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Eccentricity of HLX-1

Roberto Soria★

International Centre for Radio Astronomy Research, Curtin University, GPO Box U1987, Perth, WA 6845, Australia

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ABSTRACT

We compare the outer radius of the accretion disc in the intermediate-mass black hole candidate HLX-1 as estimated from the ultraviolet/optical continuum, with the values estimated from its outburst decline time-scales. We fit the *Swift* 2010 outburst decline light curve with an exponential decay, a knee and a linear decay. We find that the disc has an outer radius of $10^{12} \lesssim R_{\rm out} \lesssim 10^{13}$ cm, only an order of magnitude larger than typical accretion discs in the high/soft state of Galactic black holes. By contrast, the semimajor axis is $\approx$ a few $\times 10^{14}$ cm. This discrepancy can be explained with a highly eccentric orbit. We estimate the tidal truncation radius and circularization radius around the black hole at periastron, and impose that they are similar or smaller than the outer disc radius. We obtain that $e \gtrsim 0.95$, that the radius of the donor star is $\lesssim$ a few solar radii and that the donor star is not at risk of tidal disruption. If the companion star fills its Roche lobe and impulsively transfers mass only around periastron, secular evolution of the orbit is expected to increase eccentricity and semimajor axis even further. We speculate that such extremely eccentric systems may have the same origin as the S stars in the Galactic Centre.

Key words: accretion, accretion discs – black hole physics – X-rays: individual: HLX-1.

1 INTRODUCTION

The point-like X-ray source 2XMM J011028.1−460421 (henceforth HLX-1 for simplicity) is the strongest intermediate-mass black hole (IMBH) candidate known to date (Farrell et al. 2009; Wiersema et al. 2010; Davis et al. 2011; Servillat et al. 2011). It is seen in the sky at a distance of ≈8 arcsec from the nucleus of the S0 galaxy ESO 243−49 (redshift $z = 0.0224$, luminosity distance ≈95 Mpc, distance modulus ≈34.89 mag; at this distance, 1 arcsec ≈ 460 pc). Its X-ray luminosity and spectral variability (Farrell et al. 2009; Godet et al. 2009; Servillat et al. 2011) and its radio flares detected in association with the X-ray outbursts (Webb et al. 2012) are consistent with the canonical state transitions and jet properties of an accreting BH. With a peak X-ray luminosity of $\approx 10^{42}$ erg s^{-1}, the BH mass required to be consistent with the Eddington limit is $\sim 10^4$ M$_{\odot}$. A similar value is obtained from spectral modelling of the thermal X-ray component, which is consistent with emission from an accretion disc (Farrell et al. 2009; Davis et al. 2011; Servillat et al. 2011). If these BH mass estimates are correct, HLX-1 is way too massive to have been formed from any stellar evolution process. A more likely scenario is that it is the nuclear BH (perhaps still surrounded by its own nuclear star cluster) of a disrupted dwarf satellite galaxy, accreted by ESO 243−49 (King & Dehnen 2005; Mapelli, Zampieri & Mayer 2012). HLX-1 has a point-like, blue optical counterpart ($B \sim V \sim 24$ mag near the outburst peak; Farrell et al. 2012; Soria et al. 2012, 2010). The presence of Hα emission at a redshift consistent with that of ESO 243−49 (Wiersema et al. 2010) is perhaps the strongest argument for a true physical association. It is still debated whether the optical continuum emission is dominated by the outer regions of the BH accretion disc or by a young star cluster around the BH (Farrell et al. 2012; Soria et al. 2012).

In the absence of phase-resolved dynamical measurements of the BH motion, we can use the *Swift* X-ray light-curve properties to constrain the system parameters. The X-ray flux shows recurrent outbursts every ≈(366 ± 4) d (seen every late August in 2009, 2010, 2011 and 2012), due either to some kind of disc instability or to a periodic enhancement of the accretion rate. Several alternative scenarios were considered and discussed by Lasota et al. (2011), who favoured a model in which enhanced mass transfer into a quasi-permanent accretion disc is triggered by the passage at periastron of an asymptotic giant branch (AGB) star on an eccentric orbit ($e \sim 0.7$). Since the publication of that work, the detection of the third and fourth consecutive outbursts (see Godet et al. 2012 for the first report of this year's outburst) has clinched the interpretation of the recurrence time-scale as the binary period. Furthermore, additional optical photometric results have been published, based on data from the *Hubble Space Telescope* (*HST*; Farrell et al. 2012) and from the European Southern Observatory (ESO)'s Very Large Telescope (VLT; Soria et al. 2012). Thus, in this paper we revisit and update Lasota et al. (2011) orbital models and constraints in the light of the new results.

