FAR-ULTRAVIOLET OBSERVATIONS OF THE GLOBULAR CLUSTER NGC 2808 REVISITED:
BLUE STRAGGLERS, WHITE DWARFS, AND CATACLYSMIC VARIABLES

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ABSTRACT

We present a reanalysis of far-ultraviolet (FUV) observations of the globular cluster NGC 2808 obtained with the Hubble Space Telescope. These data were first analyzed by Brown and coworkers, with an emphasis on the bright, blue horizontal-branch (HB) stars in this cluster. Here, our focus is on the population of fainter FUV sources, which include white dwarfs (WDs), blue stragglers (BSs), and cataclysmic variables (CVs). We have therefore constructed the deepest FUV – NUV color-magnitude diagram of NGC 2808 and searched for variability among our FUV sources. Overall, we have found ~40 WD, ~60 BS, and ~60 CV candidates; three of the BSs and two of the CV candidates are variable. We have also recovered a known RR Lyrae star in the core of NGC 2808, which exhibits massive (~4 mag) FUV variability. We have investigated the radial distribution and found that our CV and BS candidates are more centrally concentrated than the HB stars and WD candidates. This might be an effect of mass segregation but could as well be due to the preferential formation of such dynamically formed objects in the dense cluster core. For one of our CV candidates we found a counterpart in WFPC2 optical data published by Piotto and coworkers.

Subject headings: blue stragglers — globular clusters: individual (NGC 2808) — novae, cataclysmic variables — white dwarfs

Online material: machine-readable table

1. INTRODUCTION

Globular clusters (GCs) are old, gravitationally bound stellar systems whose core stellar densities can be extremely high, reaching up to \(10^6\) stars pc\(^{-3}\). In such an environment, close encounters and even direct collisions with resulting mergers between the cluster stars are quite common, leading to a variety of dynamically formed stellar objects like blue stragglers (BSs) and close binary (CB) systems. CBs are important for our understanding of GC evolution, since the binding energy of a few very close binaries can rival that of a modest-sized GC. Thus, by transferring their orbital energy to passing single stars, CBs can significantly affect the dynamical evolution of the cluster (e.g., Elson et al. 1987; Hut et al. 1992 and references therein). This depends critically on the number of CBs. If there are only a few CBs, long-term interactions dominate the cluster evolution. By contrast, the presence of many CBs leads to violent interactions, which heat the cluster and promote its expansion and evaporation.

Interacting CBs form a particularly interesting subset of CBs and can in principle also be used as tracers of a cluster’s CB population. The best-known formation channel for interacting CBs in GCs is tidal capture of a red giant or main-sequence (MS) star by a compact object (Fabian et al. 1975). This scenario was originally proposed to account for the overabundance of low-mass X-ray binaries (LMXBs) containing accreting neutron stars (NSs) in GCs, relative to the galactic field. However, tidal capture theory predicts a comparable overabundance of interacting CBs with a white dwarf (WD) primary, i.e., cataclysmic variables (CVs). Since WDs are far more common than NSs, we would then also expect many more CVs than LMXBs in GCs. More recently, it has been realized that three-body encounters (e.g., Davies & Benz 1995) and ordinary evolution of primordial binaries (e.g., Davies 1997) may also produce significant populations of CVs in GCs. CVs produced from primordial binaries are expected mainly in the outskirts of clusters, whereas CVs formed dynamically (through tidal capture or three-body processes) should be found preferentially in the dense cluster cores. Thus, the observation of the relative abundances and distribution of CVs within a cluster’s core and halo can tell us about the relative efficiency of these different CV formation scenarios.

However, despite their impact on cluster evolution and their importance for our understanding of CB formation and evolution channels, there have been only a few detections of interacting CBs in GCs during the past few decades. Finding and studying these systems has proven to be extremely difficult, since the spatial resolutions and detection limits of most available telescopes are too limited for their detection. Only with the improved sensitivity and imaging quality of Chandra and the Hubble Space Telescope (HST) has it become possible to finally detect significant numbers of CVs and other binary systems in GCs (e.g., Grindlay et al. 2001; Albro et al. 2001; Edmonds et al. 2003a, 2003b; Knigge et al. 2002, 2003 and references therein).

1 Based on observations made with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under NASA contract NAS5-26555.
Far-ultraviolet (FUV) imaging is particularly well suited for the detection of CVs (and also BSSs and young WDs) in GC cores. This is because these objects are characterized by relatively blue spectral energy distributions and emit significant amounts of radiation in the FUV. By contrast, the ordinary stars that make up the bulk of the cluster are too cool to show up in observations at such short wavelengths. As a consequence, crowding is not a severe problem in FUV imaging studies of GCs, even in the dense cluster cores. This is a significant advantage compared to optical GC surveys.

To date, the only deep FUV study of a GC with the principal purpose of identifying CVs (as well as BSSs and WDs) has been that of 47 Tuc (Knigge et al. 2002, 2003). There we found 16 CV candidates (including four variable objects that were previously known or suspected CVs), 19 BSSs (including four variables), and 17 hot WDs. The population of CV candidates was particularly interesting, since their number was broadly consistent with tidal capture predictions (but note that most of these candidates have not yet been confirmed).

Here we present a reanalysis of HST-based FUV observations of another GC, namely, NGC 2808 (α = 09h12m02s, δ = −64°51′47″). This intermediate-metallicity GC ([Fe/H] = −1.36; Walker 1999) lies at a distance of 10.2 kpc and is reddened by $E(B - V) = 0.18$ ± 0.01 mag (Bedin et al. 2000). The cluster has a very dense and compact core, with a core radius of 0″26 and a tidal radius of 15″55 (Harris 1996).

