UIT Detection of Hot Stars in the Globular Cluster NGC 362

Ben Dorman\textsuperscript{1,2}, Ronak Y. Shah\textsuperscript{3}, Robert W. O’Connell\textsuperscript{3}, Wayne B. Landsman\textsuperscript{4}

Robert T. Rood\textsuperscript{3}, Ralph C. Bohlin\textsuperscript{5}, Susan G. Neff\textsuperscript{1}, Morton S. Roberts\textsuperscript{6},

Andrew M. Smith\textsuperscript{1}, and Theodore P. Stecher\textsuperscript{1}

ABSTRACT

We used the Ultraviolet Imaging Telescope during the March 1995 Astro-2 mission to obtain a deep far-UV image of the globular cluster NGC 362, which was formerly thought to have an almost entirely red horizontal branch (HB). 84 hot ($T_{\text{eff}} > 8500$ K) stars were detected within a radius of 8\textquoteleft 25 of the cluster center. Of these, 43 have FUV magnitudes consistent with HB stars in NGC 362 and at least 34 are cluster members. The number of cluster members is made uncertain by background contamination from blue stars in the Small Magellanic Cloud (SMC). There are six candidate supra-HB stars which have probably evolved from the HB. We discuss the implications of these results for the production of hot blue stars in stellar populations.

\textit{Subject headings:} globular clusters: general—globular clusters—individual (NGC 362)—stars: evolution—stars: horizontal-branch—ultraviolet—stars

\textsuperscript{1}Laboratory for Astronomy & Solar Physics, Code 681, NASA/GSFC, Greenbelt MD 20771
\textsuperscript{2}NAS/NRC Resident Research Associate, NASA/GSFC
\textsuperscript{3}Astronomy Dept, University of Virginia, P.O.Box 3818, Charlottesville, VA 22903-0818
\textsuperscript{4}Hughes/STX Corporation, Code 681, NASA/GSFC, Greenbelt MD 20771
\textsuperscript{5}Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218
\textsuperscript{6}National Radio Astronomy Observatory, Charlottesville, VA 22903
1. Introduction

The temperature structure of the horizontal branches of globular clusters is controlled by the distribution of envelope masses of stars as they reach the zero-age-horizontal branch (Rood 1970; Dorman 1992) after losing mass on the red-giant branch (RGB). The mass and metallicity of the envelope govern the temperature of stars on the ZAHB and their later evolution. For $M < 1 M_\odot$, smaller envelopes produce hotter stars, other things remaining constant. All clusters show a spread in HB color which implies a finite range in envelope mass. But clusters have very different HB temperature distributions, some with entirely hot stars and others with entirely cool (i.e. $B - V \gtrsim 0.2$) stars (reviewed in Zinn 1993). This variety of HB morphologies can, in principle, be produced by (i) differences in abundances, which affect the opacity of the envelope or equilibrium in the hydrogen burning shell; (ii) differences in the masses of stars on the RGB due to age, and thus in the HB masses assuming mass loss is similar among clusters, or (iii) variations in net mass loss, amounting to $\sim 0.2-0.4 M_\odot$, during RGB evolution.

Most of the variation in HB morphology among Galactic globular clusters correlates with differences in the mean metal abundance, which has therefore been called the “first parameter”. However, observed differences in HB’s at a given metal abundance imply that it is necessary to invoke at least one more factor, i.e., a “second parameter.” Many argue (e.g., Lee, Demarque, & Zinn 1994) that the “global” second parameter is age, i.e. that in general the underlying cause behind the bluer HBs is a greater age because of (ii) above. The identification of age as the second parameter is, however, highly controversial (e.g., Stetson, VandenBerg, & Bolte 1996).

In this paper we report the detection on far-ultraviolet images of hot HB stars in NGC 362, an important globular cluster well known for having red HB morphology, and in a companion paper (O’Connell et al. 1997) we report similar detections in 47 Tuc. NGC 362 is often compared with NGC 288, which has similar abundance but a blue HB; this pair is one of the most important for second parameter studies (Bolte 1989; Green & Norris 1990; Sarajedini & Demarque 1990; VandenBerg, Bolte & Stetson 1990, Dickens et al. 1991). Ground-based color-magnitude diagrams (CMDs) show that NGC 362 has an almost entirely red HB. Lee, Demarque, & Zinn 1994 using data from Harris (1982) gave its HB type index $(B - R)/(B + V + R) = -0.87$, based on $B : V : R = 3 : 4 : 77$ from photographic data in $R > 1'57$. Harris (1982) detected 3 stars with colors blueward of the instability strip; however radial velocities indicate that the membership of two of these is doubtful (R. C. Peterson 1995, private communication).

