

CONSTRAINTS ON HELIUM ENHANCEMENT IN THE GLOBULAR CLUSTER M3 (NGC 5272): THE HORIZONTAL BRANCH TEST

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ABSTRACT

It has recently been suggested that the presence of multiple populations showing various amounts of helium enhancement is a common feature among globular star clusters. In this scenario, such a helium enhancement would be particularly apparent in the enhanced luminosity of the blue horizontal branch (HB) stars compared to the red HB stars. In this *Letter*, we test this scenario in the case of the Galactic globular cluster M3 (NGC 5272), using high-precision Strömgren photometry and spectroscopic gravities for blue HB stars. We find that any helium enhancement among the cluster's blue HB stars must be significantly less than 1%, thus ruling out the much higher helium enhancements that have been proposed in the literature.

Subject headings: stars: abundances — Hertzsprung-Russell diagram — stars: evolution — stars: horizontal-branch — globular clusters: general — globular clusters: individual (M3 = NGC 5272, M13 = NGC 6205)

1. INTRODUCTION

Globular star clusters (GC's) have traditionally been assumed to be excellent approximations to so-called "simple stellar populations," which are idealized systems in which all stars were formed at precisely the same time, from a chemically homogeneous cloud. However, recent observations, both photometric and spectroscopic, have cast some serious doubt on this long-standing paradigm.

ω Centauri (NGC 5139) was the first GC where the presence of large abundance anomalies were identified. In this cluster, not only such light elements as C, N, O, F, Na, Mg, and Al, but also the Fe-peak, s-process, and r-process elements, are seen to vary by large amounts from one star to the next (e.g., Johnson et al. 2008, and the extensive list of references provided therein). Many of these abundance patterns seem to extend all the way down to the main sequence (e.g., Stanford et al. 2008). This strongly suggests that such abundance anomalies owe their origin to multiple star formation episodes within the cluster, each accompanied by a corresponding enrichment of the intracluster medium by the ejecta of the massive and intermediate-mass stars which were formed in the prior stellar generations. Note that, while a large spread in Fe-peak abundances has only been detected in ω Cen, many of ω Cen's abundance anomalies have also been found in other clusters, albeit often at a (much) less dramatic level (see, e.g., Gratton et al. 2004, for a recent review).

Analyses of the multiple main sequences found in the deep color-magnitude diagrams (CMD's) of ω Cen strongly suggest that the *helium abundance* in the cluster may somehow also have changed dramatically from one star formation episode to the next (e.g., Norris 2004; D'Antona et al. 2005;

Piotto et al. 2005). Recent evidence suggests that other clusters may also show sizeable Y variations. According to the deep CMD analysis of NGC 2808 by Piotto et al. (2007), multiple populations with different helium abundances are also present in this cluster. Strong arguments have also been raised in favor of helium enhancements among at least some of the stars in NGC 6388 and NGC 6441 (see, e.g., Catelan et al. 2006; Caloi & D'Antona 2007, and references therein). Interestingly, these four figure among the most massive of all Galactic GC's.

Very recently, it has been suggested that multiple star formation episodes in GC's, accompanied by widely different levels of helium enrichment, are in fact not the exception, but instead the rule among GC's (D'Antona & Caloi 2008). In the particular case of M3 (NGC 5272), such a claim had previously been made also by Caloi & D'Antona (2008), on the basis of an analysis of the period distribution of M3's RR Lyrae variables and the color extension of the HB blueward of the instability strip. Due to the recognized need to assume a very sharply peaked mass distribution to account for the sharply peaked shape of the RR Lyrae period distribution in M3 (Rood & Crocker 1989; Catelan 2004; Castellani et al. 2005), D'Antona & Caloi suggested that the mass distribution of HB stars is *always* sharply peaked, the color spread routinely observed in GC CMD's being instead due to internal variations in the helium abundance Y . It is important to emphasize that such a spread in Y is *not* strictly required to explain the observed period distributions: the case for helium enhancement, at least in the case of M3-like clusters, rests almost entirely on the presence of color spreads among HB stars.