The data set that we analyze in the following has already been studied by Brown et al. (2001), but with a focus on the bright, blue horizontal-branch (HB) stars in the cluster core. More specifically, Brown et al. (2001) discovered a population of subluminous HB stars in NGC 2808 that might have undergone a late helium flash while descending the WD cooling curve. By contrast, here we are mainly interested in the dynamically formed stellar populations (CVs and BSSs), as well as the young WDs in this cluster. Since these are faint objects and normally difficult to detect, we first construct a new, deep color-magnitude diagram (CMD) in which many of these objects show up and then search for variability among our FUV sources (since this is ubiquitous among CVs and is also seen in BSSs located in the instability strip).

In § 2, we discuss the data and the data reduction. In § 3, we present our far- versus near-ultraviolet (FUV – NUV) CMD and describe our search for variability among our catalog stars. Our results are summarized in § 4.

2. OBSERVATIONS AND DATA REDUCTION

NGC 2808 was observed with the Space Telescope Imaging Spectrograph (STIS) on board the HST in 2000 January–February. The original purpose of these observations was to provide geometric distortion corrections for the STIS camera. However, such calibration data are of course also of scientific interest, as already shown by Brown et al. (2001). Images were taken using the F25QTZ and F25CN270 filters, which are located in the far- and near-UV wavebands, with central wavelengths of 1590 Å (FUV, F25QTZ) and 2700 Å (NUV, F25CN270), respectively. The plate scale is 0″0248 pixel$^{-1}$, resulting in a field of view of 25″ × 25″ for both filters. The exposure times for the single exposures vary between 480 and 538 s. The observations were positioned on the cluster center; Figure 1 shows the combined images. The mosaic images were constructed using MONTAGE2 (Stetson 1994), which registers all the image frames to a single reference frame, incorporating shift, scale, rotation, and distortions determined from positions of the brightest stars.

The resulting FUV and NUV mosaic images show a strange shape that is due to the small offsets and rotation of the single exposures with respect to each other. The diameter of the mosaic is ≈2100 pixels or ≈52″. Since the cluster’s core radius is 16″, the complete core is covered by our mosaic images.

As can be seen immediately, the NUV mosaic is extremely crowded. On the other hand, crowding is not a problem in the
FUV image. Note that the effective exposure times vary strongly across both mosaics. This is responsible for the increased background noise in the outskirts of the mosaics, where exposure times are low compared to those in the central regions (which have maximum exposure times of 8906 s [NUV, F25CN270] and 8916 s [FUV, F25QTZ]).

2.1. Source Detection

As already mentioned in § 1, we reinvestigate the same data set studied by Brown et al. (2001), but with a different focus. Here our main goal is to search for faint and/or variable FUV sources (CVs, BSSs, and WDs). We therefore take special care to detect even weak sources in the FUV images, which allows us to construct a very deep CMD.

As noted above, the exposure time is not uniform across the FUV mosaic, which means that the outer parts of the image (with the lowest exposure times) have the noisiest background. In order to avoid both a large number of false detections in these regions (caused by noise peaks) and multiple detections in the halos of bright stars, we created a noise map, which we used to smooth the image. As a first step, we then used the DAOFIND routine of DAOPHOT (Stetson 1991) running under IRAF2 on smooth the image. As a first step, we then used the DAOFIND routine of DAOPHOT (Stetson 1991) running under IRAF2 on smooth the image to detect FUV sources.3 We overplotted the resulting source coordinates on the FUV mosaic and inspected them by eye. Overall, this source finding technique appeared to work well for bright sources (except for a few multiple detections around bright stars, which we deleted by hand). However, it did not work as well for faint sources, especially in the deep central part of the mosaic. Thus, we added a further 211 sources by hand. In total, our catalog of FUV sources contains 521 entries.

Source detection in the NUV mosaic is a tedious task because of the severe crowding and depends critically on the DAOFIND detection threshold. If the detection threshold is too high, no faint sources are detected in the center of the mosaic (which has maximum exposure time). The situation can be improved by lowering the detection threshold, but this also leads to false detections in the noisy outskirts. (The same is true for the FUV mosaic but is less of a problem, since crowding is much less severe. We could therefore simply adopt a relatively high threshold in DAOFIND and add the missing sources by hand.) However, it is important to realize that our goal is not to detect all NUV sources but to locate NUV counterparts to our FUV sources. In practice, we therefore chose to work with an intermediate threshold, designed to yield most of the detectable NUV counterparts while keeping the number of false detections at bay. This is important, because if there are too many false detections, some are matched erroneously to real FUV sources.

In order to match the FUV and NUV catalogs, we first transformed the NUV coordinates onto the frame of the FUV mosaic. We then checked for common pairs within a tolerance of 1.5 pixels; this resulted in 306 matches. Careful inspection of the registered NUV image around unmatched FUV sources revealed an additional 50 NUV counterparts within this tolerance that had not been detected by DAOFIND. Increasing the tolerance to 2 pixels added another 23 matches. These additional matches are located mainly in the outskirts of the mosaic, where our coordinate transformation is slightly less accurate, thus justifying an increased matching tolerance. All stars listed in Brown et al. (2001) were found in our FUV catalog; however, 25 of them did not have NUV matches within 2 pixels. Closer inspection by eye revealed that these stars are either located in the outer regions of the mosaic and have probable NUV counterparts outside the 2 pixel tolerance radius, or they have faint NUV counterparts that are located in the most crowded inner area and were not initially detected by DAOFIND. We therefore added these missing matches by hand.

