Another Faint Ultraviolet Object Associated with a Globular Cluster X-ray Source: The Case of M92

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Abstract

The core of the metal-poor galactic globular cluster M92 (NGC 6341) has been observed with Wide Field Planetary Camera 2 (WFPC2) on the Hubble Space Telescope through visual, blue, and mid-UV filters in a program devoted to studying the evolved stellar population in a selected sample of galactic globular clusters. In the UV (m_{255}, m_{255} - U) color-magnitude diagram, we have discovered a faint "UV-dominant" object. This star lies within the error box of a low-luminosity globular cluster X-ray source (LLGCX) recently found in the core of M92. The properties of the UV star discovered in M92 are very similar to those of other UV stars found in the core of some clusters (M13, 47 Tuc, M80, etc.)—all of them are brighter in the UV than in the visible and are located in the vicinity of a LLGCX. We suggest that these stars are a new subclass of cataclysmic variables.

Subject headings: stars: evolution — globular clusters: individual (M92) — novae, cataclysmic variables — ultraviolet: stars

1. Introduction

Despite their rarity, they are the exotic creatures that attract the crowds at the zoo; similarly, the exotic objects in the stellar zoo attract our attention. Unusual environments often lead to relatively large populations of the exotic. So it is with the cores of the galactic globular cluster (GGCs), which have long been thought to harbor a variety of exotic objects—blue stragglers, low-mass X-ray binaries, cataclysmic variables, millisecond pulsars, etc. Most of these objects are thought to result from various kinds of binary systems whose nature and even existence can be strongly affected by dynamics in the dense cluster cores.

When a binary system contains a compact object (like a neutron star or white dwarf) and a close enough secondary, mass transfer can take place. The streaming gas, its impact on the compact object, or the presence of an accretion disk can give such systems observational signatures that make them stand out above ordinary cluster stars. These signatures might include X-ray emission, significant radiation in the ultraviolet (UV), emission lines, or rapid time variations. The first evidence for such objects in globular clusters was the discovery of X-ray sources. One population of X-ray sources with \( L_X > 10^{34.5} \) ergs s\(^{-1}\) (the so-called low-mass X-ray binaries, or LMXBs) are thought to be binary systems with an accreting neutron star because of their X-ray bursts. LMXBs are very overabundant (a factor 100) in GGCs with respect to the field, presumably because the high stellar density has led to many capture binaries.

Given the existence of neutron star systems in GGCs, one might expect to find many more analogous systems involving white dwarf binaries (WDs). In the field, binary systems in which a WD is accreting material from a late-type dwarf, i.e., a main-sequence or subgiant star, are observed cataclysmic variables (CVs). CVs are well-studied objects in the field, where they are thought to form by the evolution of primordial binaries. They come in many varieties depending on stellar masses, mass transfer rates, magnetic field strength, etc. In GGCs, one can expect even more variety because CVs located in dense clusters could have been created by dynamical processes (Hut & Verbunt 1983; Bailyn 1995), while the CVs in low-density clusters result from primordial binary systems (Verbunt & Meylan 1988).

Numerical simulations (e.g., DiStefano & Rappaport 1994) suggest that more than 100 white dwarf binaries might be found in massive clusters like 47 Tuc and ω Cen, and several tens in more typical clusters. Despite the expectation of large numbers of CV-like stars, searches have turned up only a relatively small number. Of course, part of the problem arises because of the difficulty of searching for rather faint objects in crowded globular cluster fields. However, by exploiting the high resolution of Hubble Space Telescope (HST), it has become possible to search GGC centers for several of the anticipated CV signatures. Still the number of candidates is small.

