ON THE PERIOD DISTRIBUTION OF CLUSTER RR LYRAE STARS TO CONSTRAIN THEIR HELIUM CONTENT: THE CASE OF ω CENTAURI

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ABSTRACT

We present new sets of nonlinear, time-dependent convective hydrodynamical models of RR Lyrae stars assuming two metal (Z = 0.0005, Z = 0.001) and three helium abundances (Y = 0.24, 0.30, 0.38). For each chemical composition, we constructed a grid of fundamental and first overtone models covering a broad range of stellar masses and luminosities. To constrain the impact of the helium content on RR Lyrae properties, we adopted two observables—period distribution and luminosity amplitudes—that are independent of distance and reddening. The current predictions confirm that the helium content has a marginal effect on the pulsation properties. The key parameter causing the difference between canonical and He-enhanced observables is the luminosity. We compared current predictions with the sample of 189 RR Lyrae stars in ω Cen and found that the period range of He-enhanced models is systematically longer than observed. These findings apply to metal-poor and metal-intermediate He-enhanced models. To further constrain the impact of He-enhanced structures on the period distribution, we also computed a series of synthetic horizontal branch (HB) models and found that the predicted period distribution, based on a Gaussian sampling in mass, agrees quite well with observations. This applies not only to the minimum fundamentalized period of RR Lyrae stars (0.39 versus 0.34 days) but also to the fraction of Type II Cepheids (2% versus 3%). We also computed a series of synthetic HB models assuming a mixed HB population in which the 80% is made of canonical HB structures, while the 20% is made of He-enhanced (Y = 0.30) HB structures. We found that the fraction of Type II Cepheids predicted by these models is almost a factor of two larger than observed (5% versus 3%). This indicates that the fraction of He-enhanced structures in ω Cen cannot be larger than 20%.

Key words: globular clusters: individual (NGC 5139) – stars: abundances – stars: evolution – stars: horizontal-branch – stars: oscillations – stars: variables: RR Lyrae

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1. INTRODUCTION

The stellar content of globular clusters (GCs) considered an optimal realization of a simple stellar population, since they are coeval and chemically homogeneous stellar systems, has been questioned. The spectroscopic evidence of star-to-star variations in the abundance of C, N, and Na as well as of Al and O in many cluster red giant (RG) stars dates back to 40 years ago (Osborn 1971). Moreover, the molecular band strengths of CN and CH seem to be anti-correlated (Smith 1987; Kraft 1994) and anti-correlations between O–Na and Mg–Al have been observed in evolved (RG, horizontal branch [HB]) and in unevolved (main sequence [MS]) stars of all the GCs investigated with high-resolution spectra (Pilachowski et al. 1983; Gratton et al. 2004).

More recently, accurate and deep Hubble Space Telescope optical photometry disclosed the presence of multiple stellar populations in several massive GCs. Together with the most massive Galactic GC ω Cen (Anderson 2002; Bedin et al. 2004) multiple stellar sequences have been detected in GCs covering a broad range of metal content: NGC 2808 (Piotto et al. 2007), M54 (Stiegel et al. 2007), NGC 1851 (Calamida et al. 2007; Milone et al. 2008), and 47 Tuc (Di Criscienzo et al. 2010; Nataf et al. 2011). Some of these multiple sequences (ω Cen, NGC 2808, NGC 1851) might be explained either with an He-enhanced (Norris 2004; Lee et al. 2005; D’Antona & Caloi 2008; Piotto et al. 2007) or with a CNO-enhanced (Calamida et al. 2007; Cassisi et al. 2008) sub-population. However, no general consensus has been reached concerning the physical mechanisms, the evolutionary history, and the fraction of these stellar components (Bergbusch & Stetson 2009).

