Mass Loss of Different Stellar Populations in Globular Clusters: The Case of M4

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Abstract

In a Globular Cluster (GC), the mass loss during the red giant branch (RGB) phase and the helium content are fundamental ingredients to constrain the horizontal-branch (HB) morphology. While many papers have been dedicated to the helium abundance in different stellar populations, small efforts have been made to disentangle the effects of mass loss and helium content. We exploit the nearby GC NGC 6121 (M4), which hosts two well-studied main stellar populations, to infer both helium and RGB mass loss. We combine multi-band Hubble Space Telescope photometry of RGB and main-sequence (MS) stars of M4 with synthetic spectra to constrain the relative helium content of its stellar populations. We find that the second-generation stars in M4 are enhanced in helium mass fraction by $\Delta Y = 0.013 \pm 0.002$ with respect to the remaining stars that have pristine helium content. We then infer the mass of the HB stars by searching for the best match between the observations and HB populations modeled assuming the helium abundance of each population estimated from the MS. By comparing the masses of stars along the HB, we constrain the mass loss of first- and second-generation stars in M4. We find that the mass lost by the helium-enriched population is $\sim 13\%$ larger than the mass lost by the first-generation stars ($\Delta M = 0.027 \pm 0.006 M_\odot$). We discuss the possibility that this mass-loss difference depends on helium abundance, the different formation environment of the two generations, or a combination of both.

Key words: globular clusters: individual (NGC 6121) – Hertzsprung–Russell and C–M diagrams – stars: evolution – stars: horizontal-branch

1. Introduction

Although globular clusters (GCs) have been studied for over 50 years, we have not yet reached a full understanding of the variegate description of the morphology of the horizontal branch (HB). It has been easily settled that the “first parameter” governing the HB is the metallicity (iron content [Fe/H] and an associated value of [$\alpha$/Fe]), but the “second parameter” governing the cluster-to-cluster differences at fixed metallicity remained amply discussed until the end of last century (see, e.g., Fusi Pecci et al. 1993), and includes age (Sarajedini & King 1989), helium abundance (Norris 1981; Norris et al. 1981), differences in the red giant branch (RGB) mass loss due to dynamics, and/or rotation (Fusi Pecci 1987).

In this context, the new century full evidence that nearly all Galactic GCs host multiple stellar populations likely with different helium abundances (D’Antona et al. 2002) provided a new approach to the problem. Indeed, helium-rich stars evolve faster than stars with lower helium content ($Y \sim 0.250$). As a consequence, for a fixed age, they will produce less-massive, hotter HB stars, which exhibit bluer colors than HB stars with pristine helium abundance (e.g., Iben & Renzini 1984; D’Antona et al. 2002; D’Antona & Caloi 2004), as do stars experiencing a larger mass loss on the RGB. This helps to solve the mystery of the bimodal HBs, like in NGC 2808 (Catelan et al. 1998), where indeed populations with different helium abundances have been discovered (D’Antona et al. 2005; Piotto et al. 2007).

In the case of NGC 2808, the helium abundance of multiple populations inferred from multiple main sequences (MSs) is a powerful tool to break the degeneracy between helium and mass loss in HB models. Adding the contribution of a further parameter in shaping the HB morphology generally does not resolve this problem. In most papers on HB modeling, age is inferred from the comparison of isochrones with observations of MS and sub-giant branch (SGB) stars, and it is not dependent on the HB morphology. While age can be constrained, both helium content and mass loss must be simultaneously varied to reproduce different HB morphologies. The shortcoming of this approach is a strong degeneracy between these two quantities that cannot be unequivocally constrained especially when the helium variations are small and do not produce a significant increase in the HB luminosity level. Small efforts have been made to change this traditional approach.

An important new tool is now available: recent works, based on multi-band Hubble Space Telescope (HST) photometry, have constrained the helium content of multiple stellar populations in a large sample of GCs by using MS and RGB stars (Lagioia et al. 2018; Milone et al. 2018, and references therein), thus providing a solid prospect of breaking the degeneracy of the parameters involved in the HB morphology.

