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HOT HORIZONTAL-BRANCH STARS: THE UBIQUITOUS NATURE OF THE "JUMP" IN STRÖMGREN *u*, LOW GRAVITIES, AND THE ROLE OF RADIATIVE LEVITATION OF METALS[1,2]

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ABSTRACT

A "jump" in the blue horizontal-branch (HB) distribution in the (V, $u-y$) color-magnitude diagram has recently been detected in the globular cluster (GC) M13 (NGC 6205) by Grundahl and coworkers. Such an effect is morphologically best characterized as a discontinuity in the (u, $u-y$) locus, with stars in the range 11,500 K $\lesssim T_{\rm eff} \lesssim$ 20,000 K deviating systematically from (in the sense of appearing brighter and/or hotter than) canonical zero-age HB models. In this article, we present Strömgren u, y photometry of 14 GCs obtained with three different telescopes (ESO Danish, Nordic Optical Telescope, and the *Hubble Space Telescope*) and demonstrate that the jump in Strömgren u is present in every GC whose HB extends beyond $T_{\rm eff} \gtrsim$ 11,500 K, irrespective of metallicity, mixing history on the red giant branch (RGB), or any known parameter characterizing our sample of GCs. We thus suggest that the u jump is a ubiquitous feature, intrinsic to *all* HB stars hotter than $T_{\rm eff} \simeq$ 11,500 K. We draw a parallel between the ubiquitous nature of the u jump and the well-known problem of low measured gravities among blue HB stars in GCs and in the field. We note that the "gravity jump" occurs over the same temperature range as the u jump and also that it occurs in every metal-poor cluster for which gravities have been determined—again irrespective of metallicity, mixing history on the RGB, or any known parameter characterizing the surveyed GCs. Furthermore, we demonstrate that the u jump and the gravity jump are connected on a star-by-star basis. We thus suggest that the two most likely are different manifestations of one and the same physical phenomenon. We present an interpretative framework which may be capable of simultaneously accounting for both the u jump and the gravity jump. Reviewing spectroscopic data for several field blue HB stars, as well as two blue HB stars in NGC 6752, we find evidence that radiative levitation of elements heavier than carbon and nitrogen takes place at $T_{\rm eff} \gtrsim$ 11,500 K, *dramatically* enhancing the abundances of such heavy elements in the atmospheres of blue HB stars in the "critical" temperature region. We argue that model atmospheres which take diffusion effects into account are badly needed and will likely lead to better overall agreement between canonical evolutionary theory and the observations for these stars.

Subject headings: diffusion — stars: abundances — stars: atmospheres — stars: evolution — stars: horizontal-branch — stars: Population II

1. INTRODUCTION

Galactic globular clusters (GCs) are the oldest known objects for which accurate ages can be derived. For this reason, they play a major role in posing a lower limit to the age of the universe, thus constraining cosmological models (e.g., van den Bergh 1992; Bolte & Hogan 1995; VandenBerg, Bolte, & Stetson 1996; Chaboyer, Demarque, & Sarajedini 1996; Mould 1998) and scenarios for the early formation history of the Galaxy and its nearby companions (e.g., Eggen, Lynden-Bell, & Sandage 1962; Mironov & Samus 1974; Searle & Zinn 1978; Zinn 1980, 1993; Brocato et al. 1996; Buonanno et al. 1998).

From an observational point of view, for reliable GC ages to be determined it is extremely important that the Population II distance scale be accurately established (Renzini 1981)—a task which has thus far not been successfully accomplished, even with the advent of *Hipparcos* (e.g., Catelan 1998; Koen & Laney 1998; Carretta et al. 1999a). From a theoretical point of view, it is crucial that the color-magnitude diagrams (CMDs) of GCs be accurately reproduced by theoretical isochrones and synthetic CMDs, so that the stellar structure and evolution models, as well as the model atmospheres used to transfer the predicted log L and $T_{\rm eff}$-values into observed magnitudes and colors, can be relied on for ages to be determined from the observations (e.g., VandenBerg et al. 1996; Salaris, Degl'Innocenti, & Weiss 1997; VandenBerg & Irwin 1997; Cassisi et al. 1999; VandenBerg 1999).

Of primary interest for these purposes are the main-sequence (MS) and horizontal-branch (HB) evolutionary phases. More specifically, both the MS turnoff luminosity and the HB morphology are sensitive to age, with the former being the standard clock for GC age determination

[1] Based on observations made with the NOT, operated on the island of La Palma jointly by Denmark, Finland, Iceland, Norway, and Sweden, in the Spanish Observatorio del Roque de los Muchachos of the Instituto de Astrofisica de Canarias.

[2] Based on observations obtained with the Danish 1.5 m telescope at the European Southern Observatory, La Silla, Chile.

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(Iben & Renzini 1984). The horizontal part of the HB in the (V, $B-V$)-plane, covering the RR Lyrae instability strip, most of the red HB, and part of the blue HB [$(B-V)_0 \gtrsim 0.1$ mag], is the primary Population II "standard candle" (e.g., Gratton 1998). Although still quite uncertain as an age derivation method, HB morphology in external galaxies is increasingly being used to place constraints on their ages and star formation histories (e.g., Da Costa et al. 1996; Geisler et al. 1998). This highlights the importance of adequately interpreting the physical properties of HB stars in Galactic GCs and in the field.

This notwithstanding, there are several long-standing open problems in the interpretation of observed HBs which have yet to find widely accepted explanations. Among these, we may quote the following:

1. The "Oosterhoff-Arp-Sandage period-shift effect," which affects the pulsation properties of RR Lyrae variables (Oosterhoff 1939; Arp 1955; Sandage 1981). For recent discussions, see, for instance, Smith (1995), Caputo (1998), Catelan, Sweigart, & Borissova (1998), Clement & Shelton (1999), De Santis & Cassisi (1999), Layden et al. (1999), and Sweigart (1997a, 1997b).
2. The "second parameter phenomenon"; besides metallicity [Fe/H] (the "first parameter"; Sandage & Wallerstein 1960), there must be *at least* one additional parameter determining HB morphology (Sandage & Wildey 1967; van den Bergh 1967). For recent discussions, see, e.g., Chaboyer et al. (1996), Stetson, VandenBerg, & Bolte (1996), Buonanno et al. (1997, 1998), Kraft et al. (1998), Sweigart (1997a, 1997b), and Sweigart & Catelan (1998).
3. HB "bimodality" (Harris 1974) and "gaps" (Newell 1973; Lee & Cannon 1980). For recent discussions, see Catelan et al. (1998), Ferraro et al. (1998), Caloi (1999), and Piotto et al. (1999).
4. The origin and nature of blue subdwarf (sdB) stars in the field (Greenstein 1971) and in GCs (Caloi et al. 1986; Heber et al. 1986). Blue subdwarfs are often called "extreme" (or "extended") HB (EHB) stars (Greenstein & Sargent 1974). Following original suggestions by Caloi (1989) and Greggio & Renzini (1990), these stars and their progeny are now widely believed (e.g., Jørgensen & Thejll 1993; Bressan, Chiosi, & Fagotto 1994; Dorman, O'Connell, & Rood 1995; Yi, Demarque, & Oemler 1998) to be the main contributors to the ultraviolet light emanating from elliptical galaxies and the bulges of spirals that are commonly referred to as the "UV-upturn phenomenon" (Code 1969). For recent discussions on the origin and evolution of EHB stars, see D'Cruz et al. (1996), Rood, Whitney, & D'Cruz (1997), and Sweigart (1997b).
5. Unexpectedly low surface gravities, as inferred from fitting Balmer line profiles for both field (Saffer et al. 1994, 1997; Mitchell et al. 1998) and GC (Crocker, Rood, & O'Connell 1988; de Boer, Schmidt, & Heber 1995; Moehler, Heber, & de Boer 1995; Moehler, Heber, & Rupprecht 1997; Bragaglia et al. 1997) blue HB (BHB) stars.
6. The anomalous "jump" in the (V, $u-y$) CMD at the BHB region, recently detected by Grundahl, VandenBerg, & Andersen (1998) in their study of the Galactic GC M13 (NGC 6205).

The above problems are probably somewhat intertwined and remain essentially open. It is thus clear that much needs to be accomplished for a comprehensive understanding of the physical properties of HB stars to be achieved. Unless this is properly done, it will remain dubious whether such stars can be reliably employed to determine distances and ages and hence to constrain cosmology and models for the formation history of galaxies.

Our goal, in the present article, is to address the last two issues listed above: the low log g values measured for BHB stars and the Grundahl et al. (1998) "jump." We shall demonstrate the following:

1. The u jump is a ubiquitous feature, likely present in every single metal-poor GC which hosts HB stars with $T_{\rm eff} \gtrsim 11{,}500$ K.
2. The u jump and the similar feature present in log g, log $T_{\rm eff}$ diagrams are probably different manifestations of the same physical phenomenon and intrinsic to all BHB stars, whether in the field or in GCs.
3. The physical reason for the occurrence of the jumps in u and log g is most likely radiative levitation of elements heavier than carbon and nitrogen into the stellar atmosphere, rather than a stellar interior/evolution effect.

In § 2 we describe the observations, using three different telescopes, which have led to the compilation of our large database of CMDs in the Strömgren system. Our adopted data reduction procedures are also described in § 2. In § 3 we demonstrate that the jump in u is a ubiquitous feature, occurring in all studied GCs at essentially the same location in $T_{\rm eff}$, irrespective of any parameters characterizing the globulars; in § 4 we demonstrate that there is a strong correlation between the jump in u and the low gravities found among BHB stars in GCs and the field; in § 5 we address what constraints these conclusions impose on noncanonical models which have been proposed to account for the gravity anomalies; in § 6 we point out that radiative levitation of elements heavier than carbon and nitrogen is well documented among both field and GC BHB stars lying in the "critical" $T_{\rm eff}$ range where the jump takes place and argue that model atmospheres with dramatically enhanced abundances of such heavy elements (as observed) may be able to explain the failure of canonical models to reproduce both the bright u magnitudes and the low measured gravities. Finally, in § 7 we provide a summary of our results. Some consequences of our proposed scenario are also laid out, as are our concluding remarks.

2. OBSERVATIONS AND DATA REDUCTION

The observations reported in this work have been collected from the Nordic Optical Telescope (NOT), the Danish 1.54 m telescope on La Silla, and the *Hubble Space Telescope* (*HST*) archive (M13). The ground-based data were obtained in the Strömgren u and y filters, whereas the *HST* observations made use of their close WFPC2 analogs, the F336W and F555W filters, respectively.

Data from NOT were collected during observing runs in 1995, 1997, and 1998. Stars from the lists of Olsen (1983, 1984) and Schuster & Nissen (1988) were observed on two nights in 1995 and four nights in 1998 under photometric conditions to derive the transformation between the instrumental magnitudes and the standard system. The data for M13 have been described by Grundahl et al. (1998). For M3 (NGC 5272), M5 (NGC 5904), M12 (NGC 6218), M15 (NGC 7078), M56 (NGC 6779), and M92 (NGC 6341), the data were obtained using a thinned AR-coated 2048 × 2048 pixel CCD camera, with 0".11 pixel size, thus covering approximately 3'.75 on a side. Most of the observations were obtained using tip/tilt correction (the HiRAC camera), and the FWHM of nearly all our images ranged between 0''.45 and 1''.0. There was no significant variation of the point-spread function (PSF) over the field of view. In M3 and M92 we observed two overlapping fields, with one field centered on the cluster center to ensure a large sample of HB and red giant branch (RGB) stars. For M12 and M56 our fields were centered on the cluster center. The data for M5, M12, M15, and M56 were obtained under non-photometric conditions and were consequently not calibrated.

The data from the Danish 1.54 m telescope were collected during two observing runs in May and October of 1997. For both runs we used the Danish Faint Object Spectrograph and Camera equipped with a thinned, AR-coated 2048×2048 pixel CCD camera. The field covered was approximately 11' in diameter. During the October observing run data were collected for NGC 288, NGC 1851, M2 (NGC 7089), M79 (NGC 1904), and NGC 6752, all of which were observed on several photometric nights; approximately 150 different standard stars again from the lists of Olsen (1983, 1984) and Schuster & Nissen (1988) were also observed. The data for NGC 6397 and M30 (NGC 7099) were collected during the observing run in 1997 May, and only a small fraction of these are used for this paper. The data for these two clusters have not yet been calibrated. For all the observations the seeing ranged between 1''.3 and 2''.2. As most of the stars used as standard stars were rather bright ($V = 8$–10 mag), the telescopes (NOT and the Danish 1.54 m) were defocused during these observations in order to avoid saturating the CCD.

All photometric reductions of the cluster frames were done using the suite of programs developed by P. B. S.: DAOPHOT, ALLSTAR, ALLFRAME, and DAOGROW (see Stetson 1987, 1990, 1994). Flat fields were obtained on each night during evening and morning twilight. Photometry for the defocused standard stars was derived using large-aperture photometry. Based on the frame-to-frame scatter for the bright stars in the clusters with calibrated photometry, we estimate that the errors in the photometric zero points are below 0.02 mag for the observations from NOT and less than 0.03 mag for the data from ESO. The larger errors for the ESO data are due to the poorer seeing encountered during the observations, which makes the estimation of the aperture corrections in crowded fields more uncertain. Of the clusters studied, M2, M3, M13, M79, M92, NGC 288, NGC 1851, and NGC 6752 have data from photometric nights.

