HST UV Observations of the Cores of M3 and M13

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ABSTRACT

We present preliminary results from HST/WFPC2 observations of the central regions of the of the Galactic globular clusters M13 & M3. The clusters are almost identical in most respects including chemical composition, but there are dramatic differences in both the horizontal branch (HB) and blue straggler (BSS) populations. The M13 HB has a long blue tail extending 4.5 mag in $V$, reaching well below the level of the main sequence turn-off. M3 has no such feature. M3 & M13 are thus an extreme case of the “second parameter problem” in HB morphology. Also present in the M13 HB are two gaps similar to those seen in the clusters NGC 6752 and NGC 2808. M3 has a specific frequency of BSS three times larger than that of M13. Our results imply that neither age nor cluster density, two popular second parameter candidates, are likely to be responsible for the observed differences.

Subject headings: globular clusters: individual(M3,M13)—stars: horizontal-branch—ultraviolet: stars—stars: evolution

\textsuperscript{1}Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS5-26555

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1. Introduction

We are involved in two projects obtaining Hubble Space Telescope (HST) photometry of globular cluster stars. The goal of the first is to obtain the largest most complete possible samples of a number of prototype clusters. The second is an investigation of clusters suspected or known to have a significant population of UV bright stars. Here, we report preliminary results for observations of the central regions of one cluster from each project, M3 (NGC 5272) from the first and M13 (NGC 6205) from the second.

Both clusters are nearby, northern hemisphere clusters with low reddening (see Table 1). Their metallicities are very similar—indeed in many respects the clusters are almost twins. M3 has been well studied photometrically dating back to Sandage (1953). Its color-magnitude diagram (CMD) often serves as the textbook example used to demonstrate globular cluster sequences. M13 was also a target of early photometric studies (Arp 1955). From the outset its CMD, in particular the horizontal branch (HB), was obviously different from that of M3. After the emergence of the “second parameter” problem (e.g., Sandage & Wildey 1967; Rood (1973)), M3 & M13 could have been discussed as a second parameter pair, although they have not been discussed in that context as of-otherwise different from that of M3. After the emergence of the “second parameter” problem (e.g., Sandage & Wildey 1967; Rood (1973)), M3 & M13 could have been discussed as a second parameter pair, although they have not been discussed in that context as often as, e.g., the NGC 288/NGC 362 pair (with the notable exception of Catelan & de Freitas Pacheco 1995). M13 was chosen as one of our HST targets because of its very blue far-UV color. However, our results are so striking in the context of the second parameter problem that we present preliminary results here.

2. Observations

We have obtained WFPC2 observations of the galactic globular clusters M3 (Cycle 4: GO-5496; PI F. Fusi Pecci) and M13 (Cycle 5: GO-5903; PI F.R. Ferraro). We describe here results obtained using the V (F555W), U (F336W) and the mid-UV filters (F225W) mapping the cluster cores. The CMDs presented here are preliminary results of the four WFPC2 fields obtained with the the PC located on the cluster center. The exposures taken in each filter in M3 are listed in Table 1 by Ferraro et al. (1997a). The total times in M 13 are 32s in F555W, 560s in F336W and 200s in F225W. Details of the data reduction will be given elsewhere. A brief description of the procedure can be found in Ferraro et al. (1997a).

3. Results

Figure 1 shows the V, U − V CMDs for the two clusters. All stars measured in the HST field (PC1 + WFCs) are shown. The M3 sample contains more than 29,000 stars; in M13 there are ~ 11,000 stars, and the limiting magnitude is about 0.5 mag brighter. The main sequences are clearly defined from the red giant branch (RGB) tip down to about 2 mag below the main sequence turnoff (MS-TO).

The MS, sub-giant branch (SGB), and the red giant branch (RGB) are quite similar in the two clusters. The asymptotic giant branch (AGB) of M3 is somewhat more prominent than in M13. However, the HBs and blue straggler sequences are dramatically different.

The M13 HB extends much further to the blue than that of M3. There is a very long HB blue tail, extending about 1.5 mag below the MS-TO. The HB shows two gaps at V ∼ 15.9 and V ∼ 17.8. Except for a few stars the M3 HB terminates at a point corresponding to the upper gap in M13.

