CONSTRAINING THE TRUE NATURE OF AN EXOTIC BINARY IN THE CORE OF NGC 6624*

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ABSTRACT

We report on the identification of the optical counterpart to Star1, the exotic object serendipitously discovered by Deutsch et al. in the core of the Galactic globular cluster NGC 6624. Star1 has been classified by Deutsch et al. as either a quiescent cataclysmic variable or a low-mass X-ray binary. Deutsch et al. proposed StarA as a possible optical counterpart to this object. We used high-resolution images obtained with the Hubble Space Telescope to perform a variability analysis of the stars close to the nominal position of Star1. While no variability was detected for StarA, we found another star, referred to here as COM, showing a clear sinusoidal light modulation with amplitude $\Delta m_{F435W} \sim 0.7$ mag and an orbital period of $P_{\text{orb}} \sim 98$ minutes. The shape of the light curve is likely caused by strong irradiation by the primary heating of one hemisphere of the companion, thus suggesting a quite hot primary.

Key words: binaries: close – globular clusters: individual (NGC 6624) – novae, cataclysmic variables

Online-only material: color figures

1. INTRODUCTION

The high stellar densities typical of globular clusters (GCs) make stellar interactions very likely events. Therefore, it is expected that stellar evolution is strongly affected by the environment in these systems and that GCs are efficient furnaces of exotic populations, i.e., systems thought to result from the evolution of various kinds of binary systems originating from or hardened by stellar interactions (Clark 1975; Hills & Day 1976; Bailyn 1992; Ferraro et al. 2001, 2009; Ivanova et al. 2008). Indeed, low-mass X-ray binaries (LMXBs), cataclysmic variables (CVs), millisecond pulsars, and blue straggler stars are preferentially found in GCs (Bailyn 1995; Paresce et al. 1992; Ransom et al. 2005; Pooley & Hut 2006; Ferraro et al. 2006, 2012). Within this vast zoology, CVs and LMXBs deserve particular attention (see, for example, Ivanova et al. 2008; Knigge 2012 for a review).

CVs are binary systems composed of an accreting white dwarf (WD) and, typically, an unevolved companion in its core-hydrogen-burning phase. They are relatively abundant and since their variability is easy to detect, they represent an ideal benchmark to interpret other classes of close binary systems. CVs provide the opportunity to study binary systems with long-term, stable mass transfer and their analysis is an open window on the physical mechanisms driving the evolution of many other types of contact binaries. CVs are believed to be the progenitors of Type Ia supernovae; moreover, there is increasing evidence that some aspects of the accretion process taking place in CVs are similar to those observed in binary systems involving neutron stars (NSs) or black holes (BHs; see, for example, Long & Knigge 2002; Körding et al. 2008).

Depending on the intensity of the WD magnetic field, the accretion of matter from the secondary star onto the primary can occur either via an accretion disk in non-magnetic CVs, or across the magnetic field lines in the case of polar CVs. CVs have typical separations $a \sim R_\odot$ and orbital periods in the range $P_{\text{orb}} = 80$–500 minutes. Changes in the periods of CVs are linked to changes in the structure of the donor and to the physical mechanism that drives the accretion of matter onto the WD.

LMXBs are Roche-lobe-filling binary systems consisting of an NS or a BH accreting mass from a low-mass star. Such systems are believed to be the progenitors of millisecond pulsars. In GCs, most of the NSs or BHs lose their primordial binary companion when they form. Then, these compact objects can capture a new companion via binary exchange, physical collisions with giants, or tidal capture. Tidal capture is a poorly efficient formation mechanism in GCs (Ivanova et al. 2008); physical collisions typically lead to the formation of NS-WD LMXBs, the so-called ultra-compact X-ray binaries (UCXBs; Ivanova et al. 2005), while binary exchanges may lead to the formation of binary systems with any kind of companions. LMXBs span a vast range of orbital periods, from a few minutes (see the case of 4U 1820-30 in NGC 6624—Stella et al. 1987—or M15-X2—Dieball et al. 2005) to several hours. They are typically characterized by soft X-ray spectra.

Deutsch et al. (1999, hereafter D99) reported on the serendipitous discovery of an exotic object in the core of NGC 6624. With the aim of observing StarK (4U 1820-30; Stella et al. 1987; King et al. 1993; Anderson et al. 1997), which is a UCXB, they used the Space Telescope Imaging Spectrograph (STIS) on board the Hubble Space Telescope (HST) with the long-slit configuration (0.5′ × 3′). At a few arcsec from StarK and within the field of view covered by the slit, they found two additional stars. One of the two objects (Star1), located at 4′6′′ from StarK, showed strong and broad emission lines and a very weak continuum. This object has been classified as a classical CV in a quiescent state (Wu 1992), although the observed spectrum did not allow unambiguously excluding the possibility that Star1 is a quiescent LMXB.