The *HST* data for M13 were retrieved from the Canadian Astronomical Data Center (CADC) in Victoria and reduced with DAOPHOT, ALLSTAR, and ALLFRAME. We have not calibrated these data since our purpose with their inclusion in this work was to check whether or not the *u*-band jump was present. The reductions followed the standard reduction procedures used by team members for stellar photometry with *HST* (see, e.g., Stetson et al. 1998, 1999).

3. THE UBIQUITOUS NATURE OF THE JUMP IN STRÖMGREN *u*

3.1. *The u Jump as a Ubiquitous Feature*

The jump in Strömgren *u* was first detected very recently by Grundahl et al. (1998) in their photometric study of M13. As an explanation for the effect, Grundahl et al. tentatively suggested that "helium-mixing" models (see § 5 below) might account for their observations.

During the reduction of Strömgren data from other observing runs, it was found that the *u* jump was present in all clusters with a sufficiently blue HB. Given the potentially dramatic implications that mixing of helium into the envelopes of HB stars would have on the Population II distance scale and GC ages, we decided to undertake a comprehensive and systematic study of CMDs for all our observed GCs. Here we restrict our discussion to the *u* and *y* bandpasses, since we have found that the jump detected by Grundahl et al. (1998) is definitely most pronounced when the $(u, u-y)$-plane is employed.[11]

Table 1 shows the GC data set employed in this paper. In column (1) the cluster NGC number is given, as provided in The New General Catalogue of Nebulae and Clusters of Stars; in column (2) the cluster name in Messier's catalog is shown. The cluster metallicity [Fe/H], reddening $E(B-V)$, core concentration c, log of the central density ρ_c (in $L_\odot$ pc^{-3}), and Galactocentric distance $R_{\rm GC}$ (in kpc) are given in columns (3)–(7) (data from Harris 1996). The telescope employed for the observations is given in column (8). In columns (9), (10), (11), and (12), $\mathscr{X}^{\rm jump}$, $(u-y)_0^{\rm jump}$, $T_{\rm eff}^{\rm jump}$, and mass location $M^{\rm jump}$ (in mag units, degrees Kelvin, and $M_\odot$, respectively) of the low-temperature "cutoff" of the jump in Strömgren *u*, estimated as described in § 3.2, are given. In column (13) information about the presence of a corresponding "gravity jump" is supplied (question marks indicate clusters whose blue HBs have not been surveyed for log g values as of this writing). Finally, an estimate of the degree of mixing among cluster RGB stars is provided in column (14), based on the spectroscopic data from the references quoted in the final column. Again, question marks indicate clusters for which data are either not available or insufficient to reach any conclusion. In several cases, it is clear that (further) spectroscopic studies would be very helpful. Note also that we have added M80 (NGC 6093) to our sample, since the photometry by Ferraro et al. (1998, their Fig. 5) clearly illustrates that in the F336W and F555W filters this cluster has an HB morphology very similar to M13's. Thus we claim that this cluster shows the jump as well.

Figure 1 shows a mosaic plot with the $(u, u-y)$ CMDs for the 14 GCs in the present sample (M13 is shown twice, the data from the *HST* being plotted separately from the NOT data). The CMDs are plotted in order of decreasing [Fe/H], following the entries provided by Harris (1996). The Messier or NGC number of the cluster is given in each panel, along with the corresponding [Fe/H] value and the telescope employed to obtain the displayed data—where "ESO" stands for the Danish 1.54 m, "NOT" for the Nordic Optical Telescope, and "*HST*" for the *Hubble Space Telescope.* Zero-age HB (ZAHB) models kindly provided by VandenBerg et al. (1999), as transformed to the Strömgren system using Kurucz (1992) color-temperature relations, are also shown in each panel; these take into account the α-element enhancement observed for most metal-poor GCs (e.g., Carney 1996).

In order to fit the ZAHB models to the observations we adopted the reddenings given in Table 1 (mostly from

[11] We suspect from our observations that the effects of the *u* jump may also be present in the other Strömgren filters, although to a much smaller extent.

TABLE 1

SAMPLE OF GCs AND JUMP PARAMETERS

NGC (1)	Messier (2)	[Fe/H]	$E(B-V)$ (3)	c (4)	$\log \rho_c$ (5)	R_{GC} (6)	Telescope (7)	$\mathscr{X}^{jump}$ (8)	$(u-y)_0^{jump}$ (9)	$\log T_{eff}^{jump}$ (10)	M^{jump} (11)	g-Jump? (12)	Mixing (13)	References (Mixing) (14)
288	...	−1.24	0.03	0.96	1.84	11.4	ESO	0.70 ± 0.04	0.98 ± 0.05	4.07 ± 0.01	0.57	Yes	M[a]	1, 2, 3, 4, 5, 6, 7, 8, 9
1851		−1.26	0.02	2.24	5.17	16.8	ESO	0.73 ± 0.04	1.00 ± 0.05	4.06 ± 0.01	0.57	?	?	...
5904	M5	−1.33	0.03	1.87	3.94	6.1	NOT	0.74 ± 0.06	...	...	...	Yes	M	10, 11, 12, 13, 14, 15
6218	M12	−1.48	0.17	1.38	3.27	4.6	NOT	0.73 ± 0.07	...	...	...	?	?	...
1904	M79	−1.54	0.01	1.72	4.01	18.5	ESO	0.71 ± 0.04	0.99 ± 0.05	4.06 ± 0.01	0.59	Yes[b]	?	...
6205	M13	−1.56	0.02	1.49	3.32	8.3	NOT	0.69 ± 0.03	0.98 ± 0.05	4.07 ± 0.01	0.58	Yes[c]	E	10, 13, 14, 16, 17,
							HST	...	...	...	...			18, 19, 20, 21, 22, 23
5272	M3	−1.57	0.01	1.85	3.56	11.9	NOT	0.89 ± 0.06	1.16 ± 0.05	4.03 ± 0.01	0.60	Yes	M	10, 19, 24
6752		−1.61	0.05	CC[d]	4.92	5.3	ESO	0.80 ± 0.04	1.08 ± 0.05	4.05 ± 0.01	0.60	Yes	E	6, 25, 26, 27, 28
6093	M80	−1.62	0.18	1.95	4.82	3.1	*HST*	...	...	...	...	?	?	...
7089	M2	−1.62	0.05	1.80	3.89	10.3	ESO	0.69 ± 0.05	0.98 ± 0.05	4.06 ± 0.01	0.59	?	?	...
6397		−1.91	0.18	CC	5.69	6.0	ESO	0.92 ± 0.05	...	...	...	Yes	M/E	3, 4, 29, 30
6779	M56	−1.94	0.20	1.37	3.27	9.5	NOT	0.92 ± 0.10	...	...	...	?	?	...
7099	M30	−2.12	0.03	1.38	3.27	4.6	ESO	0.84 ± 0.05	...	...	...	?	?	...
7078	M15	−2.22	0.09	CC	5.37	10.3	NOT	...	...	...	...	Yes	E	31
6341	M92	−2.33	0.02	1.81	4.30	9.5	NOT	0.87 ± 0.05	1.14 ± 0.05	4.02 ± 0.01	0.66	Yes	E	13, 14, 29, 32

[a] E = extensive and M = moderate.

[b] Inferred from Bragaglia et al. 1997; however, a single star (out of seven in their sample) is clearly found inside the jump region.

[c] Inferred from our own Hβ photometry. Details will be published elsewhere.

[d] CC = core-collapsed.

REFERENCES.—(1) Pilachowski & Sneden 1983; (2) Gratton 1987; (3) Caldwell & Dickens 1988; (4) Bell 1991; (5) Dickens et al. 1991; (6) Croke 1993; (7) Croke et al. 1999; (8) Shetrone 1998a; (9) M. D. Shetrone 1999, private communication; (10) Pilachowski, Wallerstein, & Leep 1980; (11) Sneden et al. 1991; (12) Shetrone 1996a; (13) Shetrone 1996b; (14) Shetrone 1996c; (15) Smith et al. 1997; (16) Hatzes 1987; (17) Wallerstein, Leep, & Oke 1987; (18) Brown, Wallerstein, & Oke 1991; (19) Kraft et al. 1992; (20) Kraft et al. 1993; (21) Kraft et al. 1997; (22) Pilachowski et al. 1996; (23) Klochkova & Mishenina 1998; (24) Kraft et al. 1995; (25) Cottrell & Da Costa 1981; (26) Bell, Hesser, & Cannon 1984; (27) Suntzeff & Smith 1991; (28) Shetrone 1998b; (29) Bell, Dickens, & Gustafsson 1979; (30) Bell, Briley, & Norris 1992; (31) Sneden et al. 1997; (32) Pilachowski 1988.

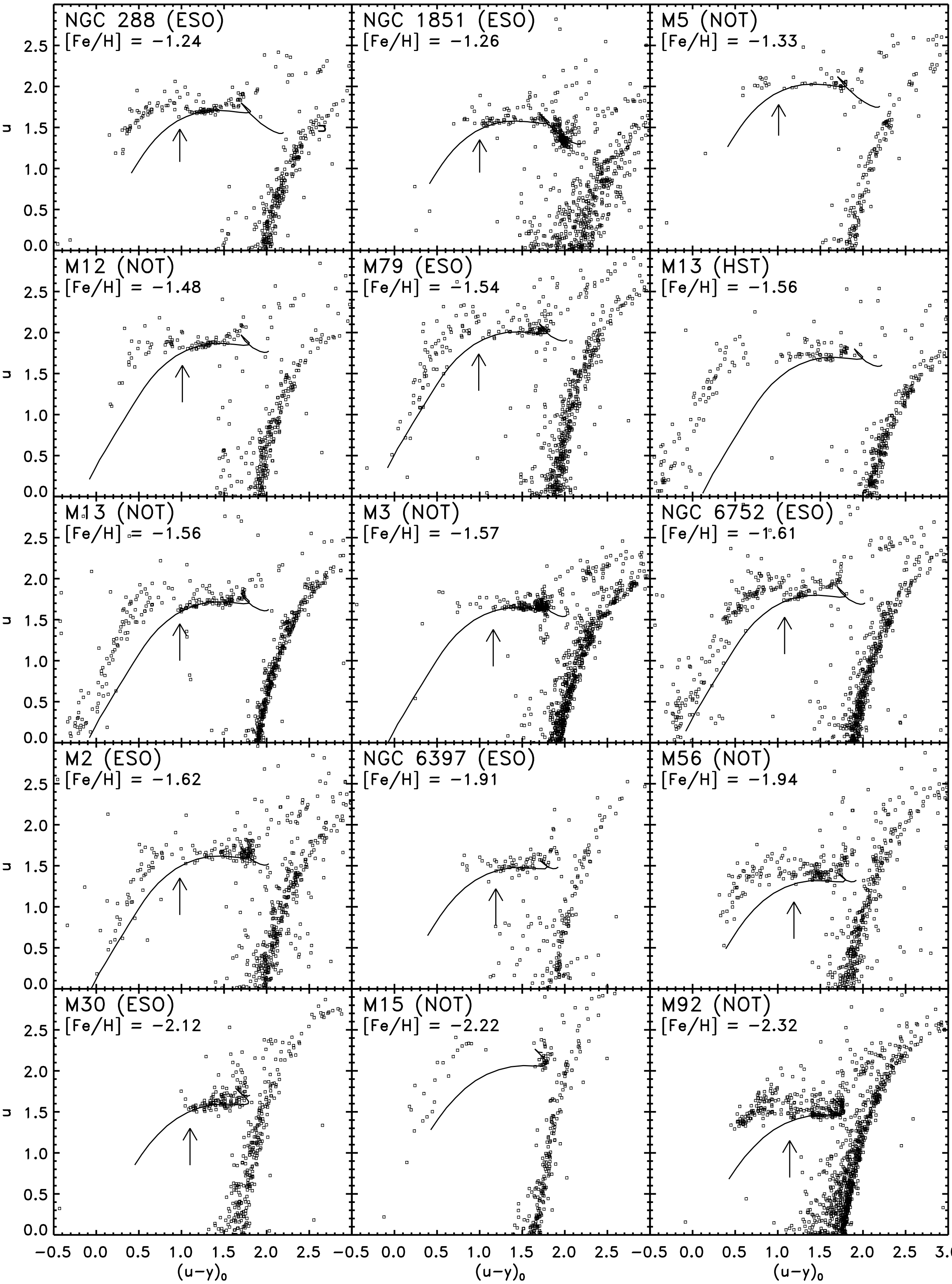

FIG. 1.—Mosaic plot showing the (u, $u-y$) CMDs of 14 Galactic GCs around the HB region. The cluster names, [Fe/H] values, and an acronym describing the telescope utilized to obtain the corresponding data are shown in each panel, at the upper left-hand corner. The clusters are presented in order of decreasing metallicity from the upper left to the bottom right. The telescope acronyms are as follows. ESO: Danish 1.54 m (Chile); NOT: Nordic Optical Telescope (Canary Islands, Spain); *HST*: *Hubble Space Telescope.* Canonical ZAHB models (from VandenBerg et al. 1999) for the appropriate metallicities are plotted. The required shifts have been applied to account for the reddening and distance modulus of each GC, enforcing satisfactory matches between the data and models at the red end of the distributions. Note that for convenience we have allowed the zero point on the luminosity axis to "float." Note also that a "jump" at intermediate $u-y$ colors is present in all GCs, and that its onset, indicated by vertical arrows, appears to occur at approximately the same color for them all, irrespective of [Fe/H]. See text for more details. The "glitch" in the ZAHB near $u-y = 1.6$ mag arises because $u-y$ is not a monotonic function of temperature coolward of the Balmer maximum at $T_{\rm eff} \sim 9000$ K.

