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DISCOVERY OF FAINT ULTRAVIOLET SOURCES IN THE GLOBULAR CLUSTER NGC 6624 WITH THE *HUBBLE SPACE TELESCOPE*[1]

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ABSTRACT

Using the Faint Object Camera (FOC) on the *Hubble Space Telescope* (*HST*), we have identified three faint ultraviolet sources in the innermost ~15 arcseconds of the globular cluster NGC 6624. These sources are in addition to the previously discovered UV counterpart to the X-ray source 4U 1820−30, which is observed in the same field. At 1400 Å, the sources have dereddened fluxes of 4.4×10^{-16} to 1.8×10^{-15} erg cm^{-2} s^{-1} Å^{-1}. The faintest source is within the field of view of an existing *HST*/FOC *B* image; its *B* magnitude is ~23.4, or $M_B \sim 7.8$. The two fainter sources may be hot white dwarfs, although it would be unusual to observe two of these objects at such a young age. Alternatively, one or more of the sources could be hot, helium-burning subdwarfs. In particular, the brightest source may be on the extreme blue end of the horizontal branch, which would be notable, as NGC 6624 is a metal-rich cluster with a red horizontal branch. Finally, one or more of these stars could be cataclysmic variables. We briefly discuss future observations that could distinguish among these possibilities.

Subject headings: Galaxy: globular clusters: individual (NGC 6624) — ultraviolet: stars

1. INTRODUCTION

Observations of globular clusters at ultraviolet wavelengths provide valuable information about hot stellar populations, which, in turn, increases our understanding of the later stages of stellar evolution. In the dense environments of globular-cluster cores, the characteristics and distribution of hot stellar populations can also provide clues to the role that stellar interactions may play in altering the standard course of evolution of some fraction of the stars (see, e.g., Bailyn 1995 for a review). In recent years, the resolving power and sensitivity of the *Hubble Space Telescope* (*HST*) have provided a significant improvement over the capabilities of *IUE* and other satellites, and have led to a number of discoveries of UV-bright stars in globular clusters.

In this paper we report the discovery of three UV-bright objects in NGC 6624, on the same image as the ultraviolet counterpart of the low-mass X-ray binary 4U 1820−30, discussed in a previous paper (King et al. 1993, hereafter Paper I). NGC 6624 is a metal-rich ([Fe/H] = −0.37) globular cluster at a distance of 8.1 kpc (Djorgovski 1993). It has the central power-law density cusp usually associated with core collapse (Lugger et al. 1987), and contains a number of blue straggler stars near its center (Sosin & King 1995, hereafter Paper II) as well as two pulsars (Biggs et al. 1994). The UV flux detected by *IUE* (Rich, Minniti, & Liebert 1993) is almost entirely due to the LMXB, so these three UV-bright objects have never been previously observed.

2. OBSERVATIONS

NGC 6624 was observed on 1992 August 13 with the f/96 relay of the Faint Object Camera (FOC), in three bandpasses: F430W ("*B*"), F480LP ("*V*"), and F140W, a far-ultraviolet filter ($\lambda_0 \simeq 1370$ Å, $\Delta\lambda \simeq 500$ Å). All of the images were geometrically corrected and flat-fielded by the standard STScI pipeline. The FUV data consist of a pair of 22 × 22 arcsecond images, taken in the camera's "zoomed" format, with a total exposure time of 3594 s. The sum of the two FUV images is shown in Figure 1 (Plate L6); this sum will be called "the F140W image" in what follows. The cluster core appears near the center of this image, as does 4U 1820−30 (Paper I). The *B* and *V* images are smaller 11 × 11 arcsecond frames; two overlapping fields in each filter cover about 35% of the UV image. Photometry of stars in these latter images has been given in Paper II.

Outside of the central part of the F140W image, there are many faint peaks visible—most with only a few counts in their highest pixel. We identified peaks by eye, and then verified that all were more than 5 σ above the mean background level, and that all appeared on both of the individual exposures. A comparison with the *B* and *V* images revealed that nearly all of the F140W peaks corresponded to bright red giants or blue stragglers, which appear on the FUV image because of the large redleak of the F140W filter. One UV source, however, had only a faint *B* counterpart and was entirely absent from the *V* image, and must therefore be genuinely UV-bright. We designate this source as "star 1" in the following discussion.[2]

Since the *HST* optical data cover only ~35% of the UV image, we repeated this UV-to-optical matching procedure using a ground-based *B*-band image of NGC 6624, kindly provided by G. Piotto and S. Djorgovski (Paper II). The limiting magnitude of the ground-based image is much brighter ($B \simeq 19$) due to crowding, but is sufficient to identify which of the remaining F140W sources are cooler stars seen through the filter's red leak, and which are genuinely UV-bright. We thus found two more UV-bright stars, hereafter designated "star 2" and "star 3."