On the basis of its position in the HST Faint Object Camera and Wide Field Planetary Camera 2 (WFPC2) images, D99 identified a faint star (see their Table 1), named StarA, as the possible optical counterpart to Star1. This identification was mostly based on the relative positions between StarK and StarA,
defined by the World Coordinate System (WCS) of the HST headers. Given the internal uncertainties (~0.5), the authors were not able to discard other possible counterparts. In order to constrain the preliminary D99 identification, we performed a detailed analysis of a set of optical and UV HST images of the core of NGC 6624. We found that StarA does not show any evidence of variability, while a close object (at 0.15) is characterized by a clear light modulation. Here we propose that this object is the real counterpart to Star1, we determine its period, and discuss the possible nature of the system.

2. Observations and Data Analysis

For the present analysis we used a combination of HST WFPC2 and Advanced Camera for Survey—High Resolution Channel (HRC) images. The WFPC2 images have been obtained through three different proposals and we will group them here into two samples. The first sample (WFPC2_A; Prop ID: 11975—PI: Ferraro) consists of 13 images obtained in four different filters: F555W (three images with \( t_{\text{exp}} = 100 \) s), F336W (three with \( t_{\text{exp}} = 700 \) s), F255W (four with \( t_{\text{exp}} = 1200 \) s), and F170W (two with \( t_{\text{exp}} = 1200 \) s and one with \( t_{\text{exp}} = 1300 \) s). The second sample (WFPC2_B; Prop ID: 10841, 11988—PI: Chandar) consists of a total of 40 images obtained with the F450W filter with \( t_{\text{exp}} \) ranging between 300 s and 400 s. The HRC data consist of 20 F435W images with \( t_{\text{exp}} = 200 \) s each (Prop ID: 10401—PI: Chandar). HRC images have been corrected for Pixel Area Map by using the files available in the HST Web site. The HRC pointings fall almost completely within the Planetary Camera (PC) field of view, which is approximately located on the cluster center. For this work we used only the PC and HRC images.

For all data sets, the photometric reduction has been performed by using DAOPHOTII (Stetson 1987). Tens of bright and isolated stars have been selected in each frame to model the point-spread function. A first star list has been obtained for each image by independently fitting all the star-like sources detected at the 3\( \sigma \) level from the local background. In order to exploit the high spatial resolution of the HRC images, we forced (for details see Dalessandro et al. 2011, 2013) the positions of stars identified in at least 10 HRC images to be fitted in all the WFPC2-PC images by using ALLFRAME (Stetson 1994).

WFPC2 instrumental magnitudes have been corrected for the charge transfer efficiency effect by using prescriptions and equations reported by Dolphin (2000). Magnitudes were then reported to the VEGAMAG photometric system by following Holtzman et al. (1995) and zero points provided in the dedicated HST Web page. Also, the instrumental HRC \( m_{F435W} \) magnitudes have been calibrated to the same photometric system by using zero points and equations by Sirianni et al. (2005). We then reported the WFPC2_B \( m_{F450W} \) measures to the HRC \( m_{F435W} \) system by applying small zero points estimated using the main-sequence (MS) stars in common between the HRC and WFPC2_B samples.

For each star, different magnitude estimates were homogenized (see Ferraro et al. 1991, 1992) and their weighted mean and standard deviation were finally adopted as the star magnitude and its photometric error. Instrumental coordinates have been roto-translated to the absolute coordinates system by using the catalog of astrometric standards Guide Star Catalog 2.3 and the cross-correlation software CataXcorr. At the end of the procedure, the typical accuracy of the astrometric solution is of the order of 0.1.

3. The Optical Counterpart to Star1

We identified StarA (see Figure 1) in our catalog by using its coordinates in the HST WCS reported by D99 and the finding charts in their Figure 3.
With the aim of inferring the orbital period and nature of Star1, we performed a detailed variability analysis of StarA. For this purpose we used the HRC and WFPC2_B samples, since they are the data sets with a number of exposures large enough for this kind of analysis. In this way, we can use 60 homogeneous measures (see Section 2) covering a total baseline larger than four years (Figure 2) starting at MJD[0] = 53429.89947762 days, which corresponds to the oldest image of our sample.

