makes one wonder why if $\epsilon_{(n)G}$ was also assumed to be so small, there was not another stellar generation. The figure also shows that if all stars from the last generation were still part of the cluster ($\alpha_{(n)G} = 1$) the value of the $M_{\text{tot}}$ upper limit would be reduced also by a factor of 10, for any assumed value of $\epsilon_{(n)G}$.

6. Concluding Remarks

Regarding the formation of GGCs we have shown that the efficiency of star formation in each stellar generation can be derived from the helium enhancement $\Delta Y$ between consecutive generations. We have derived individual and total star formation efficiencies for a sample of GGCs. Regarding the evolution of clusters, we have shown that the relative fraction of stars from consecutive stellar generation is also directly dependent on the observed value of $\Delta Y$ between them. Finally, by means of some basic assumptions, and demanding for all generations to have originally a full IMF, we have shown how to infer the original total mass in stars for each stellar generation and have derived the possible mass range of the clouds ($M_{\text{tot}}$) out of which each of our considered clusters formed.
6.1. Evaluation of the Model

Here we use the main constraints imposed by photometric and spectroscopic studies on the models of secondary stellar generations in GCs, derived by Renzini et al. (2015), as a benchmark to evaluate our model.

Variety and predominance are two important criteria to be taken into account for models of GCs. Variety deals with the fact that no two GCs are identical. Some present a minimum of two stellar generations (as perhaps considered in most models in the literature), but other may present multiple (up to seven) generations. Predominance indicates that the present mass in the various secondary generations exceeds in most cases the mass detected in the first generation. This issue leads in most models to a mass budget problem to account for the detected contamination. This has led us to assume a much larger first stellar generation, now depleted by the loss of stars through tidal interactions, and naturally to a much more massive primordial cloud. We assign an OK to our model in both issues, as done by Renzini et al. (2015) for the original interactive massive binary model from de Mink et al. (2009), noticing, however, that this model accounts only for two stellar generations and that the second one has a totally different IMF as it is to form only low-mass stars.

CMDs and appropriate two-color plots indicate that star formation in GCs happened in bursts (called “discreteness” in Renzini et al. 2015) and that it is not a continuous process, although see also the recent paper by Ventura et al. (2016) claiming instead a continuous process. In our model star formation with a full IMF occurs in well-separated bursts. The collapse of the leftover cloud is halted by the energy injected by the collection of massive stars that resulted from the last episode of star formation. As they evolve, they further contaminate the leftover gas with the new products that will characterize the next burst of star formation. The separation between bursts is then defined by the evolution time of massive stars (~40–50 Myr). This is in full agreement with “discreteness” of stellar generations in GCs.

The fact that in most GCs the various generations of stars share the same [Fe/H] abundance implies a total inability of the residual clouds to capture the ejecta from SN from former generations, which Renzini et al. (2015) calls SN avoidance. This in our model results from SN blowout, from the strong acceleration of the SN blast waves, and from their shells of swept-up matter, experienced either when they find the strong density gradient expected for the residual compact cloud held by gravity (see Tenorio-Tagle et al. 2015, 2016) or when overtaking several wind sources, which by enhancing the energy of the SN bubble makes them accelerate (Silich & Tenorio-Tagle 2017). Acceleration leads to the immediate fragmentation of the swept-up shell and to the rapid streaming of the SN ejecta between shell fragments and out of the remaining cloud. Only in the case of very massive and compact clouds will an SN taking place in the very central regions be totally retained, and thus in such massive cloud cases there is a possibility of enhancing the metal abundance of the leftover cloud causing a noticeable Fe spread, as in the most massive GCs.

In our model, the observed helium enrichments \(\Delta Y_f(1-L_0)\) and masses \(M(1)_*\) of subsequent generations are taken into account defining the star formation efficiencies and thus deserves an OK for both items. It is in fact He enrichment, the quantity that defines here the chronology of subsequent stellar generations as well as their efficiency of star formation, which fully accounts for the mass budget.

As in Paper I, IMBs are here held responsible for thoroughly contaminating the leftover gas with H burning products, while newly formed stars effectively hold the further collapse of the cloud. It is not until the end of the SN II era (say ~40 Myr after the onset of the last episode of star formation) that gravity wins again and the collapse of the leftover cloud leads to another stellar generation.

On the basis of the present analysis, we suggest the use of the \(\Delta Y_f(1-L_0)\) versus \(\epsilon\) diagram as powerful tool for tracing the formation properties of Galactic GCs.

This work made use of v2.1 of the Binary Population and Spectral Synthesis (BPASS) models as last described by Eldridge et al. (2017).

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