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

[2] We note that another possible "blue star" appears in the *B* and *V* images (Paper II), but since it is not detected in F140W, we do not discuss it here.

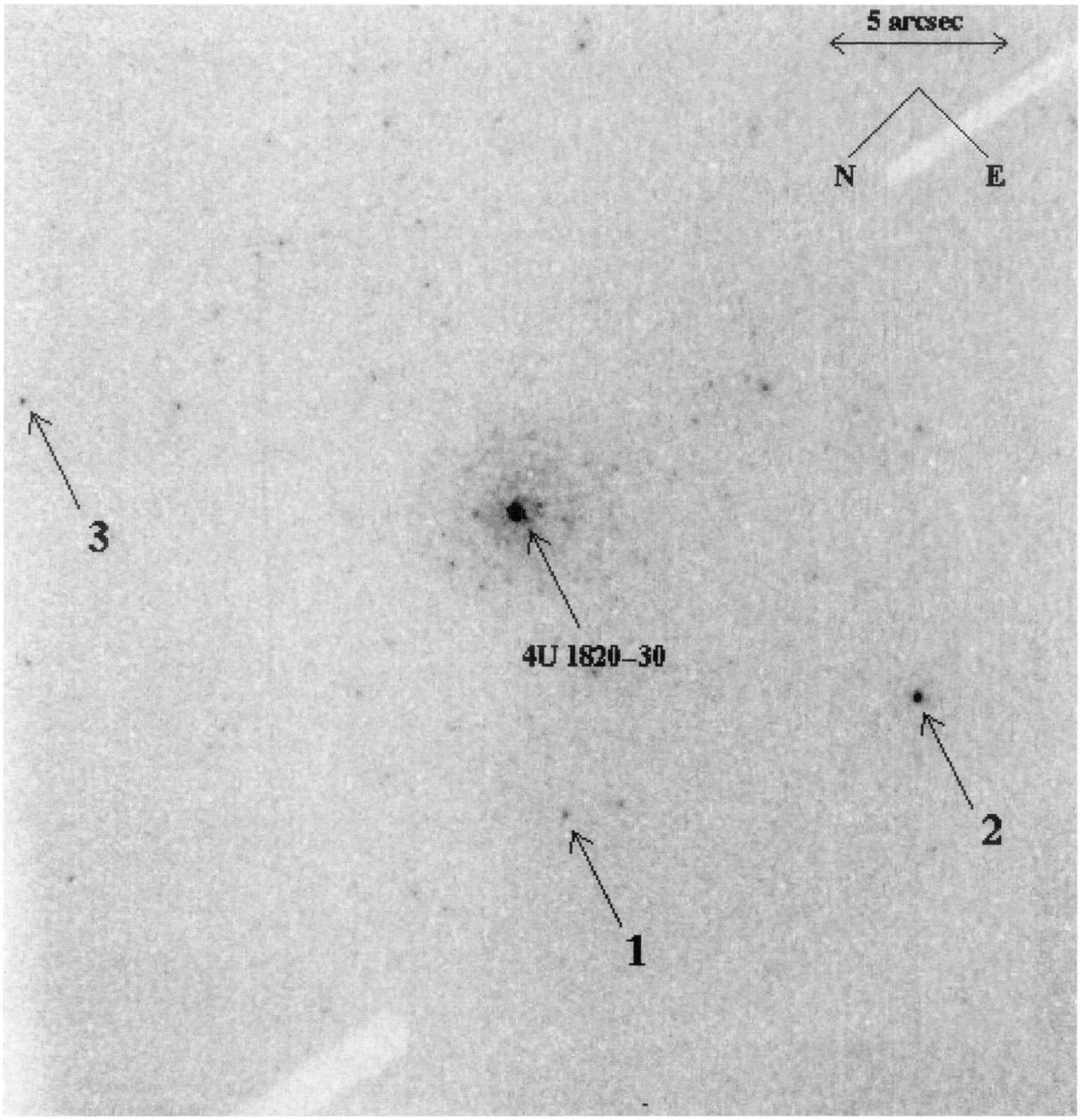

FIG. 1.—F140W far-ultraviolet image of the center of NGC 6624. The bright object near the center of the image is the X-ray source 4U 1820−30; the positions of our three fainter UV-bright objects are indicated. The other faint objects are red giants and blue stragglers, seen though the filter's red leak.

