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THE NATURE OF THE HOT STARS IN THE BULGE OF GLOBULAR CLUSTER NGC 6388 †

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Abstract. The metal-rich bulge globular clusters NGC 6388 and NGC 6441 show distinct blue horizontal-branch tails in their color-magnitude diagrams. They are thus strong cases of the well known *Second Parameter Problem.* In addition, the horizontal branches in these globular clusters show an upward tilt toward bluer colors, which cannot be explained by canonical evolutionary models. We will discuss several scenarios which have been proposed to explain these two features and present observations obtained to test these scenarios.

Key words: stars: horizontal branch, stars: evolution, globular clusters: individual: NGC 6388

1. INTRODUCTION

Ever since its discovery over 30 years ago (Sandage & Wildey 1967; van den Bergh 1967), the 2nd parameter effect has stood as one of the major unsolved challenges in the study of the Galactic globular clusters. While it was recognized quite early that the horizontal branch (HB) becomes redder on average with increasing metallicity, many pairs of globular clusters are known with identical metallicities but markedly different HB morphologies, e.g., M 3 versus M 13. Thus some parameter(s) besides metallicity (the 1st parameter) must affect the evolution of the HB stars in these globular clusters. Possible 2nd parameter candidates include the globular cluster age, mass-loss along the red giant branch (RGB), helium abundance Y, α-element abundance, cluster dynamics, stellar rotation, deep mixing, etc.

HST observations by Rich et al. (1997) have found that the metal-rich globular clusters NGC 6388 and NGC 6441 ([Fe/H] ≈ -0.5) contain an unexpected population of hot HB stars and therefore show a prominent 2nd parameter effect. Ordinarily metal-rich globular clusters have only a red HB clump. However, NGC 6388 and NGC 6441 possess extended blue HB tails containing $\sim 15\,\%$ of the total HB population. Quite remarkably, the HBs in both clusters slope upward with decreasing B–V with the stars at the top of the blue tail being nearly 0.5 mag brighter in V than the well-populated red HB clump. Moreover, the RR Lyrae variables in these clusters have unusually long periods for the cluster metallicity,

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leading Pritzl et al. (2000) to suggest that NGC 6388 and NGC 6441 may represent a new Oosterhoff group. For all of these reasons the HBs of NGC 6388 and NGC 6441 are truly exceptional.

In the next section we will discuss the implications of NGC 6388 and NGC 6441 for the 2nd parameter effect and will review a number of scenarios for explaining the HB morphology of these clusters. The following sections will then describe the high and medium resolution spectra that we have obtained to test these scenarios.

2. HB MORPHOLOGY: PROBLEMS AND SCENARIOS

The presence of hot HB stars in globular clusters as metal-rich as NGC 6388 and NGC 6441 may provide an important diagnostic for understanding the 2nd parameter effect for the following reason. In intermediate-metallicity globular clusters such as M 3 the HB spans a wide range in color that extends both blueward and redward of the instability strip. The location of a star along the HB is then quite sensitive to changes in the stellar parameters. In fact, this is why the HB is "horizontal". In metal-rich globular clusters, however, the situation is quite different. Due to their high envelope opacity, metal-rich HB stars are normally confined to a red clump. To move such stars blueward requires a larger change in the stellar structure. Thus any 2nd parameter candidate capable of producing hot HB stars in a metal-rich globular cluster might also have other observational consequences. Indeed, the upward sloping HBs in NGC 6388 and NGC 6441 suggest that the 2nd parameter in these globular clusters is affecting both the temperature and luminosity of the HB stars.

Can canonical models explain the upward sloping HBs in NGC 6388 and NGC 6441? In principle, one could produce hot HB stars in these globular clusters by increasing the cluster age or by enhancing the amount of mass-loss along the RGB. Rich et al. (1997) considered both of these possibilities but found neither of them to be satisfactory because the required increase in the cluster age is quite large and because the frequency of stellar interactions within the cores of these clusters seems too low to produce the additional RGB mass-loss. This conclusion was further supported by the theoretical HB simulations of Sweigart & Catelan (1998, hereafter SC98). They found that the HB morphology predicted by canonical HB models is flat in the (M_V vs. B–V) plane. Increasing the cluster age or the RGB mass-loss simply moves the models blueward in B–V without increasing their luminosity. Thus canonical HB models cannot account for the HB morphology of NGC 6388 and NGC 6441. In particular, two of the most prominent 2nd parameter candidates – age and RGB mass-loss – do not work.