A catalog listing all our FUV sources is given in Table 1. We include sources without NUV counterparts in Table 1 because these are likely to include additional WD and CV candidates.4 Among the sources with NUV counterparts, we have marked all pairs that were matched with the higher tolerance of 2 pixels or were added by hand. In total, our catalog contains 521 FUV sources, including 403 with NUV counterparts. All 295 sources listed in Brown et al. (2001) are also contained in our catalog.

2.2. Aperture Photometry

Aperture photometry was obtained using DAOPHOT (Stetson 1991). Following Brown et al. (2001), we chose an aperture radius of 4 pixels and used an annulus of between 4 and 10 pixels for sky subtraction. An exposure map was created that accounts for the different exposure times at different locations in the composite image. For the calibration to the STMAG system we used the aperture corrections derived by Brown et al. (2001), namely, 1.83 and PHOTFLAM of 1 $10^{-16}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (counts s$^{-1}$)$^{-1}$ for the F25QTZ data and 1.44 and PHOTFLAM of 3.92 $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (counts s$^{-1}$)$^{-1}$ for the fluxes obtained with F25CN270.5

The results of aperture photometry depend on the coordinates of the source that has to be measured, or, to be more precise, on the “centering.” Several centering algorithms are available under PHOT in DAOPHOT running under IRAF. Brown et al. (2001) created their coordinate list by centering on each star by eye. We used their photometry as a point of reference and hence adopted a Gaussian centering algorithm, since this yielded the best agreement with their measurements. Figure 2 displays the magnitude differences between our photometry and that of Brown et al. (2001) in both the FUV and NUV bands. Overall, the agreement is very good, with a few notable exceptions discussed below.

For star 516 (No. 29 in Brown et al. 2001), the difference between our photometry and that of Brown et al. (2001) is 0.6 mag in the FUV. This star is located in the outer regions of the FUV mosaic and appears somewhat elongated. This might be because the object is a blend of two sources or because the point-spread function (PSF) is smeared out since the coordinate transformations used to construct our mosaic are least reliable in the outermost regions of the image. The latter effect would be exacerbated by the asymmetric FUV PSF and might cause the brightness to be underestimated when using a small aperture of only 4 pixels. The situation is similar for star 500 (No. 13 in Brown et al. 2001), which is 0.45 mag fainter in our photometry, is also located close to the edges of the mosaic, and appears somewhat elongated. However, a difference greater than 0.1 mag in the FUV occurred for only 17 stars, and a difference greater than 0.15 mag occurred for only five stars.

4 An FUV source may lack an NUV counterpart because (1) it is too faint and blue to show up in the NUV mosaic or (2) a counterpart exists but was not found because of the severe crowding in the NUV image.

5 We noticed a typographical error in Brown et al. (2001), namely, PHOTFLAM in the F25CN270 is 3.92 $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (counts s$^{-1}$)$^{-1}$, not 3.29 $10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ Å$^{-1}$ (counts s$^{-1}$)$^{-1}$.  

2 IRAF (Image Reduction and Analysis Facility) is distributed by the National Astronomy and Optical Observatory, which is operated by AURA, Inc., under cooperative agreement with the National Science Foundation.

3 Note that the smoothed image was only used for source detection; all photometry was performed on the unsmoothed images.
### TABLE 1

