THE ASTROPHYSICAL JOURNAL, 395: L21–L24, 1992 August 10

THE ULTRAVIOLET-BRIGHT STARS OF OMEGA CENTAURI, M3, AND M13

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Received 1992 March 31; accepted 1992 May 26

ABSTRACT

Far-ultraviolet (1620 Å) images were obtained of the globular clusters ω Cen, M3, and M13 with the Ultraviolet Imaging Telescope (UIT) on the *Astro-1* mission. The large field of view and solar-blind response of UIT allow complete identification of all UV-bright objects in these clusters. Two new UV-bright stars are detected within 2′ of the center of ω Cen and have been spectroscopically investigated with the short-wavelength spectrograph on the *International Ultraviolet Explorer* (*IUE*). The known UV-bright stars ROA 5701 (in ω Cen), vZ 1128 (M3) and Barnard 29 (in M13) are also conspicuous on the UIT images.

The *IUE* spectra of the UV-bright stars UIT-1 and UIT-2 in the core of ω Cen superficially resemble those of Population I mid-B stars. However, the absorption lines of the core UV-bright stars are significantly weaker than in Populations I stars, consistent with their membership in the cluster. Synthetic spectra calculated from low-metallicity Kurucz model stellar atmospheres are compared with the spectra. The best fits are obtained for effective temperature $T_{\rm eff} = 18{,}000$, and luminosity $\log L/L_{\odot} = 3.0$ for UIT-1, and $T_{\rm eff} = 19{,}000$, $\log L/L_{\odot} = 2.6$ for UIT-2. These objects are insufficiently luminous to be classical hydrogen-burning post-AGB stars. They may be evolved hot horizontal branch stars which have brightened by more than 3 mag since leaving the zero-age horizontal branch. Another possibility is that they are post early–AGB stars which leave the AGB before the onset of thermal pulsations. The spectra and luminosity of the core UV-bright stars suggest that similar objects could provide the source of the ultraviolet light in elliptical galaxies.

Subject headings: globular clusters: individual (M3, M13, Omega Centauri) —
stars: post–asymptotic giant branch — ultraviolet: stars

1. INTRODUCTION

The UV-bright stars in globular clusters occupy the leftmost region of the HR diagram, ranging in luminosity from the blue horizontal branch to the tip of the asymptotic giant branch (AGB). Those stars with luminosities near the tip of the AGB are usually interpreted as being post–AGB stars evolving toward their final white dwarf phase (Renzini 1985). The less luminous candidates may be evolved hot horizontal branch (HB) stars (Caloi 1989), or possibly the result of binary star evolution (Fujimoto & Iben 1991). The spectra and statistics of the UV-bright stars are useful for constraining poorly known theoretical parameters (such as mass loss) that govern post–HB evolution. The UV-bright stars are also of interest for other reasons: they provide bright background sources for probing the Galactic halo, their Lyman continuum flux may govern the ionization of the cluster or the halo, and they may provide clues to understanding the origin of the ultraviolet light in elliptical galaxies (deBoer 1985).

The compilation of deBoer (1987) lists 46 UV-bright stars (defined as having $B-V \lesssim 0.2$ and $M_V \lesssim 0$) in Galactic globular clusters. This list is certainly incomplete, largely because of two selection effects in ground-based searches. Hot ($T_{\rm eff} >$ 20,000 K) UV-bright stars may not be detected in the visible because of crowding in the cluster core or because of their large bolometric correction. Ultraviolet imagery enormously reduces both of these selection effects. The numerous cluster members cooler than 7500 K are essentially invisible at 1620 Å, so that UV-bright stars can be resolved in the cluster core. In addition, a star with $\log L/L_{\odot} = 3$ and 9000 K $< T_{\rm eff} <$ 70,000 K will be at least 2 mag brighter than any star on the zero-age HB and conspicuous on the UV images. The Ultraviolet Imaging Telescope (UIT, Stecher et al. 1992) is especially well-suited to observations of globular clusters because of its large 40′ field of view and its solar-blind CsI cathode.

During the first flight of the *Astro* observatory in 1990 December, we obtained UIT far-ultraviolet images of the globular clusters M79, NGC 1851, ω Cen, M3, and M13. Conspicuous on the UIT images are the known UV-bright stars, NGC 1851 – UV5, ROA 5701 (in ω Cen), Barnard 29 (in M13), and vZ 1128 (in M3). The UV images of M79, including a newly discovered hot UV-bright star, are discussed in Hill et al. (1992). The images of NGC 1851 will be discussed in Parise et al. (1992). In this *Letter*, we discuss the brightest stars in the remaining three globulars, and in particular two new UV-bright stars discovered within 2′ of the center of ω Cen.

Balloon ultraviolet images of M3 and M13 have been previously obtained by Laget et al. (1992) at a longer (2000 Å) wavelength and with poorer (12″) spatial resolution. In a subsequent paper (Landsman et al. 1992), we will present an ultraviolet color magnitude diagram of ω Cen and will discuss the spatial distribution of the blue HB and hot subdwarf stars.