This failure of canonical HB models to produce upward sloping HBs has prompted the study of other noncanonical solutions. Theoretical models show that the HB luminosity at a fixed metallicity depends on two parameters: the helium abundance Y and the core mass M_c. This fact led SC98 to suggest three noncanonical scenarios involving increases in either Y or M_c which might potentially produce upward sloping HBs.

The first ("high-Y") scenario assumes that the stars in NGC 6388 and NGC 6441 formed with a high primordial helium abundance due to a peculiar chemical enrichment history in these clusters. From theoretical models we know that HB tracks at high helium abundances have very long blue loops which deviate considerably from the zero-age HB (ZAHB). The HB simulations of SC98 show that such high-Y tracks can indeed produce upward sloping HBs as seen in NGC 6388 and NGC 6441 provided Y is very large ($\gtrsim 0.4$). However, this scenario can be ruled out because it predicts too large a value for the number ratio R of HB stars to RGB stars brighter than the HB (Layden et al. 1999) as well as too bright a luminosity for the RGB bump (Raimondo et al. 2002).

The second ("rotation") scenario is based on the fact that internal rotation within an RGB star can delay the helium flash, thereby leading to a larger core mass and to greater mass-loss near the tip of the RGB. This increase in M_c together with the corresponding decrease in M will shift a star's HB location towards higher effective temperatures and luminosities. HB simulations show that this scenario can also produce upward sloping HBs similar to those observed in NGC 6388 and NGC 6441. The problem, however, is to understand how the blue HB stars could have the high rotation rates required by this scenario.

The third ("helium-mixing") scenario is motivated by the large star-to-star abundance variations which are found among the red-giant stars within individual globular clusters and which are sometimes attributed to the mixing of nuclearly processed material from the vicinity of the hydrogen shell out to the stellar surface (Kraft 1994). The observed enhancements in Al are particularly important because they indicate that the mixing is able to penetrate deeply into the hydrogen shell (Cavallo et al. 1998). Such mixing would dredge up fresh helium together with Al, thereby enhancing the envelope helium abundance and leading to a brighter RGB tip luminosity and hence greater mass-loss. Thus a helium-mixed star would arrive on the HB with both a higher envelope helium abundance and a lower mass and would therefore be both bluer and brighter than its canonical counterpart - just what is needed to produce an upward sloping HB. Indeed, the HB simulations of SC98 confirm that helium mixing can produce HB morphologies similar to those in NGC 6388 and NGC 6441. However, the existence of helium mixing can be questioned on several grounds. The O-Na and Mg-Al anticorrelations observed in turnoff stars of NGC 6752 by Gratton et al. (2001) indicate that the Al enhancements are more likely due to primordial pollution from an earlier generation of asymptotic-giant-branch (AGB) stars than to deep mixing on the RGB. It is also questionable whether the mixing currents could overcome the large gradient in the mean molecular weight within the hydrogen shell of a RGB star. Thus helium mixing seems unlikely.

A number of additional solutions have been offered to explain the HB morphologies of NGC 6388 and NGC 6441. One of the earliest solutions, suggested by Piotto et al. (1997), was a spread in metallicity. In this case the blue HB stars would be metal-poor compared to the stars in the red HB clump. Because the HB becomes brighter in V with decreasing metallicity, the blue HB stars would also be brighter. Thus a metallicity spread might also produce an upward sloping HB. This possibility was studied by Sweigart (2002), who showed that upward sloping HBs similar to those in NGC 6388 and NGC 6441 would require the stars at the top of the blue HB tail to be approximately 2 dex more metal-poor than the stars in the red HB clump. However, Raimondo et al. (2002) have noted that the progenitors of the blue HB stars should appear as a population of metal-poor giants lying well to the blue of the metal-rich RGB. Since such metal-poor giants are not seen in the color-magnitude diagrams of NGC 6388 and NGC 6441, Raimondo et al. (2002) conclude that any metallicity spread must be small.

