Formation Constraints Indicate a Black Hole Accretor in 47 Tuc X9

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Abstract

The luminous X-ray binary 47 Tuc X9 shows radio and X-ray emission consistent with a stellar-mass black hole (BH) accreting from a carbon–oxygen white dwarf. Its location, in the core of the massive globular cluster 47 Tuc, hints at a dynamical origin. We assess the stability of mass transfer from a carbon–oxygen white dwarf onto compact objects of various masses, and conclude that for mass transfer to proceed stably, the accretor must, in fact, be a BH. Such systems can form dynamically by the collision of a stellar-mass BH with a giant star. Tidal dissipation of energy in the giant’s envelope leads to a bound binary with a pericenter separation less than the radius of the giant. An episode of common-envelope evolution follows, which ejects the giant’s envelope. We find that the most likely target is a horizontal-branch star, and that a realistic quantity of subsequent dynamical hardening is required for the resulting binary to merge via gravitational wave emission. Observing one binary like 47 Tuc X9 in the Milky Way globular cluster system is consistent with the expected formation rate. The observed 6.8-day periodicity in the X-ray emission may be driven by eccentricity induced in the ultra-compact X-ray binary’s orbit by a perturbing companion.

Key words: binaries: close – globular clusters: individual (47 Tuc) – stars: black holes – X-rays: binaries

1. Introduction

X9 is the most luminous (a few \(10^{33}\) erg s\(^{-1}\)) hard X-ray source in the massive globular cluster 47 Tuc (Grindlay et al. 2001). With a UV-bright variable optical counterpart and hints of variability on timescales from minutes to hours, the source has generally been classified as an accreting white dwarf (Paresce et al. 1992; Edmonds et al. 2003; Heinke et al. 2005; Knigge et al. 2008). This consensus was challenged by the detection of persistent radio continuum emission from the system (Miller-Jones et al. 2015), much brighter than ever detected from a cataclysmic variable at this X-ray luminosity. Instead, the ratio of radio to X-ray flux is consistent with that observed for quiescent stellar-mass black holes (BHs).

Several other properties of the source are also unusual for an accreting white dwarf. The X-ray spectrum shows very strong emission tentatively identified as O viii (Heinke et al. 2005), and double-peaked C iv emission was detected in far-UV STIS spectroscopy (Knigge et al. 2008). This latter line itself is not unusual for white dwarf accretors, but the separation of the two emission peaks was nearly \(\sim2100\) km s\(^{-1}\), with emission extending to at least 4000 km s\(^{-1}\) from rest, consistent with the C iv being produced in an accretion disk around a compact object more massive than a white dwarf.

Bahramian et al. (2017) presented a comprehensive analysis of the voluminous X-ray data for X9. They found a 28.2 minute periodic signal in the X-ray light curves taken with two independent Chandra instruments at different epochs, which they identified as the likely orbital period for the system. This short period implies an ultra-compact system with a white dwarf donor, which is backed up by the lack of evidence for strong hydrogen emission (Miller-Jones et al. 2015). The X-ray spectrum is best fit by photoionized gas with overabundant O. The evidence of C and O emission features suggest that the donor is a carbon/oxygen white dwarf (COWD). Bahramian et al. (2017) also show evidence for substantial (factor of \(\sim8\)) variations in the X-ray luminosity on a super-orbital timescale of 6.8 days. These variations have no straightforward explanation, but could possibly be due to a precessing and/or warped accretion disk (see, e.g., Kotze & Charles 2012).

The ratio of radio to X-ray luminosity in X9 is most consistent with an accreting BH. At the observed X-ray luminosity (a few \(10^{33}\) erg s\(^{-1}\)) accreting neutron stars (NSs) only rarely show similar radio luminosities, and these systems are nearly all “transitional” millisecond pulsars that also show unusual, short-term, X-ray and radio variability not seen in X9 (e.g., Bogdanov et al. 2015; Deller et al. 2015). Nonetheless, the phenomenology of accreting NSs at these X-ray luminosities is not well understood. Hence, while the existing data for X9 provide compelling evidence for an ultra-compact low-mass X-ray binary with a CO white dwarf donor, they do not definitively distinguish between a BH or NS accretor.

