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DEEP *HST* PHOTOMETRY OF NGC 6388: AGE AND HORIZONTAL BRANCH LUMINOSITY*

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ABSTRACT

We present the first deep color-magnitude diagram (CMD) of the Galactic globular cluster NGC 6388, obtained with the *Hubble Space Telescope*, that is able to reach the main-sequence turnoff point of the cluster. From a detailed comparison between the cluster CMD and that of 47 Tucanae (NGC 104), we find that the bulk of the stars in these two clusters have nearly the same age and chemical composition. On the other hand, our results indicate that the blue horizontal branch and RR Lyrae components in NGC 6388 are intrinsically overluminous, which must be due to one or more, still undetermined, non-canonical second parameter(s) affecting a relatively minor fraction of the stars in NGC 6388.

Subject headings: stars: horizontal-branch – stars: variables: RR Lyrae – Galaxy: globular clusters: individual (47 Tucanae, NGC 6388, NGC 6441) – Galaxy: globular clusters: general – Galaxy: bulge

1. INTRODUCTION

NGC 6388 and NGC 6441 are two of the most intriguing Galactic globular clusters. Hints of their special nature were provided early on by the study of their integrated far-ultraviolet light by Rich, Minniti, & Liebert (1993), which revealed a surprisingly strong far-UV flux for these moderately metal-rich ($[Fe/H] \simeq -0.60$ and -0.53, respectively; Harris 1996) bulge globular clusters.

The far-UV flux in well-resolved Galactic globular clusters has long been known to be dominated by hot horizontal branch (HB) stars (e.g., Dorman, O'Connell, & Rood 1995), especially when individual UV-bright post-asymptotic giant branch stars, which are present in globular clusters in non-statistically significant numbers, are not present. Accordingly, the most likely explanation for the mysterious far-UV flux in NGC 6388 and NGC 6441 was immediately recognized to be hot HB stars. However, while the association of blue HB stars with the UV-upturn phenomenon in unresolved elliptical galaxies is often made (see, e.g., O'Connell 1999 for a review), in the case of globular clusters no resolved object had been known with a metal-rich composition and a blue HB morphology. This is a natural consequence of stellar evolution, since producing such hot stars is much easier at low and intermediate metallicity than it is at high metallicity (e.g., Fusi Pecci et al. 1993). This, in fact, is reflected upon the well

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known "first parameter" of HB morphology—namely, metal-rich clusters have red HB's, whereas metal-poor clusters tend to have blue HB's. As a consequence, the existence of blue HB stars in NGC 6388 and NGC 6441 would represent a dramatic example of the so-called "second-parameter phenomenon" of HB morphology—namely, the presence of clusters deviating from the main trend between HB type and metallicity among Galactic globular clusters.

Spectacular confirmation of the presence of blue HB stars in both NGC 6388 and NGC 6441 was first provided by Rich et al. (1997), who presented *Hubble Space Telescope* (*HST*) photometry for both these globular clusters from the comprehensive snapshot survey of Galactic globular clusters by Piotto et al. (2002). Besides finding strong blue HB components in both clusters—which actually go down at least as deep as the limit of their photometry, i.e., somewhat above the turnoff point—a very remarkable feature of the published diagrams is the presence of a *strongly sloped* HB where other globular clusters normally have a much more nearly "horizontal" HB. As emphasized by Sweigart & Catelan (1998, hereafter SC98), such a sloped HB cannot be simply the result of an older age or of enhanced mass loss along the red giant branch (RGB): both of these second parameter candidates are able to move a star horizontally along the HB, but neither is able to increase the luminosity of a blue HB star compared to the red HB or RR Lyrae components in the same cluster. Likewise, while strong differential reddening might explain the sloping HB of a red HB cluster (e.g., Catelan & de Freitas Pacheco 1996), it is obviously insufficient to explain the *production* of RR Lyrae and blue HB stars. SC98 conclude, as a consequence, that *non-canonical* second parameter candidates must be at play in the case of NGC 6388 and NGC 6441.

A different view has been expressed, however, by Raimondo et al. (2002, hereafter R02). Exploring the possibility of explaining the anomalously sloped HB of the cluster, the authors computed models in which the allowed ranges in chemical abundance and mixing length parameters were changed with respect to the standard case. Some of their models did reveal significantly sloped HB's (see also Brocato et al. 1999), but in fact as a consequence of an anomalously *faint red HB* (in V), in comparison with a blue HB with a V-band luminosity completely in line with the canonical models (see, e.g., their Fig. 2). As a consequence, the conclusions by SC98 remain valid only if it can be proven that the red HB's of NGC 6388 and NGC 6441 are not significantly fainter than found in other globular clusters of comparable metallicity, such as 47 Tucanae (NGC 104).