The detection of blue HB stars in clusters with red HB’s is important because it implies that RGB mass loss is either bimodal—perhaps the result of more than one mass loss process—or that the range of RGB mass loss is larger than had previously been thought.

2. Observations

We observed NGC 362 with the Ultraviolet Imaging Telescope (UIT) and obtained deep, wide-field images at 1600 Å. The UIT is a 38-cm Ritchey-Chrétien telescope with a 40' diameter field of view and solar-blind detectors for imaging at vacuum-UV wavelengths (see Stecher et al. 1992 for details). It flew as part of the Astro-2 UV observatory on the Space Shuttle Endeavour during 1995 March. The data were recorded on I1a-O film, which was scanned with microdensitometers at 20\(\mu\)m resolution at Goddard Space Flight Center. The resulting density images were converted to intensity, flat-fielded, and flux-calibrated using the batch data reduction procedures developed for the purpose (Hill et al. 1996). The calibration datasets used here are the “Flight 22” versions. The resulting images have a plate scale of $1''14$/pixel. Point sources on the
NGC 362 image have FWHM $\sim 4''$ owing to jitter in the pointing system aboard the Shuttle.

UIT images of NGC 362 were obtained with the far-UV $B5$ filter, which has a peak wavelength $\lambda_0 = 1620 \text{ Å}$ with width $\Delta \lambda = 230 \text{ Å}$ (Stecher et al. 1992). Here, we use the longest exposure for the analysis (frame FUV2897; exposure time 808.5 s) since it is nowhere saturated. Astrometry was obtained using a combination of the Tucholke 1992a and the CCD images of Montgomery & Janes (1994, hereafter MJ94), using objects in common with the HST Guide Star Catalog. The far-UV image of cluster is shown in Figure 1 (Plate X).

Photometry was obtained using an Interactive Data Language (IDL) implementation of DAOPHOT I (Stetson 1987), which has been modified to accommodate the noise characteristics of film. Photometry was performed both using aperture methods and point spread function (PSF) methods, with results that agree within the PSF fitting/sky background errors except in the few crowded regions. Typical errors for the UIT photometry are 0.15 mag, including uncertainty in the aperture correction of 0.10 mag owing to a variable PSF. We quote FUV magnitudes on the monochromatic system, where $m_\lambda(\lambda) = -2.5 \log(F_\lambda) - 21.1$, and $F_\lambda$ is in units of erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. We refer to $B5$ magnitudes below as $m(162)$ and $B5 - V$ colors as $(162 - V)$.

Because of UIT’s large field and the suppression of the cool main sequence and RGB in the UV, the samples of UV-bright stars (generally with $T_{\text{eff}} > 8000 \text{ K}$) we find are complete, even in the cluster core. Due to the failure of UIT’s mid-UV camera on the Astro-2 mission, however, we require ground-based photometry to estimate temperatures. Kent Montgomery and Kenneth Janes have kindly provided us with CCD $BVI$ photometry of NGC 362, a summary of which can be found in MJ94. For the common region (13 square arcmin) excluding the crowded center ($\sim 30''$), we use the MJ94 data to construct UV-optical color-magnitude diagrams.

The cluster lies near the Small Magellanic Cloud (SMC) in projection, and it is necessary to consider contamination by background main sequence stars in the Cloud. As basic parameters we adopt the following (Shaw & White 1986, Trager, King & Djorgovski 1995, Djorgovski 1993): $(m - M)_0 = 14.67; E(B - V) = 0.04; \text{ and a half-light radius } R_{0.5} = 40''. The cluster center is taken to be $\alpha_{2000} = 01^h 03^m 14^s 3, \delta_{2000} = -70^\circ 50' 54''. In computing the FUV apparent distance modulus, we have adopted the Galactic UV reddening law of Cardelli, Clayton & Mathis (1989) according to which $A(B5)/E(B-V) = 8.06$. Estimates for the tidal radius of the cluster range from 9'85 (Tucholke 1992b) to 14'85 (Trager, King & Djorgovski 1995).