We found that StarA does not show any evidence of flux modulation (Figure 2). For this reason, we extended the variability analysis to all stars lying within ~1′′ of StarA and we detected a clear luminosity variation up to about ΔmF435W = 0.7 mag (Figure 2) in a faint star (hereafter named COM_Star1) located ~0.15 north-west from StarA (Figure 1). Although D99 considered the possibility that this star might be the counterpart of Star1 (see their Section 2.2), their analysis was focused only on StarA. It is also important to note that the position of COM_Star1 is fully compatible with that of the STIS spectrum observed by D99.

Both stars are relatively faint objects and they do not show any UV emission in the F255W and F170W frames. This is compatible with the UV limits reported by D99 for StarA and the detection limits of our data.

The positions of both StarA and COM_Star1 in the optical (mF555W, mF336W − mF555W) and (mF555W, mF435W − mF555W) color–magnitude diagrams (CMDs) are shown in Figure 3. StarA is likely an MS star, its magnitudes mF555W, mF435W, and mF555W are fully consistent with what was found by D99, once differences in the adopted photometric systems are properly taken into account (see their Table 1). COM_Star1 is slightly bluer than StarA by Δ(mF435W − mF555W) ~ 0.2 and Δ(mF336W − mF555W) ~ 0.4, and is located at the blue edge of the MS in both CMDs.

We analyzed the light curve of COM_Star1 by using the Graphical Analyser of Time Series, which is a private software developed at the Bologna Observatory by P. Montegriffo. We looked for possible solutions to the observed light curve in the period range P ~ 30–700 minutes, which well contains the period distribution of known CVs and LMXBs. By following Saha & Hoessel (1990), we estimated that in this period range and with the available data set, the probability of deriving the correct period of a variable star is always larger than ~80%.

In Figure 4, we show the Lomb periodograms (Lomb 1976) for both StarA and COM_Star1. While StarA does not show any significant peak, COM_Star1 shows a prominent one at frequency = 14.67 cycles day−1 (corresponding to Porb ~ 98 minutes) with a confidence level larger than 3σ (considering Poissonian noise).

We find that the light curve of COM_Star1 is well folded by a period Porb ~ 98 minutes. The period-folded light curve is shown in Figure 5 where we adopted as reference time MJD[0]. The time baseline covered by the adopted data set corresponds to about 24,500 COM_Star1 cycles, during which the estimated period seems to be stable. Therefore, we conclude that the periodic signal detected in the observed light curve likely corresponds to the orbital period of COM_Star1.

With the adopted data set, the orbital period of COM_Star1 is sampled approximately eight to nine times. The light curve shows a quite regular, almost sinusoidal behavior. The flux modulation of COM_Star1 also shows some noisy aperiodic variability (flickering), with a few measures appearing as strong outliers to the general behavior. In particular, at ϕ ~ 0.4, we observe a single measure brighter by about 1 mag than the observed luminosity at the maximum. As recently shown by Ingram & van der Klis (2013) and Scaringi (2014), such aperiodic variability is likely the result of fluctuations in the mass-transfer rate at different radii.

4. RESULTS AND DISCUSSION

If Star1 is a CV (D99), the value of the period best folding the light curve of COM_Star1 places this system approximately at the peak of the period distribution of known CVs.

1 Since Porb is very close to the HST orbital period (PHST ~ 96 minutes), we adopted the approach described by Zurek et al. (2009), finding a quite small probability (~1%) that Porb is an alias of PHST.
Indeed, the light curve of COM-Star1 is very similar to those observed in some of the recently confirmed polar CVs (Margon et al. 2013), and in the well-studied cases of V1974 Cygni (Nova Cygni 1992; De Young & Schmidt 1994) and V2275 Cygni (Balman et al. 2005). The sinusoidal shape can be interpreted as being caused by the orbital revolution of a hemisphere of the secondary star heated by radiation from the hot WD. In fact, as detailed by Kovetz et al. (1988), when an outburst occurs, the WD hydrogen-rich envelope is ejected in a few months and the WD outer layer remains at a temperature of the order of $\sim 10^5$ K, irradiating the secondary star and keeping high rates of mass transfer ($\sim 10^{-8} - 10^{-9} M_\odot$ yr$^{-1}$) for some centuries. Consistently, V1974 and V2275 Cygni have been observed just one to two years after their nova outburst phase and show sinusoidal light curves. For the case of Star1, we do not have knowledge of its most recent outburst and we do not observe any appreciable difference in the luminosity of COM-Star1 between the data presented by D99 and that shown in this work. However, the possibility of a heating mechanism also in the case of COM-Star1 is suggested both by the sinusoidal shape of its light curve and by the observed ($m_{F336W} - m_{F435W}$) color variation as a function of the orbital phase. In fact, we estimate a temperature variation ranging between $T \sim 5000$ K and $T \sim 9000$ K, thus yielding a lower limit of about $\Delta T \sim 4000$ K.