In this Letter we assess the theoretical constraints on the nature of 47 Tuc X9 that arise from its formation. We analyze the stability of mass transfer from COWDs onto NS and BH accretors of a range of masses, to determine which lead to ultra-compact X-ray binaries (UCXBs). Subsequently, we investigate the likely formation rates of BH—white dwarf binaries, to see whether a BH accretor is realistic.

2. Stability Analysis

We assume, for the time being, that 47 Tuc X9 descends from a dynamically formed binary containing a carbon–oxygen white dwarf (COWD) and a compact object, either an NS or a stellar-mass BH. Such binaries, if they attain sufficiently small pericenter separations, emit gravitational radiation and spiral together until the white dwarf fills its Roche Lobe. After mass starts to transfer to the compact object there are two possibilities. The mass transfer can be unstable; i.e., it takes place at an ever-faster rate until the entire white dwarf is accreted into a disk around the compact object. This will lead to a luminous transient, but not a long-lived UCXB. Alternatively, the mass-transfer rate may reach a maximum and then decline.
We have varied the physical assumptions that make up our model to investigate how they affect the stability. In particular, we vary the maximum rate at which the compact object can accrete mass,

$$M_{\text{max}} = f_{\text{Edd}} M_{\text{Edd}}. \quad (1)$$

where $M_{\text{Edd}}$ is the Eddington accretion rate. In Bobrick et al. (2017) we set $f_{\text{Edd}} = 1$. We also vary the size of the common envelope that forms at high mass-transfer rates, $R_{\text{CE}}$, as a multiple of the orbital semimajor axis $a$, and the viscous timescale on which the common envelope extracts energy from the orbit, which we write as a multiple of the orbital timescale, $P_{\text{orb}}$, i.e., $\tau_{\text{visc, CE}} = N_{\text{CE}} P_{\text{orb}}$.

In our earlier work using $1.4 \, M_\odot$ NS accretors we found that the details of the physical prescription had little effect on the mass-transfer stability, and that can be seen by the way that the curves in Figure 1 bunch together at low accretor masses. However, at high accretor masses the evolution becomes more sensitive to how effectively the accretion energy drives mass out of the binary. The assumptions required for stable mass transfer are on the high side; accretion of tens of times the Eddington rate, coupled with a loosely bound common envelope that is inefficient at dragging on the orbit.

What is clear, however, is that we cannot form a stable system with an NS accreting from a COWD. Our most optimistic assumptions require the accretor to be at least six solar masses, which is higher than any model predicts for the most massive NSs (Özel & Freire 2016). This implies that if the donor star in 47 Tuc X9 is a COWD, then the accretor must be a BH.

This finding might, at first sight, appear to be inconsistent with reported observations of NSs accreting from COWDs. However, where these binaries are in the field, the donors can equally well be helium stars where all the helium-rich material has already been accreted or lost, leaving just a carbon–oxygen core. However, for an X-ray binary in a globular cluster, such as 47 Tuc X9, this scenario is unlikely for two reasons. First, the progenitors of helium-star UCXBs are relatively massive, so the UCXB forms less than 2 Gyr after star formation (van Haarfen et al. 2013). Given the age of 47 Tuc this would require an unfeasibly long-lived UCXB. Second, there is no reason to think that the He-star UCXB channel would be enhanced in globular clusters. The only other UCXB in a globular cluster reported to have a COWD donor is 4U 0513-40 (Koliopanos et al. 2014). In that case, however, the authors’ diagnosis of a COWD donor is based on the lack of an iron line, which is in fact likely caused by the low metallicity in the globular cluster: a helium-rich donor fits better with the observed Type-I X-ray bursts observed from the system (Koliopanos, private communication). Hence, 47 Tuc X9 is the only binary for which a COWD donor is required. Given this requirement, we go on to consider dynamical formation of BH–COWD binaries.

### 3. Dynamical Formation of BH–COWD Binaries

It is challenging to form close BH–COWD binaries with large mass ratios in the field because the final stage of mass-transfer from the white dwarf’s progenitor is then typically stable owing to the large mass ratio. This leads to a wide binary. Given this, and the interactive dynamical environment provided by the core of 47 Tuc, it is natural to consider...
dynamical formation mechanisms. The processes relevant to BH–WD binary formation in globular cluster cores have been described in detail by Ivanova et al. (2010) and we gratefully adopt their analysis as the foundation of this section. We first analyze the expected rates and properties of BH–COWD binaries formed by collisions of BHs with giant stars, then briefly discuss the hardening of the resulting binaries so that they merge.