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3. PHOTOMETRY AND ASTROMETRY

We used the *apphot* aperture photometry package in IRAF to measure fluxes of the three UV-bright sources on the F140W image. We used an aperture with a radius of 3 pixels (=0"066), with the sky value measured in an annulus between 5 and 10 pixels from each star, and then applied an aperture correction of 2.54 mag (Paresce 1992) to determine the count rates of each source. We also measured the two individual UV exposures separately, which were taken 1.5 hr apart. None of the sources varied in brightness between the two observations, to the accuracy of our measurements (~0.2 mag).

The FOC photometric system has been calibrated by medium- and narrowband observations of spectrophotometric standard stars (Greenfield et al. 1991). The resulting estimate of the *HST*/FOC quantum efficiency is combined with synthetic photometry to yield filter sensitivities, which allow the count rate from a source to be converted into a flux F_λ in ergs cm^{-2} s^{-1} $Å^{-1}$. We thus used the inverse filter sensitivity listed in the F140W image header (1.412×10^{-16} erg cm^{-2} $Å^{-1}$ $count^{-1}$) to find fluxes for the three sources, which are listed in Table 1. The listed errors combine the measurement errors with the uncertainty in the absolute calibration of the FOC f/96 relay, estimated to be ~20% (Sparks 1991).

Next, we wished to correct the fluxes for interstellar extinction. For NGC 6624, Zinn (1980) has measured $E(B-V) = 0.25$, while Reed, Hesser, & Shawl (1988) found $E(B-V) = 0.28$. For consistency with Paper I, we adopt $E(B-V) = 0.25$ and $A(1400\ Å)/E(B-V) = 8.48$ (Savage & Mathis 1979), but note that the resulting reddening correction is uncertain by ≳0.25 mag. The final dereddened fluxes, which should be accurate to ~30%, are listed in Table 1. In the rightmost column of Table 1 we list the absolute magnitude in the F140W bandpass, using the monochromatic *HST* magnitude system (in which $m_\lambda = -2.5 \log F_\lambda - 21.1$), and a distance modulus of 14.54.

We also obtained an *HST* magnitude in F430W for star 1 of 22.6 ± 0.5, using DAOPHOT (Paper II). This magnitude is uncertain because the star is very faint; it is below the magnitude cutoff used in our previous study. The corresponding dereddened magnitude and flux are 21.5 ± 0.5 and $F_\lambda = 8.7 \pm 5.1 \times 10^{-18}$ erg cm^{-2} s^{-1} $Å^{-1}$, respectively. Finally, we used color transformations derived from synthetic photometry (King, Anderson, & Sosin 1994) to estimate a *B*-magnitude of ~23.4, or $M_B \sim 7.8$, assuming that star 1 has an optical color similar to that of 4U 1820−30, and that the color equations derived for main-sequence stars can be applied to such a blue star. From the ground-based image discussed earlier, we can estimate an upper limit of 19 for the *B*-magnitudes of stars 2 and 3.

Combining the two flux measurements for star 1, we derive a flux ratio of $F(1400\ Å)/F(4300\ Å) = 51 \pm 32$, which corresponds to a power-law slope in the range from −2.6 to −3.9. Although somewhat uncertain, the implied spectral slope is nearly as steep as that of a Rayleigh-Jeans spectrum; we estimate a lower limit on the temperature of star 1 of $T_{\rm eff} \gtrsim 40{,}000$ K.

Finally, we found absolute positions for each UV-bright source, by applying the coordinate transformation derived in Paper II. These positions are listed in Table 2.