We defer discussion of the statistical significance of the gaps until the final data reduction has been performed. Since other clusters (NGC 6752—Buonanno et al. 1996; NGC 2808—Ferraro et al. 1990 and Sosin et al. 1997) show similar gaps, we adopt their reality as a working hypothesis. M3’s long blue HB tail has not been seen in earlier published CMDs (Guarnieri et al. 1993; Montgomery & Janes 1994) which did not reach sufficiently deep. We had anticipated its existence on the basis of the very blue integrated (15 − V) color (van Albada, de Boer, & Dickens 1981; Dorman, O’Connell, & Rood 1993). The blue tail is present in two unpublished ground based studies of the outer parts of the cluster. Stetson (1996) gives a preliminary CMD based on CFHT B, V photometry which shows an HB extending well below the MS-TO, similar to ours. The lower HB gap is probably present in Stetson’s data. The upper gap is not present, but it is difficult to evaluate this difference because the different photometric systems and preliminary state of both data sets. In another preliminary reduction, Paltrinieri et al. (1997) present B, V data obtained with the Calar-Alto 1.23 m telescope for stars > 200″ from the cluster center. The HB reveals the long blue tail and shows both of the gaps present in the HST data.

Note that the traditional RR Lyrae “gap” occurs at the right end of the M13 HB. The U − V color is
not very sensitive to \( T_{\text{eff}} \) in the range of the RR Lyrae and red HB. The entire “horizontal” part of the M3 HB (i.e., \( V \approx \) constant) is compressed into such a small range that no part of the HB appears horizontal in the \( V, U - V \) CMD, and the cool end of the HB terminates in a clump. The hotter part of the M3 HB (\( U - V < 0.3 \)) overlaps the corresponding portion of the M13 HB. The redder part of the HB can be seen more easily in the \( m_{255}, m_{255} - U \) CMD (Fig. 2). The location and morphology of the main branches seen in these colors is strikingly different from that produced by optical filters: the normally bright RGB is actually faint here, and the HB is far from being “horizontal”. The M3 HB is seen as a very narrow, straight “diagonal” branch extending upward to the left away from the giant branch. The obvious “gap” is the RR Lyrae gap. The M3 HB terminates just where the HB begins to turn down (\( T_{\text{eff}} \gtrsim 12000 \text{ K} \)) in \( m_{255} \) because of the increasing bolometric correction. The M13 HB starts on the hot side of the RR Lyrae gap, rises to the maximum where significant bolometric corrections set in, and the long blue HB tail is compressed into a very short sequence. For stars cooler than \( U - V \sim 0.3 \), the M13 stars are more luminous than those in M3 in the comparable color range. This result is expected if the reddest HB stars in M3 are near or past core helium exhaustion and on their way to the lower AGB.

In Fig. 1 M13 shows a small population of Blue Straggler Candidates (BSS), about a dozen, which are clearly separated from the main branches. The population of BSS in M3 is far larger. Indeed there are so many faint BSS in M3 that it is easy to mistake them for a distortion of the SGB near the turnoff. One can more cleanly select BSS in the \( (m_{255}, m_{255} - U) \) CMD (Fig. 2). The solid horizontal line at \( m_{255} = 19 \) is the magnitude limit used by Ferraro et al. (1997a) in their detailed study of the M3 BSS to separate bright from faint BSS. Again we see many more BSS in M3 than M13. Specifically, in M3, Ferraro et al. (1997a) find 171 BSS stars: 72 in the bright sample and 99 in the faint one. M13 has only 35 BSS stars: 11 in the bright sample and 24 in the faint one.

Note that the light sampled in the two clusters turns to be almost the same: \( \sim 10 \times 10^4 L_\odot \) and \( \sim 12 \times 10^4 L_\odot \) for M13 and M3 respectively, so that the number of BSS per unit of sampled luminosity in M3 turns to be about three times higher than in M13.

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Fig. 1.— The \((V, U-V)\) color magnitude diagram for M3 (upper) and M13 (bottom). Measurements were taken in the HST F363W and F555W filters and transformed to the Johnson system using the calibrations given in Holtzmann et al. (1995).

Fig. 2.— The \((U, m_{255}-U)\) color magnitude diagram for M3 (left) and M3 (right). Measurements were taken in the HST F255W and F363W filters. The F363W data has been transformed to the Johnson system as in Fig. 1. The \( m_{255} \) magnitudes are on the STMAG system.
4. Discussion

Table 1 summarizes many of the parameters of the two clusters. Given the almost identical [Fe/H], we can discuss the differences in HB morphology in terms of the second parameter problem. The second parameter most often considered is age (e.g., Lee, Demarque & Zinn 1994). To check for an age difference between M13 & M3 we have drawn the mean ridge through the main branches, adopting the usual procedure which eliminates the most discrepant objects. Figure 3 shows the result obtained by overlapping the cluster mean loci aligning the HBs where the ZAHB is well populated in both clusters. This was accomplished by applying a vertical shift 0.6 mag to the M3 data. We plot both the $V$, $U-V$ and $V$, $U-V$ CMDs. The MS, SGB, and lower RGB mean ridge lines are seen to be almost coincident. (We do not consider the small differences shown in the plot to be significant.) The M13 upper RGB is sparsely populated and it is not clear at this point whether the difference in ridge lines shown in Fig. 3 is significant.