In this paper, we exploit HST multi-band images of the nearby GC NGC 6121 (or M4) to infer the age and the average helium abundance of the first- and second-generation (1G, 2G) MS stars. These helium determinations will be used to constrain, for the first time, the mass loss of 1G and 2G stars individually, by modeling the HB.

M4 is one of the most studied clusters in the context of multiple stellar populations and is an ideal target for our purpose, especially due to the simplicity of its chemical patterns. High-resolution spectroscopy of RGB stars revealed two distinct groups of stars: a first generation with lower sodium ([Na/Fe] $\sim 0.1$) and high oxygen ([O/Fe] $\sim 0.5$), and a second stellar generation enhanced in sodium ([Na/Fe] $\sim 0.45$).
with lower oxygen ([O/Fe] ~ 0.2); see Marino et al. (2008), Villanova & Geisler (2011). Moreover, the 1G and 2G stars define two distinct sequences that can be followed continuously along the entire color–magnitude diagram (CMD), from the RGB tip (e.g., Marino et al. 2008) toward the bottom of the MS (e.g., Milone et al. 2014).

The HB of NGC 6121 is bimodal and is well populated on both sides of the RR-Lyrae instability strip. Furthermore, high-resolution spectroscopy of HB stars demonstrated that red and blue HB stars belong to the 1G and 2G, respectively, thus providing strong evidence of the connection between the HB morphology and the occurrence of multiple stellar populations (Marino et al. 2011; Villanova et al. 2012).

2. Photometry

To identify the 1G and 2G stars along the CMD of M4 and investigate their mass loss, we used literature photometry derived from images collected through the Wide-Field-Channel of the Advanced Camera for Survey (WFC/ACS) and the Ultraviolet and Visual Channel of the Wide Field Camera 3 (UVIS/WFC3) on board HST. Specifically, we used WFC/ACS photometry in F814W from Anderson et al. (2008), see their Table 1), UVIS/WFC3 photometry in F275W, F336W and F438W from Piotto et al. (2015), see their Table 1), and photometry collected through the F606W, F625W, and F658N bands of ACS/WFC and the F395N, F467M, F547M bands of UVIS/WFC3 from Milone et al. (2018, see their Table 1). Cluster members and field stars have been selected through the analysis of proper motions, as described in greater detail in the previous papers; the latter have been excluded from our analysis.

The photometry in the F275W, F336W, F438W and F814W bands is used to derive the $m_{F275W} - m_{F336W}$ versus $m_{F275W} - m_{F438W}$ two-color diagram of SGB stars and the “chromosome map” (ChM) of MS stars plotted in panels a and b of Figure 1, respectively. These diagrams are used to identify the 1G and 2G stars, which are colored red and blue, respectively, in Figure 1, while the two groups of 1G and 2G stars along the RGB are identified by using the ChM by Milone et al. (2017). As an example, Figure 1(c) shows the selected 1G and 2G stars along the MS, SGB, and RGB of M4 in the $m_{F814W}$ versus $m_{F275W}, m_{F336W}, m_{F438W}$ pseudo-CMD.

3. The Helium Abundance of Stellar Populations in M4

To infer the relative helium content of 1G and 2G stars, we applied to M4 the procedure introduced by Milone et al. (2012) and used in various papers from our group (e.g., Milone et al. 2018, and references therein). Briefly, we analyzed the CMDs $m_{F814W}$ versus $m_{F275W}, m_{F336W}, m_{F438W}$, where $X = F275W, F336W, F395N, F438W, F467M, F475W, F606W, F625W$ and F658N, and we derived the MS fiducial lines of 1G and 2G stars in each CMD.

