Faint Ultraviolet Objects in the Core of M13: Optical Counterparts of the Low Luminosity X-ray Source?

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ABSTRACT

The core of the galactic globular cluster M13 (NGC 6205) has been observed with WFPC2 on the Hubble Space Telescope through visual, blue and mid- and far-UV filters in a programme devoted to study the UV population in a sample of Galactic globular clusters. In the UV Color Magnitude Diagrams derived from the HST images we have discovered three faint objects with a strong UV excess, which lie significantly outside the main loci defined by more than 12,000 normal cluster stars. The positions of two of the UV stars are nearly coincident (7$''$ & 1$''$) to those of a low luminosity X-ray source recently found in the core of M13 and to a 3.5$\sigma$ peak in the X-ray contour map. We suggest that the UV stars are physically connected to the X-ray emission. The UV stars are very similar to the quiescent nova in the globular cluster M80, and they might be a, perhaps new, subclass of cataclysmic variable.

Key words: globular clusters: individual: M13 – stars: Cataclysmic Variables – ultraviolet: stars – stars: evolution

1 INTRODUCTION

A growing number of Galactic Globular Clusters (GGCs) have been found to contain X-ray sources. Hertz and Grindlay (1983) first proposed that two distinct populations of X-ray sources might exist in globular clusters: high luminosity X-ray sources with $L_X > 10^{34.5}$ erg sec$^{-1}$ and low luminosity X-ray sources with $L_X < 10^{34.5}$ erg sec$^{-1}$ (hereafter LLGCXs). There are about a dozen high luminosity X-ray sources found in early surveys, and now more than 30 LLGCXs sources in 19 GGCs are listed in the recent compilation of Johnston and Verbunt (1996). The presence of X-ray bursts provides compelling evidence that the high luminosity objects are binary systems with an accreting neutron star (the so-called Low Mass X-ray Binaries, LMXB). The nature of LLGCXs is still not clear. Recently, Bailyn (1995, but see also Verbunt et al. 1994 and Hasinger, Johnston, & Verbunt 1994 for a full discussion of the topic) has reviewed the most plausible formation scenarios for LLGCXs and has concluded that the brightest LLGCXs (with $L_X > 10^{32}$ erg sec$^{-1}$) might be transient neutron star binary systems in quiescent state (since no X-ray burst has been identified in these objects). Alternatively, they might result from the superposition of multiple faint LLGCXs as recently found in NGC 6397 and NGC 6752 (Cool et al. 1993, 1995).

These fainter LLGCXs ($L_X < 10^{32}$ erg sec$^{-1}$) might be cataclysmic variables (CVs), binary systems in which a white dwarf (instead of a neutron star) is accreting material from a late type dwarf, i.e. a MS-SGB star (van Paradijs 1983; Hertz & Grindlay 1983). Some of the dimmest LLGCXs do appear to be CVs (Cool et al. 1993, 1995). But in other clusters like 47 Tuc, there are other objects in addition to the CVs found by Paresce, deMarchi, & Ferraro (1992) that could be the source of the observed X-rays (Hasinger et al. 1994). Most of the CVs located in core-collapsed clusters could have been created by dynamical processes (Hut & Verbunt 1983; Di Stefano & Rappaport 1994; Bailyn 1995), while the CVs in low-density clusters can be primordial binary systems (Verbunt & Meylan 1988).

The search for optical counterparts for LLGCXs is essential to determining their origin and the role of the dynamical history of the parent cluster. The advent of the Hubble Space Telescope (HST) has made it possible to search for candidate objects in the most crowded regions of the GGCs. Still, some additional identifying characteristic must be used to select the optical counterpart of a LLGCX from the 100’s of stars within the typical X-ray position error box. For example, blue, variable objects (candidate CVs) have been found to fall within the error boxes of some LLGCXs (Paresce et al. 1992, Cool et al. 1993, 1995). However,
Fox et al. (1996) presented

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and the extinction law of Savage and Mathis (1979).

Egovski (1993), a reddening previously identified in sources in the field of view of M13 (eight of these had been (HRI) observations of the GGC M13 and identified 12 X-ray candidates, are detected.

We adopt distance modulus \((m - M)_0 = 14.29\) (Djorgovski 1993), a reddening \(E(B-V) = 0.02\) (Peterson 1993), and the extinction law of Savage and Mathis (1979).