Piotto et al. (1997) also suggested that NGC 6388 and NGC 6441 might contain two stellar populations with different ages. This possibility has been further explored by Ree et al. (2002). Their population models for NGC 6388 and NGC 6441 are able to produce blue HB stars provided these stars are older by 1.2 Gyr and metal-poor by 0.15 dex compared to the stars in the red HB clump. Such a small difference in metallicity between the blue and red HB stars avoids the problem with the missing metal-poor giants discussed above. However, while such models might produce bimodal HBs, they do not produce an upward sloping HB. As shown by SC98, differences in age merely move an HB star horizontally along the HB, and, as shown by Sweigart (2002), a metallicity difference of 0.15 dex is too small to produce a significant HB slope. Thus the Ree et al. (2002) models do not account for a key property of the HBs in NGC 6388 and NGC 6441. Ree et al. (2002) also suggest that the long RR Lyrae periods might be explained if these stars are highly evolved from the blue HB. While such stars would have long periods, they would also evolve rapidly across the instability strip on their way to the AGB. Explaining the observed number of RR Lyrae stars under such a scenario would therefore be very difficult (Pritzl et al. 2002).

A more promising possibility is based on the suggestion by D'Antona & Caloi (2004) that the stars in globular clusters with blue HB tails are born in two events: a first generation of helium-normal stars and a second generation of helium-rich stars which subsequently form from the ejecta of the intermediate-mass AGB stars of the first generation. Since a helium-rich star has a lower turnoff mass at a given age, it will be bluer on the HB than a helium-normal star. It will also be brighter due to the increased energy output of the hydrogen-burning shell. Thus the spread in the internal helium abundance predicted by this scenario will lead to a spread in color along the HB, with the red clump stars corresponding to the helium-normal, first generation stars and the blue tail stars being progressively more helium-rich as the effective temperature increases. An upward sloping HB is a natural consequence of this spread in helium. The fact that the HB slope is more prominent in NGC 6388 and NGC 6441 than in other blue tail globular clusters may be simply due to their higher metallicity which requires a larger increase in helium in order to force a star blueward of the red clump. We emphasize that this scenario differs from the high-Y scenario, mentioned above, in which all of the stars are helium-rich and the helium-mixing scenario in which the spread in helium arises from deep mixing on the RGB.

All of the above scenarios which can produce an upward sloping HB predict that the gravities of the blue HB stars should be lower than the gravities of canonical blue HB stars. In 1998 we observed some of the brighter objects in both clusters ($B < 18$; four stars in NGC 6388, three in NGC 6441) to test this prediction. Unfortunately the results only added to the confusion as most of the stars had *higher gravities* than predicted by canonical evolution (Moehler et al. 1999). It took us four years and three rejected proposals to convince the ESO TAC to give us observing time for another test of the above described scenarios: With proposal 69.D-0231 we obtained high resolution spectra of four cool blue HB stars in NGC 6388 to determine their metallicities and rotation velocities. In addition, we observed medium resolution spectra of about a dozen blue HB stars along the blue tail to determine their effective temperatures and surface gravities. By comparing the observed values to those predicted by the various scenarios, we hope to distinguish among the scenarios.

3. HIGH RESOLUTION SPECTROSCOPY

The high resolution spectra were obtained with the UVES spectrograph at the ESO VLT with the standard setting DIC1 (390+564) and a slit width of 1″. This setting covers the wavelength ranges 3720–4520 Å in the blue arm and 4605–5585 Å and 5674–6610 Å in the red arm (2 CCDs) at a resolution of 45 000 (blue) and 37 000 (red). This is the same setting as used by the SPY project (Karl et al., these proceedings). We therefore reduced the data with the UVES context within MIDAS, with the additional correction by a flat field shifted in wavelength direction as done by the SPY consortium to avoid ripples in the resulting one-dimensional spectrum. The details will be described in a forthcoming paper.

3.1. Analysis and results

To analyze the high resolution spectra, we first estimated effective temperatures from B–V colors corrected for a reddening of 0.37 mag. Keeping these temperatures fixed, we estimated the surface gravities by fitting the Balmer line profiles as described in Moehler et al. (2004). Using these values we did a first abundance determination by spectrum synthesis, using the LINFOR program*. Then we changed the effective temperature until the abundances from Fe I and Fe II agreed to within 0.15 dex. The surface gravity was again determined by fitting the Balmer line profiles. Figure 1 shows a section of the spectra of three HB stars together with the synthesized spectrum (the fourth star is the coolest one and therefore most difficult to analyze due to severe line blending). We find no significant deviations from the overall metallicity of NGC 6388 in these spectra and therefore no supporting evidence for a possible metal deficiency in these blue HB stars. We also do not find rotation velocities in excess of 10 km s^{-1}, which is in good agreement with the values found for blue HB stars in other globular clusters. We do find a *very tentative* evidence for a possible helium enrichment. In this temperature range, however, the helium lines are very weak and extremely sensitive to temperature variations, so that we so not want to place much emphasis on this *possible* result.

