In invited review

Hot Stars in Globular Clusters: A Spectroscopist’s View

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ABSTRACT. Globular clusters are ideal laboratories to study the evolution of low-mass stars. In this work we concentrate on three types of hot stars observed in globular clusters: horizontal branch stars, UV-bright stars, and white dwarfs. After providing some historical background and information on gaps and blue tails, we discuss extensively hot horizontal branch stars in metal-poor globular clusters, especially their abundance anomalies and the consequences for the determination of their atmospheric parameters and evolutionary status. Hot horizontal branch stars in metal-rich globular clusters are found to form a small but rather inhomogeneous group that cannot be explained by one evolutionary scenario. Hot UV-bright stars show a lack of classic post–asymptotic giant branch stars that may explain the lack of planetary nebulae in globular clusters. Finally, we discuss first results of spectroscopic observations of white dwarfs in globular clusters.

1. HISTORICAL BACKGROUND

Globular clusters are the closest approximation to a physicist’s laboratory in astronomy. They are densely packed, gravitationally bound systems of several thousand to about $10^6$ stars. The dimensions of the globular clusters are small compared with their distance from us; one-half of the light is generally emitted within a radius of less than 10 pc, whereas the closest globular cluster has a distance of 2 kpc and 90% lie more than 5 kpc away. We can thus safely assume that all stars within a globular cluster lie at the same distance from us. With ages on the order of $10^9$ yr, globular clusters are among the oldest objects in our Galaxy. Contrary to the field of the Galaxy, globular clusters formed stars only once in the beginning. Because the duration of that star formation episode was short compared with the current age of the globular clusters, the stars within one globular cluster are essentially coeval. In addition, all stars within one globular cluster (with few exceptions) show the same initial abundance pattern (which may differ from one cluster to another).

Because we know today that Galactic globular clusters are old stellar systems, people are often surprised by the presence of hot stars in these clusters since hot stars are usually associated with young stellar systems. The following paragraphs will show that hot stars have been known to exist in globular clusters for quite some time.

About a century ago, Barnard (1900) reported the detection of stars in globular clusters that were much brighter on (blue-sensitive) photographic plates than they appeared visually: “Of course the simple explanation of this peculiarity is that these stars, so bright photographically and so faint visually, are shining with a much bluer light than the stars which make up the main body of the clusters.”

In 1915, Shapley started a project to obtain colors and magnitudes of individual stars in globular and open clusters (Shapley 1915a). In the first globular cluster (M3; Shapley 1915b), he found a double-peaked distribution of colors, with a red maximum and a blue secondary peak. He noticed that, in contrast to what was known for field dwarf (i.e., main-sequence) stars, the stars in M3 became bluer as they became fainter. Ten Bruggencate (1927, p. 130) used Shapley’s data on M3 and other clusters to plot magnitude versus color (replacing luminosity and spectral type in the Hertzsprung-Russell diagram) and thus produced the first color-magnitude diagrams (“Farbenhelligkeitsdiagramme”). In these color-magnitude diagrams (CMDs) ten Bruggencate noted the presence of a red giant branch that became bluer toward fainter magnitudes, in agreement with Shapley (1915b). In addition, however, he saw a horizontal branch (“horizontaler Ast”) that parted from the red giant branch and extended far to the blue at constant brightness. Greenstein (1939) observed a CMD for M4 and noticed that while hot main-sequence stars were completely missing, there existed a group of bright stars above the horizontal branch and on the blue side of the red giant branch. Similar stars appeared also in the CMDs presented by Arp (1955).

As more CMDs of globular clusters were obtained, it became obvious that the horizontal branch morphology varied quite considerably between individual clusters. The clusters observed by Arp (1955) exhibited extensions of the blue horizontal branch toward bluer colors and fainter visual magnitudes, i.e.,

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1 Shapley (1930, p. 26, footnote) disliked the idea of plotting individual data points—he thought that the small number of measurements might lead to spurious results.
toward hotter temperatures\(^2\) (see Fig. 1). In some of Arp’s CMDs (e.g., M15, M2), these blue tails show gaps at varying brightness (see § 2.1 for details).

About 25 years after their discovery, the first ideas about the nature of the horizontal branch stars began to emerge: Hoyle & Schwarzschild (1955) were the first to identify the horizontal branch stars with post–red giant branch stars that burn helium in the central regions of their cores.

Sandage & Wallerstein (1960) noted a correlation between the metal abundance and the horizontal branch morphology seen in globular cluster CMDs: the horizontal branch (HB) became bluer with decreasing metallicity. Faulkner (1996) managed for the first time to compute zero-age HB (ZAHB) models that qualitatively reproduced this trend of HB morphology with metallicity without taking into account any mass loss but assuming a rather high helium abundance of \(Y = 0.35\). Iben & Rood (1970), however, found that “In fact for the values of \(Y\) and \(Z\) most favored \((Y \geq 0.25 \rightarrow 0.28, \ Z = 10^{-3} \rightarrow 10^{-4})\), individual tracks are the stubbiest. We can account for the observed spread in color along the horizontal branch by accepting that there is also a spread in stellar mass along this branch, bluer stars being less massive (on the average) and less luminous than redder stars.”

Comparing HB models to observed globular cluster CMDs, Rood (1973) found that an HB that “…is made up of stars with the same core mass and slightly varying total mass, produces theoretical c–m diagrams very similar to those observed….A mass loss of perhaps 0.2 \(M_\odot\) with a random dispersion of several hundredths of a solar mass is required somewhere along the giant branch.” The assumption of mass loss on the red giant branch diminished the need for very high helium abundances.

While Sweigart & Gross (1974, 1976) showed that HB tracks including semiconvection covered a larger temperature range, Sweigart (1987) noted that even with semiconvection a spread in mass was still necessary to explain the observations.

Caloi (1972) investigated the ZAHB locations of stars with very low envelope masses \((\leq 0.02 \ M_\odot)\) that lie along the extended or “extreme HB” (EHB) at high effective temperatures (>20,000 K) and found that they can be identified with the subdwarf B stars known in the field (Greenstein 1971). Sweigart, Mengel, & Demarque (1974) and Gingold (1976) studied the post-HB evolution and found that, in contrast to the more massive blue HB stars, EHB models do not ascend the second (asymptotic) giant branch (AGB) but evolve directly to the white dwarf domain.

Thus, our current understanding sees HB stars as stars that burn helium in a core of about 0.5 \(M_\odot\) and hydrogen in a shell. The more massive the hydrogen envelope is, the cooler is the resulting star. The masses of the hydrogen envelopes vary from 0.02 \(M_\odot\) to more than 0.2 \(M_\odot\) for metal-poor hot HB stars.\(^3\)

Hot HB stars eventually evolve up the AGB. The less massive envelopes of the even hotter EHB stars \((M_{env} \leq 0.02 \ M_\odot, \ \ T_{eff} > 20,000 \ K)\) do not support hydrogen shell burning, and EHB stars do not climb the AGB but evolve directly to the white dwarf domain and are thus also called AGB manqué stars (Greggio & Renzini 1990). For a review on HB evolution, see Sweigart (1994). In the CMD, hot HB stars populate the blue HB and the brighter part of the blue tail. The transition from hot to extreme HB stars takes place toward the fainter part of the blue tail at \(M_v \approx 3\) mag.

However, hot HB stars are neither the brightest nor the bluest stars in globular clusters: Shapley had already (1930, p. 30) remarked that “Occasionally, there are abnormally bright blue stars, as in Messier 13, but even these are faint absolutely, compared with some of the galactic B stars.” This statement refers to stars like those mentioned by Barnard (1900), which in CMDs lie above the HB and bluerward of the red giant branch (see Fig. 1). This is also the region where one would expect to find central stars of planetary nebulae, which are, however, rare in globular clusters; until recently (Jacoby et al. 1997), Ps 1 (Pease 1928), the planetary nebula in M15 with its central star K648, and IRAS 18333–2357 in M22 (Cohen & Gillett 1989) remained the only such objects known in globular clusters (see also § 4).