If confirmed, this scenario would not only have major implications for our understanding of how GC's form, but also represent a major deviation from the canonical paradigm, dominant since the late-1960's/early-1970's (Castellani et al. 1969; Iben & Rood 1970; Faulkner 1972; Rood 1973), which ascribes the color spread seen among HB stars to the stochastic nature of mass loss on the red giant branch (RGB). In the canonical scenario, blue HB stars lose significantly more mass as they climb up the RGB than do their red HB counterparts. In contrast, in the D'Antona & Caloi (2008) scenario the bluer HB stars owe their bluer colors to a higher initial Y .

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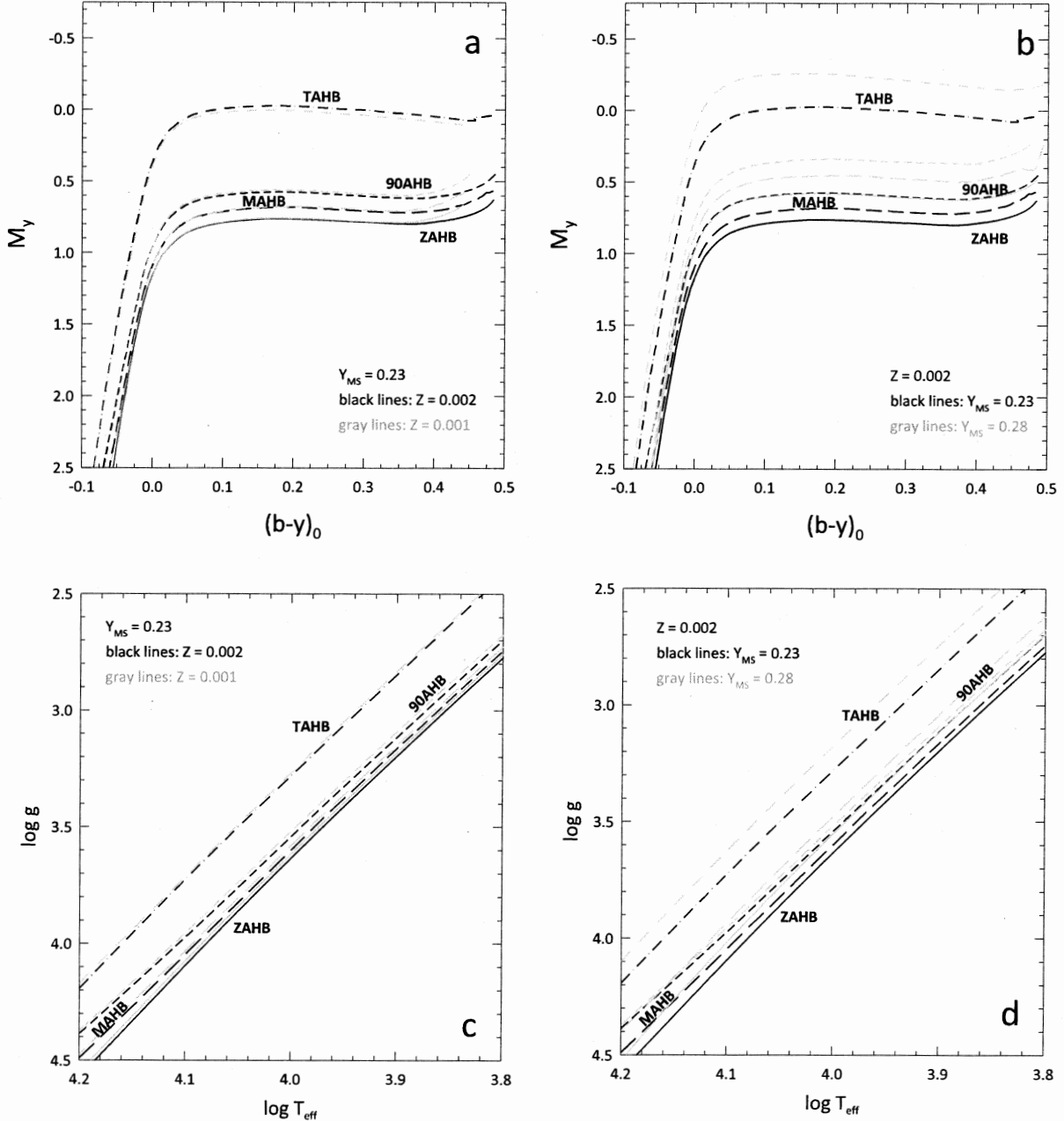