★ E-mail: roberto.soria@icrar.org

2 SIZE OF THE ACCRETION DISC

2.1 Predictions for a standard disc model

At a distance of 95 Mpc, the characteristic size of the region responsible for most of the soft, thermal ($kT \approx 0.2$ keV) X-ray emission is $\sim$ a few $\times\ 10^9$ cm (inferred from fits to *XMM–Newton*, *Chandra* and *Swift* spectra), and is consistent with being constant during the decline of individual outbursts, and over the three recorded outbursts (Farrell et al. 2009; Davis et al. 2011; Servillat et al. 2011; Soria et al. 2011; Farrell et al. 2012; Soria et al. 2012). This suggests that the soft X-ray emission traces the true inner radius of the disc, bounded by the innermost stable circular orbit around the BH. Instead, much less is known about the outer disc radius, from ultraviolet (UV)/optical/infrared (IR) observations; it is still debated how much of the blue optical emission comes from an irradiated disc, and how much from a possible cluster of young stars around the BH. If the disc is the dominant UV/optical emitter, the *HST* and VLT studies of Farrell et al. (2012) and Soria et al. (2012), respectively, agree on an outer disc radius $\approx 10^{13}$ cm $\sim$1 au. If a substantial contribution comes from unresolved young stars, we can take that value as an upper limit to the true disc size. A ratio of outer/inner disc radii $\sim 10^3$ is significantly smaller than observed in transient Galactic BHs with Roche lobe filling donors, where typical outer radii are $\sim 10^{11}$ cm $\sim$ a few $\times 10^4$ times the innermost stable circular orbit (Hynes et al. 2002, 1998; Zurita Heras et al. 2011). This serves as a warning that we have to disentangle what scales with BH mass and what does not, when using scaled-up Galactic BH models to interpret HLX-1. While the inner disc depends directly on the BH mass, the outer disc depends mostly on the donor star and binary separation.

There is an alternative way to estimate the outer disc size, based on the X-ray outburst decline time-scale. Following King & Ritter (1998) and Frank, King & Raine (2002), we assume that the outbursting disc is approximately in a steady state with surface density

$$\Sigma \equiv \rho H \approx \frac{\dot{M}_{\rm BH}}{3\pi\nu}, \tag{1}$$

where $\dot{M}_{\rm BH}$ is the central accretion rate and ν is the kinematic viscosity. When the whole disc from $R_{\rm in}$ to $R_{\rm out}$ is in a hot, high-viscosity state, the total mass in the disc is

$$M_{\rm disc} = 2\pi \int_0^{R_{\rm out}} \Sigma R \, {\rm d}R \approx \frac{\dot{M}_{\rm BH} R_{\rm out}^2}{3\nu} = \frac{-\dot{M}_{\rm disc} R_{\rm out}^2}{3\nu}, \tag{2}$$

where we have neglected other sources of mass loss from the disc apart from BH accretion. In equation (2), ν is interpreted as an average value of the kinematic viscosity over the whole disc; in practice, we take the value of ν near the outer edge of the disc (King & Ritter 1998). Integrating equation (2), we obtain the well-known exponential decline for the disc mass

$$M_{\rm disc} = M_{\rm disc,0} \exp\left(-3\nu t/R_{\rm out}^2\right), \tag{3}$$

and consequently also for the accretion rate

$$\dot{M}_{\rm BH} = \frac{3\nu M_{\rm disc,0}}{R_{\rm out}^2} \exp\left(-3\nu t/R_{\rm out}^2\right), \tag{4}$$

and the outburst luminosity $L \sim L_{\rm X} \sim 0.1 \dot{M}_{\rm BH} c^2$. In summary, we expect to see a luminosity

$$L_{\rm X} \approx L_{\rm X,0} \exp\left(-3\nu t/R_{\rm out}^2\right), \tag{5}$$

where $L_{\rm X,\,0}$ is the value at the outburst peak, declining on a time-scale

$$\tau_{\rm e} \approx R_{\rm out}^2/(3\nu), \tag{6}$$

as long as the rate at which the disc mass is depleted during the outburst decline is much larger than any ongoing transfer of mass from the donor star. For the viscosity at the outer edge of the disc, we take the usual parametrization $\nu = \alpha c_{\rm s} H$ (Shakura & Sunyaev 1973), where α is the viscosity coefficient in the hot state, $c_{\rm s}$ is the sound speed and H is the vertical scale-height. In the simplest, order-of-magnitude approximation, we can take an outer disc temperature of $\approx 10^4$ K (enough to keep it in the hot state), corresponding to $c_{\rm s} \approx 2 \times 10^6$ cm s^{-1}, and a vertical height $H \approx 0.1R$. This gives from equation (6)

$$R_{\rm out} \sim 6 \times 10^5 \, \alpha \, \tau_{\rm e} \ {\rm cm}, \tag{7}$$

which we shall directly compare with the observations.