Apart from analyses of individual stars such as VZ 1128 in M3 (Strom & Strom 1970 and references therein) and Barnard 29 in M13 (Traving 1962; Stoeckley & Greenstein 1968), the first systematic work on these bright blue stars was done by Strom et al. (1970). All stars analyzed there show close to solar helium content, contrary to the hot and extreme HB stars, which in general are depleted in helium (Heber 1987; Moehler et al. 2000c; see also § 2 of this paper). Strom et al. identified the brightest and bluest UV-bright stars with models of post-AGB stars (confirming the ideas of Schwarzschild & Härn 1970) and the remaining ones with stars evolving from the HB toward the AGB. This means that all of the stars in their study are in the double-shell–burning stage. Zinn, Newell, & Gibson (1972) performed a systematic search for such stars using the fact that they are brighter in the \(U\) band than all other cluster stars. This also resulted in the name “UV-bright stars” for stars brighter than the HB and bluer than the red giant branch.\(^4\)

Most of the UV-bright stars found in ground-based searches are cooler than 30,000 K, although theory predicts stars with temperatures up to 100,000 K (e.g., Schönberner 1983; Renzini 1985). The ground-based searches, however, are biased toward

\(^2\) The change in slope of the HB toward higher temperatures is caused by the decreasing sensitivity of \(B-V\) to temperature on one hand and by the increasing bolometric correction for hotter stars (i.e., the maximum of stellar flux is radiated at ever shorter wavelengths for increasing temperatures, making stars fainter at \(V\) on the other hand.

\(^3\) Because of the higher opacities in their envelopes, metal-rich HB stars are cooler than metal-poor ones with the same envelope mass. Therefore, hot metal-rich HB stars must have less massive envelopes than metal-poor ones, reducing the upper limit to, e.g., \(\approx 0.15 \ M_\odot\) for solar-metallicity hot HB stars.

\(^4\) As the flux maximum moves to ever shorter wavelengths for increasing temperatures, hot UV-bright stars may be rather faint not only in \(V\) but also in the \(U\) band (see also § 4). Thus, UV-bright stars will appear brighter than the HB and bluer than the red giant branch only if they are cool and/or luminous.
cooler stars because of the large bolometric corrections for hotter stars. It is therefore not surprising that space-based searches in the vacuum UV (Ultraviolet Imaging Telescope [UIT]; Stecher et al. 1997) discovered a considerable number of additional hot UV-bright stars in a number of globular clusters (see also § 4).

Space-based observatories also contributed a lot of other information about hot stars in globular clusters: Observations with the UIT showed the unexpected presence of blue HB stars in metal-rich globular clusters such as NGC 362 (Dorman et al. 1997) and 47 Tuc (O’Connell et al. 1997). At about the same time, Hubble Space Telescope (HST) observations of the core regions of globular clusters showed long blue tails in metal-rich bulge globular clusters (Rich et al. 1997). These metal-rich globular clusters are discussed in more detail in § 3. The interest in hot old stars like HB and UV-bright stars has been revived and extended by the discovery of the UV excess in elliptical galaxies (Code & Welch 1979; de Boer 1982) for which they are the most likely sources (Greggio & Renzini 1990, 1999; Dorman, O’Connell, & Rood 1995; Dorman 1997; Brown et al. 1997; see also §§ 3 and 4 of this paper).

The most recent addition to the family of hot stars in globular
clusters is the white dwarfs found in HST observations of M4 (Richer et al. 1995, 1997), NGC 6752 (Renzini et al. 1996), NGC 6397 (Paresce, de Marchi, & Romaniello 1995; Cool, Piotto, & King 1996), and 47 Tuc (Zoccali et al. 2001), which are discussed in § 5.

2. HORIZONTAL BRANCH STARS IN METAL-POOR GLOBULAR CLUSTERS

2.1. Gaps and Blue Tails

As mentioned in § 1, the more vertical extensions of the blue HB (blue tails; cf. Fig. 1) seen in the CMDs of many globular clusters often display gaps at varying brightness. Such gaps are also known for field HB stars (Newell 1973; Heber et al. 1984). For a list of globular clusters with blue tails, see Fusi Pecci et al. (1993). Catelan et al. (1998) and Ferraro et al. (1998) give comprehensive lists of clusters that show gaps and/or bimodal HBs. Ferraro et al. (1998) argue that all intermediate-metallicity globular clusters ([Fe/H] ≈ −1.5) with a very long blue tail show a gap at about 18,000 K. Piotto et al. (1999) extend the discussion to include metal-rich globular clusters and argue for a gap at constant mass, which, for differing metallicities, will result in gaps at different temperatures. In the following discussion, we will refer to the stars along the vertical extensions of the blue HB simply as blue-tail (BT) stars and the stars along the horizontal part of the HB (bluer than the RR Lyrae gap) will be called blue HB (BHB) stars. Calling the stars along the vertical extension of the BHB subdwarf B stars (e.g., Bailyn et al. 1992) or EHB stars (i.e., stars with so little hydrogen envelope that they do not burn hydrogen in a shell) makes implicit assumptions about their physical nature and evolutionary status that are in most cases not correct (a point very well illustrated in Fig. 8 of Testa et al. 2001).

Because the gaps are not expected from canonical evolutionary scenarios, various noncanonical explanations have been suggested during the past 25 years, and some of them are given below (more detailed descriptions of possible explanations for the gaps can be found in Crocker, Rood, & O’Connell 1988; Catelan et al. 1998; Ferraro et al. 1998).

Diverging evolutionary paths.—The evolution away from the ZAHB could in principle transform a uniformly populated ZAHB into a bimodal HB as stars evolve. Newell (1973) was the first to suggest this explanation for the gap seen in UBV photometry of field HB stars at temperatures corresponding to ≈12,900 K. Heber et al. (1984) suggested that the small gap at ≈20,000 K between field horizontal branch B (HBB) type and sdB stars could be explained by diverging evolution.

Support for this idea came from Lee, Demarque, & Zinn (1994), but other calculations show that the effect is not large enough to explain the gaps along the HBs (see, e.g., Dorman, Lee, & VandenBerg 1991; Catelan et al. 1998).

Mass loss.—D’Cruz et al. (1996) found that bimodal HBs become more probable for increasing metallicity because the range in mass-loss efficiency required to produce an EHB star stays constant (i.e., independent of metallicity) whereas only a very narrow range of mass-loss efficiency can produce hot HB stars at high metallicities. Thus, the number of hot HB stars is expected to decrease with increasing metallicity, opening a wide gap between cool HB and EHB stars at high metallicity. Yong, Demarque, & Yi (2000) find that mass loss on the HB could produce EHB stars (like the sdBs) in very metal-rich environments like the open cluster NGC 6791 ([Fe/H] = +0.5). While these scenarios offer good explanations for the sdB stars and the large gap discovered in the metal-rich open cluster NGC 6791 (Kaluzny & Udalski 1992; Liebert, Saffer, & Green 1994), they cannot explain the smaller gaps seen in the mostly rather metal-poor globular clusters. Rood, Whitney, & D’Cruz (1997) and Ferraro et al. (1998) also discuss variations in mass loss on the red giant branch as possible causes for gaps along the HB. Caloi (1999), however, argues that HB evolution would tend to fill in gaps in the initial ZAHB distribution if the red giant branch (RGB) mass loss were actually able to produce them.