The core of 47 Tuc has a stellar number density of about $10^5 \text{pc}^{-3}$ and a central velocity dispersion of about $12 \text{km s}^{-1}$ (Meylan 1989; McLaughlin et al. 2006). We make the simplifying assumption that these quantities are constant in time. All the collisions that we are interested in are therefore strongly gravitationally focused, so the total number of BH–WD binaries forming by direct collisions, $N_{\text{form}}$, is related to the number of BHs in the core, $N_b$, by $N_{\text{form}} = \Gamma N_b$, where

$$
\Gamma = 2\pi G f_p f_{\text{seg}} v_{\infty}^{-1} \sum_i n_i \int_{t_{\text{ce}}} \left[ M_i(t) + M_\ast \right] R_{\ast,i}(t) dt,
$$

(2)

where the sum is over stars of mass $M_i$, radius $R_{\ast,i}$, and number density $n_i$, and the integral runs over the giant phase only. The velocity at infinity, $v_{\infty}$, is taken to be the central velocity dispersion, and $M_\ast$ is the mass of the BH. Tidal dissipation of energy in the giant envelope is sufficient to lead to capture of the giant into a bound binary if the BH passes within a distance $R_{\text{coll}} = f_p R_{\ast}$, Ivanova et al. (2017) model a specific encounter between a BH and a red giant in detail using hydrodynamic simulations and find that the maximum pericenter separation at which tidal capture takes place and the envelope is completely removed is about three times the giant radius. Hence, we take $f_p = 3$. The factor $f_{\text{seg}}$ is an ad hoc correction for the enhancement of the number of red giants in the core owing to mass segregation. We let $f_{\text{seg}} = 2$ following Ivanova et al. (2010). We evaluate Equation (2) using tracks from Hurley et al. (2000) evaluated at the metallicity of 47 Tuc, $Z = 0.004$ (Harris 1996). The initial mass function is taken from Kroupa (2002) and we take the integral up to the assumed cluster age of 13.8 Gyr.

Putting these numbers together, we estimate that about 6% of BHs should have had a collision that would lead to a BH–COWD binary (see Table 1). We include collisions with horizontal-branch stars, which dominate the total numbers. Once the envelope has been ejected the resulting object will resemble a sub-dwarf B (sdB) star, which are produced after an RGB star fills its Roche lobe and the subsequent episode of common-envelope evolution removes the helium-rich envelope. We make the conservative assumption that, once the envelope has been ejected, the core “burns out” to form a hybrid white dwarf with a carbon–oxygen center. More likely is that the resulting sdB star would exhaust core He and form a helium giant, leading to a second episode of common-envelope evolution and a shorter merger time. In either case, when observed as a UCXB, we would expect such an object to be dominated by carbon and oxygen, since the helium-rich outer layers will be lost during the early mass transfer. Our analysis is roughly consistent with Ivanova et al. (2010); we find a slightly higher rate since we take the integrated stellar population over time rather than the present-day population. In conclusion, if the core of 47 Tuc contains a few tens of stellar-mass BHs then it is likely that one or more of them has acquired a degenerate carbon–oxygen companion in a collision with a giant.

By drawing from our predicted collisions uniformly in $\Gamma$ we obtain the properties expected for the post-collision binaries. In all cases, since the pericenter separation $R_{\text{peri}} \leq 3 R_\ast$, mass transfer will take place at pericenter. This mass transfer leads to common-envelope evolution and the shrinking of the binary orbit. We obtain the final orbital semimajor axis $a_\ell$ from the standard common-envelope prescription (Webbink 1984):

$$
a_\ell = R_\ast \frac{\alpha_{\text{CE}} \lambda M_\ast M_{\text{e,core}}}{2 M_\ast M_{\text{e,env}}},
$$