More than 30 low-luminosity X-ray sources with \( L_X < 10^{34.5} \) ergs s\(^{-1}\) (hereafter LLGCXs) have been discovered in 19 GGCs (Johnston & Verbunt 1996). Despite their relatively large numbers, there is no consensus model for LLGCXs (see Verbunt et al. 1994 and Hasinger, Johnston, & Verbunt 1994). The fainter LLGCXs (\( L_X < 10^{32} \) ergs s\(^{-1}\)) might well be associated with CVs (van Paradijs 1983; Hertz & Grindlay 1983).
2. There are three objects connected with conventionally detected CVs: a dwarf nova in M5 (Margon, Downes, & Gunn 1981); HST UV detections of optical counterparts to a dwarf nova in 47 Tuc (Paresce & De Marchi 1994), and possibly the historical nova in M80 (Shara & Drissen 1995).

3. Using HST, Hz emission has been observed from three objects in NGC 6397 (Cool et al. 1995) and two objects in NGC 6752 (Bailyn et al. 1996).

4. Also using HST, a number of candidate CVs have been selected on the basis of UV excess and variability: the Einstein dim source in 47 Tuc (Paresce, De Marchi, & Ferraro 1992) and a few CVs candidates in NGC 6624 (Sosin & Cool 1995).

We are involved in two long-term HST projects to study in detail the evolved populations in a sample of GGCs, at different wavelengths ranging from the UV to the near IR. Although we were not specifically hunting for CVs, we have used the UV exposures to search for exotic objects in the core of GGCs. This search has been very fruitful: in our database (nine clusters) we have found that in all GGCs properly observed (with exposures deep enough and in the right UV bands) there is at least one faint object with a strong UV excess with respect to the main stellar population of the cluster. These stars are brighter in the UV than in the visible, so we will refer to them as UV-dominant (UVD). We wish to distinguish carefully between these objects and objects that are called “UV-excess” objects on the basis of their colors in the visible or perhaps near UV. Previously we reported on three UVD stars in the GGC M13 (Ferraro et al. 1997). Two of these objects have been found to lie within the error boxes of LLGCXs (Fox et al. 1996), and we argue that they are excellent CV candidates. Here we report on the discovery of another faint UVD star in the core of M92, and we suggest that this star is physically connected to the X-ray emission detected in the cluster.

2. OBSERVATIONS

HST Wide Field Planetary Camera 2 (WFPC2) frames were obtained in 1995 December (Cycle 5: GO 5969, PI: F. Fusi Pecci). We report here results obtained using the deep exposures (3600 and 2200 s) through the U (F336W) and mid-UV (F255W) filters, respectively. The color-magnitude diagrams (CMDs) presented here are results of the four WFPC2 chips (namely PC1, WF2, WF3, and WF4), obtained with the PC located on the cluster center (some further discussion of these results can be found in Ferraro et al. 1997, 1998).

All the reductions have been carried out using ROMAFOT (Buonanno et al. 1983), a package specifically developed to perform accurate photometry in crowded fields. In order to identify the objects in each field, we used the median frame, obtained by combining all single exposures in each color. The point-spread function (PSF) fitting procedure was then performed on each individual frame separately, and the instrumental magnitudes were then averaged. The instrumental magnitudes have been converted to fixed-aperture photometry and, where appropriate, calibrated to the Johnson system using equation (8) and Table 7 in Holtzmann et al. (1995). F255W magnitudes have been calibrated to the StScI Magnitude System (STMAG) system using Table 9 by Holtzmann et al. (1995).

In this paper we adopt for M92 a distance modulus \((m - M)_0 = 14.78\) from Ferraro et al. (1999a), who have recently determined moduli for a sample of 61 GGCs within the framework of a homogeneous reanalysis of the evolved sequences of the CMD.