Differences in, e.g., [CNO/Fe], rotation, etc.—Rood & Crocker (1989) suggest differences in CNO or He abundances or rotation rates as possible causes for the gaps. For hot HB stars, a decrease in CNO abundances results in bluer colors at a given envelope mass (a similar effect to that seen for a decrease in overall metallicity). Increasing the He abundance in the hydrogen envelope of a hot HB star will increase the energy production in the H-burning shell, thereby resulting in brighter HB stars (for more details see Sweigart 1997b). Rotation would delay the helium core flash in a red giant, thereby leading to an increase in the helium core mass and more mass loss, resulting in bluer and brighter HB stars (see also Buonanno, Corsi, & Fusi Pecci 1985; Peterson, Rood, & Crocker 1995; Sills & Pinsonneault 2000, for a discussion of rotation and BTs). Bimodal distributions in any of these parameters may thus create gaps along the HB.

Dynamical interactions.—A gap would be easy to understand if the stars above and below the gap were created by different mechanisms; if the stars below the gaps do not descend from red giants, there is no reason why they should form a smooth extension of the sequence defined by red giants’ descendants. The most prominent candidates for such different formation mechanisms are binary interactions such as common-envelope evolution, merging of stars, etc. (for more details see Bailyn et al. 1992; Bailyn 1995; Moehler, Heber, & Rupprecht 1997b).

Such binary scenarios create stars that resemble the sdB, sdOB, and sdO stars known from the field of the Milky Way.
but not hot HB stars. The main objection to the dynamical scenarios is that in this case the numbers of red giant (RGB/AGB) stars relative to those of "true" HB stars, which give an estimate of the cluster's original helium abundance, would vary between clusters and pretend varying primordial helium abundances (see Buonanno et al. 1985; Fusi Pecci et al. 1993). Another objection is the tight sequence in temperature and surface gravity reported by Heber et al. (1986) and Moehler et al. (1997b) for stars below the faint gap in NGC 6752. Crocker et al. (1988) cite the similar BTs in M15 and NGC 288, which are dynamically very different, as argument against the production of BT stars by dynamical interactions like merging. Ferraro et al. (1997) argue in the same way with respect to M13 and M3, which are dynamically very similar but have very different HB morphologies. Bedin et al. (2000; NGC 2808) and D'Cruz et al. (2000; ω Cen) find no radial gradient in the ratio of very faint blue stars to BHB stars, arguing against dynamical interactions as the cause for the extremely faint blue stars. Testa et al. (2001) on the other hand find the most pronounced BT in the most metal-rich, but also densest, globular cluster of their sample, NGC 6626, which also shows indications for a higher than usual helium content. See Buonanno et al. (1997) for a detailed discussion of the relation between cluster density and the presence of BTs. Soker (1998) suggests that the interaction of a red giant with a close-in planet will spin up the red giant, thereby increasing its mass loss and the temperature of the resulting HB star. The different fates of a planet inside an extended stellar envelope could then result in multimodal HB morphologies. So far, only 47 Tuc has been searched for planets, with negative results (Gilliland et al. 2000).

Atmospheric processes.—Caloi (1999) proposed the change from convection to diffusion in the stellar atmospheres as an explanation for the gaps around \((B-V)_0 = 0\). This scenario would predict chemical peculiarities in bluer stars. Grundahl et al. (1999) suggest radiative levitation of heavy elements in the atmosphere as the cause for the \(u\)-jump observed in many globular clusters—a claim that is supported by the calculations of Hui-Bon-Hoa, LeBlanc, & Hauschildt (2000). A more detailed discussion of the role of diffusion in hot HB stars can be found in § 2.4.

Helium mixing.—Helium mixing in red giants means mixing deep enough to enrich the red giant’s envelope with helium freshly produced in the hydrogen-burning shell. A red giant experiencing helium mixing will evolve to higher luminosities, thereby losing more mass than canonically expected and producing a hotter HB star. The helium enrichment of the hydrogen envelope increases the efficiency of the hydrogen shell burning and thus the luminosity of the HB star (see Sweigart 1997a, 1997b, for more details). Different amounts of mixing in the red giant precursors could thus produce HB stars in different temperature regimes and at the same time explain some of the puzzling abundance distributions found in globular cluster red giants (see Kraft 1994; Kraft et al. 1997 for reviews, but also Gratton et al. 2001 for most recent evidence of primordial abundance variations). Charbonnel, Denissenkov, & Weiss (2000) and Caloi (2001), however, argue that current observational results for both HB stars and red giants do not support the idea of helium mixing being active in globular cluster red giants.

Statistical fluctuations.—Catelan et al. (1998) used numerous synthetic HB simulations to show quite convincingly that at least some of the gaps may be due to statistical fluctuations. Ferraro et al. (1998) and Piotto et al. (1999), however, report gaps at physically similar positions (i.e., temperature or mass) in several globular clusters, arguing against statistical fluctuations.

2.2. Atmospheric Parameters (\(T_{eff}\), \(\log g\))

Early studies of hot HB stars in globular clusters had already shown discrepancies between observational results and theoretical expectations. Graham & Doremus (1966) mentioned that the comparison of \((c_1)_b\) versus \((b-y)_b\), for 50 BHB stars in NGC 6397 to models from Mihalas (1966) indicated low surface gravities and a mean mass of 0.3 \(M_\odot\) (0.4 \(M_\odot\) for solar (negligible) helium abundance, assuming \((m-M)_b = 12.0\) mag and \(E_{b-V} = 0.16\) mag. “It is clear that the accurate fixing of this parameter [\(\log g\)] is of the greatest importance for fixing limits to the masses of the horizontal branch stars since there seems no other way, at present, of determining them more directly.” Later spectroscopic analyses of HB stars (see cited papers for details) in globular clusters with and without gaps along their HBs and/or BTs reproduced this effect (cf. Fig. 2): Crocker et al. (1988) deal with five globular clusters, namely, M3, M5, M15, M92, and NGC 288 (of which M5 does not show any gap along the BHB/BB). De Boer, Schmidt, & Heber (1995) analyzed BHB stars in NGC 6397, which shows a short, horizontal BHB. Moehler, Heber, & de Boer (1995) and Moehler, Heber, & Durrell (1997a) study BT stars in M15. Heber et al. (1986) and Moehler et al. (1997b) analyze BT stars in NGC 6752, which is well known for its extremely long BT.

The ZAHB in Figure 2 marks the position where the HB stars have settled down and started to quietly burn helium in their cores. The terminal-age HB (TAHB) is defined by helium exhaustion in the core of the HB star (\(Y_c < 0.0001\)). In order to allow a better search for any common physical gaps, the stars are marked by their position relative to gaps along the HB: M92, M15, M3, and NGC 288 show a gap at \(M_r \approx 0.6–1.4\) mag (bright gap). Stars above that bright gap are marked by filled circles, stars below by open circles. M15 and NGC 6752 show a faint gap (or underpopulated region) at \(M_r \approx 3\) mag. Stars below these faint gaps are marked by filled triangles. NGC 6397 and M5 show no obvious gaps (three-pointed symbols). Figure 2 shows that the faint gap separates hot HB from EHB stars at about 20,500 K, which is somewhat hotter than the “temperature” gap for intermediate-metallicity clusters at 18,000 K suggested by Ferraro et al. (1998) and could correspond to the “forbidden mass” region discussed by Piotto et al. (1999). The bright gap roughly corresponds to the underpopulated region at \(T_{eff} \approx 10,000–12,600\) K (long-dashed line), although the dis-
tinction between stars above and below the bright gap is not as clear as for the faint gap. The BT stars below the bright gap (and above the faint gap) are hot HB stars and not hot subdwarfs like the field sdB stars. For temperatures between 11,500 and 20,500 K, the observed positions in the \((\log g, T_{\text{eff}})\) diagram fall mostly above the ZAHB and in some cases even above the TAHB.\(^7\) This agrees with the finding of Saffer et al. (1997) that field HBB stars show a larger scatter away from the ZAHB in \(T_{\text{eff}}, \log g\) than sdB stars.