If we adopt the Shakura–Sunyaev disc solution (Shakura & Sunyaev 1973; Frank et al. 2002), with Kramers opacity, we can write

$$\begin{aligned} \nu &\approx 1.8 \times 10^{14} \alpha^{4/5} \dot{M}_{16}^{3/10} m_1^{-1/4} R_{10}^{3/4} \ {\rm cm^2 s^{-1}} \\ &\approx 6.4 \times 10^{16} \, \alpha^{4/5} \dot{M}_{22}^{3/10} m_3^{-1/4} R_{12}^{3/4} \ {\rm cm^2 \, s^{-1}}, \end{aligned} \tag{8}$$

where $\dot{M}_{16}$ is the accretion rate in units of 10^{16} g s^{-1}, m_1 is the BH mass in solar units, $R_{10} \equiv R_{\rm out}/(10^{10}\,{\rm cm})$, etc. Then, from equation (6)

$$\tau_{\rm e} \approx 5.2 \times 10^6 \alpha^{-4/5} \dot{M}_{22}^{-3/10} m_3^{1/4} R_{12}^{5/4} \ {\rm s}, \tag{9}$$

i.e.

$$R_{12} \approx \left(\frac{\tau_{\rm e}}{5.2 \times 10^6}\right)^{4/5} \alpha^{16/25} \dot{M}_{22}^{6/25} m_3^{-1/5}. \tag{10}$$

The peak luminosity $L_{\rm X,\,0}$ in equation (2) can be left as a purely observational parameter, or it can itself be expressed as a function of outer disc radius, viscosity, density and BH mass, if we assume that the outburst is triggered via the dwarf-nova instability (Cannizzo 1993). (More precisely, if we assume that the outburst starts when the enhanced mass transfer due to periastron passage pushes the disc from the cold to the hot state.) In that case, the surface density at any radius immediately before the start of the outburst approaches the maximum value allowed by the S-curve in the surface-temperature phase space (King & Ritter 1998; Frank et al. 2002):

$$\begin{aligned} \Sigma_{\rm max} &\approx 11.4 R_{10}^{1.05} m_1^{-0.35} \alpha_{\rm c}^{-0.86} \ {\rm g\,cm^{-2}} \\ &\approx 1.3 \times 10^2 R_{12}^{1.05} m_3^{-0.35} \alpha_{\rm c}^{-0.86} \ {\rm g\,cm^{-2}}, \end{aligned} \tag{11}$$

where $\alpha_{\rm c} \sim 0.01$ is the viscosity parameter in the cold disc state. Taking for simplicity $H \approx bR$, where b is a constant $\sim$0.1, we can then express the maximum volume density at the start of the outburst as $\rho_{\rm max} = \Sigma_{\rm max}/H \approx \Sigma_{\rm max}/(bR)$, which is essentially independent of R, given the expression for $\Sigma_{\rm max}$ in equation (11). It is then easy to integrate the total disc mass at the start of the outburst:

$$\begin{aligned} M_{\rm disc,0} &= 2\pi \int_0^{R_{\rm out}} \Sigma_{\rm max} R \, {\rm d}R \\ &\approx (2\pi b) \int_0^{R_{\rm out}} \rho R^2 \, {\rm d}R = (2\pi b) \frac{\rho R_{\rm out}^3}{3}, \end{aligned} \tag{12}$$

the disc mass at later times

$$M_{\rm disc} \approx \frac{(2\pi b)\rho R_{\rm out}^3}{3} \exp\left(-3\nu t/R_{\rm out}^2\right), \tag{13}$$

the accretion rate (cf. equation 4)

$$\dot{M}_{\rm BH} \approx (2\pi b)(R_{\rm out}\nu\rho)\,\exp\left(-3\nu t/R_{\rm out}^2\right) \quad (14)$$

and the peak luminosity

$$\begin{aligned} L_{\rm X,0} &\approx (0.1c^2)(2\pi b)(R_{\rm out}\nu\rho) \\ &\approx (0.1c^2)(2\pi b)R_{\rm out}(\alpha c_{\rm s}H)(\Sigma_{\rm max}/H) \\ &\approx 0.1\alpha c^2(2\pi b)R_{\rm out}c_{\rm s}\Sigma_{\rm max}, \end{aligned} \quad (15)$$

where $\Sigma_{\rm max}$ comes from equation (11).