(3)

where we take the common-envelope efficiency parameter $\alpha_{\text{CE}} = 1$, and the structure parameter for the giants $\lambda \approx 1$ as found to be appropriate for low-mass stars on the horizontal branch (Wang et al. 2016). The giant’s core and envelope masses are $M_{\ast,\text{core}}$ and $M_{\ast,\text{env}}$, respectively. To derive $R_{\text{peri}}$ we consider the separation at the closest approach during the initial encounter, $R_{\text{coll}}$. For gravitationally focused encounters $R_{\text{coll}}$ is uniformly distributed between 0 and $f_p R_{\ast}$. If $a_\ell < R_{\text{coll}}$ we take the binary to be circular; otherwise we take it to be eccentric with $R_{\text{peri}} = R_{\text{coll}}$. This is a conservative assumption given that Ivanova et al. (2017) find that the pericenter separation reduces during common-envelope mass loss. Figure 2 shows the
pericenter separations $r_{\text{peri}}$ of the binaries that form as a function of core mass.

It can be seen from Figure 2 that the typical binary forms from a collision between a BH and a horizontal branch star with $M_{\text{core}} \approx 0.5 M_{\odot}$, and has a pericenter separation between 10 and 100 $R_{\odot}$. These binaries are too wide to merge in a Hubble time by gravitational wave emission without some additional help from the cluster. Ivanova et al. (2010) argued that they will undergo collisions with wide binaries and form hierarchical triples. If the outer orbit is sufficiently inclined with respect to the inner orbit, then Kozai–Lidov cycles can drive the inner binary up to high eccentricities. Gravitational wave emission at pericenter then leads to rapid circularization and ultimately mass transfer begins. They conclude that such triples should form sufficiently frequently that essentially all of the binaries that we form by collisions will be driven into mass transfer by Kozai–Lidov cycles.

If the outer binary is too wide, Kozai–Lidov cycles can be suppressed by relativistic precession of the inner binary. Adopting Equation (4) of Hamers et al. (2013) to characteristic values for our problem, we obtain the maximum outer orbital semimajor axis $a_{2,\text{max}}$ that can drive Kozai–Lidov cycles as

$$a_{2,\text{max}} = 854 R_{\odot} \left( \frac{a_1}{20 R_{\odot}} \right)^{4/3} \left( \frac{M_3}{M_{\odot}} \right)^{1/3} \left( \frac{11 M_{\odot}}{M_{\text{core}} + M_{\ast}} \right)^{2/3} \times \frac{(1 - e_1^2)^{1/3}}{(1 - e_2^2)^{1/2}},$$

where the suffixes 1 and 2 denote the inner and outer orbits and $M_3$ is the mass of the star that orbits the inner binary’s center of mass. For typical values of $e_1 = 0.5$ and $e_2 = 0.9$, $a_{2,\text{max}} = 1780 R_{\odot}$, which excludes barely any of the triples that Ivanova et al. (2010) consider. Hence, relativistic precession should have only a minor impact on this mechanism.

Based on the inferred mass-transfer rate of $\approx 10^{-9} M_{\odot} \text{yr}^{-1}$ (Miller-Jones et al. 2015) and the likely remaining white dwarf mass of a few percent of a solar mass, the likely lifetime of 47 Tuc X9’s current state is $10^7$–$10^8$ years. If all the BH–COWD binaries that form over the lifetime of 47 Tuc merge in the last Gyr—which is plausible, given the lengthy gravitational wave inspiral and Kozai cycles required to merge—this requires, on average, tens of binaries to produce a single visible UCXB today. In turn that would require a few hundred $10 M_{\odot}$ BHs in the core, which is at the very upper end of realistic values. To derive this pessimistic analysis, however, we have made several conservative assumptions. First, when considering the entire Galactic globular cluster population, 47 Tuc represents only about 2.5% of the total number of stellar encounters (Bahramian et al. 2013). Hence, if 47 Tuc X9 is the only comparable binary in the Galaxy we can divide the required formation rate by a factor of 40. Second, we neglect binaries that form via exchanges and subsequent hardening by encounters and triples. This channel is approximately equally efficient at producing BH–WD binaries (Ivanova et al. 2010). We also ignore the fact that any BHs present are likely to be in binaries with other BHs. This increases their cross section for colliding with giants, and potentially provides a built-in companion to drive Kozai cycles. Given these modifications we argue that formation rates permit a BH–COWD binary.