3. Results

We have identified a total of 84 stars ($3\sigma$ detections) on the UIT image in a area $16'/5$ square centered on the cluster. 14 of the detections lie in a knot that coincides with the optical center and is $< 14''$ in radius (see Fig. 1). There are 17 detections in common with the bluest stars found on recent HST WFPC2 images of the cluster center in the F218W, F439W filters (C. Sosin 1996, private communication), including this central clump. Of these detections, 49 match blue (i.e. $B - V < 0.2$) stars in the MJ94 list within $r = 8'/25$. 24 of these lie above the theoretical ZAHB or within $1\sigma$ of it ($m(162) < 15.4$ for stars at the blue end of the HR diagram). We have chosen not to explore potential identifications with red MJ94 stars; further work may reveal these to be hot binary companions to cool stars.

The stars detected span a large range in temperature. Fig 2 shows the UV-optical CMD we derive from the matched stars within a radius of $8'/25$ of the center. The colors we measure range from $-3.72 < (162 - V) < 0.54$, corresponding to effective temperatures of $23000 > T_{\text{eff}} > 8500 \text{ K}$. We plot the ZAHB and evolutionary sequences from Dorman et al. 1993 adopting
$[\text{Fe/H}] = -1.48$, $[\text{O/Fe}] = 0.6$. To the left is the histogram of UIT detections that do not have blue optical counterparts in the MJ94 data. Of the 3 blue stars mentioned by Harris (1982), the only radial velocity member (H1328) is clearly detected on the UIT image with $(162-V) = 0.35$.

The sources that lie near or above the plotted ZAHB in (Fig. 2) are thus possible members of an NGC 362 blue HB sequence. The 35 stars for which we do not have colors include stars too crowded for identification in the $V$-band image (including all of the stars of the central $14''$), out of the MJ94 field, or very hot objects that are intrinsically faint in $V$ but not in $m(162)$. 19 of these detections have UV magnitudes which are brighter than $1-\sigma$ below the ZAHB level at the blue extreme of the ZAHB. Adding these to the 24 stars plotted on the CMD, we estimate there are 43 stars in NGC 362 with UV magnitudes consistent with membership of this blue HB sequence. For the majority of these stars, either their location near the center of the cluster ($R < R_{0.5}$), or their location on the HR diagram with $(162-V) > -2$, strongly suggests membership (a total of 32 stars). In addition, there are six stars (four on the CMD and two in the histogram) with $m(162) < 14$. A magnitude or more brighter than the theoretical ZAHB, these are candidates for post-HB, evolved objects.

The field of NGC 362 is contaminated by young main sequence stars in the SMC. Bolte (1987) conducted deep photometry of fields to the north-east of the cluster and found a well-defined young (300 Myr) main sequence extending continuously to $(V,B-V) = (19.5, -0.2)$, and four blue stars that are about 1 mag brighter. There is a pronounced gradient in the blue star counts across the field. To complicate estimates of the background counts the image suffers from vignetting effects in the part of the field most strongly influenced by the SMC. In order to measure the contamination, we have counted stars in the largest circle centered on the cluster that does not suffer from the vignetting problem, 12′04 in radius. The number of UIT sources with $R > 3'$ lying below a line running south-east to north-west is nearly three times the number of detections above it: there are almost no stars in the NE quadrant of the image. There are a total of 179 stars in this wider field, 113 of which have $m(162) > 15.4$, i.e. fainter than the expected brightness of cluster EHB stars. There appears to be an excess of these (16) in the area occupied by the central 3′ of the cluster. Possibly there are some EHB stars in the cluster that are underluminous (cf. Whitney et al. 1994). However it is probable that the irregularity as well as the steep gradient of background counts across this field makes simple estimates of the contamination unreliable.

For the 6 stars lying $> 1$ magnitude above the HB we estimate that at most one of the post-HB candidates should be an early-B SMC background object. This is based on the number of mid-B SMC stars apparently present and assuming a Salpeter IMF. There is also a small probability of contamination by foreground stars, but it is unlikely that there will be more than one in this field. Altogether, assuming at least 32 stars close to the ZAHB are members plus at least 4 supra-HB stars, we conclude that there are 36–43 blue HB stars in the cluster.