FIG. 1.— *Panel a:* comparison between fiducial HB loci (ZAHB, MAHB, 90AHB, TAHB; see definitions in §3) for two different metallicities (*black lines:* $Z = 0.002$; *gray lines:* $Z = 0.001$), in the M_v , $(b-y)_0$ diagram. To produce this plot, the $Z = 0.001$ loci were shifted in M_v by +0.075 mag. *Panel b:* as in panel a, but for a fixed metallicity and two different helium abundances (*black lines:* $Y_{MS} = 0.23$; *gray lines:* $Y_{MS} = 0.28$), and without applying any shifts to the CMD positions. *Panels c and d:* as in a and b, but in the $\log g$, $\log T_{eff}$ plane, and without applying any shifts to the data.

Fortunately, the Y enhancement scenario can be tested, using a variety of photometric and spectroscopic tools. In particular, it is well known that HB stars with higher Y are brighter, at a given T_{eff} , due to their stronger H-burning shells (e.g., Sweigart & Gross 1976). Therefore, in the D’Antona & Caloi (2008) scenario bluer HB stars should be brighter than their redder counterparts. While this may help account for the sloping natures of the HB’s in the moderately metal-rich GC’s NGC 6388 and NGC 6441 (e.g., Busso et al. 2007, and references therein), such a CMD test has never being carried out for most of the GC’s that, according to D’Antona & Caloi, present multiple populations with increased Y . The purpose

of the present *Letter* is accordingly to present a first test of the helium enhancement scenario, in the specific case of M3, by comparing high-precision photometry for the cluster in the Strömgren (1963) system, as well as spectroscopically derived gravities, with theoretical models computed for a variety of Y values.

2. OBSERVATIONAL DATA

The CMD data used in this paper were taken from Grundahl et al. (1998, 1999), to which the reader is referred for additional details regarding the calibration of our photometry. In summary, our M3 photometry is based on a series of images obtained on the Nordic Optical Telescope, using the