2. OBSERVATIONS

A description of the *Astro-1* mission and of the UIT telescope is in Stecher et al. (1992). The observations of ω Cen, M3,

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TABLE 1

UIT DAYTIME IMAGES OF GLOBULAR CLUSTERS

Target	[Fe/H]	$m-M$	$E(B-V)$	References	$t_{\rm exp}$ (s)	Limiting m_{162}
ω Cen	−1.6	14.0	0.15	1, 2	279	16.2
M3	−1.7	14.8	0.01	2	112	14.2
M13	−1.4	14.4	0.02	2, 3	42	13.1

REFERENCES.—(1) Alcaino & Liller 1987; (2) Zinn 1985; (3) Richer & Fahlman 1986.

and M13 were taken on the daytime side of the orbit using the anti-dayglow B5 ($\lambda_0 = 1620$ Å, $\Delta\lambda = 225$ Å) filter. The magnitudes, m_{162}, given in this *Letter* are defined as $-2.5 \times \log f_\lambda - 21.1$, where f_λ is the mean flux in the B5 filter in ergs cm^{-2} s^{-1} Å^{-1}. Exposure times and limiting magnitudes for the UIT observations are given in Table 1. The UIT images of M3 and M13 are shown in Figure 1 (Plate L10), and the UIT image of ω Cen is shown in Figure 2 (Plate L11). The image of ω Cen revealed two previously unrecognized UV-bright objects within 2′ of the cluster center (Fig. 3, [Pl. L12]). We designate the brighter star as UIT-1 and the fainter star as UIT-2. The two UV-bright stars were subsequently identified on UBV CCD images of the cluster core taken for us with the 0.9 m telescope at CTIO by A. Crotts. Star positions from the catalog of Dickens et al. (1988) were used to obtain an astrometric solution for the CCD images, and coordinates for UIT-1 and UIT-2 given in Table 2 should be accurate to ~1″.

On 1991 May 10 we used the *IUE* satellite to obtain a 160 minute low-dispersion short-wavelength spectrum (SWP 41609) of UIT-1. This image was overexposed between 1250 and 1400 Å. On 1991 May 19 we obtained a 310 minute exposure (SWP 41661) of UIT-2, and a second 68 minute image (SWP 41662) of UIT-1. The *IUE* images were reduced in the standard way, except that the absolute calibration was taken from Bohlin et al. (1990).

3. RESULTS

The three brightest stars on the UIT image of M3 are vZ 1128 ($m_{162} = 10.69$), I-III-87 ($m_{162} = 13.44$), and I-V-37 ($m_{162} = 13.67$). These three stars have been recently studied with *IUE* by Buzzoni et al. (1992). They found vZ 1128 to be a post-AGB candidate with $T_{\rm eff} = 30{,}000$ K and $L/L_\odot = 3.09$. They also determined stellar parameters for I-III-87 ($L/L_\odot = 2.06$, $T_{\rm eff} = 33{,}000$ K) and I-IV-37 ($L/L_\odot = 2.04$, $T_{\rm eff} = 35{,}000$ K). The evolutionary status of these two fainter stars is uncertain, but they are insufficiently luminous to be post–AGB stars. The UIT image confirms vZ 1128 as the sole hot post–AGB star in M3.

The two brightest stars on the UIT image of M13 are the well-studied post–AGB star Barnard 29 ($m_{162} = 9.82$), and the $V = 13.93$ star II-48 ($m_{162} = 12.42$). Barnard 29 was most recently studied by Adelman & Aiken (1987), who found $T_{\rm eff} = 20{,}250$ K, and $\log g = 3.15$. II-48 was observed with *IUE* by Altner & Matilsky (1984) who determined $T_{\rm eff} = 13{,}000$ K, and $\log L/L_\odot = 2.31$. This star, along with the other hot UV-bright stars in M13 listed by deBoer (1987), has probably evolved directly off the populous blue HB in M13. The UIT image indicates that only Barnard 29 is sufficiently luminous to be a post–AGB star.

Table 2 lists the five brightest stars in the UIT image of ω Cen, excluding the foreground A stars HD 116649, HD 116798, and HD 116602. These five stars are well separated in magnitude from the remaining stars on the UIT image, which are all at least 0.6 mag fainter. The star ROA 3596 was studied by Norris (1974), who confirmed cluster membership with a radial velocity measurement and estimated $T_{\rm eff} = 18{,}000$ K from narrow-band photometry. We estimate $T_{\rm eff} = 14{,}000$ from the observed $m_{162} - V$ color, assuming $E(B-V) = 0.15$ and $R_V = 3.1$ (see below).