We defined five equally spaced reference points in the magnitude interval $m_{F814W}$ and calculated the corresponding $m_{X} - m_{F814W}$ color differences between the fiducials of 2G and 1G stars, $\Delta(m_{X} - m_{F814W})$. For example, in Figure 1(d) we overimposed the fiducials of 1G and 2G stars on the $m_{F814W}$ versus $m_{F275W}$ CMD and marked the five reference points with gray dashed horizontal lines. We plot in Figure 1(e) $\Delta(m_{X} - m_{F814W})$ calculated for the available X filters at the reference point $m_{F814W} = 17.36$ as a function of the central wavelength of the X filter.
Table 1  
| Z | Age/Gyr | ΔY_{2G,1G} | M_{tip,1G}/M_{u} | M_{tip,2G}/M_{u} | M_{c,1G}/M_{u} | M_{c,2G}/M_{u} | μ_{1G}/M_{u} | μ_{2G}/M_{u} | σ_{c}/M_{u} | KS_{1} | KS_{2} |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Sim. 1 | 2 × 10^{-3} | 12.0 | 0.013 | 0.850 | 0.833 | 0.482 | 0.480 | 0.209 | 0.209 | 0.006 | <0.01 | <0.01 |
| Sim. 2 | 2 × 10^{-3} | 12.0 | 0.013 | 0.850 | 0.833 | 0.482 | 0.480 | 0.209 | 0.209 | 0.006 | <0.01 | <0.01 |
| Sim. 3 | 2 × 10^{-3} | 11.0 | 0.013 | 0.871 | 0.852 | 0.482 | 0.480 | 0.228 | 0.255 | 0.006 | <0.01 | <0.01 |
| Sim. 4 | 2 × 10^{-3} | 13.0 | 0.013 | 0.832 | 0.813 | 0.482 | 0.480 | 0.191 | 0.217 | 0.006 | <0.01 | <0.01 |
| Sim. 5 | 1 × 10^{-3} | 12.0 | 0.013 | 0.829 | 0.810 | 0.490 | 0.488 | 0.155 | 0.188 | 0.006 | <0.01 | <0.01 |
| Sim. 6 | 3 × 10^{-3} | 12.0 | 0.013 | 0.868 | 0.852 | 0.485 | 0.483 | 0.239 | 0.264 | 0.006 | <0.01 | <0.01 |
| Sim. 7 | 2 × 10^{-3} | 12.0 | 0.040 | 0.850 | 0.806 | 0.482 | 0.475 | 0.209 | 0.209 | 0.006 | <0.01 | <0.01 |

Note. The columns list the values of metallicity (Z), age, the Helium enhancement (ΔY_{2G,1G}) between the 2G and 1G stars, the mass at the tip of the RGB for both populations (M_{tip,1G} and M_{tip,2G}), and their core mass (M_{c,1G} and M_{c,2G}), the mean value of mass loss with its spread (μ_{1G}, μ_{2G}, σ_{c}), and the p-value of the KS test for both the colour and magnitude distributions (KS_{1} and KS_{2}).

For each reference point, we calculated a reference spectrum and a grid of comparison spectra by using ATLAS 12 and SYNTH (Castelli & Kurucz 2003; Kurucz 2005; Sbordone et al. 2007). We assumed for the reference spectrum unenriched helium content, Y = 0.250, and the individual abundances of C, N, and O inferred for 1G stars by Marino et al. (2008): [C/Fe] = −0.66, [N/Fe] = 0.42, [O/Fe] = 0.45, while gravity and effective temperature are taken from the best-fit isochrone. For this purpose, we used the isochrones from the database presented in Tailo et al. (2016) of appropriate metallicity. We reach a good fit of the CMD with an age of 12.0 Gyr, \( E(B-V) = 0.43, (m-M_V) = 11.41 \) and \( Z = 0.002 \).5

Comparison spectra have different abundances of C, N, O, and Y. Specifically, [C/Fe], [N/Fe], and [O/Fe] range from \(-1.10 \) to \(-0.30 \), from 0.42 to 1.32, and from 0.05 to 0.55, respectively, in steps of 0.1 dex. The helium abundance ranges from \( Y = 0.250 \) to \( 0.280 \) in steps of 0.001. For all the spectra, we used the average abundance of iron, [Fe/H] = −1.14, and \( \alpha \) elements, [\( \alpha \)/Fe] = 0.4, which are consistent with the values estimated by Marino et al. (2008).

