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SUPER-HELIUM-RICH STARS IN GLOBULAR CLUSTERS: THE ORIGIN OF EXTREME HORIZONTAL-BRANCH

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Abstract. Recent observations of the globular cluster ω Centauri have shown that it has a double main sequence (MS), with a minority population of bluer and fainter MS well separated from a majority population of MS stars. Here we confirm that this special feature can only be reproduced by assuming a large range of helium abundance among several distinct populations in this cluster. We further show that the same helium enhancement required to reproduce this special feature on the MS can by itself reproduce the extreme horizontal-branch (EHB) stars observed in ω Cen, which are hotter than and separated from the majority population of normal HB stars. We also discuss the possibility that similar phenomena observed in the HB of other globular clusters are also due to the helium enhancement. If confirmed by further observations, this would establish that the third parameter that influences globular cluster color-magnitude diagram (CMD) morphology, in addition to metallicity and age, is indeed helium abundance.

Key words: globular clusters: individual (ω Centauri) – stars: abundances – stars: evolution – stars: horizontal-branch

1. INTRODUCTION

The Hubble Space Telescope snapshot survey of Galactic globular clusters has shown that the presence of extreme horizontal-branch (EHB) stars is not an unusual phenomenon among relatively massive globular clusters, which suggests that a third parameter, in addition to metallicity and age, is needed in order to explain the peculiar features observed on the HBs of these clusters (Piotto et al. 2002). It has been suggested for some time that more than one epoch of star formation and the accompanying helium and other elements enhancements in some globular clusters might be responsible for the presence of bimodal HBs and the EHB stars (D'Antona et al. 2002; D'Antona & Caloi 2004). While it has already been known that the HB morphology is very sensitive to helium abundance (see, e.g., Lee et

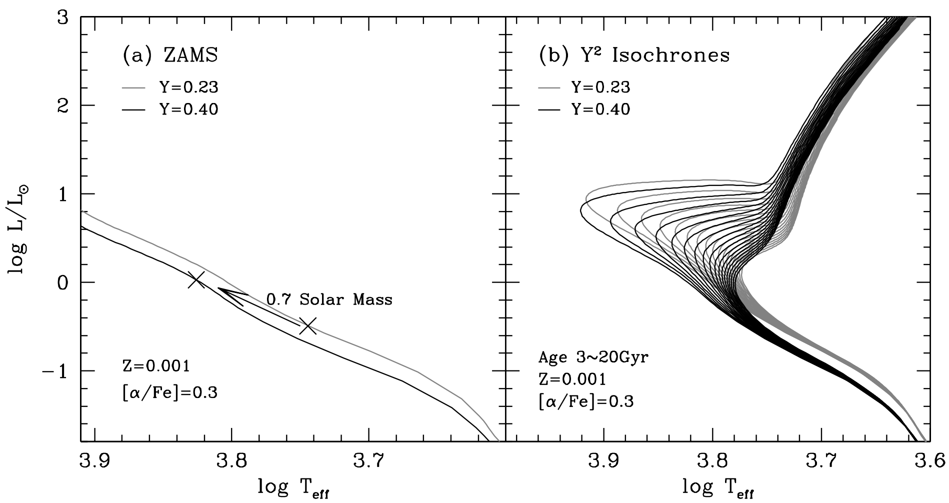

Fig. 1. New sets of Y^2 isochrones with helium enhancement. Panel (a) demonstrates the effect of helium enhancement on the zero-age main sequence for a given mass, while panel (b) illustrates the effect on the isochrones.

al. 1994), what is needed is a firm evidence that such a special helium enrichment indeed occurs in some globular clusters. This is because a star cluster is widely believed to be a coeval and chemically homogeneous system, and also the required helium enrichment is far more than that expected from standard chemical evolution models in galactic scales (i.e., $\Delta Y/\Delta Z = 1{\sim}2$).