Harris 1996), and the models were then shifted in luminosity until they matched the lower locus of the HB stars cooler than the jump. For the clusters with data obtained on non-photometric nights we have made an effort to adequately fit the red end of the HB star distributions; the ZAHB fits for clusters with calibrated photometry were used as guidance. Thus we have not made use of the reddening values reported in Table 1 for these clusters.

Important conclusions can be immediately drawn from an inspection of Figure 1:

1. The jump in u is a ubiquitous feature, present in every GC studied which has a sufficiently hot HB. (Note that the hottest BHB stars in M30 lie close to the limiting temperature for the occurrence of the jump.) Therefore, the effect is by no means restricted to the case of M13, originally investigated by Grundahl et al. (1998). Such a jump is morphologically best described as a systematic deviation, in u magnitudes and/or $u-y$ colors, with respect to the expectations of canonical ZAHB models, in the sense that the observations appear brighter and/or hotter than the theoretical predictions.
2. As found by Grundahl et al. in the case of M13, the jump occurs at intermediate temperatures only.
3. The occurrence of the jump does not depend on metallicity within the metallicity range of the clusters studied here.
4. Both clusters with *short* blue tails (e.g., M5,[12] NGC 288) and clusters with *extended* blue tails (e.g., M13, NGC 6752) show the u jump, which is thus HB morphology independent, as long as sufficiently hot BHB stars are present in any given GC.
5. The color $(u-y)_0^{\rm jump}$ appears to change little from cluster to cluster, even when the [Fe/H] values are quite different.

The occurrence of the jump is most decidedly not a spurious consequence of the telescope and/or instrumentation used, since it is independently seen with data obtained using four filter/detector combinations. We also point out that the jump is evident in all instrumental CMDs as well, thus ruling out any problems arising from the adopted data reduction or calibration procedures (§ 2) as a "cause" for the occurrence of the u jump.

More detailed information can be obtained from the entries in Table 1. Before discussing it in depth (§ 3.3), we first describe our procedure to determine the "jump parameters" $\mathscr{X}^{\rm jump}$, $(u-y)_0^{\rm jump}$, $T_{\rm eff}^{\rm jump}$, and $M^{\rm jump}$.

3.2. *Determining the Low-Temperature "Cutoff" and the "Size" of the Jump*

In order to measure the color $(u-y)_0^{\rm jump}$ which defines the onset of the jump at its "cool" end and estimate the size of the jump, we have decided to adopt the $\mathscr{X}$ and $\mathscr{Y}$ coordinates described by Crocker et al. (1988) and Rood & Crocker (1989). As can be seen from Figure 1 in Crocker et al., $\mathscr{Y}$ is indeed "tailor made" for measuring the departure of HB star distributions from theoretical ZAHBs as seen in our CMDs (Fig. 1), especially since, as already noted, the jump is best described as a systematic deviation in u magnitudes and/or $u-y$ colors with respect to the canonical ZAHBs.

Specifically, for each HB star we measured its projected distance from the ZAHB ($\mathscr{Y}$) as well as the "path length" ($\mathscr{X}$) along the theoretical ZAHB for the appropriate metallicity. The zero point for $\mathscr{X}$ was arbitrarily set at $(u-y)_0 = 0.5$ mag. In Figure 2, $\mathscr{X}$ and $\mathscr{Y}$ are plotted for all the clusters. $\mathscr{X}$ increases with increasing $u-y$, and $\mathscr{Y}$ is positive for stars lying at luminosities higher than the theoretical ZAHB model; both quantities are measured in magnitudes. Since the ZAHB models have been fitted to the HB stars cooler than the jump, these stars will have $\mathscr{Y}$-values close to zero. Dashed horizontal lines are added to locate the $\mathscr{Y} = 0.0$ and $\mathscr{Y} = 0.25$ loci. The latter value corresponds to our estimate of the change in $\mathscr{Y}$ (or "jump size") for M13, as can be seen by inspection of the middle left-hand panel in Figure 2. We have not calculated $\mathscr{X}$ and $\mathscr{Y}$ for the *HST* data set, as we do not have the models transformed to the appropriate colors and magnitudes. The ZAHB overplotted in the *HST* CMD for M13 refers to the u, y system, and not to the WFPC2 filters, and is only intended to guide the eye.

Note that our ZAHB models do not extend to very small envelope masses, implying that $\mathscr{X}$ (and hence $\mathscr{Y}$) for the hottest HB stars cannot be directly estimated on their basis. We have therefore extended the ZAHB locus, extrapolating it and adding (by hand) an extra point in our (u, $u-y$) ZAHB sequences so that these stars could be included. Similarly, the detailed morphology of the ZAHB tracks for the coolest HB stars leads to some ambiguity in the measurement of $\mathscr{Y}$ for these stars. We have thus excluded these stars from Figure 2. We emphasize that our adopted procedure to deal with the hottest/coolest BHB stars has *no* effect on the conclusions of this paper.

For all the clusters (Fig. 2)—except M15, for which there is a lack of stars—it is easy to determine the $\mathscr{X}$-location of the jump, which we simply estimate by eye. In order to assess the error in $\mathscr{X}^{\rm jump}$, we estimated by eye the minimum and maximum "tolerable" values of $\mathscr{X}^{\rm jump}$ for each cluster and adopted half the distance between these two points as our error. Since $\mathscr{X}$ is measured along the theoretical ZAHB, it has a one-to-one relationship with $(u-y)_0$; we then proceeded to calculate $(u-y)_0^{\rm jump}$ from the $\mathscr{X}$-location of the jump. An error of 0.01 mag in $u-y$ at the color of the jump corresponds to an error of approximately 56 K in temperature. The $(u-y)_0^{\rm jump}$ colors thus determined can be found in Table 1, along with the estimated errors.[13]

Having determined such colors, we evaluated the corresponding temperature $T_{\rm eff}^{\rm jump}$- and mass $M^{\rm jump}$-values characterizing the canonical ZAHB models for the metallicity of the adopted ZAHB model by cubic spline interpolation in $(u-y)_0$. These quantities are also given in Table 1 and will be discussed in § 3.3 below. Combining the error in $(u-y)_0^{\rm jump}$ with the expected photometric zero-point errors, we estimate that the typical errors in $T_{\rm eff}^{\rm jump}$ and $M^{\rm jump}$ are 300 K (smaller for M13 and NGC 6752) and 0.01 $M_\odot$, respectively. Note that our error estimates ignore any potential errors in the models, as well as uncertainties in the adopted reddening values and cluster-to-cluster differences

[12] The jump in M5 has also been detected by Markov & Spassova (1999) using broadband (U) photometry.

[13] We also estimated $(u-y)_0^{\rm jump}$ directly from the (u, $u-y$) CMDs presented in Figure 1. In all cases the agreement was better than 0.03 mag, which is within the errors in the determination of the jump location (see Table 1).

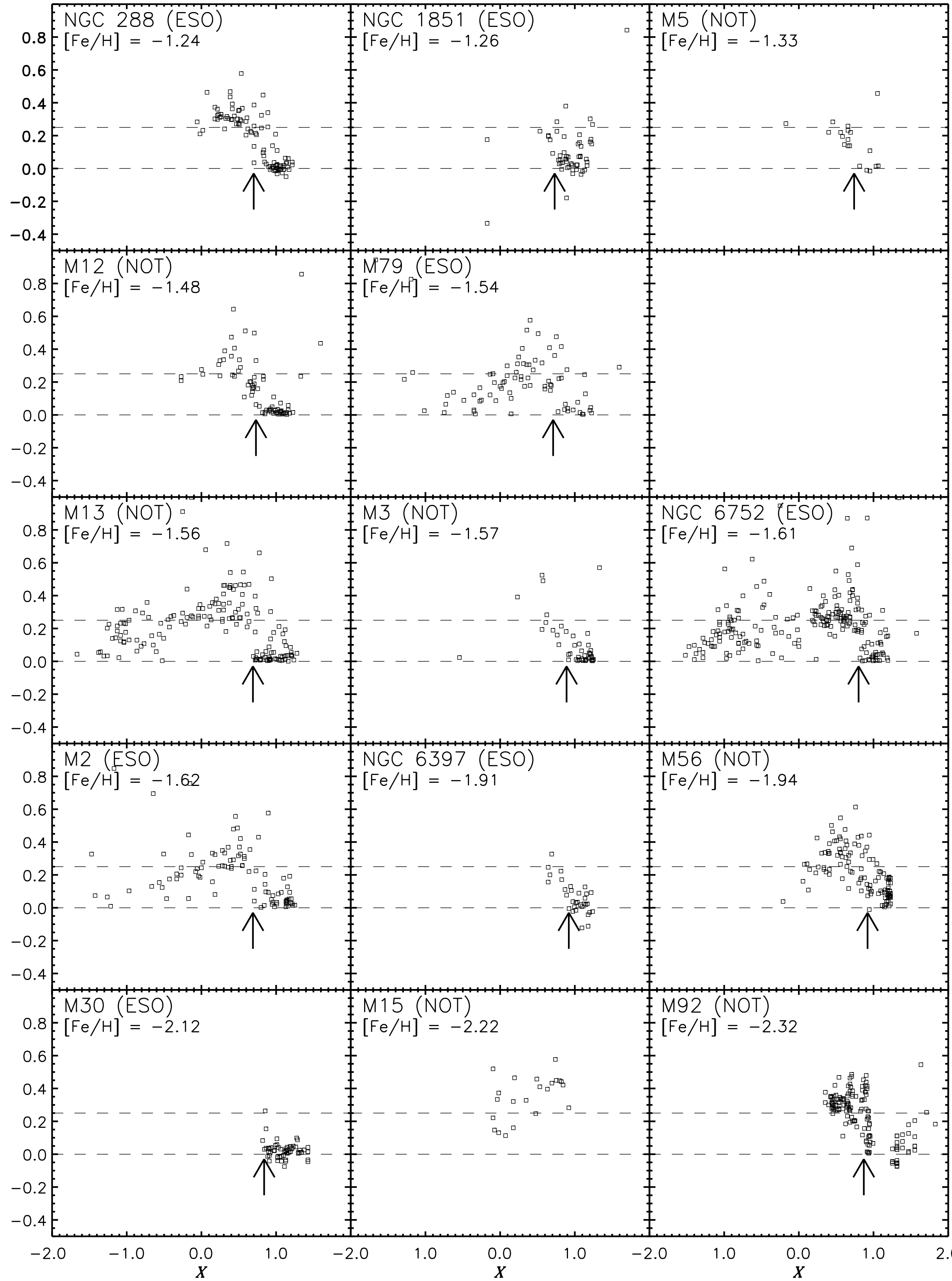

FIG. 2.—Mosaic plot showing our measured values for $\mathscr{X}$ and $\mathscr{Y}$ (§ 3.2) for each of the clusters in our sample. The vertical arrows indicate our measured position of the jump, and the dashed lines correspond to $\mathscr{Y} = 0.0$ and $\mathscr{Y} = 0.25$. Note that the reddest HB stars have been omitted from the plot (see § 3.2).

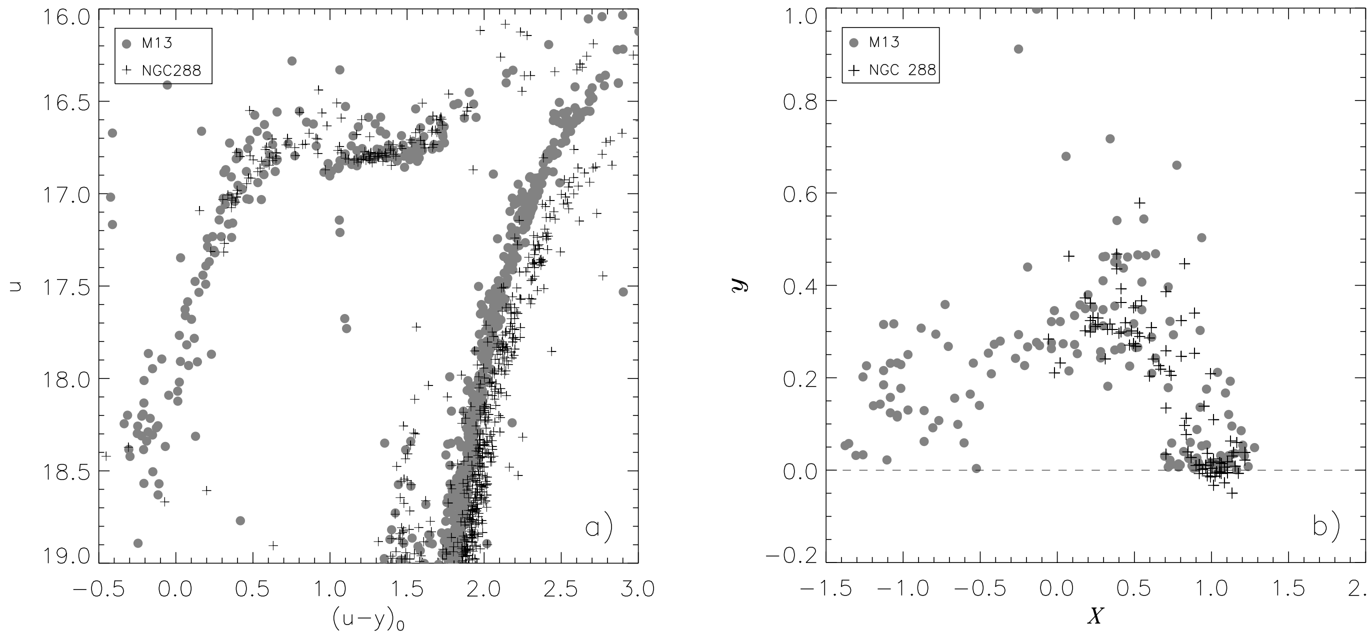

FIG. 3.—(*a*) Comparison between the M13 and NGC 288 (u, $u-y$) CMDs, utilizing the calibrated data for these clusters as described in the text. The square symbols (*gray*) and plus signs (*black*) are used for M13 and NGC 288 stars, respectively. Note the metallicity effect on the RGB color and shape: for M13, [Fe/H] $= -1.56$; for NGC 288, [Fe/H] $= -1.24$ (Harris 1996). Most importantly, the plot clearly illustrates that both the $(u-y)_0^{\rm jump}$ color and the jump size are essentially the same for the two globulars, notwithstanding the fact that bright M13 RGB stars have definitely undergone very extensive deep mixing, unlike the case in NGC 288 (see Table 1). It thus follows that neither metallicity nor the mixing history on the RGB can be responsible for the ubiquitous nature of the jump among Galactic GCs (Fig. 1). (*b*) Comparison between M13 and NGC 288 in the ($\mathscr{X}$, $\mathscr{Y}$)-plane. The symbols have the same meaning as in panel *a*.

in sample size; these may appear as an additional source of random scatter among the various clusters.

