THE SECOND-PARAMETER EFFECT IN METAL-RICH GLOBULAR CLUSTERS
A. V. Sweigart and M. Catelan
NASA/Goddard Space Flight Center, Laboratory for Astronomy and Solar Physics, Code 681, Greenbelt, MD 20771;
sweigart@bach.gsfc.nasa.gov, catelan@stars.gsfc.nasa.gov
Received 1998 February 25; accepted 1998 April 29; published 1998 June 18

ABSTRACT

Recent Hubble Space Telescope observations have found that the horizontal branches (HBs) in the metal-rich globular clusters NGC 6388 and NGC 6441 slope upward with decreasing $B - V$. Such a slope is not predicted by canonical HB models and cannot be produced by either a greater cluster age or enhanced mass loss along the red giant branch (RGB). The peculiar HB morphology in these clusters may provide an important clue for understanding the second-parameter effect. We have carried out extensive evolutionary calculations and numerical simulations in order to explore three noncanonical scenarios for explaining the sloped HBs in NGC 6388 and NGC 6441: (1) a high cluster helium abundance scenario, in which the HB evolution is characterized by long blue loops; (2) a rotation scenario, in which internal rotation during the RGB phase increases the HB core mass; and (3) a helium-mixing scenario, in which deep mixing on the RGB enhances the envelope helium abundance. All three of these scenarios predict sloped HBs with anomalously bright RR Lyrae variables. We compare this prediction with the properties of the two known RR Lyrae variables in NGC 6388. Additional observational tests of these scenarios are suggested.

Subject headings: globular clusters: individual (NGC 6388, NGC 6441) — stars: evolution — stars: horizontal-branch — stars: variables: other

1. INTRODUCTION

Many years ago Sandage & Wildey (1967) and van den Bergh (1967) discovered that the horizontal-branch (HB) morphology in the Galactic globular clusters (GCs) does not correlate tightly with the cluster metallicity. While theory and observation agree that the HB morphology on average becomes redder with increasing metallicity, there are many examples of GCs having very similar metallicities but markedly different HB morphologies, e.g., M3 versus M13 and NGC 362 versus NGC 288. Thus, some parameter besides metallicity must be affecting the evolution of the HB stars in these clusters. Indeed, theoretical HB models show that there are many possible “second-parameter” candidates, e.g., the GC age, mass loss along the red giant branch (RGB), helium abundance $Y$, alpha-element enhancement [$\alpha$/Fe], and rotation (Fusi Pecci & Bellazzini 1998).

Recent Hubble Space Telescope (HST) observations have revealed that the metal-rich GCs NGC 6388 and NGC 6441 contain a significant population of blue HB (BHB) stars and therefore exhibit a pronounced second-parameter effect (Piotto et al. 1997; Rich et al. 1997). From their analysis, Rich et al. concluded that neither a greater age nor an enhanced RGB mass loss due to dynamical effects could satisfactorily account for the BHB populations in these GCs. Understanding the origin of these BHB stars has important implications for determining the formation history of the Galaxy and for interpreting the integrated spectra of the old metal-rich stellar populations in elliptical galaxies. If, for example, age were the second parameter in these GCs, then NGC 6388 and NGC 6441 would be among the oldest, if not the oldest, GCs in the Galaxy.

Sweigart & Catelan (1998) pointed out that the HBs of NGC 6388 and NGC 6441 have a pronounced upward slope with decreasing $B - V$, with the mean luminosity at the top of the blue tail being nearly 0.5 mag brighter in $V$ than the well-populated red HB (RHB) clump. A similar upward slope is also present in the RHB itself (Piotto et al. 1997). As we shall see, such upward-sloping HBs cannot be explained within the framework of canonical theory. More specifically, they cannot be attributed to differences in age or RGB mass loss—the two most prominent second-parameter candidates. We emphasize, therefore, that these GCs may provide a crucial clue for understanding the second-parameter effect.

In this Letter, we will investigate the following noncanonical scenarios for explaining the BHB populations and, in particular, the sloped HBs in NGC 6388 and NGC 6441:

1. High-$Y$ scenario.—A high helium abundance at the time of GC formation leads to unusually long blue loops during the HB evolution.

2. Rotation scenario.—Internal rotation increases the HB core mass, making the HB both bluer and brighter.

3. Helium-mixing scenario.—Deep mixing along the RGB increases the HB envelope helium abundance, also leading to bluer and brighter HB stars.

We will explore each of these possibilities under the simplest possible assumptions and will show that each can produce sloped HBs resembling those in NGC 6388 and NGC 6441.