Additional pieces of the puzzle are provided by stellar variability and spectroscopy studies. Silbermann et al. (1994), Layden et al. (1999), Pritzl et al. (2000, 2001, 2002, 2003), and Corwin et al. (2006) have shown that the RR Lyrae variable stars in these clusters, which occupy the normally "horizontal" part of the HB, have much longer periods than field RR Lyrae stars of similar metallicity, thus strongly suggesting them to be intrinsically more luminous, as first noted by SC98. Moreover, detailed theoretical calculations by Pritzl et al. (2002) have shown that, contrary to the suggestions by Ree et al. (2002), the RR Lyrae components in both clusters cannot be explained in terms of evolution away from a position on the blue HB—and neither can the sloping nature of the HB be reproduced in this way. On the other hand, spectroscopic measurements of the gravities of blue HB stars in both NGC 6388 and NGC 6441 have revealed surface gravities that are actually *higher* than predicted by even the canonical models, thus arguing against an anomalously bright blue HB + RR Lyrae component in these clusters, but not clearly discarding the canonical models (Moehler, Sweigart, & Catelan 1999).

In an effort to shed light on this puzzling situation, we have made use of the data obtained for NGC 6388 in the course of our snapshot *HST* program to study stellar variability in the cluster, and also of archival data from both the *HST* and ground-based observatories, to produce the deepest color-magnitude diagram (CMD) ever obtained for either NGC 6388 or NGC 6441. By comparing this diagram [which clearly reveals, for the first time, the main-sequence turnoff (TO) of the cluster] with the one similarly obtained for 47 Tuc, a globular cluster of similar metallicity, we are in a position to decide on whether there are any noteworthy differences between the two that might shed light on the origin and brightness of the HB of NGC 6388. In §2 we describe the dataset used in this paper, and in §3 the reduction procedures. In §4 we show our deep CMD of NGC 6388, and compare it against 47 Tuc's. We close in §5 by discussing the implications of our results for our understanding of the origin of the peculiar HB morphology of NGC 6388.

2. OBSERVATIONAL DATA AND REDUCTION PROCEDURES

A complete description of our dataset, reduction and calibration procedures will be described in a forthcoming paper (Stetson et al. 2006, in preparation). Here we limit ourselves to briefly summarizing the most relevant information.

2.1. *The Data*

The NGC 6388 data used in this paper were obtained under *HST* Snapshot Program GO-9821 (PI B. J. Pritzl). In addition, we have retrieved data from the *HST* Archives, as obtained under Programs GO-6095 (PI S. Djorgovski) and GO-9835 (PI G. Drukier). These data were obtained with the *Wide-Field and Planetary Camera 2* (WFPC2) and the *Advanced Camera for Surveys* (ACS), using the F439W (B), F555W (V), and F814W (I) filters. Additional data were retrieved from the ESO ST-ECF Archives...

For 47 Tuc, in turn, we have used...

2.2. *Data Reduction*

The data were reduced in the standard manner, using the DAOPHOT-ALLFRAME software packages, following commonly understood reduction procedures (e.g., Stetson 1987, 1990, 1994)...

3. THE FIRST DEEP CMD OF NGC 6388

Our deep V, $B-I$ CMD of NGC 6388 is shown in Figure 1 (*open circles*), overplotted on the 47 Tuc CMD (*crosses*). To obtain this plot, we have registered the 47 Tuc red HB component to the similar feature that is present in NGC 6388, by applying shifts of +3.25 in V and +0.72 in $B-I$ to the 47 Tuc data. Note that the NGC 6388 CMD was constructed by applying the following selection criteria to our initial photometry list:...

In what follows, we go through each of the main features and branches of these CMD's in turn.

3.1. *The Main Sequence Turnoff and Subgiant Branch (SGB)*

As can be seen, when registering the red HB of 47 Tuc to that of NGC 6388, the main-sequence TO's and SGB's of both clusters overlap nicely, both in color, magnitude, and detailed shape. Stetson, VandenBerg, & Bolte (1996) have

FIG. 1.— The first deep CMD of NGC 6388 clearly revealing the turnoff point of the cluster (*crosses*) is overplotted on the 47 Tuc CMD (*open circles*) in the V, $B{-}I$ plane. See §2 for further details.