2 OBSERVATIONS

HST-WFPC2 frames were obtained on January 1996 (Cycle 5: GO 5903 PI: F. R. Ferraro) through \(V\) (F555W), \(B\) (F439W), \(U\) (F336W), mid-UV (F255W) and UV (F160BW). The exposures in each filter are listed in Table 1. A detailed description of the data processing will be presented in a forthcoming paper (Ferraro et al. 1997). Here we summarize just the main steps:

(1) All of the exposures were aligned using MIDAS, and then combined to yield a master median frame.
(2) The search for objects was performed on the master median frame using ROMAFOT (Buonanno 1983).
(3) PSF-fitting was then performed on each individual frame, and the instrumental magnitudes were then averaged. In the case of the F160BW frames, we used aperture photometry instead of the PSF-fitting technique because of the high aberration affecting the stellar images.
(4) All of the instrumental magnitudes have been converted to a fixed aperture photometry and then calibrated to the Johnson system using equation 8 and Table 7 in Holtzmann et al. (1995). F160BW and F255W magnitudes have been calibrated to STMAG system using table 9 by Holtzmann et al. (1997).

\[ \alpha_{2000} = 16 \text{ 41 41.5}, \delta_{2000} = 36 \text{ 27 37.0}, \text{Trager, King, & Djorgovski 1995}, \] so they concluded it was a LLGCX with a cluster membership probability of \(
\sim 96\%.
\]

The location of M13X-G is \(\sim 30''\ E\) and \(22''\ N\) from the cluster center, which is within the field of view of the WF2 chip in our data. For this reason we first reduced the WF2 data set and carefully searched for any object with markedly blue excess.

Fig. 1 shows the CMDs of stars detected using the WF2 data, in 4 different planes: \((V, U - V), (m_{255} - m_{160} - V), (U, m_{160} - V).\) In the frames taken through the F160BW filter the main sequence and red giant branch are invisible, and only the UV bright horizontal branch (HB) stars and a few fainter stars, including our candidates, are detected.

Inspection of these diagrams shows two extremely blue, low luminosity objects, namely \#21429 and \#23081 in our list, which stand significantly outside the main loci defined by the other cluster stars. The positions and magnitudes of these objects are listed in Table 2. These objects are close to our photometric detection threshold in all filters, and were not detected in the \(B\) band because the exposures were too short.

The possible variability of the two sources was examined by analysing each frame separately. No clear indication of variability was revealed from this analysis, but we cannot strongly exclude this possibility since the \(S/N\) is quite low.

Fox et al. (1996) reported the absolute position of the M13X-G source at \(\alpha_{2000}=16\ 41\ 44.0, \delta_{2000}=36\ 27\ 59.0.\) Figure 3 shows a region of \(\sim 60'' \times 60''\) centered on the nominal position of M13X-G. The contours of the X-ray emission from ROSAT image retrieved from the archives have been overplotted on a numerical map of the F160BW image. The locations of the two UV objects are indicated by arrows. The position of star \#23081 is \(\sim 7''\) NW of the main bump of the X-ray map. Star \#21429 is about 1" N of a 3.5" bump that Fox et al. (1996) interpreted as a background fluctuation. We suggest that the “fluctuation” is real and will refer

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to it as M13X-G-SE. Its approximate position and flux were measured from the archival image and are given in Table 2. Because of the small number of counts the position is much less well determined than that of M13X-G. While ROSAT coordinates are generally good to (< 5″), errors of 10″ in absolute position are not uncommon in HRI images (David et al. 1992). In our view, the connection between the UV stars and the X-ray emission detected in the core of M13 is strong. Among the more than 3,000 measured stars in the WF2 region (80 × 80 arcsec), we found only 2 UV objects lying outside the CMD main branches. There are only 3 faint UV objects in the entire HST field of view containing more than 12,000 normal stars. Only about 130 stars are within 7″ of the X-ray source, so the probability of a chance coincidence of one UV object with M13X-G is only about 3%. The case would be greatly strengthened if deeper observations confirm the reality of M13X-G-SE.

In subsequent data analysis we have found a third UV object (#31930) in WF3, but none in WF4 and the PC. The archival X-ray image shows no excess of emission at the location of the third UV star. However, this UV star might also be associated with a LLGCX since LLGCXs are known to be highly time-variable (Hasinger et al. 1994; Hertz, Grindlay, & Jai lyn 1993). Indeed, we predict that further ROSAT observations of M13 may find a LLGCX at this position.

In addition to being associated with LLGCXs, we think it is likely that the UV stars are also CVs. Perhaps the most solid indication for this comes from Shara & Drissen (1995). They have recently found a UV object in the globular cluster M80, which they associate with T Sco, a nova observed in 1860. The near UV properties of T Sco are very similar to those of our objects. There is possibly a LLGCX associated with T Sco, but the position from the ROSAT PSPC is not accurate enough for a definitive identification (Hakala et al. 1995). The derived X-ray to optical flux is also compatible with the value (f_X/f_V ~ 0.8 – 4.2) found by Cool et al. (1995) for three candidate CVs in NGC 6397. The UV to blue ratio of our objects is also similar to that of star 1 in Sosin & Cool (1995), a possible CV/LLGCX in the region of the X-ray source M13X-G located at (0,0). The x and y scales are in arcsec. The X-ray emission contour map has been overplotted. The location of the two UV-stars discovered in this study are indicated by arrows.