3. RESULTS

Figure 1 shows the \((m_{255}, m_{255} - U)\)-CMD for the global sample of stars detected in all the four WFPC2 chips. More than 20,000 stars have been measured in these filters in the global WFPC2 field of view. Inspection of this diagram shows that a few (five) blue low-luminosity objects lie significantly outside the main loci defined by the majority of the cluster stars. Four of them are clumped at \((m_{255} - U) \approx -1\), and one object (namely, star \#8203) shows a very strong UV color \((m_{255} - U) \approx -1.5\). This object is at only 15.7 from the cluster center (assumed at \(\alpha_{2000} = 17^h17^m07^s3; \delta_{2000} = 43\deg08'11"0; Djorgovski \& Meylan\,1993\)), just outside the core radius of the cluster \((r_c = 14"\)\). It is located at the extreme northern edge of the PC chip. This region is still very crowded, and the UV star is close (less than 1") to a horizontal-branch (HB) star and a very bright giant \((V \approx 12.8)\), which is heavily saturated in the \(V\) and \(I\) deep exposures. Hence, only measures in the F255W and \(U\) filters are possible. The possible variability of the UV source was examined by analyzing each available frame separately. No clear indication of variability was revealed from this analysis, but we cannot strongly exclude this possibility since our observations do not have much time coverage.

Fox et al. (1996) recently presented ROSAT High Resolution Imager (HRI) observations of M92 and identified seven low-luminosity X-ray sources in the field of view of the cluster. In particular, they drew attention to the X-ray source found in the core, M92C (hereafter M92X-C). M92X-C is only \(\approx 17"\) from the cluster center and has a high probability (\(\approx 99.8\%\)) of being associated with the cluster. The LLGCX is also located at the northern edge of

![Figure 1](image-url)
the PC in our HST field of view, just in the region where the UV star has been detected. Figure 2 shows a region of \( \sim 30' \times 30' \) centered on the nominal position of the M92X-C. The contours of the X-ray emission (from Fig. 2 by Fox et al.) have been overplotted on a digital map of the F255W image. The absolute positions, the observed magnitude, and the X-ray flux for the UV star and the X-ray source are listed in Table 1. Note that the X-ray luminosity has been properly scaled in order to take into account the different distance modulus adopted here with respect to that used by Fox et al. (1996).

Because the UV object is \( \lesssim 4.5' \) from the nominal position of the X-ray emission, we strongly suggest a physical connection between the two. Note that the four UV objects located in the CMD at \( (m_{255} - U) \sim -1 \) are much more distant \( (d > 37') \) from the X-ray source.

4. DISCUSSION

Faint UV stars (similar to UV 8203) have been discovered in the core of other GGCs, and some of them have been found to be nearly coincident with X-ray sources. The discovery reported in this paper makes the possibility of a chance coincidence of UV objects with the X-ray sources appear even less likely. With the strengthening evidence for a (physical) connection between UV objects and LLGCXs, it is appropriate to compare the photometric properties of a sample of faint UV stars found in the vicinity of LLGCXs in GGCs. In doing this we select some of the most recent findings.

M13. —Ferraro et al. (1997), using deep UV HST observations, found three extremely blue, low-luminosity objects in the very central region of M13. Two of them are nearly coincident with the two-peaked X-ray emission detected by Fox et al. (1996).

M5. —V101 in M5 was discovered by Oosterhoff (1941), who first suggested that it could be a CV (dwarf nova). Spectroscopic (Margon et al. 1981; Naylor et al. 1989) and photometric observations (Shara, Potter, & Moffat 1987) confirmed this suggestion. Hakala et al. (1997) detected X-ray emission associated with this object using the ROSAT HRI.

M80. —Shara & Drissen (1995) have found two UV objects in the globular cluster M80; one of them might be associated with T Sco, a nova observed in 1860. This object might be connected with a LLGCX located at 8' from the UV object, although, as suggested by Hakala et al. (1997), the position from the ROSAT Position Sensitive Proportional Counter (PSPC) is not accurate enough for a definitive identification.

NGC 6397. —Cool et al. (1998, hereafter C98) found a population of seven UV stars in the core of NGC 6397. They divided the UV star sample into two subgroups: four stars showing variability and UV excess (in the sense that they appear to be blue in the \( U \) band but are indistinguishable from MS stars in the \( V, V-I \) plane) and three nonvariable UV excess stars, which are significantly hotter than the main sequence in all observed CMD planes. They call this second class “nonflickerers” (NFs). The four variable stars are all within the ROSAT HRI X-ray error circle and have been confirmed to be CVs (Cool et al. 1995; Edmunds et al. 1999). However, they noted that “…two out of three NFs are outside the error circles of the three central X-ray sources detected with ROSAT by Cool et al. (1993).” While C98 claimed that the NF stars were a new class of faint UV stars, it is worth noting that they are very similar to the three UV stars found one year earlier in M13 by Ferraro et al. (1997).