FIG. 2.— Same as in Fig. 1, but now focusing around the HB region. The positions of the NGC 6388 RR Lyrae variables, taken from Pritzl et al. (2002), are shown as plus signs.

computed isochrones for different values of [Fe/H], [α/Fe], helium abundance Y, and the mixing length parameter $\alpha_{\rm MLT}$ (their Fig. 4); these calculations are complemented by the studies of Bolte (1990, 1992), in which ranges in [O/Fe] and [Fe/H] have also been explored. As a consequence of these calculations, and as well known, the difference in color between the base of the RGB and the main-sequence TO turns out to be a good age indicator, without a strong dependence on most of the quoted parameters. Given the fact that both the difference in magnitude between the red HB and the main-sequence TO and the difference in color between the TO point and the base of the RGB are nearly the same in both NGC 6388 and 47 Tuc, the most natural conclusion is that *both clusters have very closely the same age*.

The similarity between the detailed SGB morphology between the two clusters also places important constraints on the extent to which some evolutionary parameters besides age may be varying between NGC 6388 and 47 Tuc. For instance, by comparing the CMD in Fig. 1 with the detailed calculations by Stetson et al. (1996) and Bolte (1990, 1992), it clearly follows that large differences in [Fe/H], [O/Fe], Y, or $\alpha_{\rm MLT}$ between the (bulk of the) stars in the two clusters can be safely ruled out.[3] The lack of a large difference in $\alpha_{\rm MLT}$ and [Fe/H] between the two clusters, while not unexpected, suffices to rule out the R02 scenario, in which a combination of high metallicity and low $\alpha_{\rm MLT}$ is invoked, leading to an underluminous red HB as mentioned in §1. High metallicity and low $\alpha_{\rm MLT}$ both conspire to produce an abnormally wide color difference between the main-sequence TO and the base of the RGB, which is not seen in Fig. 1. In principle, this could be an artifact of an age for NGC 6388 that is significantly larger than for 47 Tuc. However, the close similarity between $\Delta V^{\rm TO}_{\rm redHB}$ and $\Delta(B{-}I)^{\rm TO}_{\rm RGB}$ between the two clusters, along with the similar metallicities indicated by their RGB's (see the next subsection), strongly suggests that the clusters do indeed have similar ages, chemical composition, and $\alpha_{\rm MLT}$.

To close, we note that the subgiant branch may also provide an important diagnostic of differences in rotation rates among stars in globular clusters (VandenBerg, Larson, & De Propris 1998). While VandenBerg et al. have shown that the luminosity function is the main observed feature that will change depending on the degree of internal rotation, and while we have not yet been able to produce an unbiased luminosity function for NGC 6388 down to the TO point, it should be noted that, once again, the detailed color/shape of the SGB's may also reveal differences in internal rotation between two clusters (see Fig. 4, right panel, in VandenBerg et al. 1998). Therefore, the lack of important morphological differences between NGC 6388 and 47 Tuc in this region of the CMD suggests that any difference in internal rotation between the two clusters, if present, should also be small.

3.2. *The Red Giant Branch*

The general morphology of the RGB's of 47 Tuc and NGC 6388, according to Fig. 1, is very similar. The NGC 6388 CMD is more scattered than 47 Tuc's, which may be due in part to photometric errors and in part to differential reddening, thus making it difficult to ascertain the reality of a minor metal-rich component that might be implied by the stars scattered towards the red of the main RGB component in this diagram. A sizeable metal-poor component is clearly not present (see also R02). A small deviation of the bulk of the brighter NGC 6388 RGB stars towards redder colors compared with the 47 Tuc CMD, if real, would suggest that the metallicity of the latter ([Fe/H] = −0.76 dex, according to Harris 1996) could be just slightly (i.e., by not more than a few 0.1 dex) lower than that of the former. This is in agreement with the recent spectroscopic measurements by Clementini et al. (2005) for RR Lyrae stars in NGC 6441 ([Fe/H] $\simeq -0.69$ dex, in the Zinn-West scale), a cluster which in almost every respect appears to be a "twin" of NGC 6388. Note, finally, that near-infrared photometry (e.g., Frogel et al. 2001; Valenti, Ferraro, & Origlia 2004) shows that NGC 6388 and NGC 6441 have, if anything, slightly *bluer* RGB's than 47 Tuc, contrary to what would be expected in the R02 (high metallicity, low $\alpha_{\rm MLT}$) scenario.