The star ROA 5342 is conspicuous in the catalog of Dickens et al. (1988) by its very blue color, $B-V = -0.15$. We confirm the high temperature of this star; the dereddened color of $m_{162} - V = -4.44$ is indicative of a $T_{\rm eff} = 40{,}000$ K star. We know of no other studies of this star nor of any radial velocity studies confirming cluster membership.

UIT-2 is within 22″ of the unidentified *Einstein* X-ray source HG-C (Hertz & Grindlay 1983), which has a 41″ positional uncertainty in the online *Einstein* HRI catalog. The X-ray source was also detected at the 2 σ level using the *EXOSAT* satellite (Koch-Miramond & Aurière 1987), but an improved position could not be determined. There is no particular reason to associate the UV-bright star with the X-ray source in this very crowded field, but an improved X-ray position would be desirable.

Figure 4 shows the *IUE* spectra of UIT-1, UIT-2, and ROA 5701. The spectra are dereddened using the parameterization of Cardelli, Clayton, & Mathis (1989) with $R_V = 3.1$, and assuming $E(B-V) = 0.15$ (Alcaino & Liller 1987). As noted by Cacciari et al. (1984), this reddening correction also effectively removes the 2200 Å absorption dip in ROA 5701. The spectra of UIT-1 and UIT-2 both resemble those of Population I B2–B6 stars, with absorption lines of C III (1175 Å), Si II (1265 Å), Si II + Si III (1300 Å), C II (1336 Å), and Si IV (1400 Å). A weak C IV (1550 Å) feature is seen in ROA 5701 and UIT-1 but does not appear to be present in the (noisier) UIT-2 spectrum. The lines of C II (1336 Å), Si IV (1400 Å), and C IV (1550 Å) are likely to have a substantial interstellar contribution.

Comparison with *IUE* spectra of normal B stars (Wu et al. 1983; Heck et al. 1984) shows that the strength of the absorption lines in UIT-1 and UIT-2 are weaker than in similar Population I stars (Fig. 4). The weak-lined spectra of the UV-

TABLE 2

HOT ULTRAVIOLET-BRIGHT STARS IN ω CENTAURI

Name	R.A.(2000)	Decl.(2000)	SWP	m_{162}	$V^{\rm a}$	$T_{\rm eff}$	$\log (L/L_\odot)$
ROA 5701	$13^{\rm h}27^{\rm m}29^{\rm s}.0$	−47°22′47″	7849, 8763	10.20	13.16	20000	3.2
UIT-1	13 26 45.0	−47 27 10	41609, 41662	10.84		18000	3.0
UIT-2	13 26 52.8	−47 29 45	41661	11.94		19000	2.5
ROA 5342	13 25 45.4	−47 24 02		12.20	15.89	40000:$^{\rm b}$	2.6:
ROA 3596	13 27 46.1	−47 30 59		12.37	14.01	14000:$^{\rm b}$	2.4:

[a] V-magnitudes from Norris 1974 or Dickens et al. 1988.

[b] $T_{\rm eff}$ estimated from $m_{162} - V$.