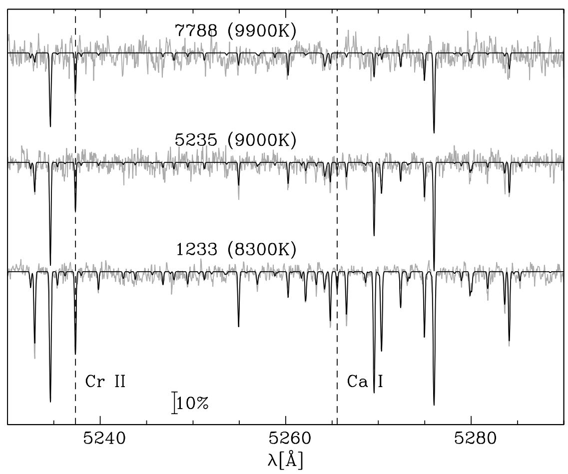

Fig. 1. Small section of the UVES spectra for the three hotter stars. The black line is the synthetic spectrum for each star and the unmarked lines are all iron lines.

4. MEDIUM RESOLUTION SPECTROSCOPY

The medium resolution spectra of stars along the blue tail were obtained with the multi-object spectroscopy mode MOS of FORS2, again at the ESO VLT.

* For a description see http://a400.sternwarte.uni-erlangen.de/∼ai26/linfit/linfor.html

We used the grism 600B with a slit width of 0.6″, corresponding to a resolution of 1200 and a wavelength range of 3700 Å to 5200 Å for all spectra. The wavelength range extended to blue or redder regions depending on the position of the slitlet on the CCD. The data were reduced as described in Moehler et al. (2004), except for the sky subtraction.

The MOS observations were obtained in very crowded fields, and due to the fact that several stars were observed simultaneously, we could not orient the individual slitlets in a way to avoid nearby stars. Therefore most slitlets contain spectra of several stars, in many cases overlapping so strongly that it is impossible to directly extract the spectrum of our intended target (see Figure 2). In order to account for this overlap we proceeded as follows.

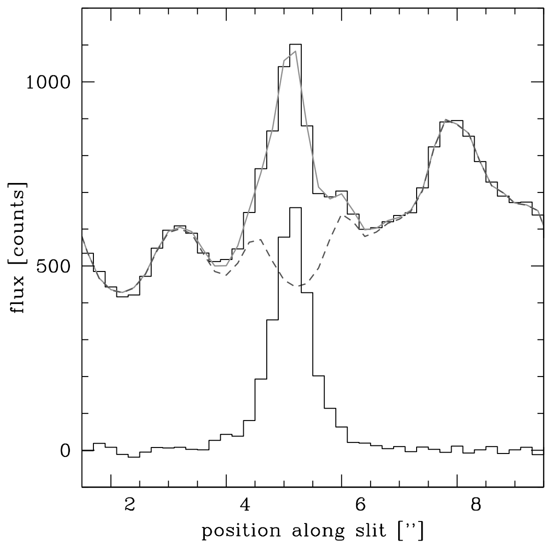

Fig. 2. The spatial light distribution along one slitlet. The upper histogram is the observed light distribution, the light continuous line gives the fit of all sources, the light dashed line marks the subtracted sky background. The lower histogram is the spatial profile of the sky subtracted image.

- We corrected the curvature of the FORS2 spectra.
- We averaged the wavelength-calibrated two-dimensional spectra along their dispersion axis between 3500 and 5200 Å (roughly the range which is later used for fitting the line profiles), thereby producing a one-dimensional spatial profile along the slitlet (cf. Figure 2, upper histogram).
- The one-dimensional spatial distribution of light was fitted with a combination of Moffat functions, i.e.,

$$I_{(x)} = bck + \sum_{j=1}^{n} I_{j(x)}$$

$$\text{with} \qquad I_{j(x)} = a_j \left(1 + \frac{4(x-b_j)^2}{c^2}\right)^{-d}.$$

For each profile the parameters a_j (amplitude) and b_j (position) were fitted individually, whereas the parameters c and d, which determine the profile width and shape (and should depend only on the seeing and instrumental broadening), had to be the same for all objects within one slitlet. We used up to 13 individual profiles to fit the full spatial light distribution along one slitlet (see Figure 2, light solid line).