To quantitatively investigate the possibility that the heating scenario applies to Star1, we compared the observed flux variation, $\Delta F_{\text{obs}} \sim 5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, as obtained from the light curve in Figure 5 to the value expected in the case of irradiation (see Pallanca et al. 2012 and references therein):

$$\Delta F_{\text{exp}}(i) = \eta \sigma \frac{R_{\text{WD}}^4 a^2}{P_{\text{orb}}^2 R_{\text{COM}}^2} \frac{i}{\pi d^2} \left( 1 - \frac{R_{\text{COM}}^2}{a^2} \right).$$

Here $\eta$ is the reprocessing efficiency (which we assumed to be $\eta = 0.5$), $\sigma$ is the Stefan–Boltzmann constant, $a$ is the apparent orbital separation ($a \sim 0.65 R_\odot$), $d$ is the distance of the system (which we assumed to be the one of NGC 6624: $d = 8.4$ kpc, from Valenti et al. 2007), $R_{\text{COM}}$ is the radius of the companion star (which we assumed to be equal to the Roche Lobe radius: $R_{\text{COM}} \sim 0.2 R_\odot$), and $i$ is the system inclination.

To determine the orbital separation (from the Kepler’s third law) and the Roche lobe radius (by following Paczyński 1971), we first derived the primary and secondary star parameters as follows. We assumed a WD mass $m_{\text{WD}} \sim 0.6 M_\odot$ typical of WDs in old stellar systems as GCs, which yields a WD radius $R_{\text{WD}} \sim 10^{-2} R_\odot$. Then, following the mass–period relation ($M_2 = 0.11 P_\text{hr}$; Warner & Woudt 2005), the mass of the secondary is $M_2 \sim 0.2 M_\odot$. We note that by projecting the companion star position in the optical CMD onto the isochrone best fitting the main evolutionary sequences of NGC 6624 (Figure 3), under the assumption that this object is still behaving as an MS star, we would obtain $M_2 \sim 0.7 M_\odot$. However, in the case of a perturbed star, such a value can be easily overestimated by a factor of two or three (see, e.g., Pallanca et al. 2010) and we therefore assumed $M_2 \sim 0.2 M_\odot$.

Note that this estimate is based only on three measures.

We adopted $E(B-V) = 0.28$ and $(m-M)_0 = 14.63$ from Valenti et al. (2007).

Figure 4. Lomb periodograms for COM-Star1 and StarA. Dashed lines are different confidence levels estimated by considering Poissonian noise.

Figure 5. Light curve of COM-Star1 folded with the estimated orbital period $P_{\text{orb}} \sim 98$ min. The gray line is a sinusoidal function of amplitude $\Delta m_{F435W} \sim 0.7$. 

Indeed, the light curve of COM-Star1 is very similar to those observed in some of the recently confirmed polar CVs (Margon et al. 2013), and in the well-studied cases of V1974 Cygni (Nova Cygni 1992; De Young & Schmidt 1994) and V2275 Cygni (Balman et al. 2005). The sinusoidal shape can be interpreted as being caused by the orbital revolution of a hemisphere of the secondary star heated by radiation from the hot WD. In fact, as detailed by Kovetz et al. (1988), when an outburst occurs, the WD hydrogen-rich envelope is ejected in a few months and the WD outer layer remains at a temperature of the order of $\sim 10^5$ K, irradiating the secondary star and keeping high rates of mass transfer ($\sim 10^{-8} - 10^{-9} M_\odot$ yr$^{-1}$) for some centuries. Consistently, V1974 and V2275 Cygni have been observed just one to two years after their nova outburst phase and show sinusoidal light curves. For the case of Star1, we do not have knowledge of its most recent outburst and we do not observe any appreciable difference in the luminosity of COM-Star1 between the data presented by D99 and that shown in this work. However, the possibility of a heating mechanism also in the case of COM-Star1 is suggested both by the sinusoidal shape of its light curve and by the observed ($m_{F336W} - m_{F435W}$) color variation as a function of the orbital phase. In fact, we estimate a temperature variation ranging between $T \sim 5000$ K and $T \sim 9000$ K, thus yielding a lower limit of about $\Delta T \sim 4000$ K. To quantitatively investigate the possibility that the heating scenario applies to Star1, we compared the observed flux variation, $\Delta F_{\text{obs}} \sim 5 \times 10^{-15}$ erg cm$^{-2}$ s$^{-1}$, as obtained from the light curve in Figure 5 to the value expected in the case of irradiation (see Pallanca et al. 2012 and references therein):

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Note that this estimate is based only on three measures.