The possible occurrence of He-enriched stars in GCs was suggested to explain not only the presence of multiple unevolved sequences but also the presence of extended blue HB tails (D’Antona & Caloi 2008, and references therein). Evolutionary prescriptions indicate that He-enriched structures, at fixed metallicity and cluster age, have a smaller turn-off mass when compared with structures constructed by assuming a canonical He content. Therefore, an He-enriched sub-population, for a fixed mass-loss rate, is characterized by smaller envelope masses and will mainly populate the hot and the extreme region of the HB (Bono 2010). Therefore, the presence of He-enriched sub-population(s) in GCs alleviates the heavy assumption of strong stochastic changes in the mass-loss rate along the red giant branch (RGB), required by the canonical scenario to populate the entire HB.

In this context ω Cen plays a key role, since it is a massive GC (Lee et al. 2009) in which have been identified several MS and sub-giant branches (Bellini et al. 2010, and references therein). Low-resolution spectra indicate that the bluest MS is more metal-rich than the redder ones, thus further supporting...
the evidence that it could be He-enhanced (Norris 2004; Piotto et al. 2005). However, Castellani et al. (2007) using star count ratio of HB and RG stars suggested that a significant fraction of extreme HB (EHB) stars in ω Cen might be aftermath of the hot helium flashers scenario. By using a broad range of synthetic color–magnitude diagrams (CMDs), Cassisi et al. (2009) found that EHB stars (T_e > 30,000 K) in ω Cen should be a mix of He-enhanced, hot helium flashers and canonical HB stars. In a spectroscopic investigation of ω Cen EHB stars, Moehler et al. (2011) found that roughly the 30% are He-poor, while the 70% have either solar or super-solar He abundances. Note that the carbon-rich stars are also He-rich stars, thus further supporting the evidence that a fraction of these stars is the progeny of the hot helium flashers scenario.

In a recent evolutionary investigation, D’Antona et al. (2010) suggest that very high He abundances (Y = 0.80) could be required to explain ω Cen EHB stars and that warm (log T_e < 10,000 K, see their Figure 2) HB stars might have He abundances ranging from the canonical to significantly higher He abundances. However, Sollima et al. (2006) using high-resolution spectra of 74 RR Lyrae stars in ω Cen found that their metallicity distribution agrees quite well with the metallicity distribution of RG stars (Calamida et al. 2009). Moreover, the distribution in the CMD of metal-intermediate RR Lyrae stars agrees quite well with the predicted metal-intermediate zero-age horizontal branch (ZAHB) based on HB models constructed assuming a canonical He content. The quoted authors pointed out that if the blue MS is made of He-enhanced, metal-intermediate MS stars, and if these structures are the progenitors of the EHB stars, then ω Cen should simultaneously host two metal-intermediate stellar populations with two different He contents.

In this investigation, we address the helium content of ω Cen RR Lyrae using their period distribution and luminosity amplitude.

2. THE THEORETICAL FRAMEWORK

The new pulsation RR Lyrae models have been computed by using the hydrodynamical code developed by Stellingwerf (1982) and updated by Bono & Stellingwerf (1994) and Bono et al. (1999, see also Smolec & Moskalik 2010 for a similar approach). The physical assumptions adopted to compute these models will be described in M. Marconi et al. (2011, in preparation). We adopted the OPAL radiative opacities released in 2005 by Iglesias & Rogers (1996, http://www-phys.llnl.gov/Research/OPAL/opal.html) and the molecular opacities by Alexander & Ferguson (1994). To constrain the pulsation properties of RR Lyrae stars in ω Cen, we adopted two metal abundances similar to the two observed peaks in the RR Lyrae metallicity distribution (Sollima et al. 2006), namely Z = 0.0005 and Z = 0.001. For each metal content we adopted three He contents to constrain the dependence of the pulsation properties of RR Lyrae stars on this crucial parameter. For each fixed chemical composition the stellar mass of RR Lyrae stars was fixed by using the evolutionary prescription for α-enhanced structures provided by Pietrinferni et al. (2006) and available on the BASTI database. Note that for each fixed metal content the mass of the He-enhanced models was estimated assuming the same cluster age (13 Gyr). Together with the luminosity predicted by evolutionary models, we often adopted a brighter luminosity level to account for the possible occurrence of evolved RR Lyrae stars. The input of the different sets of He-enhanced models is listed in Table 1, where columns from 1 to 4 give the metal and the He abundance, the stellar mass and the luminosity.

