THE BRIGHTEST CLUSTER X-RAY SOURCES

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ABSTRACT

There have been several recent claims of black hole binaries in globular clusters. I show that these candidate systems could instead be ultracompact X-ray binaries (UCXBs) in which a neutron star accretes from a white dwarf. They would represent a slightly earlier evolutionary stage of known globular cluster UCXBs such as 4U 1820–30, with white dwarf masses \( \sim 0.2 M_\odot \) and orbital periods below 5 minutes. Accretion is slightly super-Eddington and makes these systems ultraluminous sources with rather mild beaming factors \( b \sim 0.3 \). Their theoretical luminosity function flattens slightly just above \( L_{\text{Edd}} \) and then steepens at \( \sim 3L_{\text{Edd}} \). It predicts of order two detections in elliptical galaxies such as NGC 4472, as observed. The very bright X-ray source HLX-1 lies off the plane of its host S0a galaxy. If this is an indication of globular cluster membership, it could conceivably be a more extreme example of a UCXB with white dwarf mass \( M_2 \sim 0.34 M_\odot \). The beaming here is tighter \((b \sim (2.5–9) \times 10^{-3})\), but the system’s distance of 95 Mpc easily eliminates any need to invoke improbable alignment of the beam for detection. If its position instead indicates membership of a satellite dwarf galaxy, HLX-1 could have a much higher accretor mass \( \sim 1000 M_\odot \).

Key words: accretion, accretion disks – black hole physics – globular clusters: general – X-rays: binaries – X-rays: galaxies

1. INTRODUCTION

Globular clusters (GCs) host 10%–20% of the X-ray sources in galaxies like our own. This fraction rises to \( \lesssim 50\% \) in early-type galaxies (e.g., Sarazin et al. 2003). In all galaxies this implies a far higher incidence of X-ray sources per unit mass in GCs than in the field—in the Milky Way by about a factor of 100–1000. The reason for this is of course that GCs can form close binaries by dynamical capture, and many of these evolve into low-mass X-ray binaries (LMXBs). In early-type galaxies this process continues long after star formation in the field has declined, making the GC sources more prominent.

A sign of the unusual formation channels available in GCs is the prominence there of ultracompact X-ray binaries (UCXBs)—systems with very short orbital periods \( P \) down to \( \sim 10 \) minutes. For example, five out of the seven LMXBs with \( P < 30 \) minutes in the 2011 update to the catalogue of Ritter & Kolb (2003) are known to be members of GCs. These systems all appear to involve a neutron star accreting from a white dwarf companion star. In contrast, systems containing black holes are rare or absent from GCs. Clearly one would not expect high-mass X-ray binaries similar to Cygnus X-1, but there is so far no clear detection in a GC of the soft X-ray transients which constitute the majority of Galactic black hole systems. It is often suggested (e.g., Kalogera et al. 2004) that most black holes are dynamically expelled from GCs because the mass contrast with the other stellar populations makes them vulnerable to the Spitzer mass-segregation instability (Spitzer 1969).

There have nevertheless been a number of claimed or suggested detections of black hole X-ray binaries in GCs (Maccarone et al. 2007; Brassington et al. 2010; Shih et al. 2010; Maccarone et al. 2011) on the basis of luminosities up to \( 4.5 \times 10^{39} \text{ erg s}^{-1} \), exceeding the Eddington limit \( L_{\text{Edd}} \simeq 10^{38} \text{ erg s}^{-1} \) for a neutron star, together with \( \gtrsim 2 \times \) variability (to rule out superpositions of fainter sources). The same criteria applied to the much brighter \( (\sim 10^{-41}–10^{-42} \text{ erg s}^{-1}) \) source HLX-1 have led to the suggestion of a black hole mass \( \gtrsim 500 M_\odot \) (Farrell et al. 2009; Wiersema et al. 2010). HLX-1 is not known to be a member of a GC: it is associated with an edge-on S0a spiral galaxy ESO 243–39, lying off the galaxy plane in the outskirts of its bulge, and so could be a member of a GC or other type of star cluster, or of a satellite dwarf galaxy.