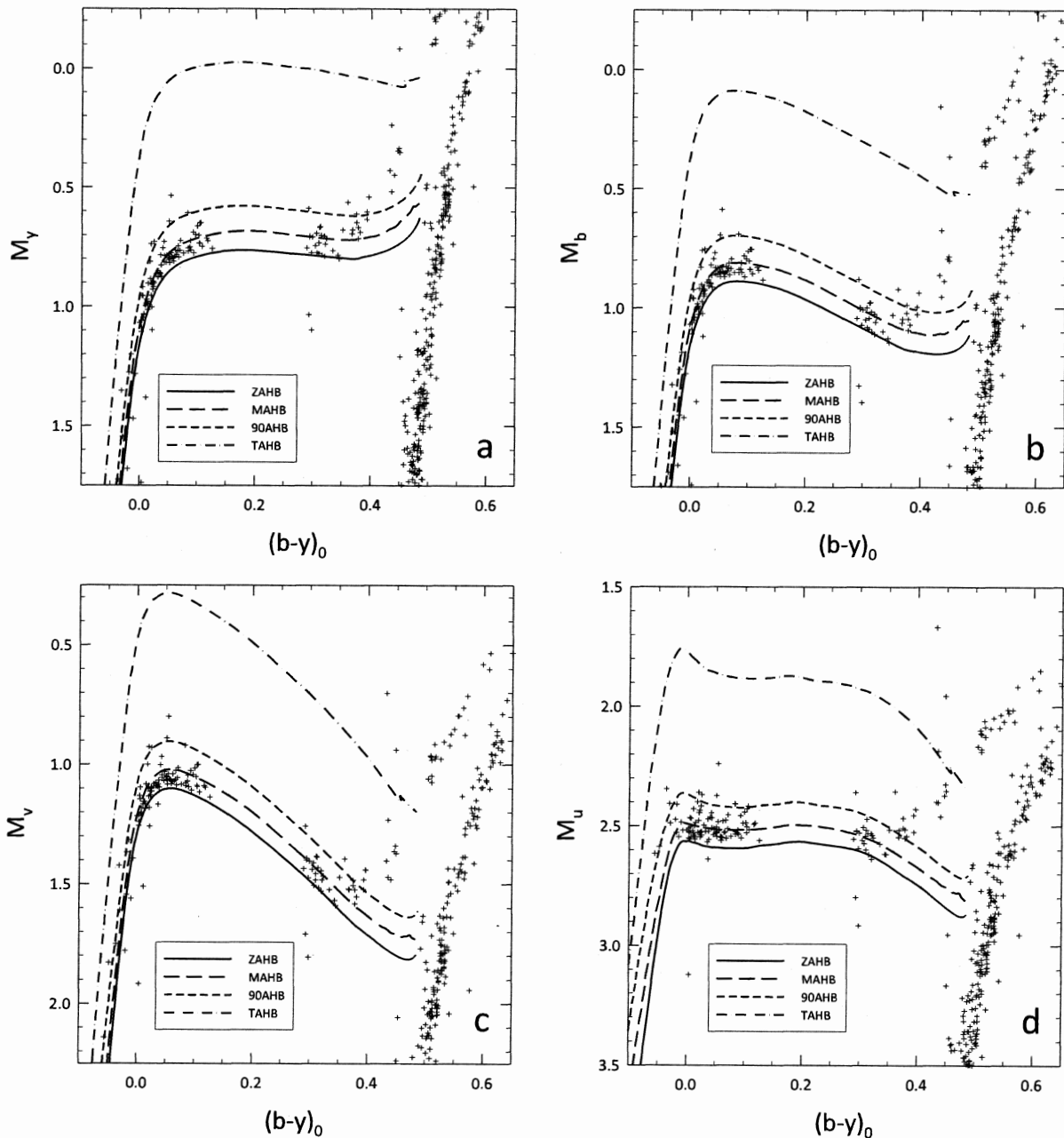


FIG. 2.— Comparison between fiducial HB sequences and the empirical data for M3, in the M_y , $(b-y)_0$ plane (panel a), M_b , $(b-y)_0$ plane (panel b), M_v , $(b-y)_0$ plane (panel c), and M_u , $(b-y)_0$ plane (panel d). In each panel, the empirical data were shifted vertically so as to produce a satisfactory match to the theoretical red ZAHB.

thinned AR-coated 2048 \times 2048 pixel HiRAC CCD camera, with 0.11'' pixel size, thus covering approximately 3.75' on a side. Two overlapping fields were observed, with one field centered on the cluster center to ensure a large sample of HB and red giant branch (RGB) stars.

In addition to the CMD data, we also used the gravities and temperatures derived by Behr (2003), on the basis of spectroscopic observations using the HIRES cross-dispersed echelle spectrograph on the Keck I telescope.

3. THEORETICAL MODELS

In the present paper, we use the evolutionary tracks computed by Catelan et al. (1998) and Sweigart & Catelan (1998) for $Z = 0.001$ and $Z = 0.002$, respectively. The $Z = 0.001$ evo-

lutionary tracks assume a main-sequence helium abundance of $Y_{MS} = 23\%$ by mass and scaled-solar heavy element abundances, whereas $Z = 0.002$ tracks were computed for several different Y_{MS} values, namely 23%, 28%, 33%, 38%, and 43%. The theoretical models were transformed to the Strömgen (1963) $uvby$ system by using the color transformations and bolometric correction tables provided by Clem et al. (2004). The same procedures were also adopted in the recent work by Catelan & Cortés (2008) and Cortés & Catelan (2008), where the period-color and period-luminosity relations of RR Lyrae stars in the Strömgen system were presented.

As noted, our helium-enhanced models were computed only for a metallicity $Z = 0.002$, which is arguably too high for