The first good evidence that some stars in a globular cluster are actually enhanced in helium came from the recent observations of ω Cen. In particular, recent analyses with isochrones (Norris 2004) and spectroscopy (Piotto et al. 2005) of the MS stars in ω Cen have shown that a large helium abundance variation is needed to reproduce the double MS (Bedin et al. 2004) observed in this cluster. Although more work is needed for a specific chemical evolution model devoted for ω Cen to understand the origin of this unusually strong helium enrichment, these observations and analyses have nevertheless provided a compelling evidence that a minority population of stars at least in one globular cluster are indeed enhanced in helium. In this paper, we report our progress in constructing population models with the super-helium-rich scenario.

2. EFFECT OF HELIUM ENHANCEMENT

In order to investigate the effect of helium abundance on the observed features in the CMD, we have first calculated new sets of Yonsei-Yale (Y^2) stellar evolutionary tracks and isochrones with helium enhancements (Kim et al. 2002; Kim et al. 2005). These tracks adopted most up-to-date input physics including a new equation of state for the low mass stars. Figure 1 demonstrates the effect of helium enrichment on the HR diagram. Helium-rich stars, in general, are brighter and bluer for a given mass because of their higher core temperature (Fig. 1a), however, since they evolve faster than helium-poor stars, they would have smaller masses for a given age, and therefore the helium-rich MS appears both bluer and

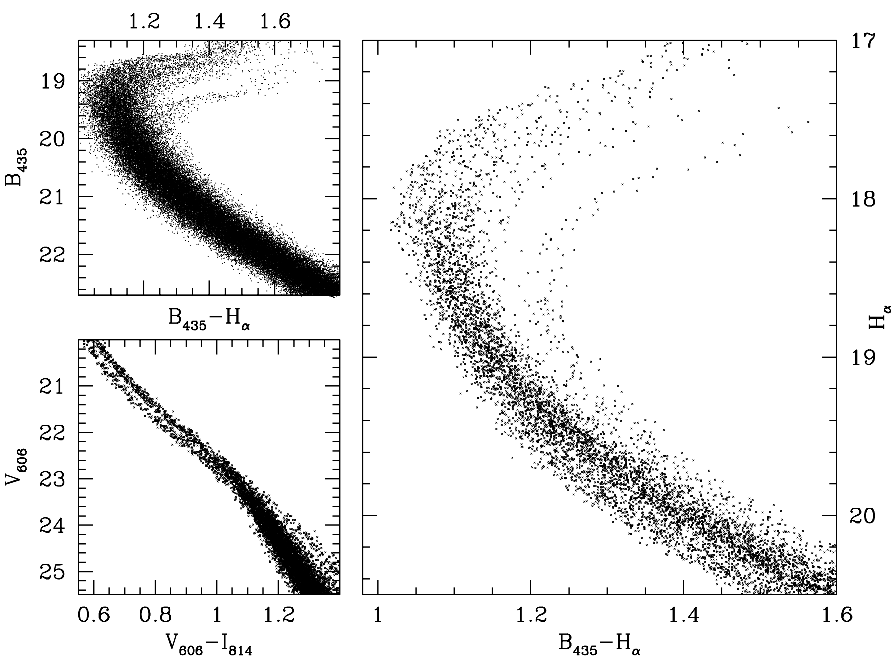

Fig. 2. Model CMDs for the main-sequence and subgiant-branch parts of ω Cen. These figures are to be directly compared with the observations by Bedin et al. (2004; see their Fig. 1).

fainter than the helium-poor MS on the isochrone (Fig. 1b). For the same reason, the mass at the tip of the red-giant-branch (RGB) of a helium-rich population is smaller than that of a helium-poor one, so that helium-rich HB stars have smaller total masses than helium-poor stars, which shifts their positions to the blue in the CMD (Lee et al. 1994).

3. POPULATION MODELS

Based on our new isochrones and the HB evolutionary tracks of Sweigart (1987) extrapolated to $Y \sim 0.4$,[1] population synthesis models are constructed following the techniques developed by Lee et al. (1990) and Park & Lee (1997). In Figure 2 we present the model CMDs for the MS and subgiant-branch (SGB) parts, based on the assumption that the helium abundances for the three most metal-rich populations are significantly enhanced among five populations with different metallicities in ω Cen (Sollima et al. 2005). These CMDs were specifically constructed with the passbands, photometric errors and total numbers of stars comparable to the observed ones of Bedin et al. (2004; see their Fig. 1), so that they can be directly compared with each other. The values of helium abundance and age are

[1] We are now in the process of constructing new sets of helium enhanced HB tracks fully consistent with our isochrones. Based on our preliminary models for ZAHB, we have confirmed that there is no serious systematic difference between our HB models and those of Sweigart (1987). We also verified that the extrapolation in Y does not produce a critical problem, by using the Sweigart & Gross (1976) HB tracks where the helium abundance is extended to $Y = 0.4$.