3.3. *The Red Horizontal Branch*

The fact that there is no significant component fainter than the bulk of the NGC 6388 red HB stars strongly suggests that any metal-rich component in this cluster (i.e., with [Fe/H] $\gtrsim$ −0.5 dex) should be very minor. Conversely, an overluminous red HB, as would be implied by a high primordial Y (SC98), is ruled out if, as appears likely, the two clusters have closely the same age and metallicity (see the previous subsections). The detailed HB luminosity function is well known to be affected by the stars' evolutionary parameters; in particular, a higher Y

[3] Note that differences of this type *are* known to affect at least some second-parameter globular clusters, as in the case of M13 (NGC 6205) vs. M3 (NGC 5272) (Stetson 1998).

in NGC 6388 than in 47 Tuc should produce more luminosity evolution away from the zero-age HB in the former (e.g., Dorman, VandenBerg, & Laskarides 1989), which is clearly not present in the observed CMD. Note that a high Y for the cluster can also be ruled out on the basis of the position of its RGB "bump" (R02).

Fig. 2 shows a blow-up of Fig. 1 around the HB region, with the RR Lyrae data from Pritzl et al. (2002) indicated as plus signs. As can clearly be seen, the RR Lyrae are overluminous with respect to the red HB by $\Delta V_{\rm RRL}^{\rm red HB} \simeq 0.xy$ mag, on average—and so is the red end of the blue HB.

3.4. *The Asymptotic Giant Branch "Clump"*

The presence of strongly populated AGB "clumps" is clearly seen in both the 47 Tuc and NGC 6388 CMD's. These are interpreted as the immediate progeny of the red HB stars. Indeed, it is well known that the bluer the HB morphology of a globular cluster, the less pronounced the resulting AGB clump (Ferraro et al. 1999), so that the majority of the stars in this phase that are seen in the NGC 6388 CMD should originate from red HB stars. It is interesting to note that the difference in V magnitude between the AGB clump and the red HB is basically indistinguishable between NGC 6388 and 47 Tuc. Unfortunately, this does not provide us with strong constraints on the difference in helium abundance or metallicity between the two populations, since the difference in magnitude between the AGB clump and the red HB is not very sensitive to either metallicity or helium abundance (e.g., Bono et al. 1995).

4. DISCUSSION

In the present *Letter*, we have shown that, apart from the blue HB and RR Lyrae components, the CMD's of NGC 6388 and 47 Tuc are basically indistinguishable, thus strongly suggesting that *there are no important differences between the bulk of the stars in these two clusters*. In particular, differences in age, metallicity, [O/Fe], Y, and $\alpha_{\rm MLT}$ between the two clusters, if present, should be small. We also find that the red HB component of NGC 6388 is neither underluminous (as would be expected in the "canonical tilt" scenario of R02) nor overluminous (as in the high Y scenario of SC98). The lack of a sizeable luminosity difference between the red HB's of NGC 6388 and 47 Tuc indicates that *the second parameter that leads to the production of an overluminous RR Lyrae + blue HB component in NGC 6388 (Fig. 2) must be non-canonical in nature*—that is, it must be neither age nor RGB mass loss, or else a sloped HB would not result (SC98). On the other hand, since only a relatively small fraction of the HB stars are found within the RR Lyrae strip or on the blue HB, only a minor fraction of the cluster stars should be affected by this non-canonical second parameter. Additional, detailed studies of the blue HB, RR Lyrae, and main sequence components in these clusters will be required before we are in a position to conclusively decide what parameter(s) is (are) responsible (see Catelan 2006 for a recent review).

These results confirm that both the RR Lyrae and blue HB stars in NGC 6388 are significantly overluminous compared to field RR Lyrae stars of similar metallicity, thus explaining the anomalously long periods that are seen among these clusters' RR Lyrae stars (see §1). On the other hand, and as previously noted (see §1), the spectroscopic measurements by Moehler et al. (1999) indicate that the blue HB stars in NGC 6388 and NGC 6441 are not overluminous with respect to canonical predictions. However, a recent reassessment of the spectroscopic gravities of blue HB stars in NGC 6388 by Moehler & Sweigart (2006) indicates that their 1999 values must have been in error by a substantial amount (in the sense that the actual gravities should be *lower*), probably due to unresolved blends in the extremely crowded inner regions of these massive ($M_V \sim -9.5$; Harris 1996) globular clusters.