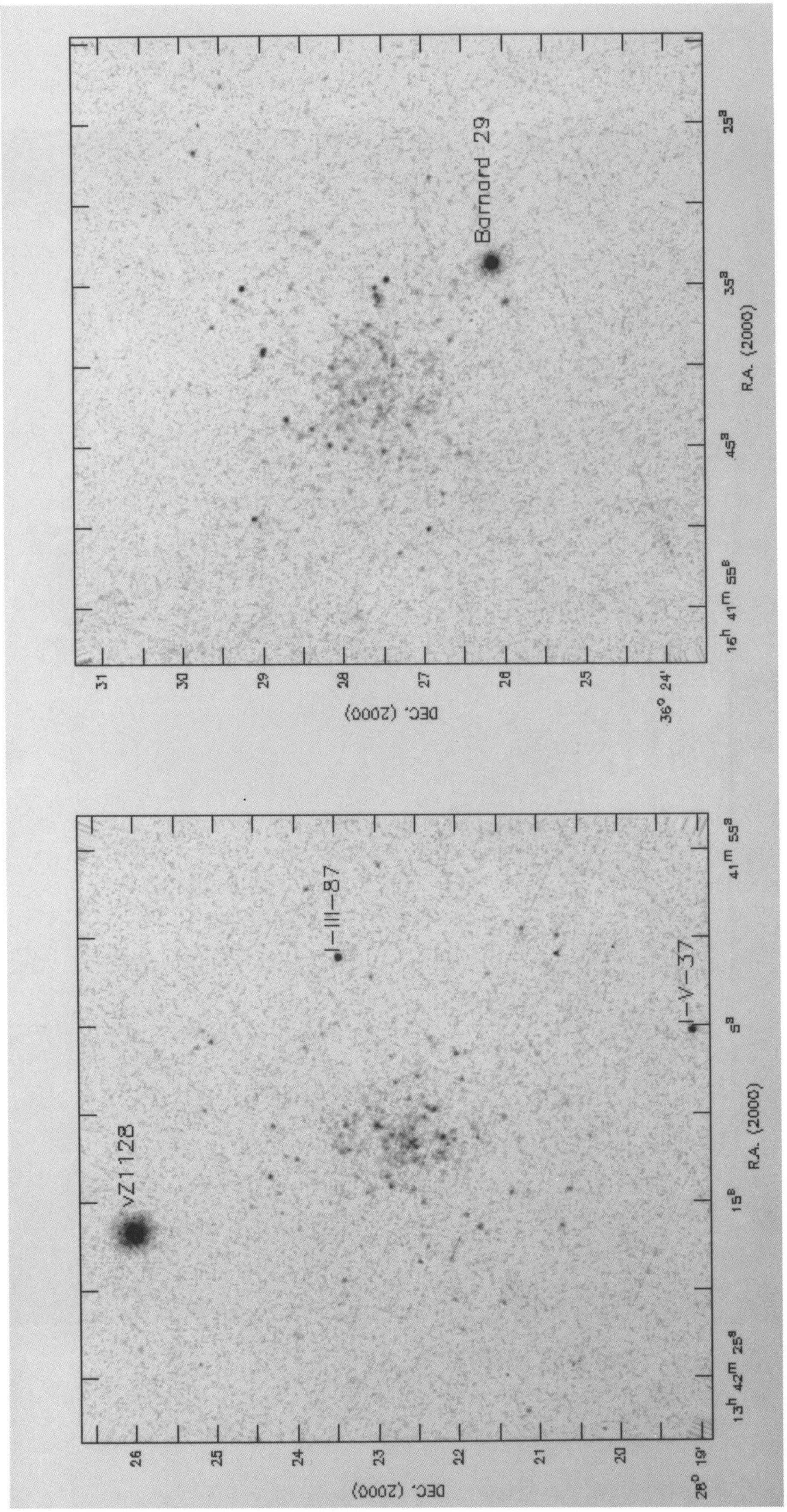

FIG. 1a

FIG. 1b

FIG. 1.—UIT B5 (1620 Å) images of (*a*) M3 and (*b*) M13

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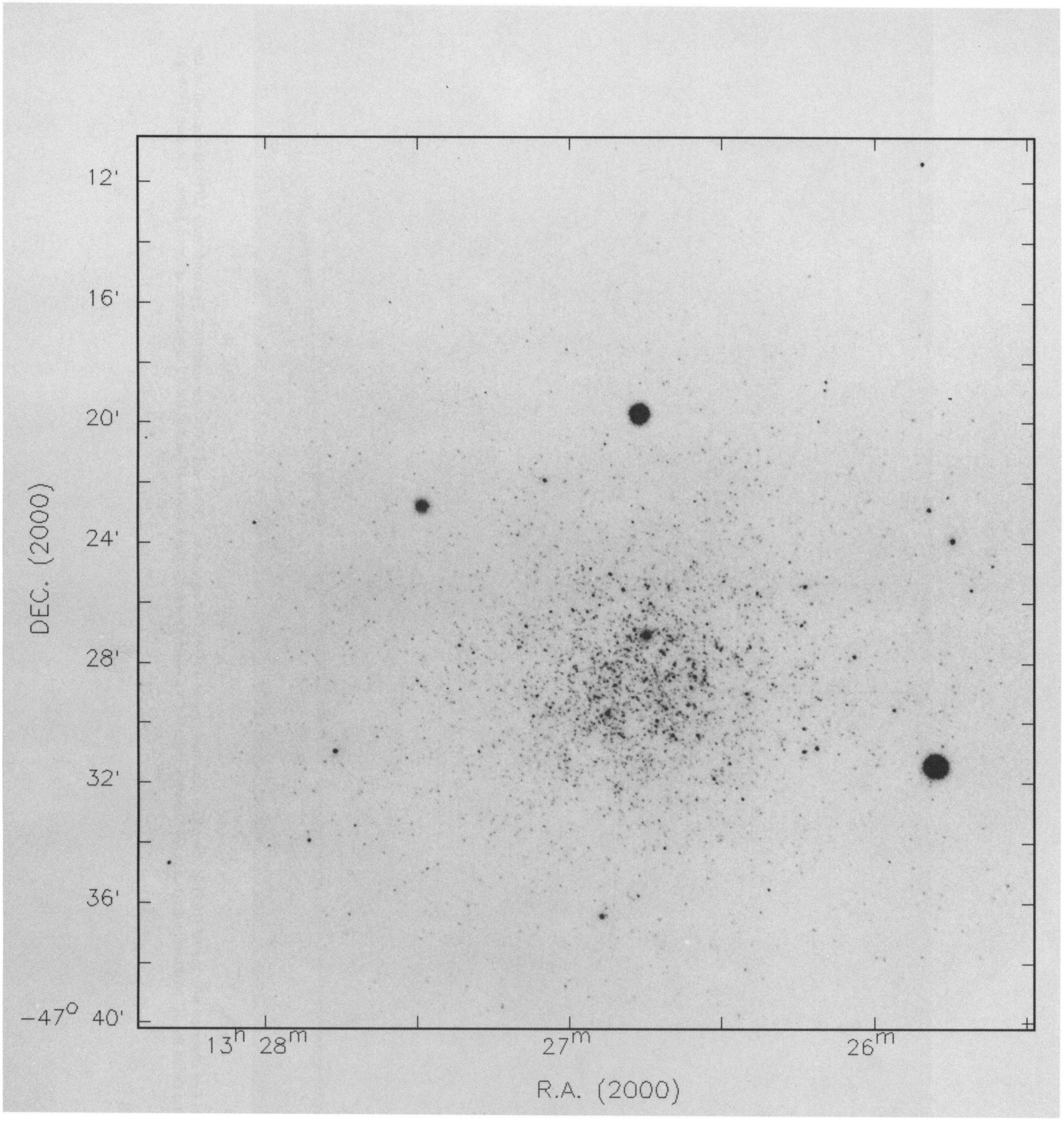