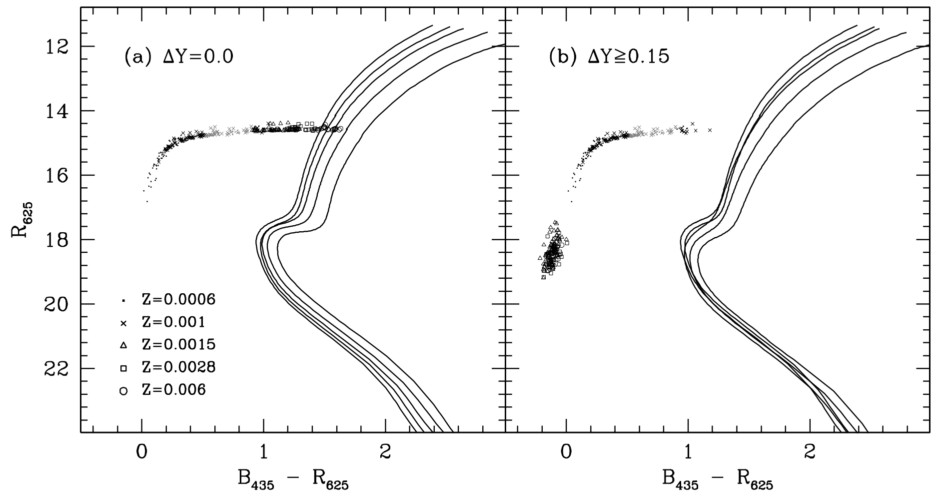

Fig. 3. Model CMDs for ω Cen. Panel (a) is for the case in which all five populations in ω Cen have the same helium abundance, while panel (b) is for the case in which the helium abundances for the metal-rich populations are significantly enhanced as in Table 1. Only the case of $\Delta Y \geq 0.15$ can reproduce the observed features on the MS and HB simultaneously. We adopted $(m - M)_R = 14.3$ and $E_{B-R} = 0.19$ in our models.

adjusted until the best matches between the models and the observed CMDs are obtained, while those for the metallicity are mostly fixed by the RGBs. Table 1 lists the input parameters used in our best model simulations. Similarly, in Figure 3, we compare two models constructed under different assumptions regarding the helium enhancement. As is clear from Figures 2 and 3, we confirm the conclusion from previous works that a large variation in helium abundance is indeed needed to reproduce the observed features on the MS to RGB, including the double MS, where the minority population of the bluer and fainter MS is both more metal-rich and super-helium-rich ($\Delta Y = 0.15$) compared to the majority population of the metal poor redder one.

In Figure 3 we have also presented corresponding synthetic HB models, which should be compared with the observed CMD by Ferraro et al. (2004; see their

Table 1. Input parameters in our best simulation of ω Cen. We adopted [α/Fe]=0.3 and η=0.46 for the mean mass-loss on the RGB. Population ratios were from Sollima et al. (2005).

Population	Z	Y	Age (Gyr)	Mass Loss ($M_\odot$)	Fraction
1	0.0006	0.231	13	0.168	0.42
2	0.001	0.232	13	0.178	0.27
3	0.0015	0.38	12	0.172	0.17
4	0.0028	0.40	11.5	0.177	0.08
5	0.006	0.42	11.5	0.201	0.05