For each fixed chemical composition, mass value, and luminosity level, we investigated the limit cycle behavior of both fundamental (FU) and first overtone (FO) pulsators by covering a wide range of effective temperatures. For each model the pulsation equations were integrated in time till the radial motions approached their limit cycle stability. This means that we can provide robust constraints not only on the topology of the instability strip (IS) but also on the pulsation amplitudes of He-enhanced models. The top and the bottom panel of Figure 1 show the period distribution of canonical (empty symbols) and He-enhanced (filled symbols) models. The predicted trend of periods with the effective temperature shown in this figure is very similar to the results shown by van Loon et al. (2007) in the left panel of their Figure 17. The circles and the squares display metal-poor and metal-intermediate RR Lyrae models.

A glance at the data plotted in Figure 1 indicates that RR Lyrae models with an He-enhanced composition show periods that are systematically longer than the canonical ones. The difference is mainly caused by evolutionary effects. The top (canonical), the middle (He-enhanced, Y = 0.30), and the bottom (He-enhanced, Y = 0.38) panels of Figure 2 show together with the modal stability of FU (solid vertical lines) and FO (dotted vertical lines) RR Lyrae stars the predicted ZAHBs (dashed line) and selected HB evolutionary models. On the basis of the evolutionary predictions plotted in this figure, we can identify two different regimes.

HB structures evolving inside the IS. The HB structures with a ZAHB location inside the IS and evolving during their central He-burning phases inside the RR Lyrae IS show, at fixed cluster age (13 Gyr) and metal content (Z = 0.001), similar mass values when moving from a canonical (Y = 0.24, D Canonical RR Lyrae pulsation models computed by Bono et al. (2003) and Di Criscienzo et al. (2004). The difference in metal content between the canonical and the He-enhanced models for Z = 0.0004 and Z = 0.0005 has a minimal impact on the pulsation properties and they are treated together.

Table 1

| Z*  | Y*  | M/M_⊙ | log L/L_⊙ |
|-----|-----|--------|-----------|
| 0.0004 | 0.24 | 0.70 | 1.6, 1.7, 1.8 |
| 0.0005 | 0.35 | 0.65 | 1.85, 1.95 |
| 0.40 | 0.60 | 1.9 |
| 0.001 | 0.24 | 0.65 | 1.5, 1.6, 1.7, 1.9 |
| 0.30 | 0.60, 0.65 | 1.8, 1.9, 2.0 |
| 0.38 | 0.60, 0.65 | 1.8, 1.9, 2.0 |

Notes.

* Metal (Z) and helium (Y) abundances by mass.

* Stellar mass (solar units).

* Logarithmic luminosity (solar units).

* Canonical RR Lyrae pulsation models computed by Bono et al. (2003) and Di Criscienzo et al. (2004).
top panel of Figure 2) He content to a moderately He-enhanced ($Y = 0.38$, bottom panel of Figure 2), since the predicted ZAHBs for these models minimally intersect the predicted RR Lyrae IS. The mass of the progenitors decreases from 0.80 to 0.70 $M_\odot$ and to 0.62 $M_\odot$ when moving from the lowest to the highest He content. The typical masses populating the IS of the canonical models range from $\sim 0.64$ to $\sim 0.69 M_\odot$, and the typical luminosity is $\log L/L_\odot \approx 1.70$. For moderately He-enhanced models the masses range from $\sim 0.64$ to $\sim 0.70 M_\odot$, and the typical luminosity is $\log L/L_\odot \approx 1.80$. Evolutionary prescriptions concerning moderately He-enhanced models ($Y = 0.30$) indicate that HB structures evolving inside the IS are a mix between structures evolving from the blue to the red and also in the opposite direction. This effect is mainly caused by the fact that an increase in He content causes an extension of the excursion toward hotter effective temperatures that these structures perform during their off-ZAHB evolution (see the bottom panel of Figure 2; Sweigart & Gross 1976; Sweigart & Catelan 1998; Figure 2 in D’Antona et al. 2010).