In the absence of clean dynamical masses \( \gtrsim 3 M_\odot \) for the claimed GC black holes and \( \gtrsim 500 M_\odot \) for HLX-1 the nature of these sources is not definitively settled. It is reasonable to ask if other interpretations are possible, and I attempt this here.

2. BRIGHT X-RAY SOURCES IN GLOBULAR CLUSTERS

The defining feature of the GC black hole candidates is their luminosity, which is super-Eddington for a neutron star. Any model of them must therefore allow for high mass transfer rates. Since all the potential donor stars in GC binaries have low masses \( \lesssim 1 M_\odot \), this obviously also explains the short lifetimes of the black hole candidates and thus their rarity. We have already noted that the types of black hole X-ray binaries found in the field—high-mass systems and soft X-ray transients—are not found in GCs. This leaves one fairly obvious alternative, the ultracompact systems mentioned above. These systems evolve in a very simple way, which naturally implies a very high mass transfer rate at a certain epoch (see, e.g., King 1988 for a discussion). The condition that a white dwarf donor should fill its Roche lobe leads to a relation

\[
P \sim 0.9 m_2^{-1} \text{ minutes}
\]

between donor mass \( M_2 = m_2 M_\odot \) and orbital period \( P \) (with the white dwarf taken as a hydrogen-depleted \( n = 3/2 \) polytrope with radius–mass relation \( R_2 \propto M_2^{1/3} \)). These very short orbital periods imply that mass transfer in these UCXB systems is driven by gravitational radiation, which gives a mass transfer rate

\[
\dot{M}_2 \simeq 1 \times 10^{-3} m_1^{2/3} m_2^{14/3} M_\odot \text{ yr}^{-1},
\]

where \( m_1 = m_1 M_\odot \) is the accretor mass. The brightest low-mass X-ray binary in a Galactic GC is 4U 1820–30 in NGC 6624, with \( L \sim (4–7) \times 10^{37} \text{ erg s}^{-1} \). This has an
orbital period $P = 11.4$ minutes (Stella et al. 1987; van der Klis et al. 1993), and so from Equation (1), presumably a current donor mass $M_2 \simeq 0.08 \, M_\odot$. Equation (2) then gives $-M_2 \simeq 7 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$, in good agreement with the observed luminosity if the accretor is a neutron star of $\simeq 1.4 \, M_\odot$. The observed X-ray bursts from this system confirm this identification and suggest that the donor is a He white dwarf (Bildsten 1995; Strohmayer & Brown 2002; Cumming 2003). I note that Bildsten & Deloye (2004) consider the effects of chemical composition and finite entropy and derive slightly more complex relations than Equations (1) and (2), in particular an exponent closer to 4.13 for $m_2$ in Equation (2). However, their Figure 1 shows that the deviations are small enough that the polytropic approximation is adequate for the purposes of this Letter, particularly for larger values of the white dwarf mass than considered by Bildsten & Deloye (2004).

The important result here is that the mass transfer rate could have been much higher in the past, when $M_2$ was larger. The initial white dwarf mass in a UCXB is set by its prior evolution. UCXBs presumably result from some kind of common envelope evolution following the dynamical capture by the neutron star primary of an evolved companion star. The degenerate core mass of the companion can range from $0.1$ to $0.4 \, M_\odot$ for helium, and up to $\simeq 0.6 \, M_\odot$ for carbon/oxygen, depending sensitively on how far the companion has evolved at the epoch of capture. It is clear that mass transfer rates well above the Eddington value are easily possible in UCXBs. Note that $L_{\text{Edd}}$ is twice the usual value since we expect hydrogen-poor accretion here, i.e.,

$$L_{\text{Edd}} \simeq 3.5 \times 10^{38}(m_1/1.4) \, \text{erg s}^{-1}. \quad (3)$$

This implies an Eddington accretion rate

$$\dot{M}_{\text{Edd}} \simeq 5 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}. \quad (4)$$