We begin in § 2 by discussing the failure of the canonical models to explain the observed HBs in NGC 6388 and NGC 6441; in § 3, we describe each of the above noncanonical scenarios in more detail; in § 4, we show that the RR Lyrae variables in NGC 6388 are brighter than field variables of similar [Fe/H], in agreement with these scenarios. Finally, in § 5 we suggest some observational tests to discriminate among these scenarios.

2. CANONICAL HB MORPHOLOGY

In order to explore the HB morphology predicted by canonical models for NGC 6388 and NGC 6441, we have constructed a grid of HB sequences with a main-sequence helium abundance $Y_{MS} = 0.23$ and a scaled-solar heavy-element abundance $Z = 0.006$ (i.e., [Fe/H] = −0.5), using the stellar evolution code described by Sweigart (1997). Adopting the Kurucz (1992) color-temperature transformations and bolometric cor-
reactions, we first computed an HB simulation with the mean mass \(M_{\text{imb}}\) for the Gaussian mass distribution and the mass dispersion \(\sigma_m\) chosen to give a well-populated red and blue HB. This canonical simulation, shown in Figure 1, predicts a completely flat HB morphology, unlike the observed HBs in NGC 6388 and NGC 6441. In order to explore any dependence on metallicity, we also carried out extensive model computations for \(Z = 0.002\) and \(Z = 0.01716\) (= \(Z_{\odot}\)), again failing to find any evidence for sloped HBs.

The HB simulation in Figure 1 indicates that the BHB population in NGC 6388 and NGC 6441 does not arise from either an older cluster age or a greater RGB mass loss. While increasing the assumed age or RGB mass loss would move an RHB star blueward, it would not increase its luminosity. We conclude, therefore, that canonical theory does not provide a straightforward explanation for the observed HB morphology in these GCs.

We have also investigated whether the slope of the RHB in NGC 6388 and NGC 6441 could be due to differential reddening, as has been claimed for several metal-rich GCs (e.g., NGC 6539: Armordroff 1988; Pal 10: Kaisler, Harris, & MacLaughlin 1997; NGC 6553: Guarnieri et al. 1998). Extensive HB simulations show that the differential reddening \(\Delta E(B - V)\) would have to considerably exceed the amounts estimated by Piotto et al. (1997) in order to transform, say, a 47 Tuc–like RHB into the sloped HBs found in NGC 6388 and NGC 6441. Moreover, the HBs in NGC 6388 and NGC 6441 are sloped in each of the four WFPC2 chips, which would not be expected if differential reddening were the cause of the sloped RHBs in the color-magnitude diagrams (CMDs) of these GCs.

Finally, we point out that inaccuracies in the transformation from the WFPC2 filter system to the “standard” Johnson-Cousins system are also unlikely to cause the sloped HBs in NGC 6388 and NGC 6441, since the instrumental CMDs clearly show sloped HBs (B. Dorman 1998, private communication). If the filter transformation were responsible, one would expect sloped HBs in the HST CMDs for other GCs (e.g., 47 Tuc and NGC 2808) from Piotto et al. (1997) and Sossin et al. (1997), which is not the case.

3. NONCanonical HB MORPHOLOGY

The failure of canonical models to explain the observed HB morphology in NGC 6388 and NGC 6441 suggests that some noncanonical process may be operating in these metal-rich GCs. In this section, we will therefore discuss three noncanonical scenarios for producing sloped HBs, beginning with the possibility of a high cluster helium abundance.

3.1. HIGH-Y Scenario

RHB stars evolve along blue loops during most of their HB lifetime. Normally, these loops cover only a small range in \(B - V\). For larger helium abundances, however, these blue loops can become considerably longer, reaching higher effective temperatures and deviating more in luminosity from the zero-age HB (ZAHB) (Sweigart & Gross 1976). Thus, at least qualitatively, one would expect the HB for a sufficiently high \(Y\) to slope upward with decreasing \(B - V\) (Catelan & de Freitas Pacheco 1996).