So far, we have assumed that the whole disc is in the hot state; this is usually the case in the early part of an outburst, especially when the outer edge of the disc is kept in the hot state by X-ray irradiation. The exponential decay continues until the outer disc annuli can no longer be kept in the hot state, so that hydrogen recombines and viscosity drops. From that moment, the outer edge of the hot disc $R_{\rm h} < R_{\rm out}$. The contribution to the accretion rate and to the continuum X-ray/UV/optical emission from the outer (cold, low-viscosity) annuli at $R_{\rm h} < R < R_{\rm out}$ becomes negligible. It was shown by King & Ritter (1998) that the central accretion rate in this second phase of the decline is

$$\dot{M}_{\rm BH} = \dot{M}_{\rm BH}(t_1)\,[1 - C(t - t_1)]\,, \quad (16)$$

where t_1 is the time after which the outer disc is no longer in the hot state, and C parametrizes the fraction of X-ray luminosity intercepted and thermalized in the outer disc. As C can be taken as a constant, equation (16) shows that the accretion rate and luminosity decline in the late part of the outburst are linear. Most importantly for our current purpose, the slope of the linear decline is such that

$$t_{\rm end} - t_1 = \tau_{\rm e} \quad (17)$$

(King & Ritter 1998), where $t_{\rm end}$ is the (extrapolated) time in which the accretion rate and luminosity go to zero.

Finally, we need to consider the case when there is ongoing mass transfer $\dot{M}_2$ from the donor star during the outburst. In that case, the asymptotic value of the luminosity in the exponential decline is not zero but $L_2 \approx 0.1(-\dot{M}_2)c^2$ (assuming a standard radiative efficiency ≈0.1). Recalling that t_1 is the time when the light curve switches from an exponential to a linear decline, and defining $L_1 \equiv L(t_1)$, equation (5) is modified as (Powell, Haswell & Falanga 2007)

$$L_{\rm X} = (L_1 - L_2)\exp\left(-3\nu\,(t - t_1)\,/R_{\rm out}^2\right) + L_2. \quad (18)$$

After the transition to a linear regime, the luminosity is

$$L_{\rm X} = L_1\left[1 - \frac{3\nu}{R_{\rm out}^2}\,(t - t_1)\right]. \quad (19)$$

Note that if $-\dot{M}_2 > 0$, the first derivative of the luminosity is discontinuous at $t = t_1$ (Powell et al. 2007), because the gradient of the exponential decay is

$$\dot{L}_{\rm X}(t_1) \approx -\frac{3\nu}{R_{\rm out}^2}\,L_1\left(1 + \frac{0.1\dot{M}_2c^2}{L_1}\right), \quad (20)$$

which is flatter than the gradient of the linear decay

$$\dot{L}_{\rm X}(t_1) = -\frac{3\nu}{R_{\rm out}^2}\,L_1. \quad (21)$$

Therefore, the exponential-to-linear transition is often referred to as the 'knee' in the light curve of transient X-ray binaries.

2.2 Comparison with the observations

We shall now fit the X-ray light curve to obtain two independent estimates of the viscous time-scale $\tau_{\rm e}$, from the exponential and the linear regime, and use them to constrain $R_{\rm out}$ from equation (10) or, using a simpler approximation for the scale-height, from equation (7). We shall then derive an independent estimate of $R_{\rm out}$ from the expression for the peak luminosity in equation (15). We studied the publicly available[1] *Swift* X-Ray Telescope (XRT; Burrows et al. 2005) data for the 2010 outburst, because it is the same outburst for which we obtained constraints on $R_{\rm out}$ from the optical continuum (Farrell et al. 2012; Soria et al. 2012). We used the online *Swift*/XRT data product generator[2] (Evans et al. 2007, 2009) to extract a light curve in the 0.3–10 keV band. We fitted the light curve with an initial exponential decay, a knee and a linear decay (Fig. 1). The shape of the X-ray outburst light curve of HLX-1 is remarkably similar to those of several transient Galactic X-ray binaries (BHs and neutron stars), modelled by Powell et al. (2007), which were successfully used to constrain the size of their accretion discs.