3. ULTRALUMINOUS X-RAY SOURCES IN GLOBULAR CLUSTERS

Compact objects accreting above their Eddington rates probably appear as ultraluminous X-ray sources (ULXs), and it is now generally accepted that a large fraction of ULXs are of this type. Disk accretion in this regime was first described by Shakura & Sunyaev (1973). In their picture, radiation pressure becomes important at the spherization radius $R_{\text{sp}} \simeq 27 m \, R_s / 4$, where $m$ is the local accretion rate in units of the Eddington value, and $R_s = 2GM_1/c^2$ is the Schwarzschild radius of the accretor. Shakura & Sunyaev (1973) explicitly considered only black hole accretors, but their picture also applies to other accretors provided that $m$ is sufficiently large to ensure $R_{\text{sp}} > R_{\text{accretor}}$ (this always holds for neutron stars with $m > 1$ for example). Inside $R_{\text{sp}}$ the disk remains close to the local radiation pressure limit and blows gas away so that the accretion rate decreases with disk radius as $M(R) \simeq M(R/R_{\text{sp}}) \simeq \dot{M}_{\text{Edd}}(R/R_s)$. The disk wind has the local escape velocity at each radius, so mass conservation shows that the wind is dense near $R_{\text{sp}}$ and tenuous near the inner disk edge. The centrifugal barrier along the disk axis creates a vacuum funnel through which the luminosity escapes.

Thus, super-Eddington accretion produces large apparent X-ray luminosities through two effects of super-Eddington accretion (Begelman et al. 2006; Poutanen et al. 2007). First, the bolometric luminosity is larger than the usual Eddington limit by a factor $\sim (1 + \ln \dot{m})$. Second, the luminosity of a ULX is collimated by a beaming factor $b$ via scattering off the walls of the central funnel, so that the apparent luminosity (inferred by assuming isotropy) is

$$L_{\text{sph}} \simeq \frac{L_{\text{Edd}}}{b} (1 + \ln \dot{m}). \quad (5)$$

Eddington ratios $\dot{m} \gg 1$ producing ULXs can arise in a number of ways in close binary accretion. Thermal-timescale mass transfer from a massive radiative donor to a lower mass compact object can give $\dot{m} \sim 5000$ or more, as in SS433 (King et al. 2000; Begelman et al. 2006), and nuclear expansion can give similar rates (Rappaport et al. 2005). Super-Eddington rates can arise during disk instabilities (King 2002), and I suggest here that UCXBs offer another steady channel. By contrast, a similar Eddington ratio $\dot{m} \gg 1$ is very difficult to produce in accretion in active galactic nuclei (AGNs). If the AGN sits in a spheroid of velocity dispersion $\sigma$ and gas fraction $f_g$, even the extreme assumption of a full dynamical accretion rate $\sim f_g \sigma^5 / G$, given by suddenly removing centrifugal support from orbiting gas, produces only $\dot{m} \lesssim 40$ (King 2010, Equation (6)). Binaries do better than AGNs because the self-gravity of the donor star allows a large gas mass to get close to the accretor simultaneously by spiraling in through near-circular orbits. (Dynamical disruption of stars in AGNs does not achieve this, as the likely parabolic orbit means that the arrival time of the gas is spread out by factors $\left(\frac{M_{\text{SMBH}}}{M_{\text{star}}}\right)^{1/2} > 10^{-3} - 10^4$; cf. Lodato et al. 2009.) Accordingly, there are no AGN analogs of ULXs.

Recently, King (2009) noted that the observed inverse correlation between soft X-ray emission and blackbody temperature ($L_{\text{soft}} \propto T_{bb}^{-3.5}$) for some ULXs (Kajava & Poutanen 2009) could be understood if the beaming factor varies as

$$b \sim \frac{73}{\dot{m}^2}, \quad (6)$$

a form which also follows from simple geometrical arguments about the funnel opening angle. (We note that this suggests that significant beaming occurs only for sufficiently super-Eddington accretors $\dot{m} \gtrsim 8.5$.) Mainieri et al. (2010) used this form of beaming to study the luminosity function (LF) of a sample of ULXs out to redshifts $z = 0.3$, finding excellent agreement. Accordingly, using Equations (3) and (5) I adopt

$$L_{\text{sph}} = 4.4 \times 10^{36} \, m_1 \dot{m}^2 (1 + \ln \dot{m}) \, \text{erg s}^{-1} \quad (7)$$

for the apparent UCXB luminosity for $\dot{m} > 8.5$, setting $b = 1$ in Equation (5) for $1 < \dot{m} < 8.5$.