FIG. 2.—UIT B5 (1620 Å) image of ω Cen. The two heavily saturated stars are the foreground A stars HD 116649 and HD 116789.

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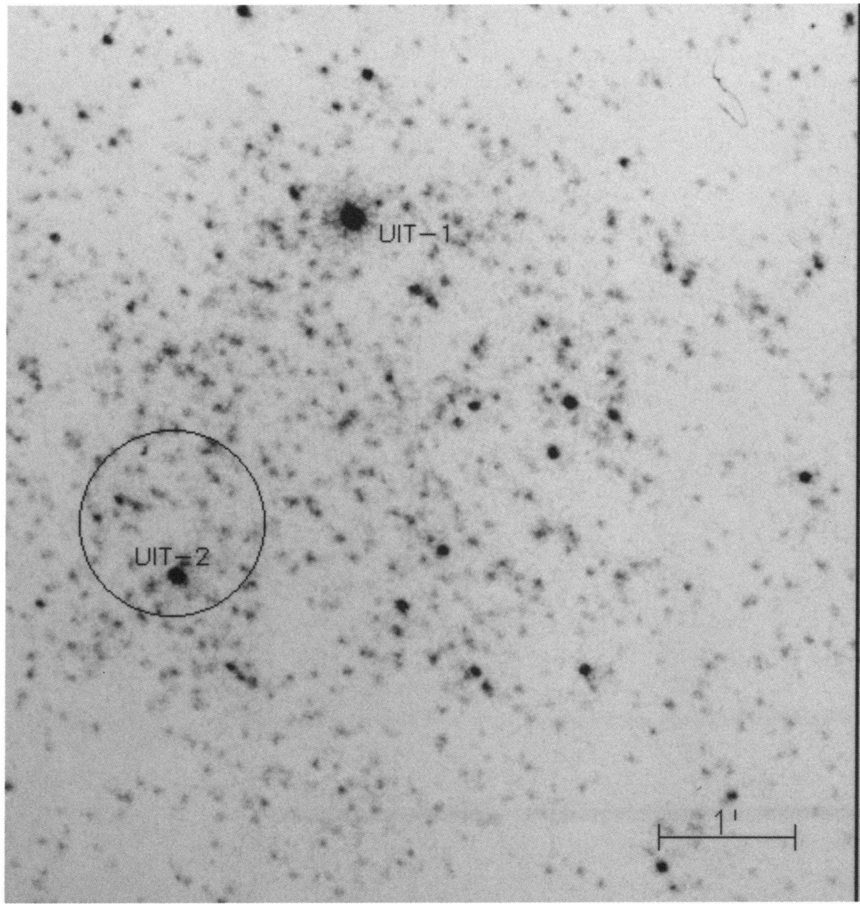