To test this possibility, we have constructed a grid of \(\approx 350\) HB sequences for \(Y_{\text{ms}} = 0.23, 0.28, 0.33, 0.38, 0.43\) and \(Z = 0.002, 0.006, \text{and } 0.01716\). For each \((Y_{\text{ms}}, Z)\) combination, we first evolved a star up the RGB without mass loss and then through the helium flash to obtain a ZAHB model at the red end of the HB. Lower mass ZAHB models were then obtained by removing mass from the envelope of this high-mass ZAHB model. Not surprisingly, the HB simulations for \(Y_{\text{ms}} = 0.23, 0.28, \text{and } 0.33\) did not show a significant slope. However, when \(Y_{\text{ms}}\) was increased to 0.38 and 0.43, a pronounced HB slope close to that in NGC 6388 and NGC 6441 was found, as illustrated in Figures 2a and 2b, respectively. There is also a hint of bimodality, as seen in the observed CMDs (Rich et al. 1997). In these simulations, we did not try to reproduce the ratio of blue to red HB stars. This ratio depends on the choice of \((M_{\text{imb}})\) and \(h\), assumed here to be 0.02 \(M_{\odot}\).

The HBs predicted by this high-Y scenario are quite bright, implying a large pulsation period for the RR Lyrae variables and a large value for the number ratio \(R\) of HB stars to RGB stars brighter than the mean RR Lyrae luminosity (Iben 1968). In addition, this scenario would imply a peculiar chemical enrichment history for NGC 6388 and NGC 6441, characterized by a very large enrichment law \(\Delta Y/\Delta Z\) (see Shi 1995; Schramm 1997).

3.2. Rotation Scenario

Since the work of Mengel & Gross (1976), it has been known that rotation during the RGB phase can delay the helium flash. As reviewed by Renzini (1977), this would have two consequences for the subsequent HB evolution. First, it would increase the helium-core mass \(M_h\) and hence the HB luminosity. Second, it would lead to enhanced mass loss near the tip of the RGB and thus to a smaller HB envelope mass. The net effect would be a shift in the HB location toward higher effective temperatures and luminosities. Thus, at least qualitatively, one might also expect a range in rotation to produce an upward-sloping HB. Could this be the explanation for the sloped HBs in NGC 6388 and NGC 6441?

To answer this question, one needs to know how much extra mass is lost at the tip of the RGB when \(M_h\) exceeds its canonical value. We determined this by evolving a number of sequences up the RGB for various values of the Reimers mass-loss parameter \(q_R\) (see Reimers 1975; Fusi Pecci & Renzini 1976). In these sequences we turned off all helium burning, thereby per-
mitting $M_*$ to exceed its canonical value without igniting the helium flash. Using these sequences, we were able to determine how the final mass $M$ decreases with increasing $M_*$ for each value of $\eta_R$. The $M$-$M_*$ relations defined in this manner were then used to compute grids of HB sequences without rotation. The masses of these canonical models were used as the mean mass $\langle M_{\text{HB}} \rangle$ for defining the mass range $M < \langle M_{\text{HB}} \rangle$ covered by these simulations. Thus the blueward extension of the HB in Figures 2c and 2d is driven solely by the increase in $M_*$ and the corresponding decrease in $M$. In both Figures 2c and 2d, the HB slopes upward, especially in the $\eta_R = 0.2$ case. Note, however, that the increase in $M_*$ for the bluer HB stars is very large ($\approx 0.1 M_\odot$), which, in turn, would require a very high main-sequence rotation rate.

3.3. Helium-Mixing Scenario

The observed abundance variations in GC red giant stars indicate that these stars are able to mix nuclearly processed material from the vicinity of the hydrogen shell out to the surface, presumably as a result of internal rotation (Kraft 1994). In particular, the observed variations in aluminum require the mixing to penetrate into the hydrogen shell (Langer & Hoffman 1995; Cavallo, Sweigart, & Bell 1998). Thus, any mixing process that dredges up aluminum will also dredge up helium. Besides increasing the envelope helium abundance $Y_{\text{HB}}$, such mixing would also increase the RGB tip luminosity and thus the amount of mass loss. Consequently, a red giant star that undergoes such helium mixing will arrive on the HB with both a higher $Y_{\text{HB}}$ and a lower mass and hence will be both hotter and brighter than the corresponding canonical star (Sweigart 1997, 1998). This suggests, at least qualitatively, that helium mixing might also lead to a sloped HB morphology.

To investigate this possibility, we have evolved a set of $\approx 100$ sequences up the RGB and through the helium flash and HB phases for various amounts of helium mixing. Two cases were considered, namely, $(M, Y_{\text{MS}}, Z) = (0.95, 0.23, 0.006)$ and $(0.87, 0.28, 0.006)$, where the mass in each case corresponds to an age of 13 Gyr at the tip of the RGB. The $\eta_R$ values used in these sequences were 0.4, 0.5, and 0.6.