3.3. *The u Jump: A Detailed Empirical Description*

Table 1 provides detailed quantitative information on the nature of the u jump in our set of GCs, as well as some of the most relevant physical parameters characterizing the latter. The most important implications from this table include the following:

1. Remarkably, the onset of the u jump occurs at a color $(u-y)_0^{\rm jump}$ which is essentially the same (within the errors) for every GC in our sample (except possibly for M3 and M92), irrespective of metallicity, central density, concentration, or mixing history on the RGB.[14]
2. Because of the low dependence of the color-temperature transformations on metallicity, it also follows from the above that the temperature $T_{\rm eff}^{\rm jump}$ is also essentially the same for all GCs in our sample, irrespective of metallicity, central density, concentration, or mixing history on the RGB.
3. Unlike $T_{\rm eff}^{\rm jump}$, the mass cutoff $M^{\rm jump}$ is found to depend on metallicity, increasing with decreasing [Fe/H] at a rate $dM^{\rm jump}/d{\rm [Fe/H]} \approx -0.09\ M_\odot\ {\rm dex}^{-1}$. Such a mass variation (at an essentially constant temperature) can be ascribed to the behavior of the canonical ZAHB models as a function of metallicity.
4. It thus follows that $T_{\rm eff}^{\rm jump}$ is the fundamental quantity characterizing the onset of the u jump, rather than the mass at that point.
5. The size of the u jump is also remarkably constant among our sample of GCs, as is evident from inspection of Figure 2.
6. No metal-poor GC is known which does not show a log g jump. Therefore, this too seems to be a ubiquitous phenomenon. However, while every GC with a log g jump also shows a u jump, the converse cannot yet be stated with certainty, given that gravities have not yet been measured for an extensive sample of GCs.
7. Importantly, the presence of a log g jump, like that of a u jump, seems to be completely uncorrelated with any physical parameter of the GCs, including the metallicity. From Figure 9 of Moehler et al. (1995), one can also see that the boundaries of the log g jump region do not vary as a function of metallicity. Remarkably, the occurrence of the log g jump also does not seem to depend on the mixing history of the GC stars during the RGB phase.
8. The presence of the u jump does not depend on the GC dynamics. In our sample we have loose GCs (M12, M30, NGC 288) showing u jumps which are extremely similar to those found in much more concentrated GCs (M80, NGC 1851). The phenomenon also extends to the realm of core-collapsed GCs with extremely high central densities (M15, NGC 6397, NGC 6752). Again, the same can be said about the log g jump.
9. The jump phenomenon—whether u or log g—does not appear to depend on the distance from the center of the Galaxy. However, since we do not have bulge, disk, or outer-halo GCs in our sample, we cannot give support to the more general conclusion that the jump phenomenon

[14] Because we only have one calibrated GC with [Fe/H] < -1.65 (M92), we caution that a small metallicity dependence of $(u-y)_0^{\rm jump}$ could be present. More data for metal-poor GCs are needed to settle this issue. We stress, however, that *if* present such a relation amounts to a change of only ~ 1000 K between [Fe/H] $= -1.3$ and [Fe/H] $= -2.3$.

does not depend on the stellar population to which the cluster belongs: bulge, disk, inner halo, or outer halo.

Figures 3*a* [$(u, u-y)$ plane] and 3*b* [$(\mathscr{X}, \mathscr{Y})$-plane] show a direct comparison between our calibrated CMDs for M13 (*circles*) and NGC 288 (*plus signs*). This figure shows that, notwithstanding the different metallicities and mixing histories on the RGB (see Table 1), M13 and NGC 288 present remarkably similar jump location, size, and overall morphology.

3.4. *On the Hot End of the Jump*

In several of the observed clusters it is evident (Figs. 1 and 2) that stars on the hot side of the jump region again approach the canonical ZAHB, as is particularly evident for M13—in which case we estimate a temperature of $T_{\rm eff} \sim$ 20,000 K for the end of the jump region. The data presented here for the other clusters with extremely long blue tails (M2, M79, and NGC 6752) appear to show that the temperature at which stars again approach the ZAHB varies. For these three the data were obtained at ESO for the central regions in seeing which was significantly poorer than for the M13 observations. Consequently, we cannot at present decide whether the apparent differences for the location of the hot end of the jump are significant or due to the effects of poor seeing and crowding. Only observations obtained under better seeing conditions can decide this issue.

4. THE CONNECTION BETWEEN THE JUMP IN STRÖMGREN *u* AND LOW BLUE HB GRAVITIES

Analysis of Table 1, as we have seen above, already hints that there may be a connection between the *u* jump and the log *g* jump. We shall now submit this preliminary conclusion to a more detailed investigation.

Figure 4 shows a star-by-star comparison between stars which are located inside the *u* jump region, on the one hand, and the log *g* jump region, on the other hand, for NGC 288 and NGC 6752 (the two clusters in our sample with the largest number of spectroscopic determinations of log *g* and log $T_{\rm eff}$). Gravities and temperatures were obtained by Crocker et al. (1988) and S. Moehler (1999, private communication) in the cases of NGC 288 and NGC 6752, respectively. As can be seen from this figure, stars located in the *u* jump region (*circles*) are univocally located inside the log *g* jump region as well. Therefore, it is clear that the two effects—the *u* jump and the log *g* jump—are connected on a star-by-star basis.

This result is also evident from an analysis of Figure 5. This plot shows the log *g*, log $T_{\rm eff}$ diagram for stars which

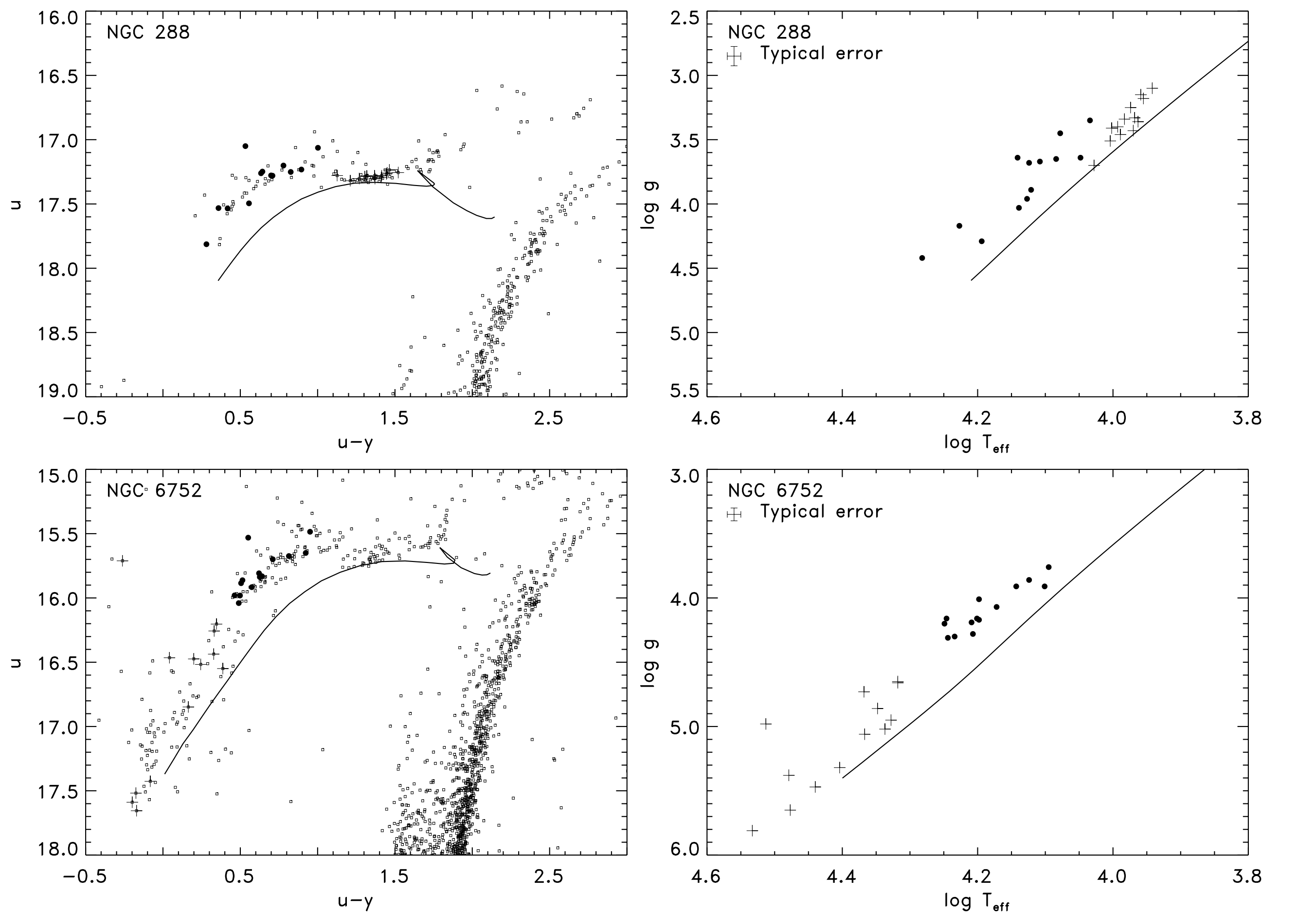

FIG. 4.—Cross check between the location of NGC 288 and NGC 6752 BHB stars on the $(u, u-y)$-plane (*left-hand panels*) and on the (log *g*, log $T_{\rm eff}$)-plane (*right-hand panels*). The small open squares represent our photometry for the cluster stars. Stars located in the jump region which have spectroscopically determined log *g* and log $T_{\rm eff}$ are overplotted as small filled circles, whereas stars located outside the jump region with spectroscopic measurements are overplotted as plus signs. Note that stars classified as jump stars based on their location in the $(u, u-y)$-plane (*left-hand panels*) are also seen to be located in the gravity jump region thus demonstrating that the *u* jump and the log *g* jump are closely connected.

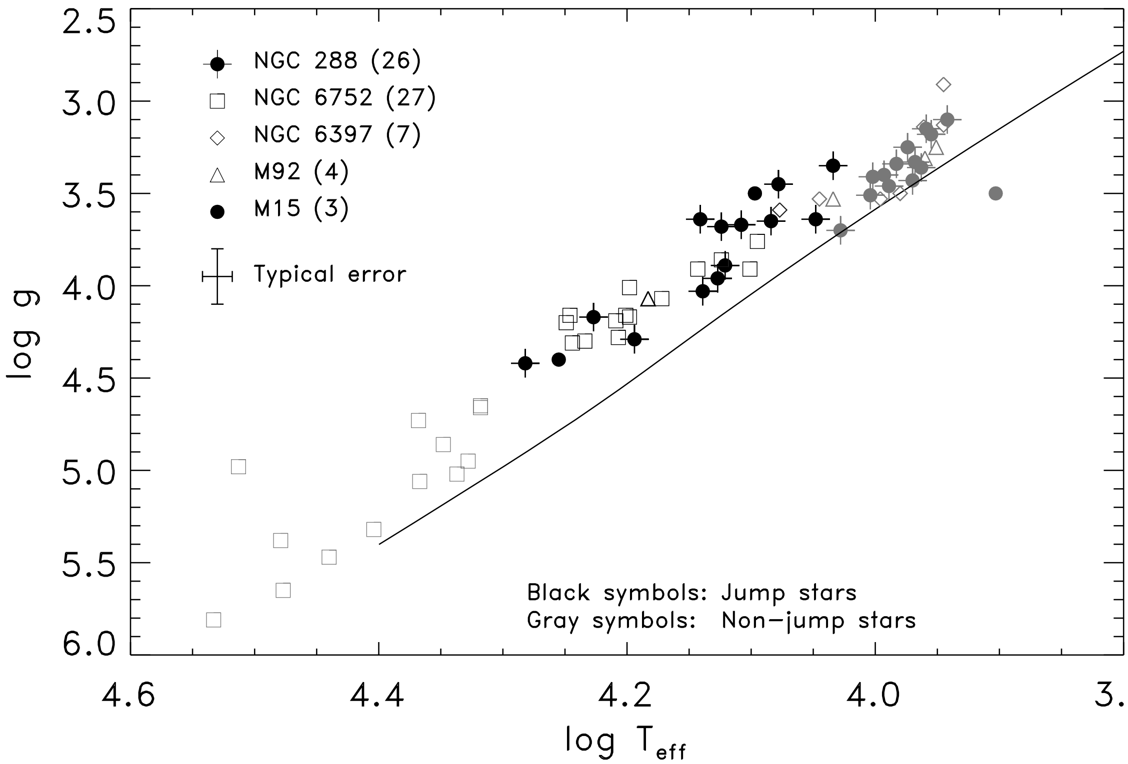

FIG. 5.—Graphical demonstration of the close connection between the so-called low-gravity stars and the *u* jump stars. This (log g, log $T_{\rm eff}$) diagram exclusively shows stars which have had their positions determined also in the (u, $u-y$)-plane. (For an impressive diagram showing most of the stars with published gravities to date, see Fig. 9 of Moehler et al. 1995.) The number of stars for which both (log g, log $T_{\rm eff}$) and (u, $u-y$) data are available is given in parentheses next to the name of the cluster (*upper left-hand corner*). Stars which lie inside the *u* jump region (in the CMD) are plotted as black symbols, whereas stars which lie outside this region are plotted with gray symbols.

have had their positions in the (u, $u-y$) diagrams evaluated on the basis of our photometry for several different GCs. Stars which are found to lie inside the *u* jump region are plotted with black symbols, whereas those lying outside the *u* jump region are shown with gray symbols. It is clear that the vast majority of the stars investigated conform to the notion that the *u* jump and the log *g* jump are different manifestations of one and the same physical phenomenon. The few stars which appear not to follow the rule—located exclusively at either the very hot or very cool ends of the jump region—can easily be accounted for on the basis of observational errors.