FIG. 3*a*

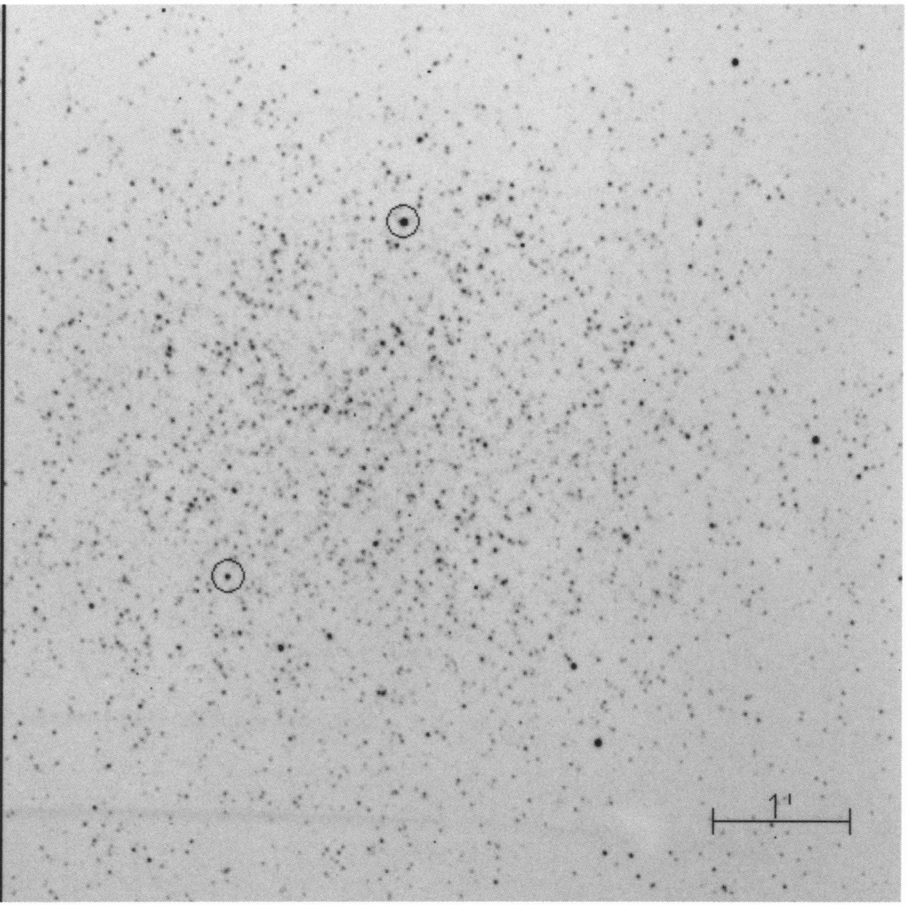

FIG. 3*b*

FIG. 3.—(*a*) Center 6.′6 of ω Cen observed with the B5 (1620 Å) filter. The saturated images of the UV-bright stars UIT-1 and UIT-2 are indicated. The circle near UIT-2 is centered on the *Einstein* X-ray source HG-C and shows the 41″ positional uncertainty. (*b*) The same region of ω Cen as observed in the Johnson *U* band at the 0.9 m telescope at Cerro Tololo. The core UV-bright stars are circled.

LANDSMAN et al. (see 395, L22)

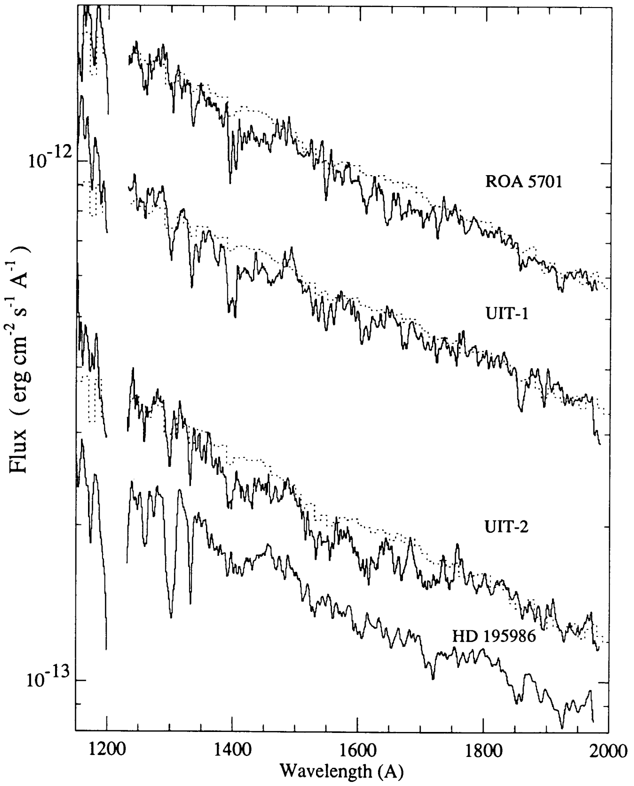

FIG. 4.—Dereddened *IUE* spectra are shown of ω Cen UV-bright stars ROA 5701, UIT-1, and UIT-2. The dotted line over each spectrum shows the best-fit Kurucz model atmosphere. The temperatures used in the model fits are given in Table 2. Also shown is an *IUE* spectrum (SWP 19292) of the normal B4 III star HD 195986. The flux scale for SWP 19292 has been divided by 1000, and the spectrum has been dereddened assuming $E(B-V) = 0.07$.