Each synthetic spectrum was convolved with the transmission curves of the filters used in this work to derive the corresponding \( \Delta (m_Y - m_{F814W}^{ambient}) \) color difference. We used the \( Y, \ [C/Fe], \ [N/Fe], \ [O/Fe] \) values of the comparison spectrum that provides the best fit with the observations, to derive the best-estimate of the relative \( Y, C, N \), and O abundances of 2G and 1G stars.

From the five positions, we find that 2G stars are enhanced in helium by \( \Delta Y = 0.013 \pm 0.002 \) with respect to the 1G. This result is consistent within \( 1\sigma \) with previous determinations based on multi-band HST photometry of RGB stars, \( \Delta Y = 0.009 \pm 0.006 \) (Milone et al. 2018) and on \( U, B, V, I \) ground-based photometry of MS stars \( \Delta Y = 0.020 \pm 0.004 \) (Nardiello et al. 2015). We also find that the 2G stars have \( \Delta \langle [C/Fe] \rangle = -0.25 \pm 0.15 \), \( \Delta \langle [N/Fe] \rangle = 0.80 \pm 0.10 \), \( \Delta \langle [O/Fe] \rangle = -0.35 \pm 0.15 \). The resulting value of \( \langle [C+N+O]/Fe \rangle \) does not change within \( 0.05 \pm 0.10 \) dex.

4. Mass Loss and Simulated HB

To constrain the mass loss of RGB stars in M4, we compared the observed color and magnitude distributions of HB stars with a grid of synthetic HB stellar population models derived from the tracks calculated by Tailo et al. (2016), with constant \( \langle [C+N+O]/Fe \rangle \) as inferred by Marino et al. (2008). The tracks are obtained via the evolutionary code ATON 2.0 (Ventura et al. 1998; Mazzitelli et al. 1999) and follow the recipe by D’Antona et al. (2002) and D’Antona & Catii (2008). In a nutshell, each HB track is derived by assuming the same helium core mass of the corresponding star at the RGB tip and decreasing the envelope mass by a quantity equal to the mass loss.

We assumed that the mass loss has a Gaussian distribution with center \( \mu \) and dispersion, \( \sigma \). We adopted for the HB stars a mass, \( M_{HB} = M_{tip} - \mu \cdot \sigma \), where \( M_{tip} \) is the stellar mass at the tip of the RGB. The value of \( M_{tip} \) is provided by the isochrone that we used to fit the MS stars (see Section 3), while \( \mu \) and \( \sigma \) are considered free parameters. In the following, we differentiate these values with the subscripts 1G and 2G to indicate the two generations of stars, respectively. The MS and RGB models include a mild mass loss following the Reimers (1975) formulation; the free parameter inside the formula has been set to \( y_{\rho} = 0.3 \), as described in Tailo et al. (2016).

We assumed that 2G stars are enhanced in helium mass fraction by \( \Delta Y_{2G,1G} = 0.013 \) with respect to the first generation, as inferred from multi-band photometry of MS and RGB stars. Thus, the 2G stars have \( Y = 0.263 \), as we assumed \( Y = 0.250 \) for the 1G ones. We generated a grid of models by assuming the same mass loss for both 1G and 2G stars with values ranging from \( \mu_{1G} = \mu_{2G} = 0.100 \) \( M_{\odot} \) to 0.280 \( M_{\odot} \) in steps of 0.001 \( M_{\odot} \). We also included, in each simulation, a spread in mass loss ranging from \( \sigma_{\mu} = 0.000 \) \( M_{\odot} \) to 0.020 \( M_{\odot} \) in steps of 0.001 \( M_{\odot} \).