5. CONSTRAINTS ON HELIUM MIXING

As an explanation for the *u* jump, Grundahl et al. (1998) tentatively suggested that very deep mixing during the RGB phase—reaching, in fact, all the way into the hydrogen-burning shell and leading to noncanonical dredgeup of helium to the envelope—could provide an explanation for their observations. This would appear to be an especially compelling explanation in the case of M13, for which deep mixing among RGB stars is extremely well documented (see Table 1).

Such helium mixing was first conjectured by VandenBerg & Smith (1988), who highlighted the implications it would have on our understanding of such problems involving the HB phase as the period-shift effect (§ 1). The idea was later revived by Langer & Hoffmann (1995) and especially by Sweigart (1997a, 1997b). It is generally assumed that mixing processes on the RGB are somehow related to stellar rotation, as in the meridional circulation theory (Sweigart & Mengel 1979; see also Kraft 1994, 1998, 1999 and Sneden 1999 for recent reviews).

As pointed out by Sweigart (1997b), one key aspect of the helium-mixing theory is that Al enhancements, according to RGB nucleosynthesis models computed by Langer, Hoffman, & Sneden (1993), Langer & Hoffman (1995), Cavallo, Sweigart, & Bell (1996, 1998), etc., can only be produced *inside* the hydrogen-burning shell.[15] Hence, any Al overabundance should necessarily be accompanied by the dredgeup of helium freshly produced inside the shell. This is a particularly important result, given that large Al overabundances are indeed observed among RGB stars in several GCs (see Table 1 and also Norris & Da Costa

[15] As discussed by Kraft (1998, his § 4.1), such model predictions are at odds with the available determinations of the Mg isotope ratios among bright GC giants which suggest that Al is produced at the expense of ^{24}Mg (e.g., Cavallo 1997). As emphasized by Shetrone (1996a, 1998b) and others, "using the current nuclear cross sections ^{24}Mg can be converted into Al but only at temperatures higher than those found in the CNO [hydrogen-burning] shell!" (Shetrone 1998b). In fact, such temperatures should be *substantially* higher than that found at the H-burning shell in the models (e.g., Langer, Hoffman, & Zaidins 1997; Denissenkov et al. 1998): $\approx 70 \times 10^6$ K, as opposed to $\simeq 55 \times 10^6$ K. Mixing to such high temperatures is completely ruled out by canonical evolutionary theory and is not envisaged in Sweigart's (1997a, 1997b) helium-mixing theory either. Thus, the basic nuclear reaction mechanism which lies at the root of the helium-mixing scenario remains unsettled. And, as emphasized by Denissenkov et al. (1998), "'unfortunately' [sic], nuclear physicists seem to have little (if any) doubt concerning the current ^{24}Mg(p, γ)^{25}Al reaction rate." For further discussion, the reader is referred to the interesting papers by Smith & Kraft (1996), Langer et al. (1997), and Denissenkov et al. (1998).

1995a, 1995b and Zucker, Wallerstein, & Brown 1996 for the impressive case of ω Cen [NGC 5139]; recent reviews have been provided by Kraft 1994, 1998, 1999 and Sneden 1999). If helium mixing were present among Galactic GCs, one would expect a correlation between HB morphology and O, Na, Mg, and Al abundance variations on the RGB. Indeed, a correlation between HB morphology and the presence/extent of signatures of deep mixing on the RGB has been independently suggested by several different authors (Catelan & de Freitas Pacheco 1995; Kraft et al. 1995, 1998; Peterson, Rood, & Crocker 1995; Carretta & Gratton 1996). In fact, helium mixing stands out as the best candidate to explain the anomalous HB morphology of the "metal-rich" GCs NGC 6388 and NGC 6441 (Sweigart & Catelan 1998; Layden et al. 1999). We thus attempt to ascertain the extent to which helium mixing on the RGB may be responsible for the u and log g jump phenomena.

5.1. *Constraints from the Morphology of the* $(u, u-y)$ *and* $(\log g, \log T_{\rm eff})$ *Diagrams*

Sweigart (1997b) has shown that it is possible to reproduce the log g, log $T_{\rm eff}$ pattern seen among all GC BHB stars observed to date by invoking helium mixing on the RGB. It is useful to recall what requirements such helium-mixed stars would have to fulfill in order to explain the jump phenomenon.

Expanding on Sweigart's (1997b) scenario, one would expect the following behavior as a function of ZAHB temperature:

1. $\log T_{\rm eff} \lesssim 4.0$.—HB progenitors (i.e., RGB stars) do not experience significant helium mixing, and HB stars accordingly lie along canonical evolutionary tracks.
2. $4.0 \lesssim \log T_{\rm eff} \lesssim 4.2$.—HB stars are somewhat more luminous than canonical models because of a larger helium abundance ($Y \sim 0.30$–0.35) in their envelopes.
3. $4.2 \lesssim \log T_{\rm eff} \lesssim 4.3$.—The increase in envelope helium abundance due to deep mixing becomes very large, $Y \sim 0.40$–0.45.
4. $\log T_{\rm eff} \gtrsim 4.3$.—The HB luminosity is dominated by the helium-burning core (as opposed to the hydrogen-burning shell at lower temperatures, which is now inert), and so the helium-mixed and canonical models essentially agree—even though the envelope helium abundance in the helium-mixed models can be $Y \gtrsim 0.45$.

Unfortunately, it is not possible to directly test for the presence of enhanced surface helium because helium is generally observed to be depleted in the photospheres of hot HB stars (e.g., Moehler et al. 1997), most likely because of diffusion processes (§ 6).

We suggest, however, that the helium-mixing pattern among BHB stars, as described above, is unlikely. We have four main arguments against helium mixing as an explanation for the jump based on the morphology of the $(u, u-y)$ and $(\log g, \log T_{\rm eff})$ diagrams:

1. The variation of Y with temperature required by Sweigart (1997b), not having been derived from first principles, can only be achieved by fine-tuning of free parameters in the helium-mixing theory. Even if one assumes that there is a "cutoff rotational velocity" beyond which mixing occurs, but below which no mixing takes place, it seems virtually impossible to produce a low-temperature cutoff for the jump which is so remarkably constant—i.e., to within $\pm \approx 500$ K—from one GC to the next, given the strong dependence of ZAHB properties on variations in GC evolutionary parameters (e.g., Sweigart & Gross 1976). In fact, given that the HB effective temperature becomes less sensitive to changes in mass as the metallicity decreases (see Fig. 7 of Buonanno, Corsi, & Fusi Pecci 1985), one would expect some intrinsic relationship between $T_{\rm eff}^{\rm jump}$ and [Fe/H]. As already mentioned (§ 3.3), any intrinsic relationship between $T_{\rm eff}^{\rm jump}$ and [Fe/H], if present at all, seems to be quite mild. This may be called the "global" fine-tuning problem. This global fine-tuning problem is a major impediment facing *any* stellar evolution–related scenario for the jump, probably pointing instead to a stellar atmospheres–based explanation (§ 6).
2. Fine-tuning is also required in the helium-mixing scenario at any given metallicity and for any given GC. Quantitative information in this respect can be obtained from detailed inspection of the plots published by Sweigart (1997a, 1997b). Figure 4 of Sweigart (1997a) is particularly relevant in this regard. This figure shows how the expected ZAHB temperature increases with increasing values of both the Reimers' (1975a, 1975b) mass-loss parameter, $\eta_{\rm R}$, and the deep mixing depth, ΔX. Thus, in order to produce a jump at fixed $T_{\rm eff}$ an increase in the mixing extent must be compensated for by a decrease in the mass-loss parameter. At $\log T_{\rm eff} = 4.1$, which is very close to the empirical value for $T_{\rm eff}^{\rm jump}$ (see Table 1), the following combinations $(\Delta X, \eta_{\rm R})$ are found: (0.00, 0.52); (0.05, 0.46); (0.10, 0.40); (0.20, 0.30). If we relax the fixed $T_{\rm eff}$ constraint and keep instead not only the age, metallicity, and original helium abundance, but also $\eta_{\rm R}$ fixed (which is the more natural assumption), a *very* large gap in log $T_{\rm eff}$ results. Figures 7–9 in Sweigart (1997b) show how the gravity-temperature plane is affected by the extent of helium mixing on the RGB. From those plots one can infer that the substantial increase in Y that would be required to reproduce the observed jump would lead to a gap in temperature encompassing several thousand degrees Kelvin, besides leading to an increase in gravity (and hence a *decrease* in luminosity). If some natural variation in $\eta_{\rm R}$ is invoked, one would most likely expect—because of the widely suggested mixing-rotation connection—that $\eta_{\rm R}$ should actually *increase*, and not decrease, with increasing mixing extent (see, e.g., § 6.2 of Kraft et al. 1995), as opposed to what would be required to eliminate the gap. These perhaps surprising predictions of the helium-mixing scenario have no counterpart in either the $(u, u-y)$ or the $(\log g, \log T_{\rm eff})$ diagrams and demonstrate the high degree of fine-tuning required for helium mixing to account for the jump phenomenon at a given metallicity and for any given GC. This may be called the "local" fine-tuning problem—not to be confused with the global, metallicity-related fine-tuning problem described above.
3. Without appealing to ad hoc hypotheses, the jump location *and* size should depend quite strongly (in the helium-mixing scenario) on the extent of deep mixing on the RGB. However, GCs in which the RGB stars have undergone extreme deep mixing—such as M13—present jump characteristics virtually identical to those of GCs whose giants seem to have undergone much less extensive deep mixing—such as NGC 288 (see Figs. 1, 3, and 5 and also Table 1).
4. In a similar vein, if deep mixing is related to stellar rotational velocity, and given that there is no a priori reason to expect rotational velocities at a given metallicity

to be the same from one cluster to the next (as supported by the observations of, e.g., Peterson, Rood, & Crocker 1995 and references therein), one would definitely expect large intrinsic scatter in $(u-y)_0^{\rm jump}$, $T_{\rm eff}^{\rm jump}$, and jump size at any given metallicity unless one resorts to ad hoc hypotheses. While there *does* seem to be a perceptible difference in the jump temperature for M3 and M13 (Table 1)—which might perhaps be related to the difference in HB rotational velocities between the two (see § 6)—we note that the jump *size* appears very similar for all clusters (Fig. 2).

We shall present an alternative scenario to explain the jump phenomenon in § 6 below.

5.2. *The Role of Field Stars*

It is well known that RGB stars in the field do not show (deep) mixing patterns nearly as large as GC giants. Since Kraft et al. (1982), the literature has become very extensive in this regard: e.g., Sneden et al. (1991, 1997); Kraft et al. (1992); Pilachowski et al. (1996); Shetrone (1996b); Hanson et al. (1998); Kraft (1994, 1998, 1999); Carretta et al. (1999b); etc. If helium mixing is responsible for the jump, one would reach the conclusion that field BHB stars should not show any evidence for a jump in u or log g similar to that seen among GCs.

However, as can be seen from the (log g, log $T_{\rm eff}$) diagrams obtained by Saffer et al. (1994, 1997), and most recently by Mitchell et al. (1998, their Fig. 5), that cluster and field BHB stars are clearly closely related as far as the jump morphology goes. In fact, according to R. A. Saffer (1998, private communication) "the cluster and field BHB distributions in the (log g, log $T_{\rm eff}$)-plane are completely consistent with one another." This implies that deep mixing is unlikely to be the primary cause for the jump phenomenon.

What is the evidence for a u jump among the field BHB stars? In order to answer this question one should ideally have a sample of BHB stars with accurately determined distances and well-calibrated Strömgren photometry, such that their absolute magnitudes could be reliably derived and plotted in a $[(u-y)_0, M_u]$ diagram as for the clusters. However, to the best of our knowledge a sample of BHB stars with accurately determined distances does not currently exist in the literature. Thus at present we cannot shed further light on the connection between the u and log g jumps for field BHB stars.