**HB structures evolving across the IS.** The HB structures with lower total masses attain their location along the ZAHB toward effective temperatures hotter than RR Lyrae IS. During their off-ZAHB evolution they cross the IS at luminosities systematically brighter than typical RR Lyrae stars. For a hot HB structure of 0.52 $M_\odot$ the luminosity at the center of the IS ($\log T_{\text{eff}} = 3.83$) is $\approx 2.30$ for the $Y = 0.24$ and $Y = 0.30$ models and becomes 2.40 for the $Y = 0.38$ models, while the period changes from $P \sim 2.0$ to $P \sim 2.4$ days. For a warm HB structure with a stellar mass of 0.62 $M_\odot$, the luminosity is $\log L/L_\odot \approx 1.76$ for $Y = 0.24$, $\approx 1.91$ for $Y = 0.30$, and $\approx 2.17$ for $Y = 0.38$, while the period increases by more than a factor of two: $P \sim 0.61$, $P \sim 0.83$, and $P \sim 1.36$ days, respectively. The main evolutionary consequence of the presence of He-enhanced models is that we can have HB structures with similar masses either evolving inside the IS or crossing the IS that are from 0.1 to $\sim 0.4$ dex more luminous than the canonical ones. The main outcome of the quoted differences is to produce RR Lyrae stars with pulsation periods that are systematically longer than the canonical ones.

The above findings concerning the increase in the period of RR Lyrae stars support the simulations provided by Sweigart & Catelan (1998) using He-enhanced models. The quoted authors investigated three different noncanonical scenarios to explain the tilted HB of two metal-rich GCs (NGC 6388, NGC 6441). They also investigated the impact on the period distribution of RR Lyrae and found that the increase in He causes a systematic increase in the luminosity, and in turn in the period of RR Lyrae stars (see their Figure 3).

Two evolutionary effects are noteworthy concerning He-enhanced HB models. Mass loss–He-enhanced models (Cassisi et al. 2009; Di Criscienzo et al. 2010) alleviate the requirement of strong changes in the mass-loss rate along the RGB. Current

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**Figure 1.** Top: period distribution of metal-poor ($Z = 0.0005$, open circles) and metal-intermediate ($Z = 0.001$, squares) first overtone RR Lyrae models. The models with canonical He content are plotted as empty symbols, while the He-enhanced ones with filled symbols and different colors (see labels). Bottom: same as the top, but for the fundamental RR Lyrae models. (A color version of this figure is available in the online journal.)