**Catalog of All FUV-NUV Sources**

| Number  | α (J2000.0) | δ (J2000.0) | FUV (mag) | ΔFUV (mag) | NUV (mag) | ΔNUV (mag) | δFUV (mag) | δNUV (mag) | Radius (arcsec) | ID (Brown) | ID (Piotto) | V (mag) | B (mag) | Comments^a |
|---------|-------------|-------------|-----------|------------|-----------|------------|------------|------------|----------------|------------|------------|---------|---------|-------------|
| 1........ | 9 12 5.454  | −64 51 26.761 | 20.808 | 0.170 | 22.187 | 0.229 | ... | ... | 26.51 | ... | ... | ... | ... | a |
| 2........ | 9 12 5.313  | −64 51 26.404 | 20.074 | 0.121 | ... | ... | ... | ... | 26.28 | ... | ... | ... | ... | |
| 3........ | 9 12 4.414  | −64 51 25.250 | 21.729 | 0.260 | 19.842 | 0.062 | ... | ... | 24.54 | ... | ... | ... | ... | |
| 4........ | 9 12 5.149  | −64 51 28.025 | 17.131 | 0.023 | 18.415 | 0.022 | 0.029 | −0.025 | 24.34 | 253 | ... | ... | ... | pv |
| 5........ | 9 12 5.969  | −64 51 30.908 | 22.210 | 0.229 | 23.169 | 0.379 | ... | ... | 25.69 | ... | ... | ... | ... | pv |
| 6........ | 9 12 4.898  | −64 51 27.503 | 21.911 | 0.198 | ... | ... | ... | ... | 23.92 | ... | ... | ... | ... | |
| 7........ | 9 12 6.306  | −64 51 32.282 | 18.579 | 0.044 | 20.252 | 0.073 | 0.261 | −0.152 | 26.50 | 289 | ... | ... | ... | |
| 8........ | 9 12 5.210  | −64 51 28.903 | 16.468 | 0.017 | 16.938 | 0.011 | 0.112 | 0.022 | 23.88 | 256 | ... | ... | ... | pv, e |
| 9........ | 9 12 6.131  | −64 51 32.254 | 16.448 | 0.017 | 17.148 | 0.012 | 0.032 | −0.088 | 25.63 | 287 | ... | ... | ... | e |
| 10......... | 9 12 5.059  | −64 51 28.739 | 18.869 | 0.050 | 18.425 | 0.022 | −0.019 | −0.065 | 23.43 | 252 | ... | ... | ... | |
| 11......... | 9 12 4.342  | −64 51 26.459 | 16.422 | 0.023 | 17.003 | 0.016 | 0.108 | −0.033 | 23.26 | 219 | ... | ... | ... | n, e |
| 12......... | 9 12 6.749  | −64 51 34.589 | 16.458 | 0.023 | ... | ... | ... | ... | 27.63 | ... | ... | ... | ... | |
| 13......... | 9 12 4.119  | −64 51 25.910 | 21.532 | 0.275 | ... | ... | ... | ... | 23.26 | ... | ... | ... | ... | |
| 14......... | 9 12 5.746  | −64 51 31.458 | 20.506 | 0.105 | 19.294 | 0.033 | ... | ... | 24.27 | ... | ... | ... | ... | pv |
| 15......... | 9 12 5.530  | −64 51 30.936 | 19.978 | 0.082 | 17.486 | 0.014 | ... | ... | 23.65 | ... | ... | ... | ... | pv |
| 16......... | 9 12 3.889  | −64 51 25.800 | 19.452 | 0.091 | ... | ... | ... | ... | 22.96 | ... | ... | ... | ... | |
| 17......... | 9 12 3.460  | −64 51 24.399 | 16.507 | 0.017 | 17.141 | 0.012 | −0.057 | −0.041 | 23.80 | 153 | ... | ... | ... | n, e |
| 18......... | 9 12 3.147  | −64 51 23.712 | 16.475 | 0.023 | 17.072 | 0.016 | −0.005 | −0.032 | 24.31 | 128 | ... | ... | ... | a |
| 19......... | 9 12 3.336  | −64 51 24.893 | 16.422 | 0.016 | 17.201 | 0.012 | 0.018 | −0.071 | 23.20 | 145 | ... | ... | ... | n, e |
| 20......... | 9 12 5.822  | −64 51 33.490 | 16.325 | 0.016 | 16.810 | 0.010 | −0.025 | −0.020 | 23.29 | 280 | ... | ... | ... | |

**Notes.—** FUV and NUV denote the difference between our FUV and NUV photometry and that presented by Brown et al. (2001). Our coordinates (α and δ) are based on the coordinate system given by the FITS headers but have been shifted to achieve the best match to the Brown et al. (2001) coordinates. This required offsets of −0.13 in α and −0.06 in δ, after which the rms differences between our coordinates and those of Brown et al. (2001) are only 0.006 in α and 0.048 in δ. However, as noted in Brown et al. (2001), although the relative astrometry is very accurate, the error in the **absolute** astrometry is much larger (−1′′−2′′). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Col. (10) lists the distance to the cluster center, which we determined from star number counts to be at α = 9h12m27s and δ = −64°51′47.78. The complete catalog is also available at CDS, Strasbourg. Table 1 is presented in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

^a Notes to col. (15): (a) The tolerance radius for matching these sources in the FUV and NUV was increased from 1.5 to 2 pixels. (n) These pairs were added by hand; see text for details. (e) These stars show a somewhat elongated shape on the FUV mosaic and are located mainly in its outer regions. (v) Good variable candidate; see text for details. (pv) Possible variable candidate, but too few measurements for a reliable statement. (nv) Unsure variable candidate; measurements on the single images agree within the errors. (pv-f) Unsure variable candidate: faint companion to a bright star. Measurements on the single images are extremely difficult and thus not very reliable.
For the NUV, we found a magnitude difference of 0.985 mag for star 426 (No. 189 in Brown et al. 2001). This seems to be a case in which Brown et al. (2001) matched a different NUV source than we did. Although we are quite confident that we correctly matched most of the stars in the FUV and NUV, this discrepancy is a useful reminder that occasional mismatches might still occur because of the extreme crowding in the NUV images. This is especially true for fainter sources, and mismatches probably contribute to the rising NUV differences toward fainter magnitudes. However, differences greater than 0.15 mag occurred for only 18 stars in the NUV. Setting aside these extreme cases, the mean absolute differences between the magnitudes of Brown et al. (2001) and ours are 0.03 ± 0.03 mag in the FUV and 0.03 ± 0.02 mag in the NUV. Thus, in general, there is good agreement between their catalog and ours. The remaining differences can be explained by the different methods used to construct the mosaic images and detect the sources, the different centering algorithms for the photometry, and the severe crowding in the NUV images.

3. RESULTS AND DISCUSSION

3.1. The FUV—NUV CMD

Figure 3 shows the FUV—NUV CMD of the core region of NGC 2808. Several distinct stellar populations can be seen, including blue HB stars, BSs, WDs, and CV candidates. Our CMD reaches approximately 2 mag deeper than that presented by Brown et al. (2001). This is because we took special care in detecting faint sources in the FUV mosaic (see § 2.1). We also note...
that we plot all sources independent of their photometric errors, whereas Brown et al. (2001) only included sources satisfying \( m < 22 \text{ mag} \) and \( \sigma_m < 0.2 \text{ mag} \) in both the FUV and NUV. However, we stress that only seven of the sources plotted have errors exceeding 0.2 mag in the FUV, and all of these have errors in the range 0.2–0.3 mag. We therefore still regard these as significant detections.