The mean metallicities and the CNO abundances ($C+N+O$) are similar (Table 1), and there is no indication of any significant peculiarity in the primordial helium abundance. Thus, the clusters must have essentially the same age; if not the sequences would not match over such an extensive range in the diagram. We can estimate the maximum age difference best from the $U$, $U-V$ CMD. The most age sensitive feature in this CMD is the difference between the HB and the SGB ($\Delta U$, see Fig. 3). From the isochrones of Dorman (1996, unpublished) we estimate that the level of the almost horizontal SGB decreases by about 0.06 mag/Gyr. Our observed difference between M13 and M3 is $\Delta U = 0.06 \pm 0.1$ mag. On this basis we estimate that M13 is $\sim 1$–1.5 Gyr older than M3. The precision of our result is somewhat compromised by the low sensitivity of the $U-V$ color to $T_{\text{eff}}$ near turn-off. On the other hand, the data for the two clusters were obtained by the same instrument using the same filters. Early studies of cluster CMDs were often hampered by limited dynamic range, whereby the bright and faint sequences were exposed at different times with different equipment. Our observations suffer none of these problems. Thus we avoid at least some of the possible pitfalls which can undermine differential age analyses (see the review in Stetson, VandenBerg & Bolte (1996)).

Earlier studies which specifically addressed the differential age of the M13/M3 pair have achieved similar results. VandenBerg, Bolte, & Stetson (1990) used the “horizontal” method, in which age is derived from the color difference between the turnoff and the lower RGB. Unfortunately, the CMDs available to them that also had well-defined turnoffs had very sparsely populated RGB’s. They estimated that M13 was 0.9–2 Gyr older than M3. The “vertical” or $\Delta V_{TO}^{HB}$ method, using the magnitude difference between the turnoff and RR Lyrae to determine age, has suffered from the fact that M13 has few RR Lyrae which might well be evolved and thus more luminous than the M3 RR Lyrae. Our results confirm that the reddest HB stars in M13 are significantly evolved away from the ZAHB. Catelan & de Freitas Pacheco (1995) have used theoretical HB models to correct for this and offer a very detailed discussion of relative age of the pair. They conclude that there is essentially no age difference with an error of $\pm 3$ Gyr. Chaboyer, Demarque & Sarajedini (1996) estimate, based on the $\Delta V_{TO}^{HB}$ technique, that M13 is $\sim 5$ Gyr older than M3.

We conclude in concordance with Stetson, VandenBerg & Bolte (1996) that 2 Gyr is an upper bound to the age difference.

Could age be responsible for the dramatically different HB morphologies? The work of Catelan & de Freitas Pacheco (1995) implies otherwise, and our data adds force to this conclusion. The extended tail we have observed in M13 implies the presence of very low mass HB stars. To produce such stars by “aging” M3 would require a large change in turnoff mass (and thus age). The required age difference would be even larger than the $\sim 5$ Gyr found by Catelan & de Freitas Pacheco (1995) from synthetic HB models. Whitney et al. (1997) using HB Hess diagrams obtain a similar estimate. In addition, they find that the mass dispersion would have to be more than twice as large in M13 as in M3. Simple measures of HB morphology such as that of Lee et al. (1994), which measure the ratio of stars relative to the RR Lyrae strip, can change dramatically within 2 Gyr. These parameters, however, do not adequately represent the differences in the HBs of M13 as compared to M3. Since an age difference large as the $\sim 5$ Gyr required to model the observed HB distributions seems to be ruled out, we conclude that age cannot be the driving second parameter, at least not for this classic pair.

Fusi Pecci et al. (1993) have shown that some second parameter characteristics, especially long blue HB tails, are correlated with cluster structural pa-
Table 1
Basic Information on the Target Clusters

|                  | M3    | M13   | Ref. |
|------------------|-------|-------|------|
| \((m - M)_V\)    | 15.05 | 14.35 | (1)  |
| \(E(B - V)\)     | 0.01  | 0.02  | (1)  |
| \([\text{Fe/H}]\) | -1.47 ± 0.01 | -1.51 ± 0.01 | (2) |
| \((15 - V)_0\)   | 3.41  | 1.63  | (3)  |
| \(c\)            | 1.85  | 1.5   | (4)  |
| \(\log \rho_0\)  | 3.5   | 3.4   | (4)  |
| \(\log (M/M_\odot)\) | 5.8 | 5.8   | (4)  |
| \(\epsilon\)     | 0.04  | 0.11  | (5)  |

(1) Peterson (1993)
(2) Kraft et al. (1992)
(3) Dorman, O’Connell, & Rood 1995
(4) Trager et al. (1993)
(5) White & Shawl (1987)

Fig. 3.— Ridge lines for the principal sequences in M3 (solid line) and M13 (dashed line) superposed by a shift of 0.6 mag. in the \(U, U - V\) panel (a) and \(V, U - V\) panel (b) CMDs. The observed difference between the HB and SGB (\(\Delta U\)) is indicated.

rameters like central density. Yet M3 & M13 have structural parameters that are identical within the errors (Table 1). So again for this pair, the second parameter is not associated with central density or concentration.