- After achieving a good fit to the observed spatial profiles we kept the parameters b_j, c and d fixed and used these profiles to fit the spatial profile now at

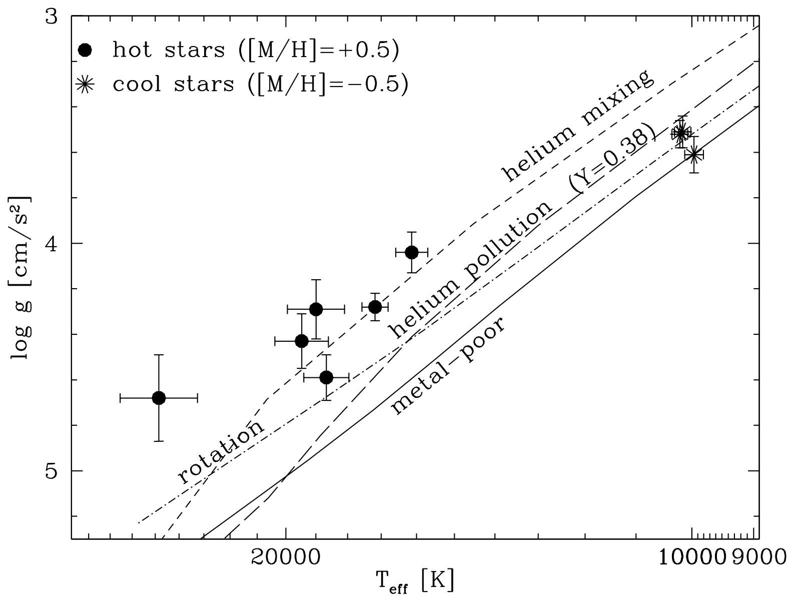

Fig. 3. Effective temperatures and surface gravities for our target stars as derived from line profile fits. Three stars have temperatures below 8000 K, where we do not trust the fit procedure, and one star showed a prominent G-band in its spectrum after the sky subtraction and was therefore not analyzed. For comparison we show the tracks discussed in Section 2.

every wavelength step. The amplitudes a_j and the spatial constant *bck* (for the true sky background) were allowed to vary with wavelength, in order to describe the various spectra.

- The sum of all profiles *minus the target profile* were then used as sky background (cf. Figure 2, dashed line) and subtracted from the wavelength calibrated two-dimensional image. The resulting image – containing only the target spectrum – was again averaged over the same wavelength range as above to verify the quality of the sky correction (see Figure 2, lower histogram).

4.1. Analysis and results

We then fitted the Balmer and helium line profiles to determine effective temperatures, surface gravities and helium abundances as described in Moehler et al. (2004), using a solar metallicity model grid to account for the effects of radiative levitation. The resulting values of $T_{\rm eff}$ and log g are shown in Figure 3, together with tracks describing the scenarios mentioned in Section 2. Obviously the hot stars show significantly lower gravities than expected. To verify if this is a luminosity effect or rather a reduction and/or analysis artifact, we used these values to estimate masses for the stars. While the three stars around 10 000 K show an average mass of 0.52 $M_\odot$, the hot stars have an average mass of 0.28 $M_\odot$, which is too low by almost a factor of 2. We therefore suspect that the sky subtraction did not work sufficiently well to really isolate the light from the hot stars. Tests with the spectra indicate that sky subtraction problems may also be the cause for the unexpectedly high gravities found previously by Moehler et al. (1999).

5. CONCLUSIONS

From our high resolution data (which include two of the three stars at 10 000 K in Figure 3) we find no supporting evidence for the low metallicity scenario. The atmospheric parameters of the stars at about 10 000 K also do not support the helium mixing scenario. The medium resolution data of the hotter and visually fainter stars unfortunately yield results that are apparently affected by systematic errors. As the hotter stars are fainter by at least 1.2 mag in B compared to the stars at about 10 000 K, the systematic problems are most probably due to crowding problems, which are more severe for fainter stars. Despite our best efforts, which yielded spectra without obvious evidence for contamination in all but one case, we apparently did not succeed in extracting from the observed data the information related *only* to the intended target. This should serve as a warning that observations in crowded regions are difficult, especially, if the targets are selected from HST observations (as was the case here).

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