The sample of HB stars has been chosen by eye in the F606W–F814W and F438W–F814W CMDs, verifying at the same time that the selected stars are consistent with being HB stars in all the analyzed CMDs. We identified as red HB stars those redder than \( m_{F606W} - m_{F814W} > 0.75 \), while we identified as blue HB those stars bluer than \( m_{F606W} - m_{F814W} < 0.75 \). We checked that this identification is consistent in the bands we analyzed.

For each individual simulation in the grid, we compared the F606W–F814W color distribution of the simulated 1G and 2G HB stars with the observed color distribution of red and blue HB ones. This choice is justified by the spectroscopic evidence that the red and blue HB of M4 are mostly populated by stars of lower and higher Na, respectively (Marino et al. 2011).

The best match between the simulated 1G stars and the observed red HB corresponds to \( \mu_{1G} = 0.209 \) \( M_{\odot} \) and \( \sigma_{\mu} = 0.006 \) \( M_{\odot} \), as listed in Table 1. In Sim. 1, we adopted for 2G stars the mass loss inferred from the first generation. Figure 2 illustrates the results from this simulation, compared to the

5 These values agree with those provided by Schlafly & Finkbeiner (2011), see also: https://irsa.ipac.caltech.edu/applications/DUST/.
observed HB (upper panel). Clearly, we obtain a poor fit with the data, as the simulated 2G stars have, on average, redder colors than the observed blue HB. Moreover the $p$-values obtained from the Kolmogorov–Smirnov (KS) test of the color and magnitude distribution are both close to zero (see Table 1). The distribution of the mass of the simulated HB, due only to the different values of $M_{\text{Tip},1G(2G)}$ (see Table 1), is described in the bottom panel of Figure 2.

This attempt shows that it is not possible to reproduce the HB of M4 by assuming the helium difference between 2G and 1G stars inferred from multiple sequences together with the same mass loss for both populations.

To better reproduce the observed color distribution of both red and blue HB stars, we used the mass loss of the first generation derived above but assumed that 1G and 2G stars have different mass losses. We generated a grid of models for 2G stars with mass losses ranging from $\mu_{2G} = 0.100 M_\odot$ to $0.290 M_\odot$ in steps of $0.001 M_\odot$, and with a dispersion ranging from $\sigma_\mu = 0.000 M_\odot$ to $0.020 M_\odot$ in steps of $0.001 M_\odot$. We obtain the best fit between the observed colors of blue HB stars and the simulations of 2G stars for $\mu_{2G} = 0.236 M_\odot$ and $\sigma_\mu = 0.006 M_\odot$, which is our Sim. 2 described in Table 1. The comparison of Sim. 2 with the observations, represented in the left panels of Figure 3, indicates that a different mass loss for 1G and 2G stars can reproduce the HB of M4, once the different helium abundances for the two populations are constrained from independent features of the CMD. We thus conclude that to correctly represent the HB stars in M4, the mass loss for the 2G has to be increased to $\Delta \mu = 0.027 M_\odot$. In this case, the mass distribution of the HB stars exhibits two separated peaks, as reported in the upper right panel of Figure 3.

For completeness, in the lower-right panel of Figure 3, we compare the observed F606W–F814W color difference, $\Delta_{V606W-V814W}$ between the MS fiducial lines of 2G and 1G derived in Section 3 (black dashed–dotted line) with the corresponding color difference between the 2G and 1G stars from Sim. 1 (blue continuous line). This figure confirms that the adopted helium difference between 2G and 1G provides a good match with the observations of MS stars.

### 4.1. Impact of Observational Uncertainties

Our analysis supports the presence of different mass loss between the 1G and 2G stars on top of their different helium abundance. We test now the impact of the uncertainties of helium abundance, age, and metallicity comparison between the observed values on this result.