Whereas the *overall* field HB population is believed to contain only a small fraction of EHB stars ($\lesssim 1\%$; Saffer & Liebert 1995; Villeneuve et al. 1995), the *halo* field appears to contain a surprisingly large population of sdB (or EHB) stars, if compared with the disk field. Mitchell (1998) estimates that "the metal-poor halo population can produce a horizontal-branch morphology that is, by a factor of $\gtrsim 7$ ($2\,\sigma$ lower limit), more heavily weighted toward the 'extreme' blue end than the horizontal branch produced by the relatively metal-rich disk population." Assuming Mitchell's arguments to be correct, this, along with the lack of abundance anomalies among field metal-poor giants, could imply that most halo EHB stars do not originate from deep mixing processes on the RGB evolutionary phase. This, of course, would *not* rule out the possibility that some EHB stars in some GCs—especially, of course, those showing extreme mixing patterns on the RGB—may indeed have undergone helium mixing during the RGB phase. More work is needed to verify Mitchell's results.

5.3. *Constraints from the Ultraviolet Photometry of GCs*

Is the u jump reported in this paper due to a deviation in the bolometric luminosity from canonical HB models, or is it due to a spectral peculiarity which makes the u band brighter without changing the bolometric luminosity? In principle, ultraviolet photometry can be used to answer this question because the stars hotter than the jump temperature emit most of their bolometric luminosity in the ultraviolet. For example, using the model atmosphere tabulation of Lejeune, Cuisinier, & Buser (1997), one finds that a star with $T_{\rm eff} = 16{,}000$ K, log $g = 4.0$, and [Fe/H] $= -1.5$ emits 73% of its bolometric luminosity shortward of 3000 Å.

Ultraviolet photometry of GCs has been obtained using both the Ultraviolet Imaging Telescope (Stecher et al. 1997) and the ultraviolet (F160BW, F218W, F255W) filters on WFPC2 (e.g., Sosin et al. 1997; Ferraro et al. 1998). The instruments are complementary in that the UIT had a large (40′ diameter) field of view but a relatively coarse (3″) spatial resolution which made it mainly useful in the outer regions of the clusters, whereas the WFPC2 images have much better resolution (0″.1) but can only record significant HB number counts in the cluster cores, because of its much smaller field of view. We note that the comparison of ultraviolet CMDs with absolute theoretical luminosities can be problematic because the reddening correction is large and the ultraviolet reddening law is known to show spatial variations in the Galaxy (Fitzpatrick 1999). In addition, UIT had a calibration anomaly reminiscent of (but not identical to) reciprocity failure (Stecher et al. 1997), while the absolute photometry using the Wood's (F160BW) filter is limited by a high contamination rate (Whitmore, Heyer, & Baggett 1996) and a PSF that varies across the field (Watson et al. 1994). However, these absolute calibration difficulties are not important when looking for an analog of the Strömgren u jump in the ultraviolet. We shall assume that the absolute level of the model ZAHB has been adjusted to match the cooler ($T_{\rm eff} < 10{,}000$ K) HB stars and look for an offset from the ZAHB for the hotter stars.

The most accurate GC photometry from UIT was obtained for NGC 6752 (Landsman et al. 1996). Not only did NGC 6752 have the deepest UIT exposure of any globular, but the cluster is sufficiently nearby that *IUE* spectra of 14 hot HB stars are available to verify the calibration. For log $T_{\rm eff} < 4.3$, the (1620 Å) ultraviolet CMD of Landsman et al. shows excellent agreement with the canonical HB tracks of Sweigart; at higher temperatures the data fall 0.1–0.2 mag below the models (also see Fig. 8). A very similar result is found for the UIT photometry of M79 by Hill et al. (1996). In the UIT CMD of ω Cen (Whitney et al. 1998), there is a significant population of stars hotter than 16,000 K lying *below* the ([Fe/H] $= -1.5$) ZAHB, but again there is no evidence for a photometric jump corresponding to that observed in u. Only for the case of M13 do the UIT data show a possible analog of the u jump. Parise et al. (1998) report an offset toward higher luminosity for stars with $4.1 < \log\, T_{\rm eff} < 4.3$.

Turning to ultraviolet WFPC2 data, Sosin et al. (1997) find an excellent fit of ZAHB models to the (F218W, B) CMD of NGC 2808, after an adjustment of the zero-point calibration. Rood et al. (1998) show a good model fit to both the (F160BW, V) and (F255W, V) CMDs for M13, and their data suggest a similar result for M80. Because the

WFPC2 result on M13 is in apparent contradiction with the UIT result of Parise et al. (1998), we have carried out a more detailed examination of both sets of data. We have performed our own reduction of the UIT data, while we have used the WFPC2 photometry kindly supplied by F. R. Ferraro & B. Paltrinieri (1999, private communication). Both CMDs are shown in Figure 6. Evidently, there is a problem in the absolute calibration in one or both data sets, because there is a 0.25 mag difference in the distance modulus needed to match a theoretical ZAHB to the cooler stars. However, the overall appearances of the CMDs are quite similar to each other, and to the ultraviolet CMD of NGC 6752 shown in Figure 8. The most striking difference is that the number ratio of cool to hot HB stars is higher for the UIT data, possibly suggesting a radial gradient in HB morphology, with the HB morphology being bluer in the core. In the ultraviolet CMDs of both M13 and NGC 6752, the data fall 0.1–0.2 mag below the models at the highest temperatures. (Rood et al. 1998 do not find this discrepancy, apparently because of their use of the oxygen-enhanced HB models of Dorman et al. 1995.) The offset to higher luminosity reported by Parise et al. is present in the UIT CMD for stars with $-3.4 < m_{162} - V < -2.1$ (13,600 K $< T_{\rm eff} <$ 21,100 K) and present to a lesser extent in the WFPC2 data. Note that this offset occurs at a $m_{162} - V$ color which is 0.75 mag bluer than would be predicted from the temperature ($\log T_{\rm eff} = 4.07$) of the jump found in the Strömgren u CMD. Also note that this offset in the ultraviolet CMD is best described as an absence of stars near the ZAHB, since the majority of the stars are still contained within the same empirical upper envelope that fits stars at lower and higher temperatures—unlike the case with the u jump and the log g jump. Thus, while there is some evidence for a luminosity offset in the ultraviolet CMD of M13, it does not appear to be simply connected to the jump observed in the Strömgren u CMD.

In conclusion, with the *possible* exception of M13, the ultraviolet data show *no* evidence for a luminosity jump corresponding to the jump reported here for Strömgren u. Interestingly, M13 is the cluster for which the strongest evidence for deep mixing is currently available (see Table 1).

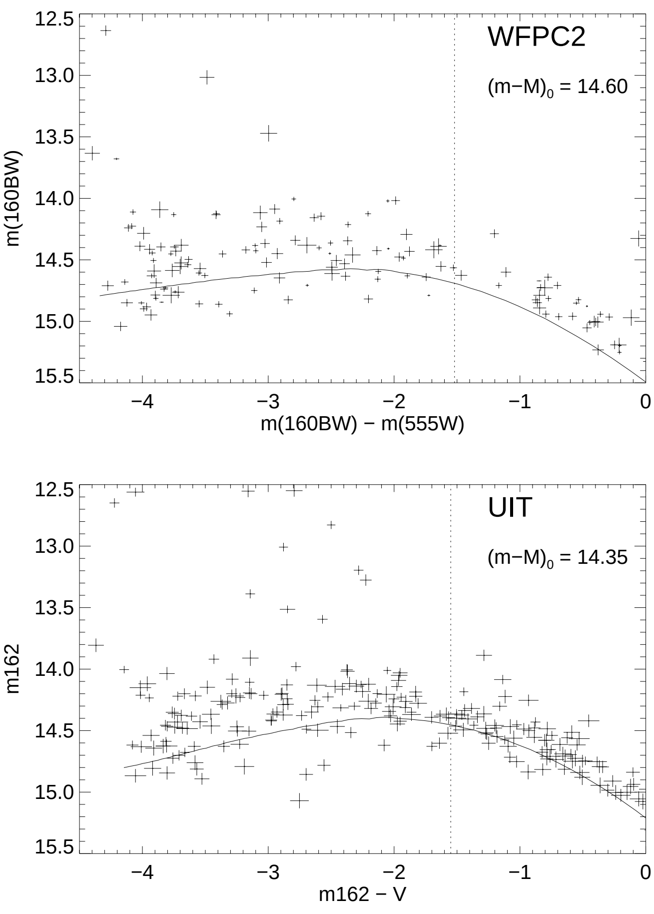

FIG. 6.—Ultraviolet CMDs of M13 obtained using WFPC2 imaging of the cluster core with the F160BW filter (*upper panel*) and using UIT ($\sim$1620 Å) imaging of the outer regions of the cluster (*lower panel*). For each CMD, a canonical ZAHB from Sweigart (see Landsman et al. 1996) with [Fe/H] $= -1.6$ which fits the cooler HB stars has been overplotted; note the different adopted distances in the two figures. The vertical dotted line on each CMD indicates the color corresponding to the "jump" temperature ($\log T_{\rm eff} = 4.07$) found for M13 from the Strömgren u CMD. The slightly different shape of the ZAHB in the two panels is due to the fact that, although the WFPC2 F160BW filter and the UIT 1620 Å (B5) filter both have effective wavelengths near 1600 Å, the width of the F160BW filter is approximately twice that of the UIT filter ($\Delta\lambda \sim 225$ Å).

6. LEVITATION OF HEAVY ELEMENTS: A POSSIBLE EXPLANATION

The Strömgren u bandpass is located just shortward of the Balmer jump, and thus the emergent flux is dominated by the hydrogen opacity. Atmospheric effects (related, e.g., to an increase in the metal opacity) that decrease the relative importance of the hydrogen opacity should result in a brighter Strömgren u flux. Figure 7 shows how the flux in different bandpasses varies as a function of metallicity for Kurucz models (taken from Lejeune et al. 1997) at three temperatures ($T_{\rm eff}$ = 11,500, 15,000, and 20,000 K), which span the range of the Strömgren u jump. At all three temperatures, the maximum brightening occurs in Strömgren u, and at $T_{\rm eff}$ = 15,000 K the model with [Fe/H] $= +0.5$ is about 0.3 mag brighter in Strömgren u than the model with [Fe/H] $= -1.5$. In contrast, in the ultraviolet ($\approx$1600 Å) bandpasses, the models with [Fe/H] $= +0.5$ either show little difference or (at $T_{\rm eff}$ = 11,500 K) are about 0.1 mag fainter than the models with [Fe/H] $= -1.5$. As discussed below, several lines of evidence suggest that radiative levitation can enormously enhance the heavy metal abundance in hot HB stars, an effect similar to that seen at a similar $T_{\rm eff}$ in the Hg-Mn stars and other helium-weak (nonmagnetic) chemically peculiar (CP), B-type stars (e.g., Dworetsky 1993). We thus suggest that the u jump reported here, and its absence in the ultraviolet, is most likely due to radiative levitation of heavy elements to suprasolar abundances.

Figure 8 shows the Strömgren u and ultraviolet CMDs of NGC 6752, with a canonical ZAHB from Sweigart (see Landsman et al. 1996) transformed to the observational planes using model atmospheres with the cluster metallicity ([Fe/H] $= -1.5$) and with a suprasolar metallicity ([Fe/H] $= +0.5$).[16] In the Strömgren u CMD, for temperatures hotter than the jump temperature, the metal-rich model provides a much better fit than the model with the cluster metallicity. The metal-rich model also provides a somewhat better fit for temperatures hotter than the jump temperature in the ultraviolet CMD, where there is some evidence for a

[16] In principle, the boundary conditions used to compute the interior models should be modified when using a metal-rich model atmosphere. However, the implications of this approximation for the results described in this paper are minor.

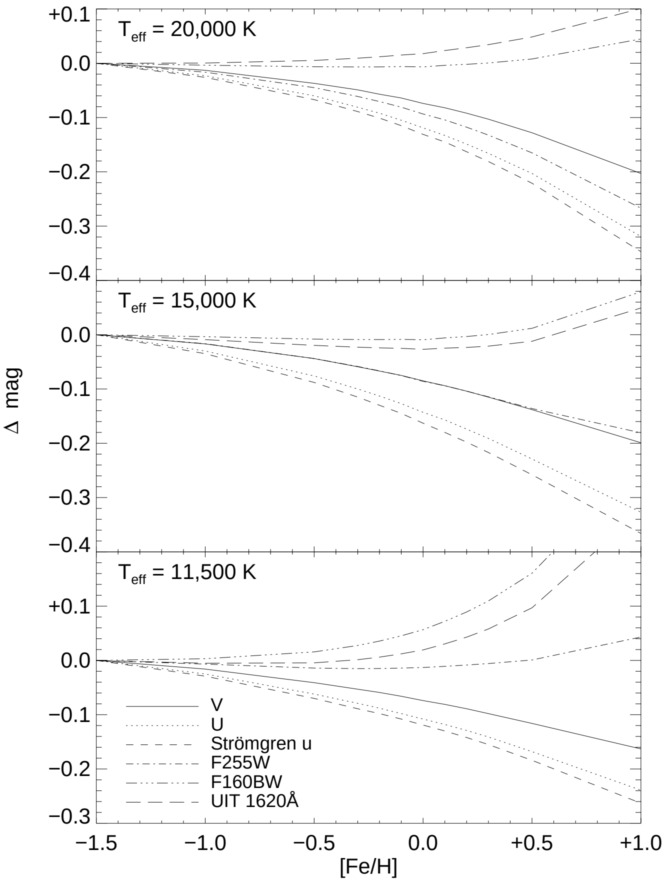

FIG. 7.—Emergent flux in different bandpasses is shown as a function of metallicity for a Kurucz model atmosphere at effective temperatures of 20,000 K (*upper panel*), 15,000 K (*middle panel*), and 11,500 K (*lower panel*) and log $g = 4.0$. Fluxes are normalized so that all bandpasses have a magnitude of 0.0 at [Fe/H] $= -1.5$. The bandpasses include the Johnson *V* and *U* filters, the Strömgren *u* filter, the ultraviolet F255W and F160BW filters on WFPC2, and the B5 (1620 Å) UIT filter.