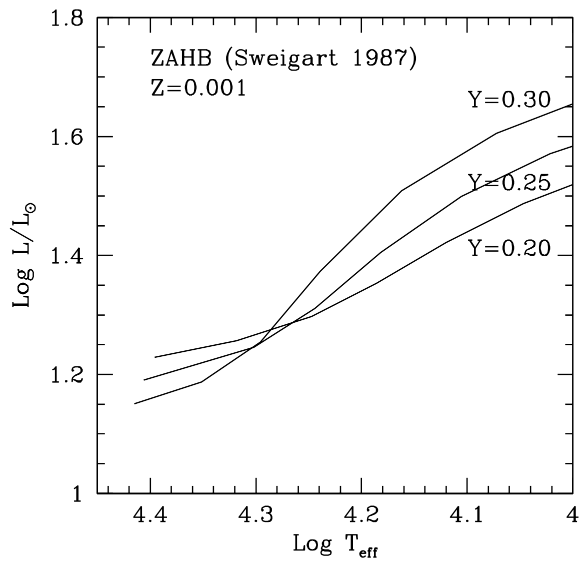

Fig. 4. The zero-age HB sequences with different helium abundances (Sweigart 1987).

Fig. 2, also see Fig. 1 of Lee et al. 2005). From models in Fig. 3a, we can see that the HB morphology generally gets redder with increasing metallicity, and the models fail to reproduce the EHB population. However, the models in Fig. 3b naturally reproduce the EHB stars observed in ω Cen with the same helium enhancements needed to reproduce the unique features on the MS. The fact that the three most metal-rich populations, including progeny of the bluer and fainter MS, all piled up on the extremely blue HB in Fig. 3b is a consequence of the large difference in helium abundance that easily overcomes the metallicity effect. In our model calculations, nothing other than the standard Reimers (1977) empirical relation was employed to estimate the amount of mass-loss on the RGB as a function of the input parameters adopted, and therefore the presence of extreme HB stars is solely the effect of helium enhancement. Under the same scenario, the complex features on the HBs of other globular clusters, such as NGC 2808, can be also explained by large internal variations of helium abundance (Lee et al. 2005; see also D'Antona et al. 2005).

An independent test for the helium-rich scenario might be provided from the FUV photometry of extreme HB stars, because the zero-age HB (ZAHB) locus is very sensitive to helium abundance. As Figure 4 illustrates, in general, helium-rich HB stars are brighter than helium-poor ones, but this trend is reversed when the effective temperature reaches $\sim$19 000 K. This is because extremely hot HB stars have very thin envelopes, with an almost negligible energy output from the hydrogen-burning shell. The total energy output is then mostly sustained by the helium-burning core, and since helium rich stars have a smaller core mass, they have a lower surface luminosity (Sweigart 1987). According to Sweigart (1987), EHB stars, therefore, would be fainter than HB stars as a result of the helium enhancement. The observed trends in UV CMD of EHB and blue HB stars in NGC 2808 (Brown et al. 2001) and ω Cen (Whitney et al. 1994) support our prediction (see Fig. 4 of Lee et al. 2005). It is important to note that spectroscopic analyses of the EHB stars in ω Cen and NGC 2808 (Moehler et al. 2002; Moehler et al. 2004) have shown anomalously high helium abundances up to about 0.3–1.0. While Moehler et al. interpreted this with the late hot flasher scenario (Brown et al. 2001), we believe that at least some of this helium enrichment might be also understood from our scenario.

4. DISCUSSION

The good agreements between the models and the observations for the appearance and population ratio of EHB stars in ω Cen suggest that the third parameter that controls HB morphology, in addition to metallicity and age, might be helium abundance. This in turn suggests that whenever the relative age is estimated from the HB morphology (Lee et al. 1994; Rey et al. 2001), a better result would be obtained by ignoring extreme HB stars or similar peculiar features on the HB. Fortunately, the effect of helium abundance on the MS and RGB is relatively small, and in most globular clusters with EHB stars, the expected helium-rich populations are a minority in terms of the population ratio. Therefore, the age dating from MS and RGB is likely to be less affected by the minority populations of helium-rich stars in these clusters. However, when one infers the relative age or other physical parameters from the integrated-light colors and spectra of globular clusters and early-type galaxies, the possible contamination from helium-rich populations should still be carefully considered, as they would make the observed colors bluer, especially in the UV. Further observations and modeling of globular clusters with peculiar features on their HBs will undoubtedly help us to establish the super-helium-rich scenario as the origin of EHB stars found in globular clusters.

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