To investigate the effects of the error in the helium estimate, we repeated the entire procedure with $\Delta Y = 0.015$ and 0.011, the two extreme values obtained in Section 3. We find that with these variations, our result changes by $-0.004 M_\odot$ in the case of $\Delta Y = 0.015$ and by $+0.004 M_\odot$ for $\Delta Y = 0.011$.

Varying the age by $\pm 1$ Gyr (Sim. 3 and Sim. 4 in Table 1) does not vary the $\Delta \mu$ value that best fits the observed HB. Thus, our result is not significantly affected by age. This is due to the variation of $M_{\text{Tip}}$ with age. If we assume a linear relation, we obtain a slope of $\Delta M_{\text{Tip}}/\Delta \text{Age} = -0.019 M_\odot$ Gyr$^{-1}$ for both the 1G and the 2G models.

When we repeat the procedure using a set of models with a lower metallicity by $\Delta[\text{Fe/H}] = -0.15$ ($Z = 10^{-3}$), the typical observational uncertainty of spectroscopic analysis (Sim. 5, as in Table 1), we obtain $\Delta \mu = 0.033 M_\odot$: a slightly larger value. In the same way with $\Delta[\text{Fe/H}] = +0.15$ ($Z = 3 \times 10^{-3}$, Sim. 6, as in Table 1), we obtain $\Delta \mu = 0.025 M_\odot$. We also obtain $\Delta M_{\text{Tip},1G}/\Delta[\text{Fe/H}] = 0.123 M_\odot$, and $\Delta M_{\text{Tip},2G}/\Delta[\text{Fe/H}] = 0.153 M_\odot$.

We estimate the error associated to $\Delta \mu$ as the sum in quadrature of the uncertainties introduced by helium, age, and metallicity determination. We have then $\Delta \mu = 0.027 \pm 0.006 M_\odot$.

### 4.2. Is the Difference in Mass Loss Necessary?

As widely discussed, mass loss and helium variations are degenerate parameters in the distribution of stars along the HB. Hence, as an alternative approach to reproduce the observed distributions of HB stars, we used the same mass loss for both the 1G and 2G stars but not the helium difference inferred from the MSs as a constraint. We simulated a grid of synthetic HBs...
where $\Delta Y_{2G,1G}$ ranges from 0.000 to 0.150 in steps of 0.001. The comparison of our grid of HB models with different $Y$ for 2G stars and the observations suggests that the synthetic HB with $\Delta Y_{2G,1G} = 0.040$, Sim. 7 in Table 1, provides the best match with data.

The comparison of Sim. 7 with the $(m_{F606W} - m_{F814W})$ versus $m_{F814W}$ and $(m_{F438W} - m_{F814W})$ versus $m_{F438W}$ CMDs is shown in Figure 4. We note how, differently from Sim. 2 (lower-left panel of Figure 3), Sim. 7 contains a group of blue HB stars more luminous than the observed ones.

The bottom-right panels of Figures 3 and 4 display the comparison of the fiducials of the observed $\Delta m_{F606W,F814W}$ (see Section 3) with the theoretical $\Delta m_{F606W,F814W}$ obtained from isochrones having different helium content inferred from Sim. 2 and Sim. 7, respectively. Clearly, this comparison suggests that an equal mass loss for 1G and 2G stars, as in Sim. 7, would result in a too high helium enhancement for 2G stars, not consistent with values inferred from the RGB and the MS.

5. Summary and Discussion

The nearby GC M4 is one of the most studied clusters in the context of multiple populations. It hosts two main populations of 1G and 2G stars with different abundances of helium, carbon, nitrogen, oxygen, and sodium that define two distinct MSs, RGBs, and asymptotic giant branches (e.g., Marino et al. 2008, 2017; Lee 2010; Piotto et al. 2015; Lardo et al. 2017). The HB of M4 is populated on both sides of the RR-Lyrae instability strip, and the red and blue HB segments are populated by 1G and 2G stars, respectively (e.g., Marino et al. 2011; Villanova et al. 2012). In contrast with more massive GCs that exhibit extended HBs and extreme chemical compositions, M4 is considered a simple cluster in terms of multiple populations. These facts make M4 an ideal candidate to derive the RGB mass loss of different stellar populations in GCs.