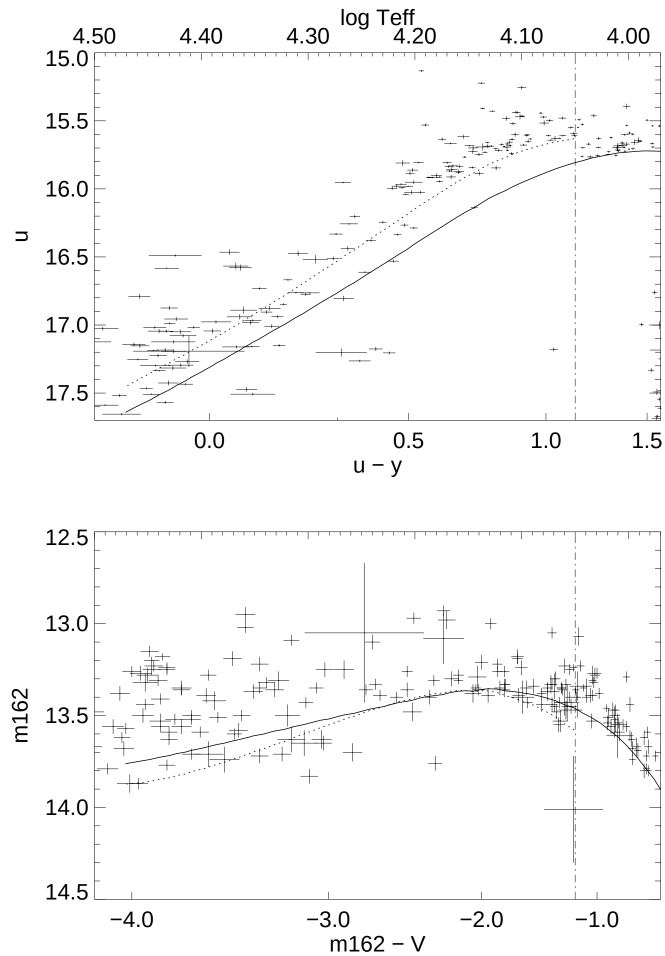

FIG. 8.—*Upper panel*: The $(u, u-y)$ CMD of NGC 6752 is shown along with a canonical ZAHB with [Fe/H] $= -1.6$ from Sweigart (see Landsman et al. 1996) transformed to the observational plane using model atmospheres with the cluster metallicity ([Fe/H] $= -1.5$; *solid line*) and a suprasolar ([Fe/H] $= +0.5$; *dotted line*) metallicity. A reddening of $E(B-V) = 0.05$ mag has been assumed. *Lower panel*: A similar plot for the $(m_{162}, m_{162} - V)$ CMD of NGC 6752 obtained from the 1620 Å UIT photometry of Landsman et al. (1996). The abscissae of both plots have been transformed to a scale linear in log $T_{\rm eff}$ using Kurucz model atmospheres; this transformation results in the larger uncertainties at high $T_{\rm eff}$ in the Strömgren *u* plot. The vertical dot-dashed line marks the position (log $T_{\rm eff} = 4.07$) of the Strömgren *u* jump. Note that (1) there is some evidence for a "negative jump" to fainter ultraviolet luminosities and (2) the use of metal-rich atmospheres brightens the ZAHB in the Strömgren *u* CMD, but not in the ultraviolet CMD.

"negative jump" to fainter ultraviolet luminosities. For temperatures cooler than the jump temperature, radiative levitation presumably does not occur. The sudden onset of the jump at a well-defined temperature, $T_{\rm eff}^{\rm jump} = 11{,}500$ K, is possibly a result of the competition between the radiative levitation and nuclear (HB) timescales: radiation forces increase with $T_{\rm eff}$, so that it is conceivable that there is a "critical temperature" above which radiative acceleration becomes effective in a time much shorter than the HB lifetime.[17]

At the high temperatures (log $T_{\rm eff} > 4.3$) and gravities of the sdB (EHB) stars, the metal-rich models in Figure 8 are too bright in Strömgren *u*, which probably indicates that radiative levitation is no longer as effective. Bergeron et al. (1988) posited the existence of additional transport processes in sdB atmospheres, such as a weak stellar wind, to explain why silicon abundances were *observed* to be strikingly lower than predicted by radiative levitation models (also see Fontaine & Chayer 1997). Studies of the pulsation modes in sdB stars suggest that radiative levitation of iron occurs in these stars (Charpinet et al. 1997) *but* does not necessarily reach the photosphere.

An important caveat in the interpretation of Figures 7 and 8 is that hot HB stars are known to have helium depletions (e.g., Moehler et al. 1995, 1997) and (as discussed below) likely do *not* show significant enhancements of most of the light ($A \lesssim 34$) elements. Both of these effects will somewhat reduce the brightening in Strömgren *u* predicted by the Kurucz models, which use a solar helium abundance and solar-scaled metallicities. In addition, the predicted ultraviolet fluxes are uncertain if the important carbon and silicon opacity sources do not scale with the heavy metals. Better predictions of the flux distribution in hot HB stars will most likely require the computation of model atmospheres with nonscaled solar abundances, for example, by

[17] The phenomenon could be, to a smaller extent, also connected to the rotational velocities of HB stars, in the sense that HBs containing faster rotators might be able to inhibit the onset of radiative levitation until a slightly higher temperature is achieved. In fact, this may provide an explanation for the (small) difference in $T_{\rm eff}^{\rm jump}$ between M3 and M13 (§ 3), since it is well known that HB stars in M13 rotate significantly faster than their M3 counterparts (Peterson 1983; Peterson et al. 1995).

TABLE 2

ABUNDANCES IN HOT HB STARS INSIDE THE "GAP" REGION

Name	T_{eff}	log g	He	C	N	Mg	Al	Si	P	Fe	Zn	Au	Reference
Feige 86	16,430	4.2	−0.8	−2.52	−2.01	−0.65	−1.18	+0.14	+2.24	+0.4	+0.44	+4.0	1
PG 0954+049	14,100	3.3	−0.44	−0.61	...	+0.60	...	+0.71	...	+0.44	...	...	2
PG 1008+689	16,900	4.1	−0.95	−1.52	...	−0.33	...	−0.04	+1.11	+0.61	...	...	2
PG 2301+259	18,000	4.0	−0.85	−0.99	+0.21	−0.68	−0.18	+0.13	+0.36	−0.04	...	...	2
NGC 6752 (CL 1083)	16,000	4.0	−0.6	...	...	−1.3	...	−1.5	<-0.4	+0.15	...	...	3

NOTE.—Log abundances relative to solar.

REFERENCES.—(1) Bonifacio et al. 1995; (2) Hambly et al. 1997; (3) Glaspey et al. 1989.

use of the opacity-sampled ATLAS12 program (Kurucz 1993).

What is the evidence that significant radiative levitation of heavy elements occurs in hot HB stars? First, we note that among the main-sequence B- and A-type stars, slow ($v \sin i < 80$ km s^{-1}) rotation appears to be a necessary condition for the appearance of abundance peculiarities (Wolff & Preston 1978; Abt & Morrell 1995). Although $v \sin i$ measurements of hot HB stars are not yet available, observations of somewhat cooler BHB stars yield upper limits of $v \sin i \lesssim 40$ km s^{-1} and there is no indication for an increase in $v \sin i$ with T_{eff} (Peterson et al. 1995; Cohen & McCarthy 1997). The observed helium depletions provide more direct evidence that chemical separation is possible in hot HB stars. On the theoretical side, the calculations of radiative levitation and diffusion processes in hot HB stars by Michaud, Vauclair, & Vauclair (1983) indicate that if the outer envelope is stable enough for the gravitational settling of helium to be efficient, then overabundances of heavy elements by factors of 10^3–10^4 are expected.

Direct evidence for radiative levitation of heavy elements comes from the echelle spectroscopy of two hot HB stars in NGC 6752 by Glaspey et al. (1989). An overabundance of iron by a factor of 50 (and a helium depletion) was found in the star CL 1083 with $T_{eff} = 16{,}000$ K (within the T_{eff} range of the jump). On the other hand, no abundance anomalies were found in the star CL 1007, which at $T_{eff} = 10{,}000$ K lies coolward of T_{eff}^{jump}. Similarly, Lambert, McWilliam, & Smith (1992) obtained high-resolution spectra of three cluster HB stars (two in M4 [NGC 6121] and one in NGC 6397) located coolward of the jump at $T_{eff} \sim 9000$ K and found no abundance anomalies. Unfortunately, there has been no further echelle spectroscopy of hot GC HB stars to confirm the Glaspey et al. result and to explore the prevalence and temperature range of suprasolar iron abundances in hot HB stars.[18] However, some additional guidance can be provided by high-dispersion analysis of helium-depleted field HB stars within the temperature range of the u jump. Table 2 shows the results of abundance analyses for the field HB stars Feige 86 (Castelli, Parthasarathy, & Hack 1997), PG 0954+049, PG 1008+689, and PG 2301+259 (Hambly et al. 1997) along with the Glaspey et al. result for the cluster HB star NGC 6752 (CL 1083). Not shown in Table 2 are the results of Heber (1991), who did not perform a full abundance analysis, but who does report chlorine abundances, respectively, enhanced by factors of 20 and 40 over solar for the BHB stars PHL 25 ($T_{eff} = 19{,}000$ K; Ulla & Thejll 1998) and PHL 1434 ($T_{eff} = 19{,}000$ K; Kilkenny & Busse 1992). In general, the hot HB stars show depletions of helium and the light elements (with the exceptions of chlorine and phosphorous), but suprasolar abundances of iron and heavier elements. Of course, one does not know the original abundances of the field hot HB stars, but observations of somewhat cooler field HB stars do suggest that they arise from a metal-poor population. For example, Gray, Corbally, & Phillip (1996) find that field HB stars between 7000 and 9000 K are metal poor (less than [Fe/H] ~ -1) and lie close to the ZAHB in the (log g, log T_{eff}) diagram.

As noted above, the abundances of most of the light metals in hot HB stars do not seem to show the same enhancement as the heavy metals. This effect can be understood in terms of two circumstances which preferentially favor saturation of the radiative forces in the light elements: the light metals generally have larger initial abundances and a less rich absorption spectrum (a few strong lines rather than many weak lines) than the heavy metals. The absence of overabundances in the light elements will make it difficult to detect the presence of radiative levitation in low-dispersion optical and ultraviolet spectra. The strongest lines in low-resolution optical spectra of hot HB stars are due to ions of the light elements such as C II, Mg II, and N II. Similarly, in the ultraviolet the strongest lines are due to ions of the light elements, although in this case one expects the continuum to be depressed by the presence of numerous weak iron-peak lines. Such a depression of the far-UV continuum might have been seen by Vink et al. (1999), who analyzed a far-UV spectrum of M79 obtained with the Hopkins Ultraviolet Telescope. They suggest that the agreement between their synthetic and the observed spectrum could be improved if the surface abundances of the hot HB stars in M79 were enhanced by radiative levitation.

IUE spectra of GC HB stars (Cacciari et al. 1995) do not show any especially strong absorption features and, in particular, do not show the strong Si II photoionization resonances, which dramatically distort the far-ultraviolet continuum in the ApSi stars (Lanz et al. 1996). Thus, silicon is almost certainly not enhanced to suprasolar abundances in GC BHB stars.

As we have seen previously (§ 4), the u jump is strongly correlated with the log g jump. What is the effect of radiative levitation on the derived gravities of hot HB stars?

The gravities are derived by finding the gravity of a model (of a given temperature and metallicity) which best

[18] After this paper was submitted, a preprint became available reporting on Keck spectroscopy of BHB stars in M13 (Behr et al. 1999) which effectively verifies the Glaspey et al. results and the radiative levitation scenario laid out in the present section. Note that the onset of radiative levitation, as derived from the Behr et al. work (their Fig. 1), coincides to a remarkable degree of accuracy with T_{eff}^{jump} as determined in our § 3 (see also Table 1). An even more recent (but less accurate) spectroscopic analysis of BHB stars in NGC 6752 (Moehler et al. 1999b) has also confirmed the enhanced Fe (but "normal" Mg) pattern discussed in this section.

fits the Balmer line profiles (e.g., Saffer et al. 1994; Moehler et al. 1995). Either the temperature must be determined independently (e.g., from the ultraviolet continuum), or the gravity and temperature can be determined together from simultaneous fitting of multiple Balmer lines. Thus, to determine how radiative levitation of heavy elements can alter the derived gravity, one must also consider how the temperature is derived. This exercise was performed by Moehler et al., who compared derived gravities for hot HB stars in M15 using models with both solar and $0.01 \times$ solar metallicity (close to the cluster metallicity). They found that gravities could be underestimated by at most 0.1 dex if the HB stars had solar metallicities and metal-poor models were used to analyze them. They concluded that radiative levitation was insufficient to explain the size ($\sim$0.2 dex) of their observed low-gravity anomaly (the log g jump). In fact, their exercise is consistent with our Strömgren u study in that it requires that heavy-element abundances be significantly *above* solar, in order for radiative levitation to be the origin of the anomaly. This statement is supported by the study of Leone & Manfrè (1997), who, in their analysis of helium-weak stars, found that the derived log g value could be underestimated by up to 0.25 dex if a solar metallicity model were used to determine the gravity of helium-weak stars with a heavy metal abundance 10 times solar.