**Figure 2.** Top: predicted RR Lyrae instability strip at fixed metal content ($Z = 0.001$) based on canonical pulsation models. The solid and the dotted vertical lines display the instability strip for fundamental and first overtone RR Lyrae. The almost horizontal dashed line shows the predicted zero-age horizontal branch, while the solid lines selected HB evolutionary models (BASTI database) of different stellar masses. Middle: same as the top, but for moderately He-enhanced models ($Y = 0.30$). Bottom: same as the top, but for He-enhanced models ($Y = 0.38$). (A color version of this figure is available in the online journal.)
predictions also indicate that the mass-loss rate of RG stars is independent of their He content. This means that if we assume multiple populations with different He contents the ZAHB from the red HB to the EHB will be naturally populated with structures of different total mass. Lifetime—evolutionary prescriptions indicate that the central He-burning lifetime of He-enhanced structures is longer than for canonical HB (Cassisi et al. 2009; D’Antona et al. 2010). The difference with the most He-enriched models ranges from 10% for red HB stars to 30% for EHB stars (log $T_e \approx 4.3$). The increase in the lifetime is caused by the fact that they are fainter, since the He-core mass of He-enhanced models is slightly smaller than the canonical ones. In these structures, the H shell plays a marginal role, since the envelope mass is quite small. The HB region in which the H shell becomes relevant in the energy budget is for effective temperatures cooler than log $T_e \approx 4$, and indeed in this region He-enhanced structures are brighter than canonical ones. However, the He-burning lifetime of He-enhanced models is longer over the entire temperature range. The difference is smaller and appears counter intuitive, since the former structures are, at fixed effective temperature, brighter than the latter ones. The increase in the He-burning lifetime is mainly caused by the fact that the hydrogen-burning shell in the He-enhanced structures is more efficient, due to the increase in the mean molecular weight (see Figure 6 in Bono 2010). This means that the moderately He-enhanced sub-population is expected to populate the entire HB.

3. COMPARISON WITH OBSERVATIONS

To constrain the He content of RR Lyrae stars in ω Cen, we adopted the period distribution. The reasons to use this observable are threefold. (1) ω Cen hosts a sizable sample of RR Lyrae stars (189: 100 RRc, 89 RRab; Kaluzny et al. 2004; Weldrake et al. 2007). (2) The distance modulus of ω Cen was fixed using the K-band period–luminosity relation of RR Lyrae stars (Del Principe et al. 2006) and with the tip of the RGB (Bono et al. 2008). However, different authors are still adopting distance moduli that differ by more than 0.3 dex (Cassisi et al. 2009; D’Antona et al. 2010). The period distribution is distance and reddening independent. (3) The census of bright variables in this cluster is complete (Kaluzny et al. 2004; Weldrake et al. 2007).

Figure 3 shows the period distribution of RR Lyrae stars in ω Cen using the sample adopted by Del Principe et al. (2006). The period distribution was smoothed using a Gaussian kernel (for more details see Di Cecco et al. 2010). The comparison between theory and observations brings forward interesting results. (1) The period range covered by He-enhanced models is systematically larger than observed. The discrepancy becomes even more clear if we account for the fact that variables with periods longer than ≈0.9 days are classified as Type II Cepheids. (2) The He-enhanced models do predict FO periods that are systematically longer than observed. Note that the minimum period for FO pulsators based on canonical models agrees quite well with observed values in GCs (Caputo et al. 2000; Di Criscienzo et al. 2004). (3) Metal-poor (top) and metal-intermediate (bottom) He-enhanced models show the same behavior. (4) The period range covered by canonical RR Lyrae models agrees quite well with the observed one.

The anonymous referee suggested to provide a more detailed comparison between theory and observations using synthetic HB models. To accomplish this goal, we computed a series of synthetic HB models using the same theoretical framework adopted by Percival et al. (2009). Note that the main aim of this approach is to constrain the impact that different HB sub-populations characterized by different He contents have on the period distribution of RR Lyrae stars. We adopted two different assumptions concerning the mass distribution to populate the synthetic HBs. In particular, we adopted a linear sampling and a Gaussian sampling. In the former case we distributed—for each chemical composition—4000 artificial stars according to the evolutionary lifetimes predicted by a detailed grid of HB models. Data plotted in the left panels of Figure 4 show the synthetic HBs, while the right panels display the period distribution of the objects located between the blue edge of the FOs and the red edge of the FU mode. In the comparison

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10 The long period tail of RR Lyrae stars in ω Cen includes seven objects with periods ranging from ~0.81 to ~0.87 days and with mean visual magnitudes ranging from 14.32 (V31) to 14.56 (V78) mag. These objects are well separated from Type II Cepheids, since there is a group of six variables with periods ranging from ~0.97 to ~2.27 days and mean visual magnitudes that are at least half-magnitude brighter than long period RR Lyrae stars. Their mean visual magnitude ranges from 13.32 (V134) to 13.98 (V2; Kaluzny et al. 1997). The sample of Type II Cepheids in ω Cen also includes three Type II Cepheids with periods ranging from ~4.27 to 29.35 days (Kaluzny et al. 1997; Matsunaga et al. 2006).
was fundamentalized (log period distribution of the synthetic HB models (black line) plotted in the left panels and the observed period distribution (red dashed line). The period of the first overtones (A color version of this figure is available in the online journal.)