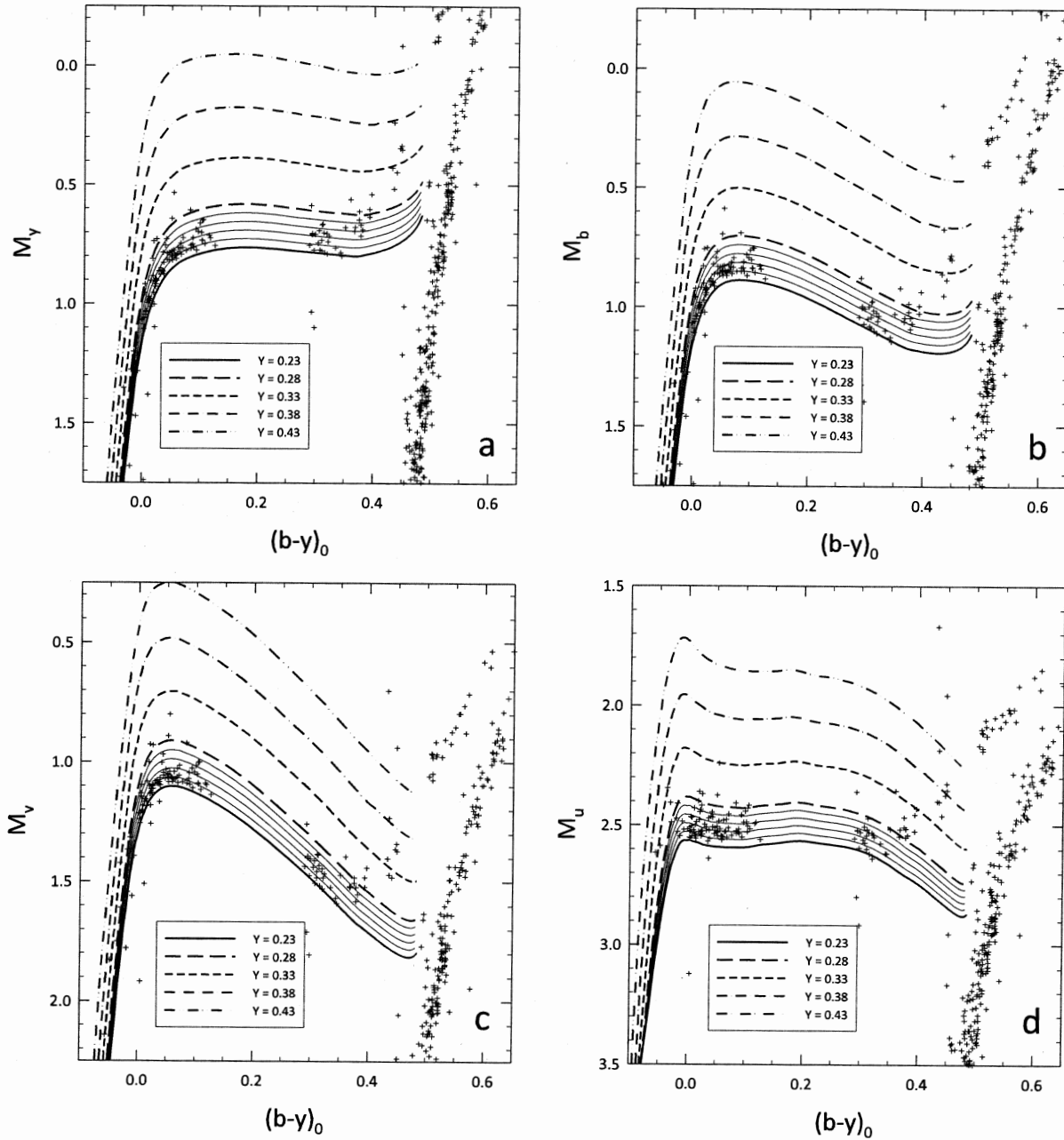


FIG. 3.— As in Figure 2, but plotting only the ZAHB's, for the several different X_{MS} values indicated. The *thin solid lines* indicate the interpolated ZAHB loci for Y_{MS} values between 24% and 27%, in intervals of 1%.

M3, even in the Carretta & Gratton (1997) scale (which favors a metallicity for the cluster closer to 1.4×10^{-3}). However, since we are primarily interested in constraining the *change* in Y when going from the red to the blue HB, the exact choice of Z value turns out to be of minor relevance for our purposes. This is better shown in Figure 1a, where our models for $Z = 0.001$ and $Z = 0.002$ are compared in the M_y , $(b-y)_0$ diagram. To produce this plot, we have first registered the low-metallicity zero-age HB (ZAHB) sequence to its higher-metallicity counterpart. This was achieved by shifting the former by $+0.075$ mag in M_y . This clearly leads to an excellent match over the entire range of ZAHB colors, except (as expected) at the red extreme (which is irrelevant for our purposes).