47 Tuc.—At least two objects with a strong UV excess have been identified in the error box of X-ray source in the center of 47 Tuc: V1 (Paresce et al. 1992) and V2 (a blue variable discovered by Paresce & De Marchi 1994; see also Shara et al. 1996). V1 lies within the error circle of the X-ray source X0021.8–7221 detected by Einstein (Bailyn et al. 1988) and in the vicinity of a low-luminosity X-ray source (X9 in Table 2 of Verbunt & Hasinger 1998). Verbunt & Hasinger (1998) also identified V2 as a candidate optical counterpart of their source X19.

NGC 6752.—Bailyn et al. (1996) report the identification of two candidate CVs in NGC 6752. Both stars fall at the edge of the error circle of the X-ray source identified as B by Grindlay (1993). These stars are plotted as empty circles in Figure 3. Contrary to the behavior shown by all the other

| Table 1 |

**UV Star and X-Ray Source in the Core of M92**

| Object     | \( \alpha_{2000} \) | \( \delta_{2000} \) | \( U \) | \( m_{255} \) | \( L_X \) |
|------------|---------------------|-------------------|------|---------|--------|
| 8203       | 17h06m55.9s         | 43° 08' 24.39''   | 22.63| 20.97   | ...    |
| M92X-C     | 17h06m3.3s          | 43° 08' 23.0''    | ...  | ...     | 4.6 \( \times 10^{32} \) |
object candidates, they have a quite strong rise up toward red wavelengths, suggesting that these objects have quite different spectral characteristics with respect to the other objects listed above. Their positions in the CMD (see Fig. 3 by Bailyn et al.) resemble the CVs found by C98 in NGC 6397; however, observations at wavelengths shorter than $B$ are needed in order to better constrain the spectral behavior of these stars. For these reasons we exclude them from the following discussion.

The absolute magnitude in different photometric bands for the 10 UV stars possibly connected with X-ray emission in the eight GGCs quoted above are listed in Table 2. Also reported are the adopted distance moduli and reddening.

![Graph showing UV stars within LLGCs error-boxes.](image)

**Fig. 3.**—Comparison between the photometric characteristics of the UV stars discovered in M92 and a sample of UV stars found within the error boxes of LLGCs in other GGCs (see Table 2). The absolute magnitudes obtained through various filters are plotted as functions of the filter effective wavelength. Different symbols refer to different clusters. The approximate location of each filter in terms of effective wavelength is labeled at the bottom of the figure.