Knowing the atmospheric parameters of the stars and the distances to the globular clusters allows us to determine masses for the stars (cf. Moehler, Heber, & de Boer 1994, 1995; Moehler et al. 1997b; de Boer et al. 1995). While the stars in M3, M5, and NGC 6752 have mean masses consistent with the canonical values, the hot HB stars in all other clusters show masses that are significantly lower than predicted by canonical HB evolution—even for temperatures cooler than 11,500 K where the stars do not deviate from the canonical tracks in surface gravity. Scenarios like the merging of two helium-core white dwarfs (Iben & Tutukov 1984) or the stripping of red giant cores (Iben & Tutukov 1993; Tuchman 1985) produce low-mass stars that are either too hot (merger) or too short lived (stripped core) to explain the low-mass HB stars.

In addition, some UV observations suggest discrepancies between theoretical expectations and observational results: the International Ultraviolet Explorer (IUE) and Hopkins Ultraviolet Telescope (HUT) spectra of M79 (Altner & Matilsky 1993; Dixon et al. 1996) suggest lower than expected gravities and higher than expected metallicities for hot HB stars (but see Vink et al. 1999, who do not need low surface gravities to fit the HUT data). Hill et al. (1996) find from UIT photometry

\(^7\) Crocker (1991) finds from the analysis of spectra for BHB stars in M3 and M13 that the M3 stars cooler than 11,200 K stay very close to the ZAHB (the one star at \(T_{\text{eff}} \approx 12,500\) K shows lower \(\log g\)). The M13 stars cooler than 11,200 K stay mostly close to the ZAHB, but the majority of stars in that cluster are hotter and show lower \(\log g\).
of M79 that stars bluer than $m_{152} - m_{249} = -0.2$ mag lie above the ZAHB whereas cooler stars scatter around the ZAHB. Parise et al. (1998; UIT data of M13) find a lack of stars close to the ZAHB at a color (temperature) range similar to the low log g range shown in Figure 2. Whitney et al. (1998) claim from UIT observations that the bluest HB stars in ω Cen have lower than expected luminosities and that a considerable number of stars lie below the ZAHB. This is confirmed by HST observations of D’Cruz et al. (2000), who find a “blue hook” feature at the extremely hot end of the BT in ω Cen and also several sub-ZAHB stars. These blue hook stars could be similar to the helium-rich sdB found in M15 (Moehler et al. 1997a). Landsman et al. (1996) on the other hand find good agreement between UIT photometry of blue stars in NGC 6752 and a standard ZAHB (in position and HB luminosity width) for $(m-M)_0 = 13.05$ mag and $E_{B-V} = 0.05$.

Thus far, we have discussed results from low- to medium-resolution spectra. High-resolution spectra offer further insights into the nature of hot HB stars, especially their abundances and rotational velocities, which are discussed in the next two sections. We will come back to the problems described here in § 2.5.

2.3. Rotational Velocities

Peterson (1983, 1985a, 1985b) found from high-resolution spectroscopic studies of BHB stars in M3, M4, M5, M13, and NGC 288 that clusters with bluer HB morphologies show higher rotation velocities among their HB stars, which supports the idea that rotation affects the distribution of stars along the HB. However, the analysis of Peterson et al. (1995) shows that, while the stars in M13 (which has a long BT) rotate on average faster than those in M3 (which has only a short BHB), the stars in NGC 288 and M13 show slower rotation velocities at higher temperatures. These results are consistent with those reported for BHB and BT stars in M13 by Behr et al. (2000b), who determined rotational velocities for stars as hot as 19,000 K (considerably hotter than the stars analyzed by Peterson et al. 1995). They found that stars hotter than about 11,000 K have significantly lower rotational velocities than cooler stars and that the change in mean rotational velocity may coincide with the gap seen along the BHB of M13. In addition, the results of Cohen & McCarthy (1997) for M92 and Behr, Cohen, & McCarthy (2000a) for M15 show that HB stars cooler than ≈11,000–12,000 K in general rotate faster than hotter stars.

Sills & Pinsonneault (2000) study theoretical models for the rotation of HB stars and find that the observed rotation of cool BHB stars in M13 can be explained if the RGB stars have rapidly rotating cores and differential rotation in their convective envelopes and if angular momentum is redistributed from the rapidly rotating core to the envelope (most likely on the HB). If, however, turnoff stars rotate with less than 4 km s$^{-1}$, a rapidly rotating core in the main-sequence stars (violating helioseismological results for the Sun) or an additional source of angular momentum on the RGB (e.g., mass transfer in close binaries or due to planets as described by Soker & Harpaz 2000) is required to explain the rotation of BHB stars. The change in rotation rates toward higher temperatures is not predicted by the models but could be understood as a result of gravitational settling, which creates a mean molecular weight gradient that then inhibits angular momentum transport in the star. Sweigart (2001) suggests that the weak stellar wind invoked to reconcile observed abundances in hot and extreme HB stars with diffusion calculations (cf. § 2.4) could also carry away angular momentum from the surface layers and thus reduce the rotational velocities of these stars.

Soker & Harpaz (2000) argue that the distribution of rotational velocities along the HB can be explained by spin-up of the progenitors due to interaction with low-mass companions, predominantly gas giant planets, in some cases also brown dwarfs or low-mass main-sequence stars (especially for the very hot EHB stars). The slower rotation of the hotter stars in their scenario is explained by mass loss on the HB, which is accompanied by efficient angular momentum loss. This scenario, however, does not explain the sudden change in rotational velocities and the coincidence of this change with the onset of radiative levitation.

2.4. Atmospheric Abundances

It was realized early on that the BHB and BT stars in globular clusters show weaker helium lines than field main-sequence B stars of similar temperatures (NGC 6397, Searle & Rodgers 1966; M5, M13, M92, Greenstein & Münch 1966; M13, M15, M92, Sargent 1967). Greenstein, Truran, & Cameron (1967) had already suggested diffusion to explain this He deficiency.

Michaud, Vaucclair, & Vaucclair (1983) performed the first theoretical study of diffusion effects in hot and extreme HB stars. Using the evolutionary tracks of Sweigart & Gross (1976), they found for the metal-poor models that “in most of each envelope, the radiative acceleration on all elements [i.e., C, N, O, Ca, Fe] is much larger than gravity which is not the case in main-sequence stars.” The elements are thus pushed toward the surface of the star. Turbulence affects the different elements to a varying extent but generally reduces the overabundances. Models without turbulence and/or mass loss (which may reduce the effects of diffusion) predict stronger He depletions than are observed. A weak stellar wind could alleviate this discrepancy (Heber 1986; Michaud et al. 1989; Fontaine & Chayer 1997; Unglaub & Bues 1998 discuss this effect, albeit for hotter stars).

The extent of the predicted abundance variations varies with effective temperature, from none for HB stars cooler than about 5800 ± 500 K (due to the very long diffusion timescales)

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8 Michaud (1982) and Charbonneau & Michaud (1988) showed that meridional circulation can prevent gravitational settling and that the limiting rotational velocity decreases with decreasing log g. Behr et al. (2000a) note that two of the HB stars hotter than 10,000 K show higher rotational velocities and much smaller abundance deviations.
to 2–4 dex in the hotter stars (the hottest model has $T_{\text{eff}} = 20,700$ K), and also depends on the element considered. The overabundances in the two hottest models (12,500 and 20,700 K) are limited to 3 dex for relatively abundant elements by the saturation of lines. Less abundant elements such as Fe, Eu, Ga could show much larger overabundances before their lines saturate (up to 5 dex for original values of [M/H] $= -2$).