To aid in the interpretation of the CMD, we have also calculated and plotted a set of theoretical tracks. In the following, we first briefly describe the construction of the theoretical tracks and then discuss the various stellar populations within our CMD.

3.1.1. Synthetic Photometry

Since MS stars and red giants are too cool to show up in our CMD, we only present theoretical tracks for the zero-age horizontal branch (ZAHB), the zero-age main sequence (ZAMS), and the WD cooling curve in NGC 2808. For all our synthetic tracks, we adopted a distance of 10.2 kpc and a reddening of \( E(B - V) = 0.18 \pm 0.01 \) (Bedin et al. 2000).

For our ZAHB track, we interpolated on the grid of oxygen-enhanced ZAHB models provided by Dorman (1992) to generate a set of models\(^6\) at the cluster metallicity of \([\text{Fe/H}] = -1.36\). We then used SYNPHOT within IRAF STSDAS to calculate the FUV and NUV magnitudes of stars on this sequence. This was achieved by interpolating on the Kurucz grid of model stellar atmospheres and folding the resulting synthetic spectra through the response of the appropriate filter+detector combinations.

The ZAMS is included because BSs are expected to lie near and slightly to the red of this sequence. In order to generate this track, we used the fitting formulae of Tout et al. (1996) to estimate the appropriate stellar parameters. The corresponding FUV and NUV colors were then again estimated from the Kurucz model grid within SYNPHOT.

Finally, our theoretical WD sequence was constructed by interpolating on the Wood (1995) grid of theoretical WD cooling curves, adopting a mean WD mass of 0.55 \( M_\odot \). The models were then again translated to the observational plane by carrying out synthetic photometry with SYNPHOT, using a grid of synthetic DA WD spectra kindly provided by B. Gänsicke (see Gänsicke et al. 1995).

3.1.2. HB Stars

NGC 2808 is one of the most extreme examples among the GCs with unusual HB morphology, as first noted by Harris (1974). Since then this cluster has received considerable attention. In general, metallicity is regarded to be the first parameter that influences HB morphology. However, several GCs show different HB morphologies, although their metallicities are similar (Rich et al. 1997). This led to the suggestion of a second parameter responsible for the unusual behavior of the HB stars in these clusters. Many parameters have been suggested (e.g., age, mass loss, and stellar rotation), but a thoroughly convincing explanation is still lacking (see, e.g., Rood et al. 1993; Recio-Blanco et al. 2004). NGC 2808 shows a bimodal HB and one of the longest blue HB tails, the so-called extreme HB (EHB), with prominent gaps between the red HB (RHB), blue HB (BHB), and EHB (e.g., Clement & Hazen 1989; Ferraro et al. 1990; Byun & Lee 1991; Sosin et al. 1997; Walker 1999; Bedin et al. 2000). Only three other GCs are known that show bimodal HBs, as well as gaps along their HBs, namely, NGC 6229, NGC 6388, and NGC 6441 (Catelan et al. 1998). Sosin et al. (1997) discussed various mechanisms that might be responsible for the HB multimodality, none of which represents a satisfactory explanation. They suggested that a combination of effects might result in such an HB morphology, some of which might be unique to NGC 2808.

In our CMD, the two distinct clumps of bright stars around FUV \( \sim 16 \text{ mag} \) correspond to the blue (FUV \( - \text{NUV} \sim -0.7 \text{ mag} \)) and extreme (FUV \( - \text{NUV} \sim -1.2 \text{ mag} \)) HB stars. The red HB stars are too cool to show up in the FUV or NUV images. As already reported by Brown et al. (2001), a gap within the EHB, as seen in optical CMDs for this cluster, is not evident in the FUV \( - \text{NUV} \) CMD. Instead, the EHB clump is extended toward fainter magnitudes. Brown et al. (2001) suggested that these subluminous EHB stars (as well as the EHB gap in the optical CMDs) can be explained by a late helium core flash that these stars undergo while they descend the WD sequence. The recent findings of Moehler et al. (2004) and Momany et al. (2004) generally support this theory. For a comprehensive analysis of the HB stars in the FUV \( - \text{NUV} \) CMD, we refer the reader to Brown et al. (2001).

3.1.3. Blue Stragglers

A trail of stars can be seen in Figure 3, starting from the BHB clump and reaching down below the theoretical ZAHB sequence toward the faint red corner of our CMD. These sources show magnitudes fainter than the ZAHB but brighter than the ZAMS. The location of these objects agrees with the expected location of BSs, which are thought to be dynamically formed objects resulting from a collision or coalescence of two or more MS stars. They are more massive than normal cluster MS stars, and therefore we expect them to be already somewhat evolved. This explains their location slightly above and to the red of the ZAMS. We find 61 BS candidates, but we caution that this should not be taken as a strict number, since the various zones in our CMD partly overlap and the discrimination between the CV and BS candidates, in particular, is difficult (see below).