TABLE 2

| Cluster | Name | $(m-M)_0$ | $E(B-V)$ | $M_I$ | $M_V$ | $M_B$ | $M_U$ | $M_{255}$ | $M_{160}$ | $M_{140}$ | $L_x$ $(10^{32})$ | Range (KeV) |
|---------|------|-----------|----------|-------|-------|-------|-------|-----------|-----------|-----------|-------------|-------------|
| M92.... | 8203 | 14.78     | 0.02     | ...   | ...   | ...   | ...   | ...       | ...       | ...       | 4.6         | 0.1-2.4     |
| M13.... | 23081| 14.43     | 0.02     | 7.69   | 6.09  | 2.36  | 1.46  | ...       | ...       | ...       | 7.4         | 0.1-2.4     |
| M13.... | 21429| 14.43     | 0.02     | 6.55   | 5.33  | 2.72  | 1.33  | ...       | ...       | ...       | 2.9         | 0.1-2.4     |
| M80..... | ...  | 14.96     | 0.18     | ...   | ...   | ...   | ...   | ...       | ...       | ...       | 7.6         | 0.5-2.5     |
| M5.....  | V101 | 13.37     | 0.03     | 5.80   | 6.2   | 3.7   | ...   | ...       | ...       | ...       | 1.1         | 0.5-2.5     |
| NGC 6397| CV1  | 11.92     | 0.18     | 6.44   | 5.75  | 6.31  | 5.47  | ...       | ...       | ...       | 1.1         | 0.1-2.0     |
| NGC 6397| CV2  | 11.92     | 0.18     | 7.70   | 6.93  | 7.65  | 6.38  | ...       | ...       | ...       | 0.9         | 0.1-2.0     |
| NGC 6397| CV3  | 11.92     | 0.18     | 8.42   | 7.64  | 7.80  | 6.29  | ...       | ...       | ...       | 0.8         | 0.1-2.0     |
| 47 Tuc  | V1   | 13.32     | 0.04     | ...   | ...   | ...   | ...   | ...       | ...       | ...       | 8.0         | 0.5-2.5     |
| 47 Tuc  | V2   | 13.32     | 0.04     | ...   | ...   | ...   | ...   | ...       | ...       | ...       | 1.3         | 0.5-2.5     |
| NGC 6752| 1    | 13.18     | 0.04     | 6.05   | 7.25  | 7.66  | 7.23  | ...       | ...       | ...       | 1.7         | 0.1-2.4     |
| NGC 6752| 2    | 13.18     | 0.04     | 6.46   | 7.59  | 8.16  | ...   | ...       | ...       | ...       | 1.7         | 0.1-2.4     |

from Ferraro et al. (1999b). Note that the distance moduli adopted typically differ from those of earlier papers; for example, the distance modulus for NGC 6397 is $\Delta(m-M)_v \sim 0.2$ mag larger than that adopted by Cool et al. (1998). All the absolute magnitudes and X-ray luminosities in Table 1 have been corrected accordingly. Note also that the X-ray fluxes were determined over different energy ranges, which are given in the last column.

In Figure 3 we plot the absolute magnitude for each star listed in Table 2 as a function of the filter's effective wavelength. In the figure different symbols refer to different clusters: triangles for M13, filled circles for M92, asterisks for M80, pentagons for 47 Tuc, large crosses for M5, and dashed lines for the three CVs in NGC 6397. For comparison, the energy distribution for the field CV U Gem is plotted as a heavy solid line. Figure 3 provides an easy way to make quantitative comparisons. In particular, all of the UV selected stars show the same overall spectral trend, and we conclude that some of the photometric properties of faint UVD stars associated with LLGCXs are in reasonable agreement with each other and U Gem. It is interesting to note that the slopes of UV 8203 in M92 and V101 in M5 appear to be steeper than the others; however, far-UV observations are required in order to confirm this impression.

Though small, the sample listed in Table 2 can still be used to derive some average properties of these objects, for example, the absolute $V, B, U$ magnitudes and $U-V$ and $U-B$ colors, which are used to characterize CVs in the field. From the data in Table 2 these figures turn out to be: $<M_V> = 6.7 \pm 0.8$, $<M_B> = 7.0 \pm 0.7$, $<M_U> = 5.9 \pm 1.0$, $<U-B> = -1.1 \pm 0.3$, and $<U-V> = -1.0 \pm 0.5$, respectively. These figures are in good agreement with the typical absolute magnitude and colors for CVs in the field ($<M_V> \sim +7$ for the dwarf novae CVs; see van Paradijs 1983).

We may push our working hypothesis that the UVD objects are physically associated with the X-ray sources further. The X-ray luminosity of each source is listed in the penultimate column of Table 2. As can be seen, they have comparable X-ray luminosity, within the range $1\times10^{32}$ ergs s$^{-1}$ (with a mean value of $<L_x> = 4 \pm 3 \times 10^{32}$ ergs s$^{-1}$).