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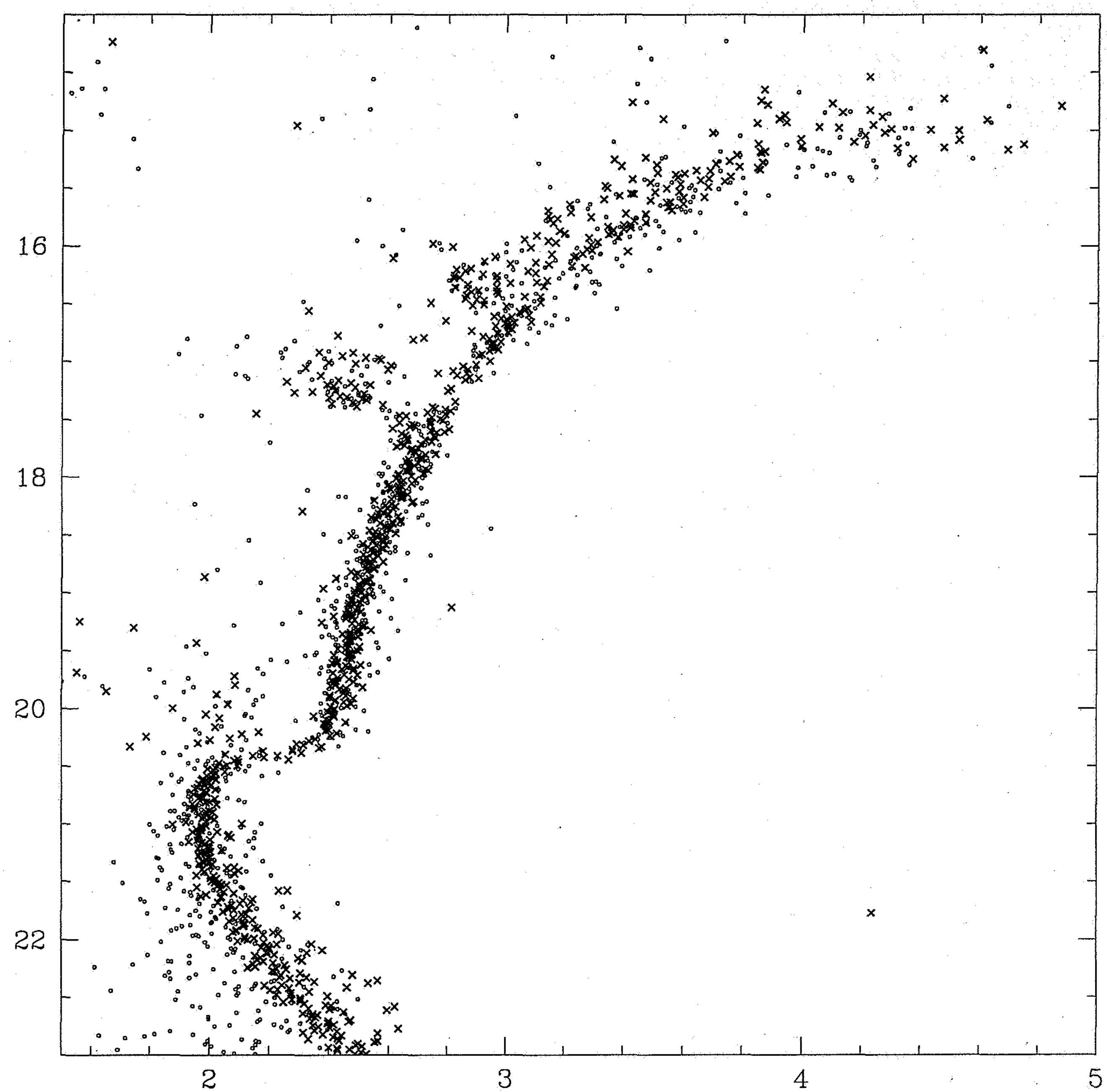
[Note for internal discussion 1: Helium-enhanced isochrones are redder *than canonical ones on the main sequence (see, e.g., Fig. 7 in Piotto et al. 2005). Peter, how real do you think the stars scattered to the left of the bulk of the MS stars may be? Just observational error? Also, what do you make of the apparent second main sequence to the right of the main one, both in 47 Tuc and NGC 6388? Do you think those could be binaries? What about the helium effect, compared with Fig. 6 in D'Antona et al. (2005)? (MC)]*

[Note for internal discussion 2: Peter, do you think you can better quantify the statement on the allowed range in [Fe/H]? I have little experience using the B–I color; if this were V–I, one could easily use the hyperbolic formulae published by Saviane et al. (2000, A&A, 355, 966). (MC)]

[Note for internal discussion 3: In the suggested Fig. 2, should we plot just one "representative" or "average" point for our RR Lyrae, or should we instead give the positions of all our previously studied variables in the CMD as well? (MC)]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