3.1.4. White Dwarfs

Figure 3 reveals a population of 40 objects that lie near the theoretical cooling curve and are therefore probably hot young WDs. Of these, 22 are brighter than FUV \( \sim 21 \) and should be detectable across the full FUV and NUV mosaics. How many WDs should we expect to see? Following Knigge et al. (2002), we can obtain a simple estimate by scaling from the number of HB stars in the same field of view. We count \( \approx 210 \) BHB and EHB stars in our CMD, but, as noted above, RHB stars are too cool to show up. We therefore estimate the total number of HB stars by adopting the ratio of (RHB + BHB + EHB)/(BHB + EHB) = 1.86 found by Sosin et al. (1997). We therefore expect a total of \( \approx 390 \) HB stars in our field of view. Given that the lifetime of stars on the HB is approximately \( \tau_{\text{HB}} \approx 10^8 \text{ yr} \) (e.g., Dorman 1992), we can predict the number of WDs above a given temperature on the cooling curve from the relation

\[
\frac{N_{\text{WD}}}{N_{\text{HB}}} \approx \frac{\tau_{\text{WD}}}{\tau_{\text{HB}}},
\]

where \( \tau_{\text{WD}} \) is the WD cooling age at that temperature (e.g., Knigge et al. 2002). WDs at FUV \( \sim 21 \text{ mag} \) on our WD sequence

\(^6\) We note that the Dorman (1992) grid only extends to the blue HB, not the extreme HB (EHB). For a detailed analysis of EHB stars in NGC 2808, the reader is referred to Brown et al. (2001).
have a temperature of $T_{\text{eff}} = 38,000$ K and a corresponding cooling age of $\tau_{\text{WD}} \approx 4 \times 10^6$ yr. We therefore predict a population of approximately 16 WDs brighter than FUV $= 21$, which is in reasonable agreement with the observed number of 22. This strongly suggests that most of our candidates are indeed WDs.

3.1.5. CV Candidates

Figure 3 reveals quite a number of stars that are located between the WD and ZAMS tracks. This is a region in which we might expect to find CVs. We estimate that there are $\approx 60$ sources in this “CV zone.” How does this number compare to theoretical predictions? We can attempt to answer this question by scaling the number of tidal capture CVs predicted for 47 Tuc to NGC 2808. To this end, we use the simplified estimate for the capture rate in GC cores (Heinke et al. 2003),

$$\Gamma \propto \rho L_{\text{c}}^5 r_c^2,$$

where $\rho$ is the central luminosity density and $r_c$ is the core radius. On this basis, we find that the total number of dynamically formed CVs in NGC 2808 should be quite similar to 47 Tuc, for which Di Stefano & Rappaport (1994) predicted a population of $\approx 190$ active CVs formed via tidal capture. For 47 Tuc, Di Stefano & Rappaport (1994) found that approximately half of the captures would take place within one core radius. A CV formed outside the core drifts toward the center because of mass segregation. Thus, a given active CV should be found in the core today if its age exceeds the relaxation timescale at the location where it formed. Given our detection limits, we cannot hope to detect the very oldest CVs, since these are also the faintest. In order to obtain a rough estimate, we assume that we can detect most CVs whose secondaries have not yet been whittled down to brown dwarfs, but none of the latter. Thus, our dividing line is between CVs whose orbital periods are still decreasing and the so-called period bouncers, whose periods are lengthening (see Di Stefano & Rappaport 1994 for details). On the basis of Figure 2 in Di Stefano & Rappaport (1994), the oldest CVs we can detect therefore have ages on the order of $10^9$ yr. This is comparable to the relaxation timescale at the half-mass radius of NGC 2808, so some, but probably not all, dynamically formed active CVs should have had time to reach the core. Given this ambiguity, we assume that between 50% and 100% of the active CVs in NGC 2808 should be within our field of view. However, only about half of these are above our adopted detection limit, yielding a final prediction of between 45 and 95 CVs. We stress that this is an extremely rough estimate, but it does bracket the observed number of sources in our CV zone. Thus, a significant fraction of these candidates might indeed be CVs.

We caution that other sources might also occupy our CV zone. We have to consider the possibility that mismatches might have occurred, although special care has been taken in detecting and matching the FUV and NUV sources (see §3.1.2). Noninteracting WD-MS binaries without accretion would also lie in the CV zone. However, according to our ZAMS, a turnoff star with a mass of $0.85 M_\odot$ would have an NUV magnitude of $\approx 23$. These objects would therefore be expected in the CV zone but close to the WD cooling sequence, where we find about 10 objects. If we do not consider these 10 sources, our number of CV candidates would be rendered to $\approx 50$, which is still consistent with our above estimates. In principle, our CMD may also contain background or foreground sources. However, we expect the field star contamination to be negligible (see, e.g., Ratnatunga & Bahcall 1985).

3.1.6. Cumulative Distributions of the Stellar Populations

Figure 4 shows the cumulative radial distributions of the stars that show up in our CMD. We distinguish between HB stars (dotted line), CV candidates (dot-dashed line), WD candidates (long-dashed line), and BS candidates (short-dashed line). Figure 4 (top) shows the distribution if all stars of the corresponding population are considered, independent of their magnitude. However, as pointed out in §2.1, the exposure time is not uniform across our mosaic; thus, the detection limit also varies across the mosaic. For the outermost regions with the lowest exposure time, all sources at least down to FUV $= 21$ mag are detected. We try to avoid selection effects by adopting this as a limiting magnitude for our entire data set. Figure 4 (bottom) shows the cumulative distributions of the magnitude-selected data.