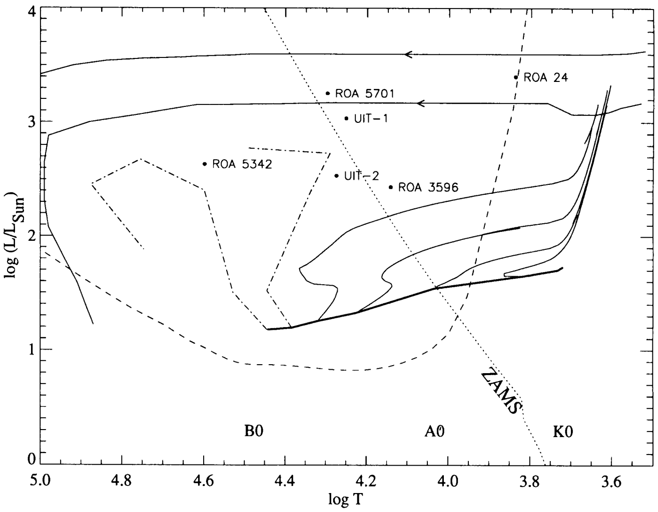

FIG. 5.—Theoretical HR diagram showing the five hot UV-bright stars in ω Cen, and the cool post-AGB candidate ROA 24. The solid lines are the $Z = 0.001$ HB models of Castellani et al. (1991), and the dot-dashed lines are the $Z = 0.001$ HB models of Caloi (1989) for total masses of 0.503 and 0.51 $M_{\odot}$. Also shown are the $M = 0.546$ $M_{\odot}$ and $M = 0.565$ $M_{\odot}$ post-AGB tracks of Schönberner (1983). The Population I main sequence is from Maeder & Meynet (1988). The dashed line indicates the approximate limiting sensitivity of the UIT image of ω Cen.

bright stars confirm their cluster membership. There was already strong circumstantial evidence for their membership given their proximity to the center of ω Cen, and the large z distance (> 800 pc) off the Galactic plane required if they were main-sequence B4 stars.

To estimate the effective temperatures given in Table 2, we fit the UV spectra to the low-metallicity LTE model atmospheres of Kurucz (1992). The best-fit models for ROA 5701 and UIT-1 have $\log g = 3.0$ and $[\mathrm{Fe/H}] = -1.5$, while the model for UIT-2 has $\log g = 3.5$ and $[\mathrm{Fe/H}] = -1.0$. The bolometric luminosity of each star is computed by scaling the best-fit model atmosphere to the assumed distance (5100 pc) of ω Cen. These luminosities are in reasonable greement with that expected from a 0.6 $M_{\odot}$ star with the surface gravities used in the model fit. The uncertainties in the derived effective temperatures are about ± 2000 K for ROA 5701 and UIT-1, and ± 4000 K for UIT-2. These errors reflect the uncertainty in defining the best model fit, and do not account for any systematic errors in the adopted value of $E(B-V)$, the UV reddening curve, or the *IUE* calibration.

Figure 5 shows the five hot UV-bright stars in ω Cen on a theoretical HR diagram along with selected evolutionary tracks. The well-known spread in metallicity among the ω Cen stars ($-2.0 \lesssim [\mathrm{Fe/H}] \lesssim -0.5$, Dickens 1989) makes it difficult to select the most appropriate tracks for comparison. Figure 5 shows the $Z = 0.001$ HB models of Castellani, Chieffi, & Pullone (1991), along with the $Z = 0.001$ extreme HB models of Caloi (1989), and the hydrogen burning post-AGB tracks of Schönberner (1983). Also shown is the position of the post-AGB candidate star ROA 24 (Gonzalez & Wallerstein 1992), which is too cool ($T_{\mathrm{eff}} = 6950$ K) to be detected on the UIT image.

4. DISCUSSION

The proximity of the UV-bright stars of ω Cen (except for ROA 5342) to the Population I main sequence in Figure 5 suggests that these stars may be the globular cluster analogs of some high Galactic latitude Population II early-type stars, which can mimic Population I when observed at low dispersion. For example, the high-latitude star PHL 174 was found by Conlon et al. (1988) to have a temperature ($T_{\mathrm{eff}} = 18{,}000$ K) and gravity ($\log g = 2.7$) close to what we estimate for UIT-1. Conlon et al. also find a metal abundance $[\mathrm{Fe/H}] = -1.0$ for PHL 174, with carbon significantly more underabundant. High-dispersion spectra of UIT-1 and UIT-2 would allow a similar abundance analysis.

What is the evolutionary status of UIT-1 and UIT-2? The stars are, respectively, 0.4 dex and 0.9 dex less luminous than the tip of the AGB near $\log L/L_{\odot} = 3.4$ (e.g., Gonzalez & Wallerstein 1992), and also less luminous than the lowest mass (0.546 $M_{\odot}$) post-AGB model constructed by Schönberner. The low-mass post-AGB stars should be observationally preferred, since the lowest mass track of Schönberner spends significantly more time ($\sim 3 \times 10^5$ yr) in the UV-bright star region of the HR diagram, then the next more massive (0.565 $M_{\odot}$) track ($\sim 2 \times 10^4$ yr). However, Greggio & Renzini (1990) warn that a simple extrapolation of the lifetimes in the Schönberner models to a lower mass would result in unrealistically large fuel consumption rates.