We can compare the observed photometric characteristics of the UV objects found in GGCs with those obtained...
for field CVs by using the values listed in Table 2 along with data from Table 1 of the recent compilation by Verbunt et al. (1997, hereafter V97), who presented a catalog with 91 CVs in the field detected during the ROSAT All Sky Survey. The upper panel of Figure 4 shows the absolute $V$ magnitude as a function of the X-ray luminosity for all field CVs with known distances listed by V97. These are plotted as small circles. The six UVD stars found in GGCs for which the $V$ magnitudes have been measured are plotted as large circles. The $V$ magnitude for the four stars for which no $V$ magnitude was directly measured has been computed from $M_V$ assuming a mean color $\langle U - V \rangle = -1$ (see above). These are plotted as large asterisks. The lower panel shows the X-ray luminosity distribution for the GGC objects (shaded histogram) compared with the distribution for the field CVs. This figure clearly shows that while the absolute $V$ magnitudes for the candidates in clusters are fully consistent with the field CVs, the X-ray emission for CVs in GGCs seems systematically higher (as already suggested by Ferraro et al. 1997; see also Fig. 4 in Verbunt & Hasinger 1998), indicating that the X-ray luminosity of objects found in GGCs is high relative to the visible compared with similar objects in the field.

There is a strong observational selection effect at work in Figure 4. The depth reached by the X-ray observations is typically only a factor of 2 or 3 below the level of the detected sources. The deepest is for NGC 6397 (Cool et al. 1993), which reaches $L_X = 3 \times 10^{31}$ ergs s$^{-1}$. Dashed lines in Figure 4 show the maximum depth reached in surveys for UVD stars/LLGCXs in M13, M92, and NGC 6397. Figure 8 of V97 shows that the vast majority of field CVs of all types are less luminous than this. A comparison of the $M_V$ for the optically identified LLGCXs with typical values implies that it was not associated with the candidate object suggested by Shara & Drissen (1995). However, we now see that $L_X/L_{opt}$ is systematically higher for GGC CVs as compared with their field sisters, and thus, the Hakala et al. (1997) argument is not valid.

Only the three field CVs with highest $L_X$ are consistent with the GGC CV candidates in Figure 4. These are the DQ Her systems V1223 Sgr, AO Psc, and TV Col. These are strongly magnetic CVs of a class referred to as intermediate polars (IPs). Grindlay (1999) suggests that IPs might dominate the ROSAT survey, since they are expected to have a ratio $F_X/F_{opt}$ greater than nonmagnetic CVs. The problem with connecting the UVD stars with magnetic CVs is that the magnetic field might truncate the inner portion of the accretion disk (Grindlay 1999). Thus, magnetic cataclysmic variables (MCVs) might not be expected to have strong UV excess.

It is worth noting that the V97 $L_X$ distributions for field dwarf novae (SU UMa, Z Cam, U Gem stars) are based on small samples (11, 7, 7) and still span 1 to 2 orders of magnitude. Larger samples could well reach into the range observed in GGCs. Indeed, since we could well be observing the bright end of a sample of several tens of assorted types of CVs in a GGC, the large observed values of $L_X$ probably do not provide a significant constraint on CV types.

Perhaps the most solid detection of CVs in a GGC are those in NGC 6397 (Edmonds et al. 1999; C98). There are several indications of mass exchange: Hz emission, X-ray radiation, spectra with emission lines, and time variability or flickering of the optical radiation. The colors of these objects become redder as the wavelength of filters employed increases. This suggests that in, for example, $V$ or $I$, the light from the cool secondary dominates a rather weak accretion disk. This is one of the factors that led Edmonds et al. (1999) and Grindlay (1999) to associate these objects with the intermediate polar class of magnetic CV. The CVs in NGC 6752 are probably similar objects.