Observations of BHB and BT stars in globular clusters support the idea of diffusion being active above a certain temperature. Abundance analyses of BHB stars cooler than 11,000–12,000 K in general show no deviations from the globular cluster abundances derived from red giants (NGC 6397, Glaspey et al. 1986; NGC 6752, Glaspey et al. 1989; M4, NGC 6397, Lambert, McWilliam, & Smith 1992; M92, Cohen & McCarthy 1997; M13, Behr et al. 1999; M15, Behr et al. 2000a; NGC 6752, Peterson et al. 2000). For stars hotter than 11,000–12,000 K, however, departures from the general globular cluster abundances are found, e.g., iron enrichment to solar or even supersolar values and strong helium depletion (NGC 6752, Glaspey et al. 1989; M13, Behr et al. 1999; NGC 288, M13, Peterson et al. 1995; NGC 6752, Moehler et al. 2000c; M15, Behr et al. 2000a; NGC 6752, Peterson et al. 2000). This agrees with the finding of Altnet & Matilsky (1993) and Vink et al. (1999) that solar metallicity model atmospheres are required to fit the UV spectra of M79.

All this evidence supports the recent suggestion of Grundahl et al. (1999) that the onset of diffusion in stellar atmospheres may play a role in explaining the jump along the HB toward brighter $u$-magnitudes at effective temperatures of about 11,500 K. This jump in $u$, $u - y$ is seen in all CMDs of globular clusters that have Strömgren photometry of sufficient quality. The observed HB stars return to the theoretical ZAHB at temperatures between 15,000 and 20,000 K (Grundahl et al. 1999, Fig. 1). The effective temperature of the jump is roughly the same for all clusters, irrespective of metallicity, central density, concentration, or mixing evidence, and coincides with the apparent gap in $T_{\text{eff}}$, log $g$ seen in Figure 2 at $T_{\text{eff}} \approx 10,000–12,000$ K. This coincides with the region where surface convection zones due to hydrogen and He ionization disappear in HB stars (Sweigart 2001).

Radiative levitation of heavy elements decreases the far-UV flux and by back-warming increases the flux in $u$. Grundahl et al. (1999) show that the use of metal-rich atmospheres ([Fe/H] $= +0.5$ for scaled-solar ATLAS9 Kurucz model atmospheres with log $\epsilon_{\text{Fe}, \odot} = 7.60$) improves the agreement between observed data and theoretical ZAHB in the $u$, $u - y$ CMD at effective temperatures between 11,500 and 20,000 K but it worsens the agreement between theory and observation for hotter stars in the Strömgren CMD of NGC 6752 (see their Fig. 8). Thus, diffusion either may not be as important in the hotter stars or the effects may be diminished by a weak stellar wind.

The gap at $(B - V)_0 \approx 0$ discussed by Caloi (1999; see § 2.1 of this paper) is not directly related to the $u$-jump because it corresponds to an effective temperature of about 9000 K and is also not seen in every cluster (which would be expected if it were due to an atmospheric phenomenon). The gap at $T_{\text{eff}} \approx 13,000$ K seen in the $c_i$, $b - y$ diagram of field HB stars (Newell 1973; Newell & Graham 1976) may be related to the $u$-jump because the $c_i$ index contains $u$.

The abundance distribution within a stellar atmosphere influences the temperature stratification and thereby the line profiles and the flux distribution of the emergent spectrum. A deviation in atmospheric abundances of HB stars from the cluster metallicity due to diffusion would thus affect their line profiles and flux distribution. Model atmospheres calculated for the cluster metallicity may then yield wrong results for effective temperatures and surface gravities when compared to observed spectra of HB stars. Self-consistent model atmospheres taking into account the effects of gravitational settling and radiative levitation are, however, quite costly in CPU time and have started to appear only quite recently for hot stars (Dreizler & Wolff 1999; Hui-Bon-Hoa et al. 2000).

2.5. Atmospheric Parameters Revisited

Analysis of a larger sample of hot and extreme HB stars in NGC 6752 (Moehler et al. 2000c) showed that the use of model atmospheres with solar or supersolar abundances removes much of the deviation from canonical tracks in both $T_{\text{eff}}$, log $g$ and $T_{\text{eff}}$, mass for hot HB stars discussed in § 2.2. However, some discrepancies remain, indicating that the low log $g$, low-mass problem cannot be completely solved by scaled-solar metal-rich atmospheres (which do reproduce the $u$-jump reported by Grundahl et al. 1999). As Michaud et al. (1983) noted, diffusion will not necessarily enhance all heavy elements by the same amount and the effects of diffusion vary with effective temperature. Elements that were originally very rare may be enhanced even stronger than iron (see also Behr et al. 1999, where P and Cr are enhanced to supersolar abundances). The question of whether diffusion is the (one and only) solution to the “low-gravity” problem cannot be answered without detailed abundance analyses to determine the actual abundances and model atmospheres that allow the use of nonscaled solar abundances (like ATLAS12; Kurucz 1992).

2.6. Where Do We Stand?

The spectroscopic analyses of BHB and BT stars in globular clusters suggest that the faint gap, or underpopulated region, at $M_V \approx 3$ mag can be identified with the transition from hot to extreme HB stars while the bright gap is probably caused by the onset of radiative levitation in the atmospheres of the hot HB stars. While the sudden change in rotational velocity at the bright gap is not yet understood, the good agreement of spectroscopic results (accounting for diffusion) with canonical evolution makes several noncanonical scenarios discussed in § 2.1 appear un-

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*a Bedin et al. (2000) report a $U$ jump for NGC 2808, and Markov, Spassova, & Baev (2001) detect it in their $UBV$ photometry of M5.
likely: Helium mixing, rotation, and high primordial helium abundance would all increase the luminosities of the hot HB stars (resulting in lower log g but canonical masses; see Crocker et al. 1988; Sweigart 1997a). Currently, however, stars with low log g show also low masses (Moehler et al. 2000c), suggesting deficiencies in the analysis rather than noncanonical evolutionary effects as cause. Dynamical interactions are unlikely to produce the tight sequence of stars in the (Teff, log g) diagram. These statements, however, are currently valid only for those (intermediate-metallicity and metal-poor) globular clusters where spectroscopic analyses of BT/BHB stars exist. More spectroscopic analyses, especially in more metal-rich clusters, would help to verify the suggestion of Pirotto et al. (1999) that the faint gap corresponds to a “forbidden” mass (which would result in cooler gap temperatures in more metal-rich globular clusters).

Still, unexplained, however, are the low masses found for cool BHB stars (which are not affected by diffusion) in, e.g., NGC 6397 and M92. For those stars, a longer distance scale to globular clusters would reduce the discrepancies. Such a longer distance scale has been suggested by several authors using Hipparcos results for metal-poor field subdwarfs to determine the distances to globular clusters by fitting their main sequence with the local subdwarfs (see Reid 1999 for an overview of the Hipparcos results). Carretta et al. (2000) present an extensive and excellent discussion of various globular cluster distance determinations and the zoo of biases that affect them. It is interesting to note that for M92 and NGC 6397 the new distance moduli are 0.3–0.6 mag larger than the old ones, thereby greatly reducing the mass discrepancies (see also Heber, Moehler, & Reid 1997). The results of spectroscopic analyses of BHB stars (cooler than 11,000–12,000 K) in globular clusters therefore favor the longer distance scale (Moehler 1999).