4. DISCUSSION

The three UV-bright stars identified here add to a growing number of faint blue stars discovered with *HST* near the centers of globular clusters. These discoveries include blue straggler stars in the central regions of 47 Tuc (Paresce et al. 1991), M15 (Ferraro & Paresce 1993), and NGC 6624 (Paper II). At fainter absolute magnitudes, UV-bright stars have been identified in NGC 6397 (Cool et al. 1993; De Marchi & Paresce 1994a), NGC 6752 (Shara et al. 1995), and M15 (De Marchi & Paresce 1994b). Some of these stars appear to be hot subdwarfs, while others are possible or likely cataclysmic variables (CVs). The faintest of the UV-bright stars identified so far are a handful of probable white dwarfs in 47 Tuc (Paresce, De Marchi, & Jedrzejewski 1995).

In Figure 2, we plot the F140W fluxes of the three UV-bright sources in NGC 6624, along with the F430W flux of star 1, and upper limits on the F430W fluxes of stars 2 and 3. A sample of the UV-bright stars identified with *HST* in other clusters is also shown, but is not meant to be complete. All fluxes have been corrected for extinction. While measurements through only two or three broadband filters hardly constrain the shape of the spectra, this plot provides an easy way to make rough comparisons of the relative brightnesses and approximate spectral slopes of UV-bright stars that have been observed with different instrumental setups. Note that *HST* magnitudes (*left-hand scale*) have the same zeropoint at all wavelengths, so a straight line on this plot corresponds to a pure power-law spectrum.

The classical theory of stellar evolution would predict only one population of hot stars in NGC 6624: carbon-oxygen white dwarfs (WDs). Young WDs evolve quite rapidly through the part of the HR diagram in which these three objects appear. Their cooling is dependent on a number of processes (D'Antona & Mazzitelli 1990); there is some uncertainty in their cooling times, and thus uncertainty in the number of WDs that we should expect to see. Using the cooling tracks of Castellani, Degl'Innocenti, & Romaniello (1994a) and blackbody model spectra, we find that the F140W flux of the faintest of our three sources (star 1) would be well-matched by a WD with an effective temperature of ~50,000 K and a luminosity of ~5 $L_\odot$. The cooling time for a WD of this luminosity is 0.7 to 1.5×10^6 yr, depending upon which of the five cooling curves tabulated by D'Antona & Mazzitelli (1990) is adopted. Our field contains ~50 horizontal-branch stars with lifetimes of ~10^8 yr; we thus expect ~0.4 to 0.8 WDs in our image down to the magnitude of star 1, which is near the detection limit. Given the crudeness of these estimates, we conclude that the

TABLE 1
FLUXES

Source	Observed F_λ (1400 Å) (erg cm^{-2} s^{-1} $Å^{-1}$)	Dereddened F_λ (1400 Å) (erg cm^{-2} s^{-1} $Å^{-1}$)	M_{140}
1	$(6.2 \pm 1.7) \times 10^{-17}$	$(4.4 \pm 1.7) \times 10^{-16}$	2.8 ± 0.4
2	$(25.2 \pm 7.0) \times 10^{-17}$	$(17.8 \pm 6.8) \times 10^{-16}$	1.2 ± 0.4
3	$(8.0 \pm 2.2) \times 10^{-17}$	$(5.6 \pm 2.1) \times 10^{-16}$	2.5 ± 0.4

TABLE 2
POSITIONS

Source	$x_{\rm F140W}$	$y_{\rm F140W}$	R.A. (J2000)	Decl. (J2000)
1	524.9	285.1	18h23m40s805 ± 0s012	−30°21'36"40 ± 0"15
2	822.2	632.6	18 23 41.078 ± 0.012	−30 21 42.47 ± 0.15
3	66.0	384.4	18 23 39.813 ± 0.012	−30 21 35.50 ± 0.15