If all of the detections with $14.2 < m(162) < 15.2$ without optical matches are EHB stars, the supra-HB stars potentially have 22 unevolved counterparts (i.e. they are within the range of core He burning evolution off the ZAHB). This gives a ratio of 4:1, which is consistent with the theoretical expectation, based on stellar lifetimes (Dorman et al. 1993). However, if a significant fraction of these stars are in fact cooler, the situation may more resemble that of M3 (Buzzoni et al. 1992). This cluster has two hot, bright objects ($T_{\text{eff}} \sim 30,000$ K, $\log L/\log L_{\odot} \sim 2$) with no

\footnote{According to the field locations given in Bolte (1987), these stars are detected by UIT with $m(162)$ between 14.4 and 15.9.}
obvious progenitors. In this case the bright stars may arise through binary evolution.

We used the MJ94 CMD to compute the relative numbers of blue and red HB stars. For simplicity the numbers we quote below are upper bounds taking the contamination as zero. There are 292 red HB stars with $R > 30''$, inside which the radial histogram shows obvious incompleteness effects, and 29 blue HB stars. The latest version of the Sawyer Hogg catalogue (C. Clement 1996, private communication) lists 7 confirmed RR Lyrae stars in the cluster, giving $B - R/(B + V + R) \sim -0.78$.

Finally, note that the exposure has insufficient depth to reach the blue straggler sequence, which would be 2 mag fainter than the ZAHB at $(162 - V) = 0$.

The integrated apparent $m(162)$ magnitude of NGC 362 is found to be $10.22 \pm 0.11$ to a radius of 8.25′′; this includes all contributions from hot stars which are too faint to be individually resolved. This is only an upper bound because of the uncertainty due to contamination. Its integrated visual magnitude is $V = 6.40$, Harris (1982)—see also Monella 1985—implying $(162 - V)_0 = 3.62$. OAO-2 (Welch & Code 1980) measured $m_\lambda(2460)_0 = 8.66 \pm 0.08$. The resulting far-to-mid UV color of $1.23 \pm 0.14$ places NGC 362 at the red end of the cluster sequence in Fig. 3 of Dorman et al. 1995. This color is consistent with a small blue HB population.

A simple estimate of the expected value of the integrated FUV/optical color may be derived—assuming the ratio of blue to red HB stars including the central 30′′ is not very different from that computed from the outer region—as follows. Using the Fuel Consumption Theorem, and the flux ratio of late to early stages we obtain $F_V(\text{HB + AGB})/F_V(\text{GB + MS}) = 0.25$. Then, assuming $N(\text{BlueHB})/N(\text{Red HB}) = 0.1$, the ratio $F_{\text{FUV}}/V$ is $\sim 1/40$, reliable to about $\pm 50\%$, or $(162 - V)_0 \sim 4 \pm 0.4$.

4. Discussion

Although the detection of blue HB stars in a cluster with a predominantly red HB does not conform to canonical expectations, no new physics is necessary to explain these observations. The novelty in the observations reported here lies in the fact that a globular cluster often cited as having an almost purely red HB has a significant blue HB component with few objects at intermediate temperatures. The simplest interpretation is that RGB mass loss in this cluster is elevated for a minority of the RGB stars, producing the lower mass blue HB component. The derived integrated UV/optical color of NGC 362 is comparable with a number of ellipticals and spiral bulges (Dorman et al. 1995), so that even the small number of stars we have detected here can have some bearing on the “UV upturn” phenomenon in galaxy populations.