The UVD objects are clearly not this sort of creature. Many have properties one might expect from a generic CV, i.e., white dwarf/main-sequence binaries with some mass exchange. They share many properties with some field CVs—X-ray luminosity, UV colors, absolute visual magnitudes. The facts that they tend to lie at the extremes of the distributions and that some do not have detected X-ray radiation may simply be a consequence of the rather low sensitivity of current surveys. In this scenario the difference between the UV-dominant CVs and those in NGC 6397 is simply a matter of the relative importance of light from the secondary and the accretion disk. For the GGC UVD stars, as with most CVs in the field, the accretion disk significantly outshines the secondary star (see, for example, Figs. 2.16–2.17 in Warner 1995).
What other options are there? It might be tempting to extend either the HB or WD sequences into the region of the UVD stars. However, the HB terminates at the helium-burning main sequence. Particularly for M13, where the observed HB extends almost to its termination, we see that the UVD stars are significantly fainter (Fig. 1 of Ferraro et al. 1997). The ordinary, i.e., carbon/oxygen, WD sequence is well observed, for instance, in M4, and all the observed WDs are fainter than \( M_V \sim 8.5 \) (see Fig. 6 by Richer et al. 1997), ~1 mag fainter than the faintest UVD in Table 2. So the UVD stars are not HB stars or carbon/oxygen white dwarfs.

Edmonds et al. (1999) have shown that at least one UVD star is not a CV. Their HST Faint Object Spectrograph (FOS) spectrum of one of the NF-UV objects identified by C98 in NGC 6397 suggests a very hot high-gravity object. They argue that this is a low-mass (~0.25 \( M_\odot \)) helium white dwarf. Such an object could arise either from mass exchange in a binary system shortly after the primary leaves the main sequence or via stellar collisions. The object has a velocity of \( \sim 250 \text{ km s}^{-1} \) relative to the cluster CVs, which is most easily explained if it still is in a binary system with a dark companion. (It might be worth noting that NGC 6397 is a post-core-collapse cluster with a very dense core, whereas the UVD objects we have found are in the moderate density clusters M13 and M92.) Could He WDs account for all GGC UVD stars? This is certainly not the case for the objects in M5, M80, and 47 Tuc, which have shown variability consistent with known CV types. He WDs would not produce X-rays in significant quantities. The chance association of three LLGCXs with such rare objects as the UVD objects we have found in M13 and M92 would seem unlikely.

5. CONCLUSIONS

We have now identified three UV-dominant objects that appear to be associated with X-ray sources in the GGCs M13 and M92. We argue that these are generically CVs, i.e., white dwarf/main-sequence binaries with some mass exchange. They share many properties with some field CVs—X-ray luminosity, UV colors, absolute visual magnitudes—although they tend to lie at the extremes of the distributions. The relatively high optical, UV, and X-ray luminosities are consistent with the notion that current surveys do not reach deep enough to detect most of the CVs in GGCs. On the other hand, cluster CVs are older and live in a dramatically different environment than their sisters in the field. Thus, it seems reasonable that cluster objects might be a new class of CVs with properties that slightly differ from those in the field.

The CVs found in NGC 6397 and NGC 6752 differ significantly from our objects. Some of these have little or no UV excess. This should not be surprising. The searches in NGC 6397 and NGC 6752 relied on Hz and R bands, whereas we used the UV. There is considerable variety in the properties of field CVs and no reason to suspect less variety in GGC CVs. Different search techniques operating at the margin of detectability will certainly turn up different kinds of objects.

The UVD objects in GGCs probably come in several varieties. (Our GGC projects do not seem to come up with simple answers.) Edmonds et al. (1999) have shown that one is a hot high-gravity object, arguably a He WD. Still, we suspect that most of these will turn out to be CVs and that many UVD objects with no X-radiation detected to date will show up as LLGCXs in more sensitive X-ray surveys. This suspicion is fueled by the belief that a significant population of generic CVs must be present in GGCs.

We have yet to make an observation directly showing the hot diffuse gas that would be the definitive evidence that our UVD objects are CVs. HST Space Telescope Imaging Spectrograph (STIS) spectra could give such evidence. It would be extremely valuable to develop a technique to identify GGC CVs using UV photometry. Cluster cores are very congested in the red, and Hz/R-band searches will obviously be incomplete because of the interference by bright red giants (see Fig. 2 of Bailyn et al. 1996). On the other hand, the cores of even the densest clusters are relatively open in the UV (see Fig. 1 of Ferraro et al. 1999b).

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