We adopted $E(B-V) = 0.28$ and $(m-M)_0 = 14.63$ from Valenti et al. (2007).
By using these values and the equation above, we finally found that in order to account for the observed flux variation $\Delta F_{\text{obs}}$, the effective temperature of the WD needs to be $T_{\text{WD}} > 45,000$ K. This temperature is at least two times larger than what was derived from the UV flux threshold of our observations and from the UV luminosity inferred by D99 from the continuum fitting of the STIS spectrum, which gives $T_{\text{WD}} < 20,000$ K. Of course, this estimate relies on the assumption that Star1 is member of NGC 6624. Unfortunately, D99 were not able to measure the radial velocity of COM Star1 and we have verified (A. Bellini 2014, private communication) that with the available HST data it is not possible to obtain a reliable proper motion measure of COM Star1 to constrain its membership.

An alternative scenario to account for the observed light curve is that Star1 is an LMXB and an NS is responsible for the irradiation of the secondary not degenerate star. Following this possibility, we have analyzed the available high-resolution Chandra X-ray spectra (Prop ID: 02400090; PI: Murray) of the core of NGC 6624. These data cannot be used to constrain the emission of Star1, since the X-ray flux is totally dominated by StarK just few arcseconds apart. D99 discussed the issue of possible confusion of the observed STIS spectrum of Star1 with that of a quiescent LMXB (see also Grindlay 1999). While the spectrum does not allow a clear distinction between a CV and an LMXB, D99 preferred to conservatively classify Star1 as a CV since this class of objects is more common. However, the light curve presented here suggests that the secondary is undergoing a heating process from a quite hot primary, thus leaving open the possibility that COM Star1 is orbiting an NS.

5. SUMMARY AND CONCLUSIONS

We have searched for the optical companion to Star1 by performing a detailed photometric variability analysis. We have found that the companion proposed by D99 (StarA) does not show any evidence of variability, while we have identified an object, named COM Star1, showing a clear light modulation with an amplitude $\Delta m_{F435W} \sim 0.7$ mag. The light curve of COM Star1 shows a periodic signal with $P_{\text{orb}} \sim 98$ minutes, which appears to be stable over a time interval of about four years and should therefore correspond to the orbital period of Star1.

The flux modulation of COM Star1 has a quite regular and sinusoidal behavior, which might be interpreted as being driven by irradiation by the primary star on one hemisphere of the non-degenerate secondary star. This scenario is further supported by some hints of temperature variations as a function of the orbital phase inferred by the $(m_{F435W} - m_{F814W})$ color variation. By performing simple calculations, we have constrained the temperature needed for the primary to efficiently heat the secondary. It results that the primary should have a temperature $T > 45000$ K. If Star1 is a CV, as preferentially suggested by D99, then this temperature lower limit is not compatible with the one inferred by the UV continuum observed by D99 and by the UV detection threshold of our images. This incompatibility might push toward the possibility that Star1 is an LMXB and the secondary is heated by an NS. We performed the analysis of the available Chandra data, but unfortunately they cannot be used to constrain the X-ray emission of Star1, since it is dominated by the flux of the ultraluminous X-ray source StarK located a few arcsec apart.

Of course, several pieces of information are still needed to fully constrain the nature of Star1. Long-term monitoring with multi-wavelength synchronized observations is urgent to derive an accurate estimate of the temperature variation on the secondary surface. In addition, ultra-deep UV observations can further constrain the nature of the primary. Chandra observations in soft ($\sim 0.3-1$ keV) and hard ($\sim 1-5$ keV) bands, in a sub-array configuration optimized to exclude as much as possible the flux of StarK, can be useful to detect and possibly characterize the X-ray emission of Star1, either via direct X-ray spectroscopy or hardness ratio analysis.

Multi-period monitoring of the light curve through high-resolution optical HST observations coupled with appropriate models for CVs and LMXBs would definitely allow a more robust analysis and would shed new light on the properties of this intriguing system.

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