We next apply the same shift in M_y also to the evolved HB sequences for $Z = 0.001$. We then derived several fiducial loci representing evolved HB stars, as follows: i) MAHB, standing for the *middle-age HB*, or HB ridgeline, which gives the average position occupied by all HB stars, assuming a uniform mass distribution along the entire ZAHB; ii) 90AHB, or *90%-age HB*, which is approximately the locus below which one should find $\approx 90\%$ of all HB stars;⁷ iii) TAHB, or *terminal-age HB*, which is simply the He exhaustion locus. As also shown in Figure 1a, once the red ZAHB's are

⁷ Note that, since the distribution of HB luminosities is not Gaussian, the MAHB is in fact slightly more luminous than the corresponding "50%-age HB" locus, which is the locus occupied by HB stars of different masses which have completed 50% of their HB evolution.

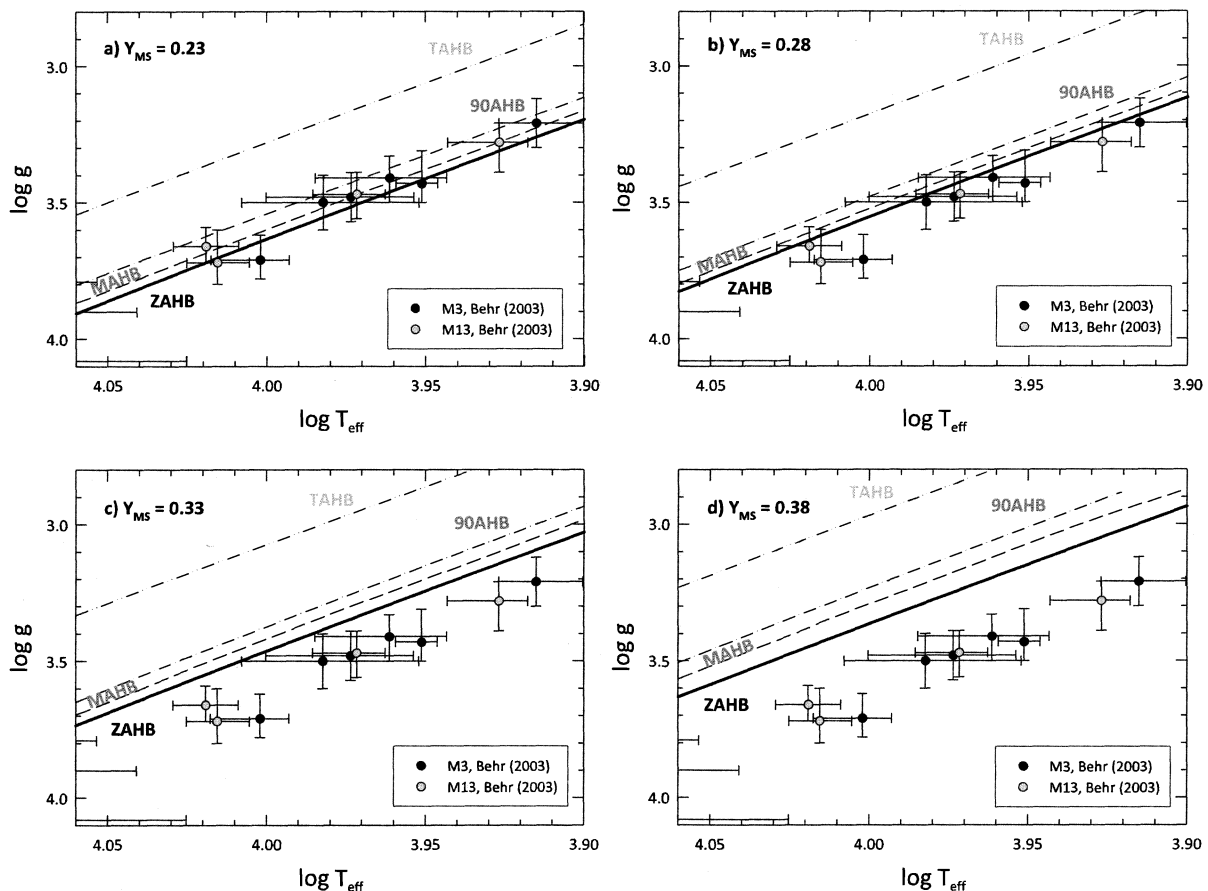


FIG. 4.— Comparison between predicted and observed loci in the $\log g$, $\log T_{\text{eff}}$ plane, for four different helium abundance values: 23% (panel *a*), 28% (panel *b*), 33% (panel *c*), and 38% (panel *d*). Empirical data are provided for M3 (black circles) and M13 (gray circles), from Behr (2003).