A likely extragalactic relative of 47 Tuc X9 is the X-ray source coincident with RZ 2109, a globular cluster in the Virgo cluster galaxy NGC 4472 (Maccarone et al. 2007). Its observed properties are consistent with a stellar-mass BH accreting from a COWD at around the Eddington limit (Zepf et al. 2007, 2008). In our model, such objects form via the same channel as 47 Tuc X9, but represent an earlier phase of the evolution with higher $M$. Figure 3 shows the evolution of the mass-transfer rate and orbital period of a typical BH–COWD UCXB at late times. The initial masses of the BH and white dwarf are 15 $M_{\odot}$ and 0.5 $M_{\odot}$. The circles and squares indicate the approximate states of 47 Tuc X9 and the RZ 2109 X-ray source. Their respective evolution timescales imply that systems like 47 Tuc X9 should be roughly 150 times as common as systems like the RZ 2109 X-ray source. Peacock et al. (2012) and Caldwell et al. (2014) discuss spectroscopy of about 1600 massive globular clusters in NGC 4472 and M 87 that encompass a total stellar mass of about $3 \times 10^5 M_{\odot}$, within which the only RZ 2109-like object observed was RZ 2109 itself. 47 Tuc X9 is as of yet unique within the $\approx 2 \times 10^7 M_{\odot}$ of massive Galactic globular clusters. Given the large uncertainty in this rough comparison, the observed ratio is compatible with our theoretical predictions.

A final question is whether the 6.8-day variability in the 47 Tuc X9’s X-ray flux could be related to the presence of a third star. If 6.8 days is the orbital period of the outer binary, it would have a semimajor axis $a_{\text{out}} \approx 40 R_{\odot}$, assuming a 15 $M_{\odot}$ BH. This is a similar separation to the dynamically formed binaries in Figure 2, and hence is closer than expected to drive Kozai–Lidov cycles, but is possible if the BH–WD binary had been hardened before acquiring this companion. Inspired by Bailyn (1987) we looked at the eccentricity induced in the inner binary by a 1 $M_{\odot}$ companion in a moderately eccentric ($e_{\text{out}} = 0.6$) orbit of 40 $R_{\odot}$, considering just the gravitational perturbation. Lidov–Kozai cycles align the orbital planes at

![Figure 3](image-url)
maximum eccentricity, so we took the triple to be coplanar. At each pericenter passage of the outer binary an eccentricity of \( \approx 10^{-3} \) is excited in the inner binary. This is sufficient to drive the observed fluctuations in the X-ray emission, assuming that X-ray luminosity \( L_X \propto M \). In this picture the mass transfer must damp the eccentricity before the next pericenter passage. The required damping timescale is shorter than the viscous timescale of the accretion disk, so this is realistic.

4. Conclusions

We have explored theoretical constraints on the formation of the luminous X-ray binary 47 Tuc X9. Following previous observational work we assume that it is a compact object (BH or NS) accreting from a carbon–oxygen white dwarf. By adapting the model of Bobrick et al. (2017) we have shown that carbon–oxygen white dwarfs only form stable X-ray binaries when orbiting BHs of more than \( 6 M_\odot \), and even then only if we allow somewhat super-Eddington accretion rates and relatively slow extraction of orbital energy during common-envelope evolution. Therefore we can rule out an NS as the accretor. This conclusion is consistent with other properties of the binary, such as the ratio of its X-ray and radio luminosities.

Analysis of the dynamical formation rates of binaries containing a BH and a carbon–oxygen white dwarf suggests that the main channel is the collision of a stellar-mass BH with a horizontal-branch star, leading to tidal capture, and once a bound binary has formed, common-envelope evolution. A combination of hardening by Kozai–Lidov cycles in dynamically formed triple systems and gravitational wave emission drives such binaries into contact in less than a Hubble time. We find that the expected formation rates are consistent with seeing one such binary in the Milky Way globular cluster system today. By extrapolation they are also consistent with the X-ray source in RZ 2109, a globular cluster in the Virgo cluster, which is in an earlier phase of its evolution. The observed 6.8-day periodicity in the X-ray emission from 47 Tuc X9 may be driven by eccentricity induced in the UCXB’s orbit by a perturbing companion.

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