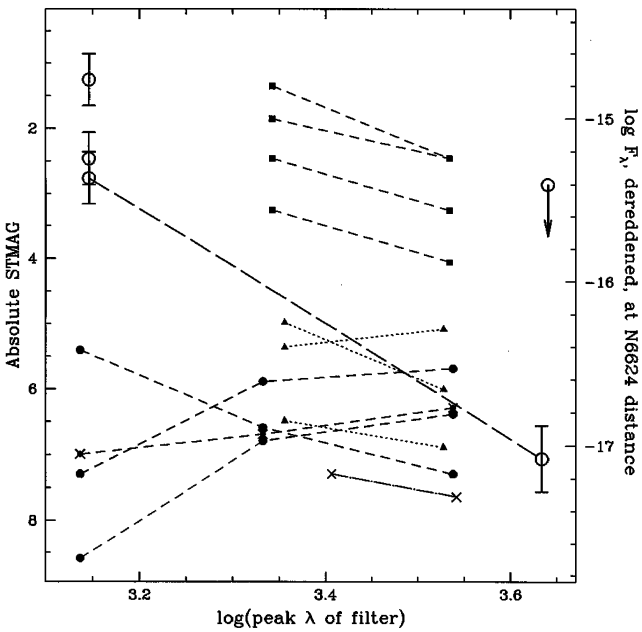

FIG. 2.—Comparison between the UV-bright stars in NGC 6624 and a sample of UV-bright stars observed in other globular clusters with *HST*. Fluxes measured through various filters are plotted at the filter's peak wavelength. All sources have had reddening removed. The left-hand scale is absolute monochromatic magnitude, while the right-hand scale is erg cm^{-2} s^{-1} $Å^{-1}$ with all sources placed at the distance of NGC 6624. The stars in NGC 6624 are plotted as open circles; the point at the upper right represents an upper limit on the *B*-band flux for the two stars with the brightest UV fluxes. Filled squares, circles, and triangles represent stars in M15, NGC 6397, and NGC 6752, respectively. The crosses mark a quiescent dwarf nova in 47 Tuc and a CV candidate in NGC 6397 (see text).

faintest of our three objects (star 1), and perhaps the next-brightest (star 3), could be CO WDs.

It is quite unlikely, however, that star 2 is such a WD: its brighter magnitude would imply a cooling age of only $\sim 10^5$ yr, so we must look for an alternative explanation for its presence. The UV fluxes and the limits on the spectral indices of star 2, as well as star 3, are compatible with their being hot subdwarf B (sdB) or subdwarf O (sdO) stars. Subdwarf B stars have been identified in numerous studies of globular clusters. The brighter populations of sdBs typically form a faint blue extension of the horizontal branch (HB) in metal-poor clusters ([Fe/H] $\simeq -1.6$). These extreme HB (EHB) objects are believed to have much thinner hydrogen envelopes than the cooler HB stars ($M_{env} \lesssim 0.05\ M_\odot$), as a result of substantial mass loss in a previous evolutionary stage—perhaps as a result of binary mass transfer (Mengel, Norris, & Gross 1976). It has been postulated that a small fraction of *metal-rich* stars evolve onto the EHB after the helium core flash, rather than the red end of the HB; this EHB population and its hot, luminous progeny could then be responsible for the far-UV upturn of the spectra of elliptical galaxies (for a review, see Dorman, O'Connell, & Rood 1995).

The models of Dorman, Rood, & O'Connell (1993) predict that hot EHB stars of the metal abundance of NGC 6624 would have $M_{bol} \simeq 1.8$ and effective temperatures of 15,000 to 25,000 K; using Kurucz (1979) model stellar spectra, we find that such objects would have $M_{140} \simeq 0.4$—about 0.8 mag brighter than the F140W magnitude of our brightest source (2). We note that the Dorman et al. models have predicted fluxes of EHB stars in other clusters that are ~0.4 mag too bright (e.g., Whitney et al. 1994); given the uncertainty in the calibration of the UV sensitivity of the FOC, it is possible that our brightest source is an EHB star. On the other hand, *no* other blue HB stars have been observed in this cluster. We note, though, that the old, metal-rich open cluster NGC 6791 has an extremely bimodal HB (Liebert, Saffer, & Green 1994), and that there is evidence for a connection between high stellar density and the presence of EHB stars (Fusi Pecci et al. 1993), so the existence of any EHB stars in NGC 6624 would be quite interesting. This possibility could easily be tested by searching for more hot HB stars elsewhere in the cluster.

Fainter hot-subdwarf populations have also been observed in globular clusters: they usually appear as a blue sequence roughly parallel to the cluster main sequence in optical color-magnitude diagrams (see, e.g., Drukier, Fahlman, & Richer 1989). These are also believed to be core-helium-burning, thin-hydrogen-envelope objects, but their lower luminosities imply smaller helium core masses than horizontal-branch stars. These stars would burn helium for $\gtrsim 10^8$ yr at high temperatures ($\gtrsim$25,000 K) and would have luminosities $\gtrsim 3\ L_\odot$, depending on mass. Their F140W absolute magnitudes would then be $M_{140} \lesssim 2.6$, apparently a good match to all three of our UV sources. D'Antona, Vietri, & Pesce (1995) have argued that the UV sources observed by De Marchi & Paresce (1994b) in the core of M15 must be such helium-burning objects.