The most striking differences seem to be between our HB stars and WD candidates, which show the least central concentration, and the BSs and CV candidates, which appear to be the most centrally concentrated populations. This is in agreement with Walker (1999) and Bedin et al. (2000), who presented deep wide-field photometry and found no radial gradient in the distribution of the EHB stars. In order to compare the cumulative distributions and to establish the statistical significance of the differences between them, we applied a Kolmogorov-Smirnov (K-S) test to the magnitude-selected data set. However, we caution that the WD, CV, and BS candidates cannot clearly be distinguished on the basis of our CMD alone; i.e., we might have sources in one sample that actually belong to another one. Applying the magnitude selection to our data yields 22 WD,

\[ \ldots \]
30 BS, and 16 CV candidates. The HB stars are brighter than our selection criterion, and 209 of them are present in our field of view.

The K-S test returns the probability that the maximum difference between the two distributions being compared should be as large as that observed, under the null hypothesis that the distributions are drawn from the same parent populations. According to this, the distributions of HB stars and WDs are consistent with one another, with a K-S probability of 64.7%. However, the distributions of BS and CV candidates differ significantly from those of the other two populations, with K-S test probabilities of 1.0% (CVs vs. HB stars), 0.5% (CVs vs. WDs), 0.4% (BS vs. HB stars), and 1.2% (BSs vs. WDs). The differences between the CV and BS distributions are not statistically significant, with a K-S probability of 49.3% (CVs vs. BSs).

The differences in the observed distributions might reflect the different masses of the various FUV populations. More specifically, CVs and BSs are expected to be considerably more massive than WDs and HB stars, since CVs are WD-MS binaries and BSs are, roughly speaking, MS stars with masses above the cluster MS turnoff. The heavy CVs and BSs thus sink toward the cluster core and as a result are more centrally concentrated than the lighter WDs and HB stars. Figure 4 shows that the differences revealed by the K-S test are indeed in the expected direction.

On the other hand, CVs and BSs are believed to be objects formed through two- or three-body interactions such as tidal capture, collisions, and mergers. These dynamical interactions take place preferentially in the dense cluster core. Thus, CVs and BSs may also be expected to be overabundant in the cluster core because that is their birthplace.

In either case, the enhanced central concentration of our CV candidates provides additional evidence that most of these sources are indeed CVs or noninteracting WD-MS binaries (as opposed to chance superpositions, foreground stars, etc.); i.e., they either segregated toward the cluster center or they formed in the dense core region.

### 3.1.7. FUV Sources with Optical Counterparts

Piotto et al. (2002) presented optical photometry for 74 GCs, among them NGC 2808. The clusters were observed with the *HST* Wide Field Planetary Camera 2 (WFPC2) in the F439W and F555W bands, with the Planetary Camera (PC) centered on each cluster’s center. We searched for optical counterparts to our FUV sources in their data set, using XXXYMATCH within IRAF. The transformation between the PC and the STIS physical coordinate systems is tied to three HB stars as reference objects that could be clearly identified by eye in both the F555W and the FUV images. Following Knigge et al. (2002), we allowed for a maximum difference of 0.8 PC pixels (corresponding to 1.5 STIS pixels). In total, we found 97 counterparts to our FUV sources. Out of these, nine are matches with MS stars, red giants, or RHB stars. These stars are too cool to show up in our FUV − NUV CMD, and thus these matches have to be explained otherwise. There are 13,156 objects in the PC field of view in both optical bands, and the complete PC field is covered by our FUV mosaic. In addition, 390 FUV sources are located inside the area covered by the PC data. Following the same statistical approach as in Knigge et al. (2002), we expect up to 13 false matches. Thus, all the matches with MS stars and red giants can be explained statistically as false matches. The remaining 88 matches are all blue objects, either BHB, EHB, or BS stars.

![Figure 5](image.png)

**Figure 5.**—Mean magnitudes vs. the $\sigma_{\text{mean}}$ derived from the individual photometries for each star.

We marked all our FUV sources for which we could find a blue optical counterpart as crosses in our FUV − NUV CMD and added their optical magnitudes and identification number from Piotto et al. (2002) to our Table 1. As can be seen, one of our CV candidates, our star 170, does have an optical counterpart with $V = 21.59$ mag and $B - V = -0.24$ mag. The blue optical color of the counterpart (well off the cluster MS) and the quality of the FUV-optical match (the FUV and optical positions agree to within 0.4 pixels) both suggest that the counterpart identification is secure.

### 3.2. Variability

As a first check for possible variability among our catalog stars, we performed photometry on all single FUV images. For this purpose we first used the processed images that had been used to create the mosaic; i.e., these images were shifted and rotated to a common logical (i.e., image pixel) coordinate system. The great advantage is that we can use our coordinate list derived from the FUV mosaic as an input to all of these processed images. The photometry was carried out in the same way as described above in § 2.2. Of course, only a fraction of our catalog stars are present in each of the individual images, and for some stars we could obtain only one measurement.

Figure 5 displays a plot of the mean magnitudes versus the corresponding $\sigma_{\text{mean}}$ calculated from all individual magnitudes derived for each star. As can be seen, some of our objects show a considerably higher $\sigma_{\text{mean}}$ than the majority. The crosses in Figure 5 denote 28 objects that show a large $\sigma_{\text{mean}}$ compared to their companions with similar brightness, and which we chose to inspect more closely. We cross-checked our method using median (instead of mean) magnitudes and $\chi^2$ (instead of $\sigma_{\text{mean}}$). In each case the same stars show an excess $\sigma_{\text{mean}}$ (or $\chi^2$).