Figure 4. Left: Hertzsprung–Russell diagram showing synthetic HB models constructed assuming a linear sampling in mass. The blue and the red lines display the first overtone blue edge and the fundamental red edge. From top to bottom the three panels display predictions based on HB models with different helium contents: $Y = 0.24$ (top), $Y = 0.30$ (middle), and $Y = 0.38$ (bottom). The number of stars located inside the instability strip is labeled. Right: comparison between the period distribution of the synthetic HB models (black line) plotted in the left panels and the observed period distribution (red dashed line). The period of the first overtones was fundamentalized ($\log P_F = \log P_{127} + 0.127$). Predicted and observed period distributions were smoothed using a Gaussian kernel. (A color version of this figure is available in the online journal.)

between predicted (solid line) and observed (red dashed line) period distribution, we fundamentalize the period of the FOs ($\log P_F = \log P_{127} + 0.127$). The predicted period distributions were smoothed using the same approach adopted for the observed one. Data plotted in the top right panel indicate that a significant fraction of HB stars populating the warm and the hot region of the HB might have a canonical helium content.

The minimum fundamentalized period is a robust observable to constrain the evolutionary properties of RR Lyrae stars (the interested reader is referred to Bono et al. 1995, and references therein). We found that the observed minimum fundamentalized period is $\sim 0.34$ days, while the predicted one, assuming a canonical helium abundance is $\sim 0.39$ days. Moreover, the predicted distribution shows a well-defined upper limit for RR Lyrae stars at $P \sim 0.87$ days as suggested by the observations. The shape of the predicted period distribution is broader than the observed one, but this difference is out of the aim of this investigation. Note that the predicted fraction of Type II Cepheids with periods $0.95 \leq P \leq 2.30$ is a factor of three smaller ($\sim 1\%$) than the observed one ($\sim 3\%$).

Empirical evidence indicates that only six Type II Cepheids with $0.95 \leq P \leq 2.3$ have been identified in $\omega$ Cen (see Kaluzny et al. 1997).

The synthetic HBs computed assuming the He-enhanced HB models with $Y = 0.30$ show a period distribution that is systematically shifted toward longer periods when compared with the observed one (see the middle right panel of Figure 4). Moreover, this period distribution shows, at odds with observations, two well-separated peaks. The comparison with the period distribution based on HB models with $Y = 0.38$ is more difficult, since these structures do not produce RR Lyrae stars, but only Type II Cepheids. However, the predicted Type II Cepheids attain visual magnitudes that are brighter ($V \leq 13.2 \pm 0.1$ mag, see the bottom right panel of Figure 4) than the observed ones (see Kaluzny et al. 1997). In passing we note that the crossing time of the He-enhanced models, at fixed metal content ($Z = 0.001$), is on average $10\%$ longer (Bono 2010) than for models with canonical He content. This means that the probability to produce Type II Cepheids for He-enhanced structures is higher than for canonical ones.

The synthetic HB models, based on the Gaussian sampling in mass, were constructed adopting for each chemical composition a slightly different value of the mean mass ($M/M_\odot = 0.62 \ [Y = 0.246], 0.61 \ [Y = 0.30], 0.60 \ [Y = 0.38]$) populating the HB and the same dispersion in mass ($\sigma = 0.02 \ M_\odot$). Data plotted in Figure 5 show that the period distribution based on synthetic HB models with Gaussian sampling in mass is very similar to the models with linear sampling. The minimum fundamentalized period of the canonical models is $\sim 0.39$ days, and the fraction of Type II Cepheids with periods $0.95 \leq P \leq 2.30$ is similar (2%) to the observed one. Moreover, the predicted period distribution shows a well-defined peak similar to the observed one. The period distributions based on He-enhanced models show discrepancies similar to synthetic HBs computed assuming a linear sampling in mass.