A difficulty with this scenario is that *two* presumably uncommon events must take place. First, a low-mass ($\lesssim 0.45\ M_\odot$) object composed of helium must be formed, probably by Roche-lobe overflow of a red giant in a close binary. Alternatively, a giant's envelope might be stripped during a close stellar encounter in the cluster core. Either event would lead to the formation of a degenerate helium white dwarf (HeWD). Next, the helium must somehow be brought to a high enough temperature to ignite. One proposal invokes a merger of two HeWDs in a binary system (Bailyn & Iben 1989), while another invokes collisions between HeWDs and red giants in the dense cluster core (D'Antona et al. 1995). Of course, if these events occur, one or more of the three sources could actually *be* a young HeWD, rather than a helium-burning star. Cooling times for HeWDs are quite uncertain, and could be significantly longer than those of CO WDs at high luminosity, so this possibility cannot be ignored.

The presence of blue stragglers in the core of this cluster implies that stellar mergers or collisions are probably taking place. The formation of binaries, in particular, plays a crucial role in the dynamical evolution of a post-collapse cluster core (Hut et al. 1993), and any observation that implies the presence of binary stars is of great interest. However, with little idea of the *frequency* of any of these phenomena, we choose not to make a numerical estimate of the birthrate of HeWDs or low-mass helium-burning stars; such an estimate would depend critically on at least two unknown parameters. Rather, we suggest that it would be more promising to attempt to observe a HeWD cooling sequence, whose presence or absence would indicate whether any of these proposals should be considered further. This could be done by a direct search for HeWDs in nearby clusters, since the ~0.4 $M_\odot$ HeWD sequence should be more luminous at a given T_{eff} than the 0.6 $M_\odot$ CO WDs. The difference in cooling times between He and CO WDs might also be observable in the WD luminosity function (Castellani, Luridiana, & Romaniello 1994b).

Finally, another alternative is that one or more of the UV stars in NGC 6624 are cataclysmic variables (CVs), which are well known as faint UV sources in the Galaxy. CVs may form by stellar interactions in dense cluster cores (Di Stefano & Rappaport 1994), although the effectiveness of this scenario has been questioned (Kochanek 1992). Observations with *HST* have recently revealed CVs in 47 Tuc (Paresce & De Marchi 1994) and M80 (Shara et al. 1995), and three candidates near the center of NGC 6397 (Cool et al. 1995). By scaling the *IUE* CV fluxes of Verbunt (1987) to the distance of NGC 6624 using the CV distances given by Berriman (1995), we find that the three UV-bright stars in NGC 6624 have fluxes compatible with the brighter of the Galactic CVs. The absolute *B*-magnitude of star 1 is also typical of field CVs (Warner 1987), and, within the errors of the present observations, its spectral slope is consistent with the steepest *IUE* CV spectra.

Such comparisons to known CV brightnesses and spectra are necessarily crude. A much clearer indicator of a CV would be variability in its UV flux. The present observations show no such variations, but two measurements of limited accuracy provide only a rather weak constraint; a monitoring study extending over several hours would be more effective. CVs could also be distinguished from WDs or subdwarfs by photometric or spectroscopic studies aimed at identifying Balmer emission lines (Cool et al. 1995) or by a search for X-ray emission (Grindlay 1993). The faintness of CVs, combined with the proximity of the LMXB, would make the latter observation difficult; it would probably require the high resolving power of *AXAF*.

5. CONCLUSIONS

We have identified three UV-bright objects on an *HST* image of the center of the globular cluster NGC 6624. Other than the LMXB, these are the only hot objects known in this cluster. The faintest source, and perhaps the next-brightest as well, could be young CO white dwarfs. The brightest source could be a blue, extreme-horizontal-branch star. Alternatively, one or more could be a helium-burning subdwarf with a different evolutionary history, a helium white dwarf, or a cataclysmic variable. The limited amount of information contained in the present observations prevents us from distinguishing between these various possibilities, and further observations—deeper imaging, wider field-of-view imaging, or spectroscopy—will be necessary. Such observations should yield new insights into the nature of evolved, metal-rich stars, the role of stellar interactions in dense stellar systems, or both.

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