The location of UIT-2 in Figure 5 is close to the $M = 0.51$ $M_{\odot}$ extreme HB model track of Caloi (1989). The identification of UIT-2 as a luminous evolved extreme HB star is quite plausible, because hot subdwarf stars are known to exist in ω Cen (Bailyn et al. 1992). This identification can be further tested after colors and magnitudes are available for all the extreme HB stars on the UIT image (Landsman et al. 1992) and comparison can be made with the expected lifetimes on the extreme HB tracks.

Brocato et al. (1990) suggested that stars which reach the AGB with a sufficiently small envelope mass may depart the AGB before the thermally pulsing phase. Compared to Schönberner's post-AGB stars, these "post early–AGB" (post–EAGB) stars move across the HR diagram relatively slowly ($\sim$20 Myr), and at a lower ($\log L/L_\odot = 2.7$) luminosity. Brocato et al. developed their model for a solar metallicity star (typical of elliptical galaxies), where the higher mass-loss rate promotes the removal of the envelope on the AGB. However, post–EAGB stars might also exist in a lower metallicity system also, provided that stars arrive on the AGB with sufficiently small envelope mass. Again, the presence of extreme HB stars in Omega Cen suggests that a post–EAGB origin for the UV-bright stars is plausible.

The four UV-bright stars in Omega Cen which are certain cluster members (ROA 5701, UIT-1, UIT-2, and ROA 3596) all have $\log T_{\rm eff} \leq 4.3$. These moderate temperatures are rather unexpected, since both the post–EAGB and the extreme HB scenarios typically predict much hotter stars. One possible explanation for this discrepancy is that the onset of radiation-driven winds in the hotter stars accelerates their evolution across the HR diagram.

Finally, we consider the possibility that the core UV-bright stars in ω Cen may be representative of the stars which provide the UV upturn in elliptical galaxies. Ferguson et al. (1991) concluded from the HUT spectrum that the 912–1700 Å light of the elliptical galaxy NGC 1399 is dominated by stars with temperatures $\lesssim$25,000 K, which is somewhat cooler than adopted in most earlier discussions of the UV upturn (e.g., Greggio & Renzini 1990). However, the similarity of hot star energy distributions in the *IUE* spectral range (1200–3200 Å) permitted only a lower limit of $T_{\rm eff} \gtrsim 20{,}000$ K to be assigned in the earlier work. Both Burstein et al. (1988) and Ferguson et al (1991) noted the weakness of the stellar absorption lines in the UV spectra of ellipticals, and especially the absence of C IV. Objects like the UV-bright stars in ω Cen are plausible candidates for the source of the UV upturn. They are low-mass, moderate-temperature, weak-lined stars with luminosities low enough that they do not violate limits on the smoothness of the UV light in M32 and the M31 bulge (O'Connell et al. 1992). Objects with similar temperatures and luminosities can presumably be produced over a wide range of abundances, though at the higher mean metallicities of ellipticals the lines should be stronger.

5. SUMMARY

We have obtained ultraviolet (1620 Å) images of the globular clusters ω Cen, M3, and M13. The UV images provide a complete identification of all UV-bright stars in these systems. The UIT images of M3 and M13 do not reveal any new post–AGB candidates. The image of ω Cen revealed two previously unrecognized UV-bright stars within 2′ of the core. The star ROA 5342 is a possible hot ($T_{\rm eff} \sim 40{,}000$ K) UV-bright star. *IUE* spectra of the core UV-bright stars resemble those of Population I mid-B stars except for the weakness of their absorption lines. The stars may be either evolved extreme HB stars, or possibly post early–AGB stars.

Our understanding of the UV-bright stars in ω Cen could be improved by a study of its complete ultraviolet color-magnitude diagram (Landsman et al. 1992) and by high dispersion spectroscopy. High-resolution spectra may be difficult to obtain from the ground for UIT-1 and UIT-2 due to stellar crowding but should be possible with the Goddard High Resolution Spectrograph (GHRS) on the *Hubble Space Telescope*.

We thank Y. Kondo for authorizing *IUE* discretionary time for this work. We also thank R. Dickens for supplying a computer-readable copy of the Dickens et al. catalog, A. Crotts for obtaining the ω Cen CCD frames, M. Bolte for supplying coordinates of subdwarfs, R. Kurucz for supplying his stellar atmosphere models, and L. Pulone for supplying his HB models. We thank A. Sweigert for critically reading the manuscript, and to B. Dorman and R. Rood for helpful conversations. We are pleased to acknowledge the hundreds of people involved with the *Astro-1* mission who made these observations possible. R. W. O. gratefully acknowledges NASA support of portions of this research through grants NAG5-700 and NAGW-2596 to the University of Virginia.

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