A super-Eddington UCXB system with a $1.4 \, M_\odot$ neutron star accretor and an Eddington factor $\dot{m} \simeq 15$ has an $L_{\text{sph}} \simeq 5 \times 10^{39} \, \text{erg s}^{-1}$, large enough to explain all the putative black hole systems in GCs. The beaming factor here is $b \simeq 0.32$. To see if this is reasonable we need to work out the LF of these systems.

4. LUMINOSITY FUNCTION

Bildsten & Deloye (2004) note that the evolution of UCXBs is so rapid that one can derive their GC LF by assuming steady-state conditions. This gives

$$\frac{dN}{dL} \propto L^{-\alpha}. \quad (8)$$

Extending the LF to luminosities where beaming is important is straightforward, following Bildsten & Deloye (2004). They note that UCXBs evolve through the observable range of luminosities on a timescale far shorter than the age of GCs or
any reasonable estimate of the time for their birthrate to change. Hence, if we know the time \( t \) that a UCXB spends above a given luminosity, then the cumulative LF \( N(\geq L) \) is directly proportional to \( t \).

To find \( t \) as a function of \( L \), I integrate the evolution equation (Equation (2)) assuming \( M_2 \ll M_1 \) gives \( t \propto M_2^{1/\beta} \), where I have generalized the exponent of \( m_2 \) in Equation (2) from the polytropic value 14/3 to a general \( \beta \) to enable comparison with Bildsten & Deloye (2004), and also assumed that the current donor mass is much smaller than its initial value. This gives \( t \propto (-M_2)^{1/\beta} \). If there were no beaming, we would now replace \(-M_2\) by \( L \) and get \( N(\geq L) \propto t \propto L^{-(\beta-1)/\beta} \) and so \( dN/dL \propto L^1/\beta-2 \) for \( m \ll 1 \) (Bildsten & Deloye 2004).

However, beaming changes both the connection between \(-M_2\) and \( L \), and also the number of systems we can see: we now have \( L \propto b^{-1} \propto m^2 \) (neglecting the logarithmic dependence on \( m \)) and \( N(\geq L) \propto t \cdot b \propto m^{-\beta}(\beta-1)/\beta-2 \). Together these give \( N(\geq L) \propto L^1(\beta-1)/2\beta-1 \), and

\[
\frac{dN}{dL} \propto L^{1/2\beta-5/2} \tag{9}
\]

for \( \beta > 3 \). If indeed there is essentially no beaming for \( 1 < \beta < 3 \) as suggested just below Equation (7), the logarithmic relation between \( L \) and \( m \) implies that there are more UCXBs than naively expected between \( L = L_{\text{Edd}} \) and \( L \approx 3L_{\text{Edd}} \), so the LF flattens there, i.e.,

\[
\frac{dN}{dL} \propto \exp(0.77) \left( 1 - \frac{L}{L_{\text{Edd}}} \right)^{-1.77} \tag{10}
\]

Enforcing continuity at the breaks \( L = L_{\text{Edd}}, 3.14L_{\text{Edd}} \), the UCXB LF is

\[
L^{-1.77}, \quad \exp[0.77(1-l)], \quad 2.93l^{-2.38} \quad \tag{11}
\]

over these ranges, where we have taken \( \beta = 4.3 \) and set \( l = L/L_{\text{Edd}} \).

5. CANDIDATE GC BLACK HOLES

Maccarone et al. (2007, 2011) discuss two black hole candidate sources in the elliptical galaxy NGC 4472. They are XMMU 122939.7+075333 (\( L \lesssim 4.5 \times 10^{39} \text{ erg s}^{-1} \)) and CXOU 122941+075744 (\( L \lesssim 2 \times 10^{39} \text{ erg s}^{-1} \)). The LF of Kim & Fabiano (2004) for NGC 4472 shows that there are some ~300 X-ray sources with \( 4 \times 10^{35} \text{ erg s}^{-1} \lesssim L \lesssim L_{\text{Edd}} \) (their Figure 2: note that the displayed LF is scaled upward by a factor 29.51 for display purposes). If a substantial fraction of these are UCXBs, as expected, the theoretical LF (Equations (9) and (10)) shows that the presence of two ultracompact neutron star ULXs with the quoted luminosities is perfectly reasonable. For the more extreme (XMMU) source the white dwarf companion has mass \( \geq 0.2 M_\odot \), the orbital period is \( P \approx 45 \) minutes, and the beaming factor is \( b \approx 0.32 \).