The similarity of the structural parameters raises questions about the origin of the BSS. BSS are thought to originate from stellar collisions and/or merging primordial binaries. Ferraro et al. (1997a) argue that the radial distribution and luminosity functions of the M3 BSS are consistent with a collisional origin for the central BSS and a merged-binary origin for those in the outer cluster. A paucity of BSS in the exterior of M13 could arise either because there were fewer binaries to begin with or because the binaries were destroyed. However, the low specific frequency of central BSS in M13 as compared to M3 is very puzzling. Perhaps, the mechanism producing BSS in the central region of M3 is more efficient than in M13 because M3 and M13 are experiencing different dynamical evolutionary phases. Alternatively, Bailyn & Pinsonneault (1995) have suggested that M3 is in a short lived phase of its dynamical evolution during which its population of primordial binaries in being rapidly converted to BSS.
It is also interesting to note that blue tails do not seem to correlate with BSS either in position within a given cluster or from cluster to cluster (Sosin et al. 1997). This suggests that BT’s do not arise from binary stars or stellar interactions.

What are known differences between M3 & M13?

Peterson, Rood, & Crocker (1995) showed that perhaps 1/3 or M13’s HB stars had relatively rapid rotation, whereas no rapid rotators were found in M3. Also supporting the idea that M13 stars on the average rotate more rapidly than those in M3 are the observations of Kraft et al. (1992) and Smith et al. (1996). They find evidence for substantially more processing of CNO elements in the envelopes of M13 RGB stars than those in M3. This mixing of processed material to the surface could be plausibly linked to rotation. Stellar rotation has long been suggested as a mechanism to enhance mass loss (Renzini 1977, Fusi Pecci & Renzini 1978, Peterson et al. 1995) which would produce a bluer HB. It is not obvious how it would relate to BSS production efficiency. M13 is more elliptical than M3. Norris (1983) noted a possible correlation between HB morpholgy, rotation and ellipticity. In the case of M13, Lupton, Gunn, & Griffin (1987) show that the ellipticity is related to the overall rotation of the cluster at a rate about 5 km sec\(^{-1}\). It is not clear that cluster rotation would affect rotation of individual stars or that rotation rates set at the time of stellar formation would “be remembered” in later stages of evolution (e.g., Pinsonneault et al. 1989). We mention rotation and ellipticity only because they are among the few parameters which have been observed to differ both in the mean between the clusters and on a star-to-star basis.

Catelan & de Freitas Pacheco (1995) also noted the difference in RGB CNO processing in their study of M3 & M13. They searched for similar correlations in other clusters. In particular they note that the most highly processed super-oxygen-poor stars (SOP) of Kraft et al. (1992) are found only in clusters with very blue HBs. Sweigart (1997) has outlined a scheme which would directly connect the SOP phenomenon to bluer HBs. He has pointed out that the higher Na and Al over-abundances in the SOP stars could only arise if helium was being mixed to the surface. The following HB phase of such stars would be bluer and slightly more luminous than for non-He enhanced stars. While He mixing may play a role in the M13/M3 difference we feel it cannot be the whole story. Suppose one considered “processing” an HB by turning on rotation which would lead to mixing in some stars. The non-rotating stars would be unaffected. Basically the red end of the HB would remain relatively unchanged while a blue tail grows. M3 has a significant population of red HB stars and RR Lyrae; M13 does not. To “convert” M3 to M13, all stars would have to undergo helium enhancement. Observations suggest otherwise. Kraft et al. (1992), Smith et al. (1996) find that not all M13 giants are SOP; some have relatively normal O. Some stars reach the HB without significant O processing. Peterson, Rood, & Crocker (1995) find that O in the redder HB stars of M13 is more-or-less normal. Indeed HB stars at a given color in both M3 and M13 have similar O. It seems that one might have to invoke a second “second parameter” beyond helium mixing to explain the M13/M3 pair—a not particularly attractive idea.

In summary, nothing simple works.

We are grateful to Peter Stetson and Don VandenBerg for providing results prior to publication. RTR & BD are supported in part by NASA Long Term Space Astrophysics Grant NAG5-700 and NAGW-4106 and STScI/NASA Grant GO-5903. The financial support by the Agenzia Spaziale Italiana (ASI) is gratefully acknowledged.

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