3. HORIZONTAL BRANCH STARS IN METAL-RICH GLOBULAR CLUSTERS

Thus far, we have dealt with BHB and BT stars in metal-poor ([Fe/H] < −1) globular clusters. As mentioned in § 1, the HB morphology correlates with metallicity, i.e., HB stars in metal-rich globular clusters will populate mainly the cool regions of the HB because for a given mass of the hydrogen envelope the resulting effective temperature decreases with increasing metallicity. The detection of sdB/sdO candidates in the metal-rich open clusters NGC 188 ([Fe/H] ≈ 0) and NGC 6791 ([Fe/H] ≈ +0.5) by UIT (Landsman et al. 1998) and optical photometry (Kuizny & Udalski 1992), followed by the spectroscopic verification of sdB stars in NGC 6791 (Liebert et al. 1994), proves, however, that at least EHB stars can be produced also in metal-rich systems (see also D'Cruz et al. 1996 for theoretical scenarios).

UV observations of elliptical galaxies, which are in general even more metal-rich than metal-rich globular clusters (based on the strength of the Mg2 index; cf. Fig. 3), showed that such old, metal-rich systems contain hot stars (Burstein et al. 1988). Stellar evolution models yield the maximum lifetime UV output for EHB stars with envelope masses Menv ≤ 0.02 M⊙ (see also Greggio & Renzini 1990, 1999), while post-AGB stars do not live long enough at high temperatures to play a significant role for the UV flux. Further evidence in support of hot subdwarfs as the cause for the UV excess in elliptical galaxies is provided by Brown et al. (1997): Their analysis of HUT spectra of six elliptical and SO galaxies shows that models with supersolar metal and helium abundances provide the best fit to the flux distribution of the observed spectra and that EHB stars are required in all fits. Most absorption line features (of C, N, Si, i.e., light elements), however, are consistent with [M/H] = −1, in contrast to the energy distribution. This may be due to diffusion in the atmospheres of the EHB stars (see § 2.4).

Dorman et al. (1995) present a thorough discussion of the observational evidence for UV excess in elliptical galaxies and compare the galaxy data to those obtained for globular clusters. Comparing the UV–visual color (15−V)0 for galaxies and globular clusters to the Mg2 metallicity index (see Fig. 3), 15 being the observed brightness at 1500 Å), they find that while the globular clusters and the galaxies occupy distinct ranges in Mg2, they overlap in (15–V)0, with the globular clusters being bluer on average. The region between globular clusters and galaxies in Mg2 is occupied by the metal-rich globular clusters 47 Tuc, NGC 6388, and NGC 6441 and the small elliptical galaxy M32 (see Brown et al. 2000 for far-UV HST observations of this galaxy). The discovery of hot stars in the metal-rich “transition” globular clusters (see § 1) is thus of special interest because analyses of these stars may provide additional information on the nature of the UV excess in elliptical galaxies.

Rich, Minniti, & Liebert (1993) analyzed IUE spectra of the cores of 11 disk globular clusters. The surface light distribution in these spectra becomes more concentrated toward shorter wavelengths for the clusters with the highest UV fluxes. The UV colors of the metal-rich globular clusters NGC 6388, NGC 6441, NGC 6624, and NGC 6637 are almost as blue as those of metal-poor globular clusters (see Fig. 3). The IUE observations of NGC 6387 and NGC 6624 could be explained by one post-EHB star or a few EHB stars, while, for NGC 6441, which shows a rise in UV flux toward shorter wavelengths (similar to elliptical galaxies), post-HB stars are the most likely sources. The ratio LUV/Ltot of the clusters showing high far-UV fluxes agrees very well with those seen in elliptical galaxies, whereas that of NGC 6388, which shows a flat UV spectrum (best explained by BHB stars), is 1 order of magnitude lower. 47 Tuc does not show any evidence for stars hotter than blue stragglers within the IUE aperture.

Some years later, Rich et al. (1997) discovered the first well-populated BTs in metal-rich globular clusters from WFPC2 photometry of the cores of NGC 6388 and NGC 6441. Most
surprisingly, the HB stars at the top of the BT are roughly 0.5 mag brighter in V than the red HB “clump,” which is strongly sloped as well. The slight HB tilt ($\Delta V \approx 0.1$ mag) expected for metal-rich globular clusters due to the variation in bolometric correction for metal-rich BHB stars (Brocato et al. 1999) is much smaller than the observed slope. Differential reddening alone is probably not the cause of this additional slope (Piotto et al. 1997; Sweigart & Catelan 1998; Layden et al. 1999). WFPC2 photometry of the core of 47 Tuc obtained within the same program does not show any evidence for a BHB or a BT nor any slope along its red HB. Layden et al. (1999) verify the slope of the BHB and red clump in NGC 6441, and recent analyses of RR Lyrae variables in NGC 6388 and NGC 6441 (Layden et al. 1999; Pritzl et al. 2000) strongly indicate that the RR Lyrae stars of these globular clusters are substantially brighter than canonical models would predict.

O’Connell et al. (1997) detected about 20 hot stars on the UIT far-UV image of 47 Tuc, which they identify with those producing the UV upturn in elliptical galaxies. Their number, however, is too small to produce a significant UV upturn in 47 Tuc. The much larger field of the UIT accounts for the different results of UIT versus IUE and WFPC2 observations. The small number of hot stars in 47 Tuc agrees with the result of Rose & Deng (1999) that only about 7% of the mid-UV light of 47 Tuc comes from stars hotter than about 7500 K (most of which are probably blue stragglers).

Dorman et al. (1997) find evidence for hot stars in NGC 362 from UIT observations. While this globular cluster is not metal-rich, its HB morphology is too red for its metallicity. Together with NGC 288, which has a predominantly blue HB at a similar metallicity, it forms a second-parameter pair of globular clusters (meaning that an additional parameter besides metallicity is necessary to explain the difference in HB morphology between these two clusters).

What are the possible origins for the hot stars in these four globular clusters?

**High–mass-loss tail.**—Dorman et al. (1997) and O’Connell et al. (1997) suggest that the hot stars in NGC 362 and 47 Tuc are simply the high–mass-loss tail of the red HB distribution. A high–mass-loss tail most probably cannot explain the much

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**Fig. 3.—**UV-visual color ($15-V$)$_0$ vs. metallicity index Mg$_2$ for globular clusters and elliptical galaxies (adapted from Dorman et al. 1995, 15 being the brightness at 1500 Å). The metal-poor globular clusters discussed in § 2 and the “transition” objects between globular clusters and elliptical galaxies are identified.
more numerous blue stars in NGC 6388 and NGC 6441. Moreover, increasing RGB mass loss moves an HB star blueward in the $V - B - V$ plane but does not increase its luminosity (the same holds true for an increase in age).

**Dynamical interactions.**—Bailyn (1995) has reviewed the binary evolution scenarios that could yield hot subdwarf stars in globular clusters (see also § 2.1). Binary evolution could be a valid explanation for 47 Tuc and NGC 362, although it is puzzling that the center of 47 Tuc (where interactions should be most pronounced) does not show any evidence for hot stars, whereas the core of NGC 362 shows a concentration of hot stars (Dorman et al. 1997). It is, however, not yet clear whether the hot stars in the core of NGC 362 are HB stars or extreme blue stragglers.

If dynamical interactions created the hot HB stars in NGC 6388 and NGC 6441, these stars should be more centrally concentrated than the RGB stars, which is not evident in the HST data. One should note, however, that Layden et al. (1999) find a much less pronounced BT in the outer regions of NGC 6441 (where of course the contamination by the field bulge population is much stronger) and suggest that the BHB/BT stars are more centrally concentrated than the red clump stars. However, binaries cannot explain the slope of the HB seen in NGC 6388 and NGC 6441.