Nearly all of the synthetic modeling of HB stellar mass distributions uses unimodal mass distributions. However, the NGC 362 HB morphology observed here is inconsistent with the hypothesis that RGB mass loss is dominated by a process with only normally-distributed stochastic scatter superposed. Either there is more than one mass loss process affecting HB morphology, or alternatively a single process may lead to a highly non-Gaussian distribution (for a discussion see D’Cruz et al. 1996). Star-to-star variation in stellar rotation rates is one potential cause for the scatter on the HB. Mixing during RGB evolution (perhaps also induced by rotation) can increase the He content of the H-burning shell regions of ZAHB stars, which also produces hot HB stars without increased mass loss (Sweigart 1997). However, the observational record is unclear: the few studies of HB rotation that have been completed, albeit for lower temperature stars (i.e. $\log T_{\text{eff}} < 4.1$; Peterson, Rood, & Crocker 1995), do not show a trend of rotational velocities with temperature within a given cluster.
NGC 362 has been regarded by many authors as a cluster with an HB morphology that is “too red” for its metallicity, although estimates for [Fe/H] do range as high as $\sim -1$ (Dickens et al. 1991). As such it has frequently been taken as a test case for the notion that HB morphology can be used as an age indicator. Currently, the age determination of NGC 362 based on main sequence and subgiant branch morphology is controversial and unlikely to be settled immediately (Stetson, VandenBerg, & Bolte 1996). However, detection of blue HB stars in this cluster is significant whether or not a young age is confirmed. For whatever the age of NGC 362 its CMD is inconsistent with a simple unimodal HB mass distribution. Of course this is not the first example of bimodality or other deviations from the usual assumptions used in HB synthesis; others are the famous example of NGC 2808 (Ferraro et al. 1990; Sosin et al. 1997), NGC 1851 (Walker 1992) and the gaps in the horizontal branches of M15 and NGC 288 (Crocker, Rood, & O’Connell 1988). The increasing evidence that more than one process affects the structure of globular cluster HB’s suggests that ages for clusters derived solely from HB morphologies are unreliable (Dorman et al. 1995).

If the turnoff fit does imply that the cluster is $\sim 2$–3 Gyr younger than the majority of the Galactic globular cluster system, then stellar systems with measurable UV flux can be produced at a relatively young age ($\sim 11$–12 Gyr). This would contradict the hypothesis that far-UV radiation is always an indicator of great age for extragalactic stellar populations (e.g. Park & Lee 1997; Bressan, Chiosi, & Fagotto 1994), which relies heavily on the assumptions of unimodality and predictability of the HB mass distribution with age and metallicity.

We are very grateful to Kent Montgomery and Kenneth Janes for providing their CCD photometry tables to us for both clusters in advance of publication and to Craig Sosin and George Djorgovski for pre-release data from HST. B.D. would like to thank both Robert S. and Robert J. Hill for many useful conversations about the data reduction. We thank Bob Cornett for providing the SMC theoretical main sequence, and Joel Parker for the ground-based image used in Figure 1. We would also like to acknowledge use of WWW resources placed online by J.-M. Perel and W. E. Harris. We would like to thank the referee, Michael Bolte, for helpful comments. Parts of this research have been supported by NASA grants NAG5-700 and NAGW-4106 to the University of Virginia and NASA RTOP 188-41-51-03.
REFERENCES

Monella, R., 1985 Coelum, LIII, 287


Tucholke, H.-J. 1992a, A&AS, 93, 293


Zinn, R. J., in The Globular Cluster–Galaxy Connection eds. Graeme H. Smith and Jean P. Brodie, (San Francisco:ASP), 38

This 2-column preprint was prepared with the AAS \LaTeX{} macros v4.0.
Fig. 1.— Far-ultraviolet (1600 Å) image of NGC 362, extracted from UIT frame FUV2789 and showing a square of side 16′50 centered on the cluster. The solid circle indicates a 3 ′ radius, while the dashed circle shows the half-light radius at 40″. The lower inset show a close-up of the central knot of UV-bright sources, while the upper inset shows a corresponding $V$-band image kindly provided by Joel Parker from data taken at CTIO in 1995 December. The dashed circles in the inset are the same radius as in the main image.
Fig. 2.— The color-magnitude diagram of NGC 362 constructed from our data and the $V$ band observations of MJ94, which cover a 13' square field centered on the cluster. The symbols indicate spatial location on the image: filled symbols are stars in the central 3', open symbols outside of this radius. Circles denote sources below the SE to NW line referred to in the text (where SMC background contamination is largest), while squares show detections above this line. We assume $E(B − V) = 0.04$ and $(m − M)_0 = 14.67$. The solid line with the small filled circles shows the ZAHB, with the post-HB evolutionary tracks shown by dotted lines. The evolutionary sequences are from Dorman et al. 1993, with [Fe/H] = −1.48, [O/Fe] = 0.60. The “mean age” SMC main sequence at $(m − M)_0 = 18.9$ is shown by filled squares joined by a dashed line, from models by Charbonnel et al. 1993 and composition parameters for the SMC given by Westerlund 1990. The synthetic magnitudes are derived from Kurucz 1992 model stellar fluxes. To the left of the figure is the histogram of stars without optical identifications but within the MJ94 field.