In addition to low gravities, the spectroscopic studies of de Boer et al. (1995) and Moehler et al. (1995, 1997) led to HB masses (derived from values of the stellar $T_{\rm eff}$, log g, V magnitude, and the cluster distance) significantly below canonical values. Heber, Moehler, & Reid (1997) found that this discrepancy could be partially alleviated by the use of the larger cluster distances indicated by some *Hipparcos* studies (e.g., Reid 1997; Gratton et al. 1997), although the derived masses were still lower than canonical values for NGC 6397 and NGC 288. The use of the long distance scale also led to absolute magnitudes brighter than canonical models, leading Heber et al. to favor noncanonical evolutionary models. However, if our hypothesis of radiative levitation is correct, then the derived masses must be considered uncertain at best, at least for HB stars in the "critical" temperature range, 11,500 K $\lesssim T_{\rm eff} \lesssim$ 20,000 K.

Recently, Caloi (1999) has also proposed that radiative levitation occurs in hot HB stars, mainly based on the suggested existence of a gap in the HB number counts in several GC CMDs near $B-V \sim 0.0$ mag. In principle, such gaps could be related to the "jumps" discussed in this paper; for example, if a luminosity jump were much more prominent in B than in V, then a gap would appear at the location of the onset of the jump in a (V, $B-V$) diagram—but *only if* $T_{\rm eff}^{\rm jump}$ could be associated with a $B-V$ color along the "horizontal" part of the HB. However, the temperature corresponding to $B-V = 0.0$ mag is $\approx$8500 K, much cooler than the 11,500 K found here for the onset of the Strömgren u jump. In addition, it appears that a gap at $B-V = 0.0$ mag is not a *ubiquitous* phenomenon (see, e.g., the appendix of Catelan et al. 1998), contrary to what might be expected in Caloi's scenario. Finally, we also note that our u, y data for M68 (NGC 4590) from ESO do not show clear evidence for a u jump because its *hottest* BHB stars are close to the temperature limit for the onset of the jump. In summary, it is unlikely that the gaps discussed by Caloi are related to the jump discussed in this paper, although the connection between HB gaps and atmosphere effects merits further investigation.

To summarize, radiative levitation of heavy elements can plausibly explain the temperature range and magnitude of both the u and log g jump as well as the low-mass problem, but further high-resolution optical and ultraviolet spectra are needed to demonstrate that the abundances of iron and other heavy elements are significantly above solar. As part of this effort, we have a current *HST* Cycle 8 program (GO-8256) to obtain STIS ultraviolet spectra of nine HB stars in NGC 6752 which span the temperature range of the jump. Also needed are model atmospheres with nonscaled solar abundances (computed, e.g., with the ATLAS12 code) to determine quantitatively whether the observed Strömgren u and gravity anomalies can be entirely explained by overabundances of heavy elements or whether additional effects such as those discussed in § 5 (i.e., helium mixing) are required. In this regard, we issue a cautionary remark on attempts to calibrate the free parameters of the helium-mixing theory (which is not a "first principles" theory) using the u and log g jump properties: before this task can be successfully accomplished, the effects of radiative levitation on the adopted model atmospheres must be taken into account. Finally, we note that there have been no theoretical studies of diffusion processes in hot HB stars since the work of Michaud et al. (1983) and that much more sophisticated calculations of radiative accelerations are now possible (e.g., Richer et al. 1998).

7. SUMMARY AND CONCLUDING REMARKS

In the present paper, we have carried out an extensive analysis of the Grundahl et al. (1998) "jump" in Strömgren u first detected in M13. With this purpose, we presented new u, y photometry of 14 GCs based on four filter/detector combinations.

The main results of our analysis of this large set of (u, $u-y$) CMDs can be summarized as follows:

1. The Strömgren u jump is a ubiquitous feature, present in every metal-poor GC with sufficiently hot BHB stars. Such a jump is morphologically best described as a systematic deviation, in u magnitudes and/or $u-y$ colors, with respect to the expectations of canonical ZAHB models, in the sense that the observations appear brighter and/or hotter than the theoretical predictions.
2. The parameter that best defines the onset of the jump is its temperature, which we find to be remarkably constant from one cluster to the next: $T_{\rm eff}^{\rm jump} = 11{,}500 \pm 500$ K; the error estimate is essentially due to measurement and/or calibration uncertainties. We do not find any significant evidence for a dependence of $T_{\rm eff}^{\rm jump}$ on metallicity. The high-temperature end of the jump appears to be situated at $\approx$20,000 K.
3. The occurrence of the jump is not related to the GC metallicity, central concentration, central density, extent of mixing on the RGB, HB morphology (provided the "critical" temperature $T_{\rm eff}^{\rm jump}$ is reached by the cluster's BHB), or Galactocentric distance.
4. The height (or "size") of the u jump is remarkably constant among our entire sample of GCs.
5. The u jump is intimately connected, on a star-by-star basis, to the low gravities (log g jump) which have been measured for GC BHB stars.

Recently, a noncanonical evolutionary scenario (helium mixing: Sweigart 1997a, 1997b) has been proposed as a possible explanation for the low BHB gravities (log g

jump)—which, as we have just remarked, seems strongly connected to the u jump. From our discussion, we were able to pose the following constraints on this scenario:

1. "Global" fine-tuning problem. Given the strong dependence of ZAHB properties on variations in GC evolutionary parameters, one would naturally expect some intrinsic relationship between $T_{\rm eff}^{\rm jump}$ and [Fe/H]. However, any intrinsic relationship between these two quantities, if present at all, seems to be quite mild—posing, in fact, a major challenge for *any* stellar evolution–related scenario for the occurrence of the jump and pointing instead to a stellar atmospheres–based solution.
2. "Local" fine-tuning problem. (Extreme) fine-tuning is also required in the helium-mixing scenario at any given metallicity and for any given GC in order for u and log g jumps such as the ones observed to be reproduced by the noncanonical models.
3. Helium-mixing theory predicts that the jump size and location should depend quite strongly on the extent of deep mixing on the RGB. However, GCs in which the RGB stars have undergone extreme deep mixing—such as M13—present jump characteristics virtually identical to those of GCs whose giants seem to have undergone little mixing, such as NGC 288.
4. If (as commonly assumed) deep mixing on the RGB is related to stellar rotational velocity, current measurements of HB rotational velocities (Peterson et al. 1995) would lead one to expect (perhaps large) intrinsic scatter in $T_{\rm eff}^{\rm jump}$ *and* jump size at any given metallicity—contrary to what our observations appear to suggest.
5. The jump phenomenon (at least in log g) is present not only among GC BHB stars, but also in the field (e.g., Mitchell et al. 1998). Since it is well known that RGB stars in the field do not show deep mixing patterns nearly as large as GC giants (e.g., Hanson et al. 1998; Carretta et al. 1999b; Kraft 1998, 1999), their progeny must clearly not have undergone helium mixing. This provides strong indication that deep mixing cannot be responsible for the jump phenomenon. In addition, it may also imply that (most) EHB (sdB) stars in the *halo* field (Mitchell 1998), and possibly also in GCs, cannot have their origin ascribed to helium mixing on the RGB.
6. With the *possible* exception of M13, the jump phenomenon is *not* seen in ultraviolet CMDs and thus does *not* appear to be caused by a jump in the bolometric luminosity, contrary to what would be expected in the helium-mixing scenario.

These observations suggest that a stellar atmosphere effect, rather than helium mixing, is the primary cause of the u and log g jump phenomenon. We propose here that radiative levitation of metals might be able to explain all aspects of the jump problem. This suggestion, which requires further development on the basis of new observations and diffusion/model atmosphere computations, is in essence based on the following main lines of evidence:

1. The temperature range of the jump is similar to that found for the chemically peculiar (Hg-Mn and helium-weak) B-type stars, which show helium depletions and large overabundances of heavy elements. Observations of (somewhat cooler) BHB stars shows them to be slow (v sin $i \lesssim 40$ km s^{-1}) rotators (Peterson et al. 1995; Cohen & McCarthy 1997), and slow rotation (v sin $i < 80$ km s^{-1}) seems to be a necessary condition for the appearance of overabundances in the B-type stars (Wolff & Preston 1978). The helium depletions observed in the hot HB stars (Moehler et al. 1995) show that chemical separation is feasible in these stars. Theoretical considerations (Michaud et al. 1983) suggest that if an HB atmosphere is stable enough to show helium depletion, then overabundances of heavy metals by factors of 10^3–10^4 might be expected.
2. An abundance analysis derived from echelle spectra of the star CL 1083 ($T_{\rm eff} = 16{,}000$ K) in NGC 6752 yielded an overabundance of iron by a factor of 50 (Glaspey et al. 1989), and observations of field HB stars within the temperature range of the jump consistently show an overabundance of iron-peak and heavier metals (Table 2).
3. Simple experiments with Kurucz model atmospheres suggest that an increase of the metallicity to suprasolar abundances can lead to 0.3 mag brightening of the Strömgren u flux, with little change or a decrease in the ultraviolet flux. The work of Leone & Manfrè (1997) suggests that an underestimate of the gravity by as much as 0.25 dex might result if super–metal-rich spectra were analyzed using models with the cluster metallicity. This implies that efforts to employ (u, y) or (log g, log $T_{\rm eff}$) diagrams to constrain noncanonical evolutionary models cannot be reliably carried out until the effects of radiative levitation on the adopted model atmospheres have been properly taken into account.

Our scenario, as laid out above, leads to several predictions, which we encourage observers to test. Among these predictions, we may highlight the following:

1. Every metal-poor GC with a sufficiently long blue tail will show the jump phenomenon.
2. Even ω Cen will show a well-defined jump in u and in log g, in spite of its large intrinsic spread in metallicity (by $\sim$1 dex; e.g., Norris, Freeman, & Mighell 1996; Suntzeff & Kraft 1996). Moreover, the low-temperature cutoff of the jump is predicted to be located at the same place in both ω Cen and NGC 288 (i.e., $T_{\rm eff}^{\rm jump} = 11{,}500 \pm 500$ K), in spite of the dramatic differences in mixing history between the two globulars (ω Cen: Norris & Da Costa 1995a, 1995b; Zucker et al. 1996; NGC 288: see Table 1).
3. Any bona fide BHB star—whether in GCs or in the field—lying in the critical temperature range 11,500 K $\lesssim T_{\rm eff} \lesssim$ 20,000 K will lie above the canonical ZAHB loci in the (u, $u-y$) and (log g, log $T_{\rm eff}$)-planes.
4. The radiative levitation hypothesis will be easily falsifiable, once additional echelle spectra of cluster hot HB stars have been obtained. (This project is feasible for the nearest GCs using the coming generation of 8 m and larger telescopes.) Should the derived iron abundances not be consistently above solar, then an alternative explanation will be required for the u and log g jump phenomenon. On the other hand, if the suprasolar iron abundances are confirmed, then metal-rich model atmospheres (with non–solar-scaled abundances) must be constructed to derive the fundamental stellar parameters.

Our GC sample is made up of inner-halo clusters only. (For the HB morphology-independent definition of "outer halo," the reader is referred to § 7 of Borissova et al. 1997 and references therein.) It would prove of interest to investigate whether the jump is present in outer-halo GCs—NGC

6229 being an ideal candidate for further examination (Borissova et al. 1999)—and in bulge GCs with blue HBs (Ortolani, Barbuy, & Bica 1997 and references therein).

As pointed out in § 5, there seems to be a significant correlation between deep mixing signatures on the RGB of GCs and HB morphology. *If* helium mixing should turn out not to be the cause, whence this correlation? One possibility is that noncanonical mixing on the RGB is related to mass loss (possibly through stellar rotation). This possibility has tentatively been raised by Catelan & de Freitas Pacheco (1995) and Kraft et al. (1995). In this regard, we would like to mention that whereas "virtually all giants in M13 mix as they approach the red giant tip" (Kraft 1998; see Fig. 10 in Kraft 1994), redward of the jump—where $\approx 50\%$ of all M13 HB stars are found—oxygen abundances appear to be "normal" (see Fig. 7 in Peterson et al. 1995). This is obviously a very surprising result: where are the RGB progenitors of such BHB stars in M13? Could the discrepancy be related, at least in part, to Langer's (1991) mass-loss scenario, whereby (some) RGB stars might appear more oxygen poor than they actually are because of forbidden O I emission from an extensive, cool, slowly expanding outer envelope—possibly implying somewhat enhanced mass-loss rates? We note that Langer's hypothesis has thus far neither been conclusively ruled out nor corroborated (see, e.g., Minniti et al. 1996 for a recent discussion).

It should also be extremely interesting to investigate the position of BHB stars in the (u, $u-y$) and ($\log g$, $\log T_{\rm eff}$)-planes in the mildly metal-rich ([Fe/H] ≈ -0.5 dex) GCs NGC 6388 and NGC 6441. As discussed by Sweigart & Catelan (1998) and Layden et al. (1999), these two globulars represent extreme examples of the second-parameter phenomenon. All of the theoretical scenarios laid out by Sweigart & Catelan predict anomalously bright HB stars, thus implying *intrinsically* low gravities and u magnitudes, even in regions outside the u and $\log g$ jump. Preliminary results from Moehler, Sweigart, & Catelan (1999a) have indicated surprisingly high gravities for BHB stars in these clusters, although more data appear to be needed to confirm such high gravities.

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