**Spread in metallicity.**—This scenario was first discussed by Piotto et al. (1997) to explain the sloped HBs found in NGC 6388 and NGC 6441. Model calculations by Sweigart (2001) show that the metal-poor end ([Fe/H] = −2.3) of the ZAHB for these variable-metallicity tracks is about 0.4 mag more luminous at the top of the BT than the canonical ZAHB for [Fe/H] = −0.5. In this case, NGC 6388 and NGC 6441 might be metal-rich analogs of ω Cen, the only other GC known to show a spread in metallicity.

Two of the mechanisms discussed in § 2.1 may also produce hot HB stars and a sloped HB in metal-rich globular clusters: both rotation and helium mixing can create brighter and hotter HB stars. Rotation and/or mixing strong enough to produce the observed slope of the HB in NGC 6388 and NGC 6441 would at the same time produce a considerable number of hot stars.

While a high primordial helium abundance can also explain a sloped HB together with a BT in a metal-rich globular cluster (Catelan & de Freitas Pacheco 1996; Sweigart & Catelan 1998), this scenario also predicts a much larger value for the number ratio $R$ (=HB/RGB) than the value recently obtained by Layden et al. (1999) for NGC 6441.

Moehler et al. (2000b) analyzed hot HB star candidates in 47 Tuc and NGC 362. Three of the four BHB stars analyzed in 47 Tuc and three of the eight observed in NGC 362 are probably members of the clusters, and their parameters and masses (except for one spectroscopic/photometric binary in 47 Tuc, which cannot be properly analyzed) agree very well with canonical evolutionary tracks.

The three spectroscopically verified hot HB stars in 47 Tuc are much hotter (10,000 K < $T_{\text{eff}}$ < 15,000 K) than the rest of the HB population, which is (except for the single RR Lyrae V9) entirely redward of the instability strip. The small number of hot HB stars in 47 Tuc and their high temperatures point to a scenario in which they have a different physical origin than the dominant red HB population (e.g., binary interactions, although the lack of central concentration remains a strong caveat for this scenario).

Because the separation between the hot and cool HB stars in NGC 362 is much smaller, it is plausible that the BHB stars arise from a small percentage of red giants with unusually high mass loss. The three probable member stars in NGC 362 are all located within 2.5 of the cluster center, while the remaining five stars (probably members of the SMC; for more details see Moehler et al. 2000b) are all more than 3.5 from the center. It would be interesting to study the stellar parameters of the hot stars in the core region, where, in addition, the relative SMC contamination should be much lower.

The atmospheric parameters derived for the hot HB stars in NGC 6388 and NGC 6441 (Moehler, Sweigart, & Catelan 1999) on the other hand place the studied stars preferentially below the canonical ZAHB. The derived gravities for most stars are significantly larger than those predicted by the noncanonical tracks (rotation, helium mixing) that reproduce the upward sloping HBs.

A spread in metallicity, which requires the BT stars to be metal-poor, would reduce the discrepancies found by Moehler et al. (1999): The authors relied on the equivalent width of the Ca $\Pi$ K line to place the analyzed stars on the hot side of the Balmer maximum. A reduction in metallicity would reduce the expected equivalent width of the Ca $\Pi$ K line also for temperatures below 9000 K to values consistent with the observed ones (including the high reddening of these clusters). If the cool solutions were chosen, all stars except one would end up close to the ZAHB computed for varying metallicity, and the problem of the high gravities would vanish.

In summary, one can state that hot HB stars in metal-rich globular clusters with few such stars (47 Tuc, NGC 362) show parameters in agreement with canonical evolution (i.e., high–mass-loss tail), although binary evolution may play a role. The numerous hot HB stars in NGC 6388 and NGC 6441, however, currently can be best explained by a spread in metallicity, accompanied by canonical evolution.

**4. UV-BRIGHT STARS IN GLOBULAR CLUSTERS**

As mentioned in § 1, UV-bright stars were originally defined as stars brighter than the HB and bluer than red giants (Zinn et al. 1972; see also Fig. 1), that are brighter in $U$ than any other cluster star.

Zinn (1974) observed spectra of 38 optically selected UV-
bright stars in eight globular clusters. He found that, at a given age and metallicity, different HB morphologies result in different UV-bright star populations; the presence/absence of “supra-HB” stars is correlated with the presence/absence of hot HB stars in M13, M15, and M3. This agrees with the theoretical expectation that hot HB stars evolving away from the HB should up as “supra-HB” stars. The more luminous UV-bright stars in all three globular clusters are consistent with post-AGB tracks. In addition, the existence of a planetary nebula and the presence of red HB stars in M15 (which is unusual for such a metal-poor globular cluster) are linked to each other: the red HB stars of red HB stars in M15 (which is unusual for such a metal-

In addition, the existence of a planetary nebula and the presence of hot HB stars identified as such solely on the UIT images. The search for UV-bright stars in globular clusters continued, and Harris, Nemec, & Hesser (1983) list 29 globular clusters with 23 (11) UV-bright stars bluer than \(B-V\) = 0 that are definite (probable) cluster members. De Boer (1985) used IUE spectra of 10 hot UV-bright stars in seven globular clusters to estimate their contribution to the integrated UV light of the respective globular clusters: Hot post-AGB stars contribute less than 3% to the total cluster light at 3300 Å, increasing to about 15% at 1500 Å and further increasing toward even shorter wavelengths. De Boer (1987) gives a compilation of 45 luminous hot UV-bright stars \(M_v < 0, (B-V)_0 < 0.2\) in 36 globular clusters.

Hot post-(extreme) HB and post-(early) AGB stars do not necessarily fulfill the original definition of UV-bright stars: As stars get hotter, the maximum of their flux distribution moves to ever shorter wavelengths, and especially the less luminous UV-bright stars evolving away from the EHB can be quite faint at visual and near-UV wavelengths. The early lists of hot UV-bright stars are thus certainly incomplete because they are based on optical searches, which favor luminous hot UV-bright stars and are also limited in their spatial coverage because of crowding in the cluster cores. As hot UV-bright stars shine up in far-UV images of globular clusters, the Ultraviolet Imaging Telescope (UIT; Stecher et al. 1997) was used to obtain ultraviolet (~1620 Å) images of 14 globular clusters. The solar-blind detectors on UIT suppress the cool star population, which allows UV-bright stars to be detected into the cluster cores, and the 40’ field of view of UIT is large enough to image the entire population of most of the observed clusters. Thus, the UIT images provide a complete census of the hot UV-bright stars in the observed clusters, which is well suited to test post-(extreme) HB and post-(early) AGB evolutionary tracks. Such a test is especially important because hot UV-bright stars probably make a significant contribution to the UV upturn observed in elliptical galaxies (Greggio & Renzini 1990; Dorman et al. 1995; Dorman 1997; Brown et al. 1997, 2000; Greggio & Renzini 1999).

The need for further information on these evolutionary stages is also illustrated by the results of Jacoby et al. (1997) for planetary nebulae in globular clusters. In their OIII imaging survey of 133 globular clusters, they found only four planetary nebulae, two of which were previously known (Ps 1 in M15 and IRAS 18333–2357 in M22; cf. § 1). Based on the planetary nebula luminosity function for metal-poor populations, they expected to find 16 planetary nebulae in their sample. However, their OIII search may have missed some old, faint planetary nebulae. In addition—even more important—their assumption that all stars in a globular cluster will eventually go through the AGB phase is not valid for globular clusters like NGC 6752, where about 30% of the HB population consist of EHB stars (with \(T_{eff} > 20,000\) K), which evolve into white dwarfs without ever passing through the thermally pulsing AGB phase. While such globular clusters are expected to be deficient in post-AGB stars, they should show a substantial population of less luminous \([1.8 < \log (L/L_\odot) < 3]\) UV-bright stars, which can be either post-EHB stars or post–early AGB stars, neither of which would produce a planetary nebula.