As a next step, we used the nonprocessed images to get more precise magnitudes for our 28 variable candidates. This is necessary, because the orientation of the PSF on these images is the same with respect to each image and not rotated as for the processed images that were used for creating the mosaic. Since...
these images now do not share a common logical coordinate system, we had to derive the coordinates for our variable candidates on each single image by using IMEXAM under IRAF. The photometry was carried out in the same way as described in § 2.2.

Stars 79, 114, 175, and 269 of our Table 1 show very high \( \sigma_{\text{mean}} \); however, these stars are located very close to bright stars, which makes it difficult to get accurate coordinates on the single images that have much shorter single exposure times than the mosaic. Consequently, these stars do not stand out as clearly as they do on the FUV mosaic, and sometimes it is not possible to distinguish them from the halo of the nearby bright star. For 18 of the other stars that we selected on the basis of Figure 5, the magnitude scatter either disappears when using the single nonprocessed image photometry, or too few measurements are available for reliable conclusions. However, for none of these 18 sources is a magnitude variation as evident as it is for star 358 (see below). We note that Proffitt et al. (2003) compared observed and predicted count rates in the FUV F25QTZ and found a much larger scatter between observations and predictions than expected from Poisson statistics. Only 6 stars out of the 28 candidates have more than five measurements and a \( \sigma_{\text{mean}} \) well beyond the expected photometric scatter, even if we take the effect described by Proffitt et al. (2003) into account, and we consider these sources “secure” variable candidates. The remaining 22 stars are labeled in Table 1 but are not discussed further here.

NGC 2808 was observed on only four days (2000 January 18 and 19 and February 16 and 20). This period is sufficient to search for signs of variability, but it is somewhat too short and too interrupted to present reliable light curves for our variable candidates. However, Figure 6 shows the magnitudes versus time for the six sources that remain good variable candidates after our analysis of the single, nonprocessed images; i.e., these stars still show a brightness variation that is well outside the expected magnitude scatter.

The six variable candidates are plotted as diamonds in Figure 3. Star 222 lies in the CV zone at FUV – NUV = 0.08 mag, making it a good CV candidate. Star 397 is located close to the WD region in our CMD but could certainly be a CV as well. As mentioned above, the WD and CV zones are likely to overlap and cannot clearly be distinguished on the basis of our CMD alone.

The light curve for star 124 in Figure 6 seems to suggest that this source might be an eclipsing binary, with the beginning of an eclipse indicated at the end of the first observing period. This star is located on our theoretical ZAMS. It is very likely that this star is a BS star, and some BSs are known to be binaries (see Livio 1993 and references therein). Stars 162 and 76 are clearly located in the BS zone of our CMD. Their light curves,
of our variable candidates, located at FUV image o60q52kxq, centered around the same star, which is marked with a black circle in both figures. As can be seen, star 358 has practically vanished.

We have reanalyzed far-UV STIS HST observations of the core region of the globular cluster NGC 2808. These data were first analyzed by Brown et al. (2001) with an emphasis on the bright BHB and EHB stars, whereas our focus has been on the population of fainter FUV sources. Taking special care in detecting the faint FUV sources, we were able to present an FUV – NUV CMD that is ≈2 mag deeper than the one presented by Brown et al. (2001). The overall agreement between their photometry and ours is good.

Various stellar populations show up in our CMD, including the BHB and EHB stars for which this cluster is well known. RHB and MS stars are too cool to show up. However, approximately 60 BS candidates are present in our CMD. About 40 sources are located close to our theoretical WD cooling curve and are probably hot young WDs. We estimated the number of WDs by scaling from the number of HB stars that are present in our field of view and found that approximately 16 WDs can be expected at FUV ≤ 21 mag. This is in reasonable agreement with the observed number of 22 at a completeness limit of 21 mag. Our CMD reveals a number of stars that are located in the CV region between the WD cooling curve and the ZAMS. Approximately 60 sources can be found in this region, but we caution that because of the photometric scatter, discrimination between the individual zones can be difficult. Using a simplified estimate for the capture rate in GC cores (Heinke et al. 2003), we found that the number of dynamically formed CVs in the core of NGC 2808 is comparable to that of 47 Tuc and broadly consistent with the number of candidates we detected. This suggests that many of our candidates might indeed be CVs. The cumulative radial distributions of the individual stellar populations indicate that our BS and CV candidates are more centrally concentrated than HB stars and the WD candidates. This may be a result of mass segregation but might also reflect the fact that CVs and BSs are mostly dynamically formed populations that were preferentially born in the dense cluster core. We compared our FUV data with optical HST WFPC2 data presented by Piotto et al. (2002) and found 88 optical counterparts for our HB and BS stars and for one CV candidate (our star 170).

We searched for variability among our catalog stars and found six good variable candidates. These stars are all located at FUV ≥ 19 mag and are distributed over the entire color range of our CMD. Two variable candidates, stars 222 and 397, lie in the CV zone of our CMD and thus are excellent CV candidates. Stars...
124, 162, and 76 are all located in the BS zone of our CMD. The light curve of star 124 suggests that this source may be an eclipsing binary, whereas the other two stars might be pulsating variables.

The most striking among our variable stars is our star 358. This is the brightest variable in our sample and shows a considerable drop-off of about 4 mag during the observation period. We identified this star as the RR Lyrae star V22 in Corwin et al. (2004). RR Lyrae stars can show large FUV amplitude variations of even up to 6–8 mag (see Downes et al. 2004; Wheatley et al. 2005).

Overall, the results of our study confirm that FUV observations are a powerful tool for studying hot, and especially dynamically formed, stellar populations in the cores of GCs.

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