matched, also the MAHB's, 90AHB's, and TAHB's agree quite well. That these loci do all depend strongly on Y can be easily inferred from Figure 1*b*. We conclude that our proposed test, which relies on the difference in brightness between red and blue HB stars, is basically insensitive to our choice of Z .

Panels *c* and *d* in Figure 1 reveal the effects of metallicity and Y , respectively, on the $\log g$ – $\log T_{\text{eff}}$ plane. As can clearly be seen, metallicity plays but a minor role in defining the position of a star on this plane, compared with Y .

Bearing these comparisons in mind, in what follows we shall use the models computed for $Z = 0.002$ in our comparison with the empirical data.

4. RESULTS

We compare the predicted loci for $Y_{\text{MS}} = 0.23$ with the empirical CMD data in Figure 2. To produce these plots, we have first corrected the empirical data for reddening using a $E(B-V) = 0.01$ (from Harris 1996) and the extinction coefficients for the Strömgren system summarized in Catelan & Cortés (2008). We then shifted the data vertically, as required to match the theoretical red ZAHB to the lower envelope of the observed distribution.

Once we do this, it becomes readily apparent that *both* the red *and* the blue ZAHB's are fairly well described by the theoretical ZAHB, without the need to invoke an increase in Y for the blue HB stars. In addition, all the other HB fiducials for a fixed Y , including the MAHB, 90AHB, and TAHB, appear to describe the empirical data fairly well, without signif-

icant evidence for an excessive number of overluminous blue HB stars, as would be expected in the helium-enhancement scenario (see Fig. 1*b*). To be sure, the evolutionary lifetimes along the canonical tracks do not provide a perfect match to the CMD distribution (Valcarce & Catelan 2008); however, it appears extremely unlikely that any such disagreements may somehow be due to internal variations in Y , since they seem to affect blue *and* red HB stars alike, as also noted by Valcarce & Catelan.

Figure 3 allows us to provide a more quantitative limit on the increase in Y between the red HB and blue HB populations that may be allowed for by our CMD data. This figure is similar to Figure 2, except that the evolved loci have been removed, and ZAHB sequences for different Y values added. As can clearly be seen, an enhancement in Y by more than 1% would hardly be compatible with the data. As a matter of fact, in the Caloi & D'Antona (2008) scenario, one should expect to see an increase in Y towards bluer colors, but this is not supported by our data. Recall, from Figure 4 in Caloi & D'Antona (2008) and Table 1 in D'Antona & Caloi (2008), that the bulk of the blue HB stars in M3 are predicted, in the helium-enhancement scenario, to be enriched in helium by 2% or more. Such a level of helium enhancement is clearly ruled out by our data.

Finally, Figure 4 compares the empirical and predicted positions of blue HB stars in M3 in the $\log g$, $\log T_{\text{eff}}$ plane, for four different helium abundances, ranging from 23% (panel *a*) to 38% (panel *d*). To produce this plot, we restrict our-

selves to temperatures cooler than 11,500 K, to avoid the well-known complications that are brought about for hotter HB stars (Grundahl et al. 1999). Consistent with the CMD analysis, the empirical gravities again seem entirely consistent with a uniform value of Y among the blue HB stars in M3. Interestingly, the available data also suggest that at least the redder blue HB stars in M13 (NGC 6205) have a similar helium abundance as in M3.

5. CONCLUSIONS

In this *Letter*, we have shown that high-precision, well-populated empirical CMD's, along with spectroscopic gravities, can be used to pose strong constraints on the presence

of helium-enriched populations in GC's. Our results strongly suggest that any populations that may have formed after a main initial burst in M3 likely preserved the same helium content as in the cluster's primordial gas, with a maximum level of helium enhancement most likely not higher than 1%. In future papers, we plan to apply similar tests to several other GC's (Valcarce et al., in preparation).

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