All this emphasizes the need for spectroscopic analyses of hot UV-bright stars to compare their parameters with evolutionary calculations. Most analyses so far, however, have been limited to the use of IUE spectra. While IUE spectra allow a good determination of \(T_{eff}\) for hot stars, they are not very suitable to determine \(g\) (see Cacciari et al. 1995). Analyses that also used hydrogen lines (line profile fits or equivalent widths) or the shape of the far-UV continuum were performed for eight optically selected hot UV-bright stars (in some cases only the most recent analysis is given): M22 II-81 (Glaspiey et al. 1985), NGC 6712 C49 (Remillard, Canizares, & McClintock 1980, only lower limit for \(T_{eff}\), NGC 6397 ROB162 (Heber & Kudritzki 1986), NGC 1851 UV5 and M3 vZ1128 (Dixon, Davidsen, & Ferguson 1994), 47 Tuc BS (Dixon, Davidsen, & Ferguson 1995), M13 Barnard 29 (Conlon, Dufton, & Keenan 1994), and \(\omega\) Cen ROA5139 (Moehler et al. 1998a). Moehler, Landsman, & Napiwotzki (1998b; ground-based observations, 10 stars) and W. B. Landsman et al. (2001, in preparation; HST observations, three stars) observed and analyzed spectra of UV-bright stars identified as such solely on the UIT images. The derived effective temperatures and gravities of all these stars are plotted in Figure 4, along with evolutionary tracks.

Obviously, the dominance of post-AGB stars among optically selected hot UV-bright stars is due to heavy bias of the selection toward the most luminous stars. The analysis of optically selected hot UV-bright stars thus gives a wrong impression of the importance of the various evolutionary phases that contribute to the UV flux of old stellar populations. The lack of classic post-AGB stars among hot UV-bright stars in globular clusters may be understood from the different lifetimes; the lifetime of Schönberner’s post–early AGB track is about 10 times longer than his lowest mass post-AGB track.
Thus, even if only a small fraction of stars follow post–early AGB tracks, those stars may be more numerous than true post-AGB stars. Because of their relatively long lifetimes, post–early AGB stars are also unlikely to be observed as central stars of planetary nebulae (see above).

Theoretical simulations would be useful to determine whether the relative populations of post-AGB and post–early AGB stars can be accommodated using existing post-HB evolutionary tracks or if additional process (e.g., additional mass loss) are necessary. Possible discrepancies are indicated by Landsman et al. (1996), who find only four post-EHB stars in UIT observations of NGC 6752, whereas 11 would be expected.

5. WHITE DWARFS IN GLOBULAR CLUSTERS

White dwarfs are the final stage of all low-mass stars (such as those discussed so far), and globular clusters should thus contain lots of them. However, these stars managed to evade detection until recently photometric white dwarf sequences were discovered in four globular clusters by observations with HST (Paresce et al. 1995; Richer et al. 1995, 1997; Cool et al. 1996; Renzini et al. 1996; Zoccali et al. 2001). These sequences not only allow the verification of timescales for the evolution of low-mass stars but also offer an independent way to determine distances to globular clusters, as suggested by Renzini et al. (1996). The basic idea is to fit the white dwarf cooling sequence of a globular cluster to an appropriate empirical cooling sequence of local white dwarfs with well-determined trigonometric parallaxes. The procedure is analogous to the classical main-sequence fitting but has two main advantages: white dwarfs have—because of diffusion—very simple atmospheres that are either hydrogen-rich (DA) or helium-rich (DB/DO), independent of their original metallicity. Thus, one can avoid the problem of finding local calibrators with the same metallicities as the globular cluster stars. In addition, white dwarfs are locally much more abundant than metal-poor subdwarfs, thus enlarging the reference sample.
Photometric observations alone, however, are not sufficient to select the appropriate local calibrators: hydrogen-rich DA’s and helium-rich DB’s can in principle be distinguished by their photometric properties alone in the temperature range 10,000 K ≤ Teff ≤ 15,000 K (Bergeron, Wesemael, & Beaufour 1995). Renzini et al. (1996) classified two white dwarfs in NGC 6752 as DB’s by this method, and Richer et al. (1997) speculate that the brightest white dwarf in M4 (V = 22.08) might be a hot (27,000 K) DB star. However, without a spectral classification, those stars could also be high-mass DA white dwarfs, possibly a product of merging.

In addition, the location of the white dwarf cooling sequence is highly sensitive to the white dwarf mass. Renzini et al. (1996) argued that the white dwarf masses in globular clusters are constrained to the narrow range 0.51 M⊙ ≤ MWD ≤ 0.55 M⊙, but some systematic differences between clusters are obvious: At a given metallicity, some globular clusters (e.g., NGC 6752) possess very blue horizontal branches whose low-mass EHB stars evolve directly to low-mass C/O white dwarfs (bypassing the AGB) and shift the mean white dwarf mass closer to 0.51 M⊙. Other clusters show only red HB stars, which will evolve to the AGB and form preferably white dwarfs with masses of ≈0.55 M⊙. In addition, low-mass white dwarfs (M < 0.45 M⊙) with degenerate He cores (instead of the “normal” C/O core) are produced if the red giant branch evolution is terminated by binary interaction before the helium core exceeds the minimum mass for the onset of helium burning. Recently, Cool et al. (1998) found three faint UV-bright stars in NGC 6397, which they suggested could be helium-core white dwarfs (supported by Edmonds et al. 1999). Massive white dwarfs on the other hand may evolve from blue stragglers or result from collisions of white dwarf binaries with subsequent merging (e.g., Marsh, Dhillon, & Duck 1995). Salaris et al. (2001) discuss the effects of atmospheric composition and mass on the white dwarf distance determination of globular clusters in more detail.

Because of the faintness of these stars, their study by spectroscopic observations is still in its infancy, but first spectroscopic observations of the white dwarf candidates in NGC 6397 (Moehler et al. 2000a), NGC 6752, and M4 (Moehler et al. 2001) showed that all of them are hydrogen-rich DA white dwarfs. Follow-up spectroscopy at better signal-to-noise ratio should allow derivation of atmospheric parameters and thereby verify the distances to these globular clusters.

6. SUMMARY

This section provides a brief summary of the most important points discussed in this paper:

1. Abundances and rotational velocities of HB stars show a sharp change at temperatures of about 11,000–12,000 K, with the cooler stars displaying the expected cluster abundances and relatively high rotational velocities. The hotter stars show rather low rotational velocities and abundances best explained by diffusion.

2. Diffusion, especially radiative levitation of heavy elements, can most probably solve the problem of the low gravities found previously for HB stars between ≈11,500 and ≈20,500 K.

3. The faint gap along the BT at Mv ≈ 3 mag separates hot HB from EHB stars. The brighter gap at Mv ≈ 0.6–1.4 mag is probably caused by the onset of radiative levitation in the atmospheres of the HB stars. Noncanonical evolutionary scenarios are probably not necessary to explain these gaps or the results of spectroscopic analyses of hot HB/WT stars.

4. The physical parameters of cool BHB stars in metal-poor globular clusters agree with canonical evolutionary tracks but yield canonical masses preferably for the long distance scale.

5. Hot HB stars in metal-rich globular clusters form a rather inhomogeneous group that cannot be explained by one evolutionary scenario.

6. Hot UV-bright stars selected by far-UV observations show the theoretically expected distribution of evolutionary stages, contrary to optically selected hot UV-bright stars, which are biased toward luminous post-AGB stars. The considerable percentage of stars avoiding the thermally pulsing AGB might explain the lack of planetary nebulae in globular clusters.

7. White dwarfs in globular clusters so far have been verified to be hydrogen-rich DA white dwarfs.

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