6. HLX-1

Soria et al. (2010) find a red optical counterpart to HLX-1. At the distance to ESO 243–49 this has a luminosity compatible with a massive GC. On the other hand, this luminosity is also compatible with the nucleus of a stripped dwarf galaxy, and in addition Wiersma et al. (2010) find a bright Hα line associated with the source. If this comes directly from the accretion flow it rules out a UCXB model, although one has still to rule out an origin in a nebula around the source—this appears unlikely in a gas-poor environment like a GC. In view of these uncertainties I consider a number of possibilities.

If HLX-1 is a UCXB in a GC, we can use Equation (7) with \( m_1 = 1.4 \) to find an estimated Eddington ratio \( m \approx 170 \), with a beaming factor \( b \approx 2.5 \times 10^{-3} \), which would require a white dwarf donor mass \( M_2 \approx 0.34 M_\odot \) and an orbital period \( P \approx 2.5 \) minutes. As a check we can estimate the distance \( D_{\text{min}} \) to the nearest object plausibly observable with this amount of beaming (i.e., without requiring an improbable “aiming” of the beam at Earth). This is given by Equations (12) or (15) of King (2009) (but note that the coefficient in the final form of Equation (15) should be 258 and not 660). This gives \( D_{\text{min}} \approx 17N^{-1/3} \text{ Mpc}, \) where \( N \) is the number of objects of this type in the host galaxy. This is comfortably smaller than the known distance of 95 Mpc, so it is not unreasonable to be in the beam of this system.

If instead of being a GC UCXB, HLX-1 involves \( 10 M_\odot \) black hole accreting hydrogen-rich material we have the coefficient on the right-hand side of Equation (7) and set \( m_1 = 10 \). This gives an Eddington ratio \( m \approx 90 \), which is quite possible for either a high-mass X-ray binary or a soft X-ray transient. The beaming factor is \( b \approx 9 \times 10^{-3} \), and the minimum reasonable distance is \( D_{\text{min}} \approx 11N^{-1/3} \text{ Mpc}. \) Finally, if HLX-1 is actually in a dwarf galaxy interacting with ESO 243–39, it is quite possible that the accretor is the central massive black hole of this galaxy with a mass \( \geq 1000 M_\odot \). In this case, the interaction with the larger galaxy can trigger accretion (King & Dehnen 2005, Lasota et al. (2011) consider other possibilities of this type.

7. CONCLUSIONS

This Letter has shown that the claimed black hole binaries in GCs are also understandable as UCXBs in which a neutron star accretes from a white dwarf. The high luminosity arises from the higher mass transfer rates expected from progenitors of known UCXBs such as \( 4U \) 1820–30, with white dwarf masses \( \sim 0.2 M_\odot \). The theoretical luminosity function of these systems agrees with the detected number. UCXBs have orbital periods of only a few minutes. Detection of such periods would strongly support a UCXB model, while measurement of secure dynamical masses would break the ambiguity between neutron star and black hole accretors. However, if the systems are indeed UCXBs both of these will prove difficult, as the mild beaming induced by super-Eddington accretion suggests that the systems are likely to be face-on. Longer superorbital periods may be seen as a result of precessions in either case. Similarly, it will be difficult to decide spectroscopically whether the accreting material is hydrogen-depleted or not, as one needs to find a line feature securely associated with the binary.

The very bright X-ray source HLX-1 could conceivably be a more extreme example of a UCXB (white dwarf mass \( M_2 \approx 0.34 M_\odot \)) if it is indeed a member of a GC. However, if it is a member of a dwarf satellite galaxy its mass could be \( \sim 1000 M_\odot \). There is currently no easy way to eliminate any of these possibilities.

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REFERENCES

Begelman, M. C., King, A. R., & Pringle, J. E. 2006, MNRAS, 370, 399
Bildsten, L. 1995, ApJ, 438, 852

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