Fig. 1 of Hakala et al. (1997). They plot the PSPC counting rate in channels 11-235 against V. The 58 HRI counts of Fox et al. (1996) correspond to about 200 PSPC counts and a counting rate of about 10^{-2} ct/sec. This places it well above band occupied by CVs, but very near T Sco.

The observed flux distribution also bears on this question. One can characterize the UV radiation in terms of a blackbody equivalent even if the radiation is not blackbody. Doing so we find a lower limit on the temperature of these stars of T_B > 40,000 K, within the temperature range (10–60,000 K) estimated for 15 field CVs by Patterson & Raymond (1985).

In order to make a more quantitative comparison with field CVs, in Fig. 2 we plot the flux of the two stars as a function of wavelength. The data for the two stars have been plotted as big filled circles (#23081) and big asterisks (#21429), respectively. The flux distribution of the dwarf novae U Gem, scaled to the distance of M13, has been also plotted for comparison (from Figure 2 by Verbunt 1987). Verbunt (1987) compiled the UV properties of field cataclysmic variables based on IUE spectra. He used the parameter $F = \log f_{1600} - \log f_{2800}$, where $f_i$ is the flux in erg cm^{-2} s^{-1} in the i wavelength) to characterize the slope of the ultraviolet continuum flux distribution. From the data

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**Table 2. M13 UV Bright Stars and X-ray Objects**

| Star     | $\alpha$ | $\delta$ | $V$ | $U$ | $m_{255}$ | $m_{160}$ | log $L_X$ |
|----------|----------|----------|-----|-----|-----------|-----------|------------|
| Star 23081: | 16 41 43.68 | 36 28 04.67 | 22.192 | 20.616 | ... | 16.948 | 32.81 |
| M13X-G:   | 16 41 44.0 | 36 27 59 | 21.046 | 19.859 | 18.503 | 17.306 | ~ 32.47 |
| Star 21429: | 16 41 45.1 | 36 27 39 | 21.508 | 19.853 | 18.773 | 16.818 |

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**Figure 2.** Map of the image taken through F160BW image in the region of the X-ray source M13X-G located at (0,0). The x and y scales are in arcsec. The X-ray emission contour map has been overplotted. The location of the two UV-stars discovered in this study are indicated by arrows.
plotted in Fig. 3 we find $F = 0.96$ and 0.76 for star #23081 and #21429, respectively. These values are higher than the mean values for the field CVs. The value for #21429 is consistent with the steepest IUE CV spectra (see figure 3 by Verbunt 1987), and while the value for #23081 is higher than that observed for any of Verbunt’s sample, it does not seem out of the question.

Thus, while the cluster UV objects and their possible X-ray counterparts have some similarities to the field CVs they are not exactly the same. In particular, the slope of their UV flux distribution may be higher and the X-ray luminosity may be higher relative to the visible. Because they are older and they live in a dramatically different environment, it seems reasonable that cluster objects might be a new class with properties that differ from those in the field.

4 CONCLUSION

HST-WFPC2 images of the core of M13 have been used to search for candidate optical counterparts to the Low Luminosity X-ray source recently found in the core of M13 (M13X-G) [Fox et al. 1996].

Based on UV-CMDs we have discovered two extremely blue objects that lie well outside the main sequences and are spatially very close to the X-ray source. One UV-star is $\sim 7''$ from the nominal position of the X-ray source. The second UV bright star is $\sim 1''$ from a 3.5$\sigma$ X-ray contour map bump, which we suggest is a weak X-ray source. A third UV object has no corresponding X-ray emission. There are no other similar objects in our $>12,000$ star HST sample.

Our objects are very similar to the quiescent nova T Sco in the globular cluster M80 and candidate CVs in other clusters. If UV bright stars are physically connected to the detected X-ray emission, then their optical/X-ray properties are similar to but different from those of field CVs. If they are CVs they may represent a new subclass. Our observations lack the sensitivity to detect the variability which would cement the identification as CVs. Detection of variability and/or H$\alpha$ emission are obvious goals for future HST studies.

Globular cluster CVs are ordinarily suspected of being formed in stellar interactions. However, several lines of evidence suggest that observed CVs and LLGCXs are not formed as predicted by classical two body stellar capture: Johnson & Verbunt (1996) note that the number of LLGCXs per cluster scales much less rapidly with cluster density than expected. Shara & Drissen note that there are far fewer CVs than expected in dense cluster cores like that of M80. If our conjectures concerning the UV objects and LLGCXs in M13 are confirmed, it will lengthen this chain of arguments, since M13 is not a post-core-collapse cluster and has moderate central density.

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