Two of the helium-mixing simulations for $Y_{\text{MS}} = 0.23$ are presented in Figures 2e and 2f. Each of these simulations covers the mass range $M < \langle M_{\text{HB}} \rangle$, where $\langle M_{\text{HB}} \rangle$ was taken to be the mass of a canonical model without helium mixing. As the helium mixing increases, the HB tracks shift blueward, giving rise to the pronounced upward slope evident in Figures 2e and 2f. In fact, the HB slope in Figure 2e slightly exceeds the observed slope in NGC 6388 and NGC 6441. There is, moreover, a hint of bimodality in this simulation. The helium abundance $Y_{\text{HB}}$ near the instability strip in Figure 2e is $\approx 0.34$.

4. Constraints from RR Lyrae Variables

We have compared the predictions of the above simulations in the period-temperature diagram with the two known RRab Lyrae variables in NGC 6388 (Silbermann et al. 1994). Temperatures were determined as in Catelan, Sweigart, & Borissova (1998; see also Catelan 1998). The result of one such comparison is given in Figure 3, where we also plot field variables of similar metallicity as well as V9 in 47 Tuc (Storm et al. 1994). The [Fe/H] values for the field variables are from Layden (1994); amplitudes and periods are taken from Blanco (1992) but in some cases from Sandage (1990). Blazhko variables were avoided. As one can clearly see, the variables in NGC 6388 and 47 Tuc have considerably longer periods and thus substantially higher luminosities than field stars of comparable metallicity. Moreover, the cluster variables seem to agree well with the displayed simulation, which in this case was taken from Figure 2e.

5. Discussion

The results in this Letter demonstrate that canonical models fail to explain the sloped HBs in NGC 6388 and NGC 6441. This has the important implication that, at least for these GCs, the two most prominent second-parameter candidates—age and RGB mass loss—cannot account for the observed HB morphology. Simulations employing noncanonical models show
that an increased initial GC helium abundance or a dispersion in the stellar rotational velocity (leading to a range in $M_\text{r}$ or $Y_{\text{HBl}}$) may account for the observed HB morphology in these two GCs. Finally, we find that the RR Lyrae variables in NGC 6388 and 47 Tuc are substantially brighter than field variables of comparable [Fe/H]—in agreement with the noncanonical scenarios.

We can suggest a variety of observational tests for differentiating among the different noncanonical scenarios, including the following.

1. **Analysis of $R$ ratios.**—The $R$ ratios differ widely from one noncanonical scenario to the next, being largest for the high-$Y$ case (Figs. 2a and 2b). A low $R$ ratio (implying $Y_{\text{MS}} \lesssim 0.35$) for NGC 6388 and NGC 6441 would argue against the high-$Y$ scenario.

2. **Deep photometry of NGC 6388 and NGC 6441.**—This would determine whether the magnitude difference between the RR Lyrae variables and the turnoff “AV” is larger than expected for a “47 Tuc–like” age, as predicted by the noncanonical scenarios (e.g., Catelan & de Freitas Pacheco 1996).

3. **RR Lyrae survey.**—NGC 6388 and NGC 6441 should be surveyed for RR Lyrae variables in order to discover new variables, especially closer to the cluster centers, and to define better the pulsation properties of the known RR Lyrae variables. In addition, we suggest a study of the RR Lyrae variables in the metal-rich GCs NGC 6304 (Hartwick, Barlow, & Hesser 1981; Layden 1995) and NGC 6652 (Ortolani, Bica, & Barbuy 1994).

4. **Surface gravities of blue HB stars.**—Measurements of log $g$ could discriminate among the different origins of the BHB stars in NGC 6388 and NGC 6441 (Crocker, Rood, & O’Connell 1988) and provide a strong constraint on whether the HBs are indeed brighter than predicted by the canonical models.

5. **High-resolution spectroscopy of red giants.**—RGB stars in NGC 6388 and NGC 6441 should be searched for evidence of deep mixing (see Kraft 1994).

6. **Planetary nebula in NGC 6441.**—The planetary nebula (PN) recently discovered by Jacoby et al. (1997) in NGC 6441 may be an invaluable diagnostic tool for constraining the models. Helium is moderately enhanced over the solar value in this PN, while oxygen is more depleted than in the super–oxygen-poor stars which are found in some more metal-poor GCs and which are indicative of deep mixing (e.g., Kraft 1994). We speculate that this PN may be the progeny of a star that experienced helium mixing.

M. C. would like to thank B. Dorman and S. Ortolani for useful discussions. This research was supported in part by NASA grant NAG5-3028. This work was performed while M. C. held a National Research Council–NASA/GSFC Research Associateship.