However, the above conclusions rely on the assumption that warm and hot HB stars are only made by HB structures either with a canonical or with an He-enhanced compositions. Recent investigations concerning the fraction of second generations, He-enhanced stars in GCs indicate that it might be of the order of 50% or even more (D’Antona & Caloi 2008). For $\omega$ Cen it was suggested that the fraction of stars with a moderate
increase in He content \((Y \leq 0.38)\) should be of the order of 20\% (Norris 2004; Lee et al. 2005). To account for the possible mix of RR Lyrae stars with different helium contents, Figure 6 shows the cumulative period distribution computed assuming the 80\% of the period distribution based on canonical HB models and the 20\% of the period distribution based on helium-enhanced HB models \((Y = 0.30)\). Note that we did not apply any normalization between the two period distributions. The cumulative period distribution based on the uniform mass distribution shows a minimum fundamentalized period that is, as expected, very similar to the period distribution based on canonical HB models. However, the fraction of Type II Cepheids with periods \(0.95 \leq P \leq 2.30\) is almost a factor of three larger (8\%) than the observed one. The outcome is similar for the cumulative period distribution based on the Gaussian sampling, but the same fraction is almost a factor of two larger (5\%) than the observed one (see the bottom panel of Figure 6).

The above findings indicate that the fraction of RR Lyrae stars with \(Y = 0.30\) cannot be larger than 20\%. The occurrence of He-enhanced structures causes a steady increase in the typical period of RR Lyrae stars and an increase in the fraction of Type II Cepheids with periods between 0.95 and 2.30 days that is not supported by observations. These results are minimally affected by the sampling in mass adopted to compute the synthetic HB models. We cannot reach firm conclusions concerning the fraction of HB stars with \(Y = 0.38\), since these structures only produce Type II Cepheids. However, the predicted visual magnitudes for these objects are systematically brighter than observed.

To further constrain the impact of the He abundance on the pulsation properties of RR Lyrae stars, we also compared observed (Kaluzny et al. 1997) and predicted V-band amplitudes for FU RR Lyrae. Note that luminosity amplitudes are also independent of cluster distance and reddening corrections.

Figure 5. Same as Figure 4, but the synthetic HB models were constructed assuming a Gaussian sampling in mass with different mean masses and the same dispersion. See the text for more details.

(A color version of this figure is available in the online journal.)

Figure 6. Top: comparison between the observed period distribution and the predicted cumulative period distribution based on the linear sampling in mass (see Figure 4). The latter was estimated assuming the 80\% of the canonical and the 20\% of the helium-enhanced \((Y = 0.30)\) period distribution. Bottom: same as the top, but the predicted cumulative distribution is based on the Gaussian sampling in mass (see Figure 5).

(A color version of this figure is available in the online journal.)
of 50% in He, when compared with canonical models and with panel shows that the set of metal-poor models with an increase plotted in this figure indicate, once again, that the He content served and predicted $V$ values are labeled. Bottom: same as the top, but for metal-intermediate ($Z = 0.001$) RR Lyrae models.

(A color version of this figure is available in the online journal.)

Figure 7. Top: comparison between observed (Kaluzny et al. 1997) and predicted $V$-band amplitudes vs. the logarithmic period for metal-poor ($Z = 0.0005$) RR Lyrae models. The adopted He abundances and luminosity levels are labeled. Bottom: same as the top, but for metal-intermediate ($Z = 0.001$) RR Lyrae models.