We used multi-band HST photometry of M4 to infer the relative helium content of its two main stellar populations and to constrain the RGB mass loss. The helium abundance was derived by extending the method by Milone et al. (2012, 2018) to MS stars of M4. In a nutshell, the ChM was first used to identify 1G and 2G stars along the MS and to derive their colors. Then, we calculated a grid of theoretical stellar atmospheres of MS stars, by assuming different helium and light-element abundance, and finally, we compared the synthetic colors with the observations. We find that we can match the observations by assuming that 2G stars are enhanced...
We exploited the helium content of the two populations inferred from multiple MSs to constrain the RGB mass loss. To do this, we simulate a grid of HBs of 1G and 2G stars with different mass loss and helium and compared the color and magnitude distributions of each simulated HB with the observations.

By assuming for M4 the values of age, reddening, and distance modulus that provide the best fit between the observed MS, SGB, and RGB and the isochrones, we find that the observations of 1G stars and the red HB are consistent with a mass loss, $\mu_{1G} = 0.209 M_\odot$. By using for 2G stars, the same helium content as inferred from multi-band photometry of MS stars, the best match between the simulated HB and the observed colors and magnitudes of blue HB stars corresponds to $\mu_{2G} = 0.236 M_\odot$. We conclude that RGB mass loss of 2G stars is larger than that of the 1G ones by $\Delta \mu = 0.027 M_\odot$.

We have demonstrated that this result is not significantly affected by uncertainties in the adopted metallicity and age. On the contrary, by assuming the same mass-loss value for both 1G and 2G stars, we would require that 2G stars are enhanced in helium by $\Delta Y = 0.013 \pm 0.002$ with respect to the first generation, which has $Y = 0.250$.

Various studies have shown that it is not possible to reproduce the HB morphology of several GCs, including M3, M13, M14, M22, M92, NGC 1851, NGC 6388, NGC 6441, and NGC 6363, by assuming the same mass-loss rate for all the stellar populations (see, e.g., Caloi & D’Antona 2008; Joo & Lee 2013; Tailo et al. 2016, 2017; VandenBerg et al. 2016; Denissenkov et al. 2017; VandenBerg & Denissenkov 2018). There are also indications that this also happens in Fornax GCs (D’Antona et al. 2013).

In this work, we used for the first time the helium abundances of 1G and 2G stars of M4, inferred from multiple MSs, to break the degeneracy between helium and mass loss in HB models and estimate the RGB mass loss. Our conclusion that 2G stars lose more mass than 1G stars apparently implies that the RGB mass loss depends on the stellar helium abundance. However, the tiny differences in radius and gravity of the red giant progenitors of the 1G and 2G stars with such a small helium content difference do not physically justify a 13% difference in the mass-loss rate. As an alternative, we could ascribe this mass-loss difference to the different formation environments of 1G and 2G stars. Indeed, all the proposed scenarios suggest that the 2G forms in the central GC regions (e.g., D’Ercole et al. 2008; Valcarce & Catelan 2011).

The higher-density environment may induce a faster initial stellar rotation (see Tailo et al. 2015), which delays the ignition of the helium flash, so that the prolonged evolution at the brightest RGB luminosities can produce a larger total mass loss.
(Mengel & Gross 1976; Fusi Pecci & Renzini 1978). This formation scenario affects the fraction of binary stars that is lower in the 2G as a consequence of the large binary disruption rate in a denser stellar environment (Vesperini et al. 2011) and is nicely confirmed by observational work by D’Orazi et al. (2010), Lucatello et al. (2015).

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