REFERENCES

Armandroff, T. E. 1988, AJ, 96, 588
Blanco, V. M. 1992, AJ, 104, 734
Catelan, M. 1998, ApJ, 495, L81
Catelan, M., & de Freitas Pacheco, J. A. 1996, PASP, 108, 166
Catelan, M., Sweigart, A. V., & Borissova, J. 1998, in ASP Conf. Ser. 135, A Half Century of Stellar Pulsation Interpretations: A Tribute to Arthur N. Cox, ed. P. A. Bradley & J. A. Guzik (San Francisco: ASP), 41
Cavallo, R. M., Sweigart, A. V., & Bell, R. A. 1998, ApJ, 492, 575
Crocket, D. A., Rood, R. T., & O’Connell, R. W. 1988, ApJ, 332, 236
Fusi Pecci, F., & Bellazzini, M. 1998, in The Third Conference on Faint Blue Stars, ed. A. G. D. Philip, J. Liebert, & R. A. Saffer (Cambridge: Cambridge Univ. Press), 255
Fusi Pecci, F., & Renzini, A. 1976, A&A, 46, 447
Guarnieri, M. D., Ortolani, S., Montegriffo, P., Renzini, A., Barbuy, B., Bica, E., & Moneti, A. 1998, A&A, 331, 70
Hartwick, F. D. A., Barlow, D. J., & Hesser, J. E. 1981, AJ, 86, 1044
Iben, I., Jr. 1968, Nature, 220, 143
Jacoby, G. H., Morse, J. A., Fullerton, L. K., Kwitter, K. B., & Henry, R. B. C. 1997, AJ, 114, 261 (erratum 115, 1688)
Kaiser, D., Harris, W. E., & MacAlpine, D. E. 1997, PASP, 109, 920
Kraft, R. P. 1994, PASP, 106, 553
Kurucz, R. L. 1992, in IAU Symp. 149, The Stellar Populations of Galaxies, ed. B. Barbuy & A. Renzini (Dordrecht: Kluwer), 225
Langer, G. E., & Hoffman, R. D. 1995, PASP, 107, 1177
Layden, A. C. 1994, AJ, 108, 1016
———. 1995, AJ, 110, 2312
Mengel, J. G., & Gross, P. G. 1976, Ap&SS, 41, 407
Ortolani, S., Bica, E., & Barbuy, B. 1994, A&A, 286, 444
Piotti, G., et al. 1997, in Advances in Stellar Evolution, ed. R. T. Rood & A. Renzini (Cambridge: Cambridge Univ. Press), 84
Reimers, D. 1975, Mem. Soc. R. Sci. Liége, 6th Series, 8, 369
Renzini, A. 1977, in Advanced Stages in Stellar Evolution, ed. P. Bouvier & A. Maeder (Geneva Obs.), 149
Rich, R. M., et al. 1997, ApJ, 484, L25
Sandage, A. 1990, ApJ, 350, 631
Sandage, A., & Wildey, R. 1967, ApJ, 150, 469
Schramm, D. N. 1997, in Critical Dialogues in Cosmology, ed. N. Turok (Princeton: Princeton Univ. Press), 81
Shi, X. 1995, ApJ, 464, 637
Silbermann, N. A., Smith, H. A., Bolte, M., & Hazen, M. L. 1994, AJ, 107, 1764
Sosin, C., et al. 1997, in Advances in Stellar Evolution, ed. R. T. Rood & A. Renzini (Cambridge: Cambridge Univ. Press), 92
Storm, J., Nordström, B., Carney, B. W., & Andersen, J. 1994, A&A, 291, 121
Sweigart, A. V. 1997, ApJ, 474, L23
———. 1998, in The Third Conference on Faint Blue Stars, ed. A. G. D. Philip, J. Liebert, & R. A. Saffer (Cambridge: Cambridge Univ. Press), 39
Sweigart, A. V., & Catelan, M. 1998, in ASP Conf. Ser. 135, A Half Century of Stellar Pulsation Interpretations: A Tribute to Arthur N. Cox, ed. P. A. Bradley & J. A. Guzik (San Francisco: ASP), 39
Sweigart, A. V., & Gross, P. G. 1976, ApJS, 32, 367
van den Bergh, S. 1967, AJ, 72, 70

Fig. 3.—Period-temperature diagram for the RR Lyrae variables in NGC 6388 (open triangles) compared with field variables of similar metallicity (filled squares); V9 in 47 Tuc (open circle) and the very metal-rich, long-period field RR Lyrae variable AN Ser (open square). Model predictions for the simulation in Fig. 2e are shown as small filled circles.