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Bolometric light curves were transformed into the observational plane using the bolometric corrections and the color–temperature transformations provided by Castelli et al. (1997a, 1997b). Figure 7 shows the comparison between observed and predicted $V$-band amplitudes for canonical (black lines) and He-enhanced (colored lines) RR Lyrae models. Data plotted in this figure indicate, once again, that the He content marginally affects the pulsation behavior of RR Lyrae. The top panel shows that the set of metal-poor models with an increase of 50% in He, when compared with canonical models and with similar luminosities ($\log L/L_\odot \approx 1.85$ versus 1.80), display very similar amplitudes and cover very similar periods. The same outcome applies to the two sets of He-enhanced, metal-intermediate He-enhanced models. The results are the same if we take into account the luminosity amplitude. However, predicted amplitudes are less robust than the pulsation periods, since they depend on the adopted mixing length parameter. Moreover, the amplitude might also be affected by an observational bias, since we still lack a complete census of $\omega$ Cen RR Lyrae affected by the Blazhko phenomenon.

Taken at face value the above results indicate that $\omega$ Cen RR Lyrae do not show a clear evidence of He-enrichment when moving from metal-poor to metal-intermediate stars. However we cannot exclude, as originally suggested by Sollima et al. (2006), the probable occurrence of two metal-intermediate sub-populations. The former one with canonical He content evolving into the RR Lyrae IS and the latter one with an He-enhanced abundance evolving into the hot and the EHB region. Note that $\omega$ Cen hosts more than 2100 hot HB stars, i.e., roughly the 65% of the entire population of HB stars (see Table 2 in Castellani et al. 2007).

To constrain the occurrence of He-enhanced RR Lyrae stars, we also computed a series of synthetic HB models using canonical and He-enhanced HB models and two different assumptions concerning the sampling in mass (linear, Gaussian). Current models further confirm the sensitivity of the minimum fundamentalized period to constrain the He content of cluster RR Lyrae. The period distribution based on canonical HB models agrees quite well with observations concerning the minimum period ($0.39$ versus $0.34$), the upper limit to the period distribution of RR Lyrae stars ($P \sim 0.87$ days), and the fraction (2% versus 3%) of Type II Cepheids ($0.95$ days $\leq P \leq 2.30$ days). These findings minimally depend on the adopted sampling in mass.

The period distribution based on He-enhanced HB models is either systematically shifted toward longer periods ($Y = 0.30$) or produce Type II Cepheids that are systematically brighter than observed ($Y = 0.38$). To further constrain the impact on the period distribution of RR Lyrae with different He contents,
we computed the period distribution of a sample made with the 80% of canonical and the 20% of RR Lyrae stars with moderate He-enhancement (Y = 0.30). We found that the fraction of Type II Cepheids predicted by the synthetic HB models computed by assuming a Gaussian sampling in mass is almost a factor of two larger than observed (5% versus 3%). This indicates that the fraction of He-enhanced structures in ω Cen cannot be larger than 20%.

More quantitative constraints concerning the individual He enhancements of RR Lyrae stars in ω Cen require accurate estimates of the A-parameter11 (Caputo et al. 1983; Sandquist 2000) using homogeneous grids of pulsation and evolutionary models constructed assuming a broad range of helium abundances (F. Caputo et al. 2011, in preparation).

Finally, in a recent investigation (Dupree et al. 2011) detected in five out of twelve RGs in ω Cen, with similar magnitudes and colors, the chromospheric He i line at 10830 Å. The strength of the He line seems to be correlated with Al and Na abundances rather than with iron. However, a more detailed non-LTE analysis of the He abundance is required before firm conclusions concerning the occurrence of a spread in helium can be safely established.

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11 The A-parameter is a diagnostic to constrain the mass–luminosity ratio of individual RR Lyrae stars. It is defined as \( A = \log L/L_\odot \sim -0.81 \log M/M_\odot \), where \( L \) and \( M \) are the luminosity and the mass of the pulsator, respectively.