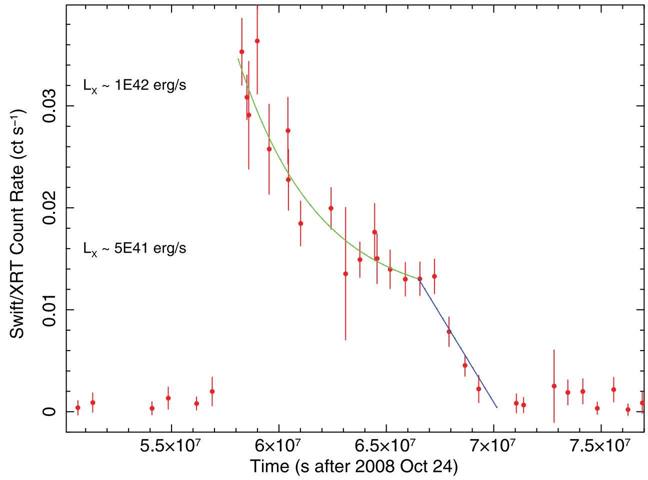

Figure 1. *Swift*/XRT light curve of the 2010 outburst, fitted with a standard X-ray transient model (exponential decay, knee and linear decay).

For the exponential part, we obtain a best-fitting time-scale $\tau_{\rm e} = R_{\rm out}^2/(3\nu) = 3.7^{+5.0}_{-1.5} \times 10^6$ s (90 per cent confidence limit). For the linear part, we have $\tau_{\rm e} = 3.5^{+1.0}_{-0.8} \times 10^6$ s. Assuming a peak luminosity of $\approx 10^{42}$ erg s^{-1} in the 0.3–10 keV band, and a bolometric luminosity a factor of 2 higher, implies an accretion rate $\dot{M} \approx 2 \times 10^{22}$ g s^{-1} at standard efficiency. The viscosity parameter $\alpha \lesssim 1$, and more likely $\alpha \sim 0.3$ (Frank et al. 2002). From equation (10), this implies $R_{\rm out} \approx 10^{12}$ cm, only very weakly dependent on BH mass and accretion rate. Using the approximation in equation (7), we also obtain $R_{\rm out} \sim 10^{12}$ cm. From the peak luminosity (equation 15), for $\alpha \sim 0.3$ we obtain $R_{\rm out} \sim 4 \times 10^{12}$ cm.

We also analysed the light curves for the 2009 and 2011 outbursts (the 2012 outburst was still ongoing as this paper went to press). They are more noisy, less easy to interpret in terms of exponential and linear branches. However, for both of them it is possible to estimate an e-folding decline time-scale, roughly corresponding to the exponential time-scale determined for the 2010 outburst. The time-scales are $\approx 5 \times 10^6$ s and $\approx 3 \times 10^6$ s for 2009 and 2011, respectively, and the peak luminosities are approximately the same in all three outbursts. Thus, we also estimate an outer radius of $\sim 10^{12}$ cm in the 2009 and 2011 outbursts, in the standard disc approximation.

[1] http://www.swift.ac.uk/user_objects

[2] Including the new treatment of the vignetting correction, introduced after 2011 August 5.

Those values are almost one order of magnitude smaller than what we estimated by assuming that most of the continuum emission comes from the hot disc; and the latter was already a surprisingly small radius compared with the binary system parameters (see Section 3). We note that both the *HST* and VLT observations (Farrell et al. 2012; Soria et al. 2012) were taken during the exponential part of the decline, i.e. when the whole disc was in a hot state. Therefore, the estimates of $R_{\rm out}$ from the optical/UV continuum should be comparable to those from the X-ray light curve. New optical observations early in the next outburst will hopefully allow us to measure the true outer disc size and luminosity.

3 ORBITAL PARAMETERS

We can now compare the size of the disc estimated from optical and X-ray flux measurements ($10^{12} \lesssim R_{\rm out} \lesssim 10^{13}$ cm) with the characteristic size of the binary system. Because of the sharpness of the outbursts rise and decline, reminiscent of Galactic X-ray binaries, we assume that the BH is accreting from a single donor star rather than active galactic nucleus (AGN)-like gas inflows. We also assume that the outburst recurrence time-scale ∼370 d corresponds to the binary period. Then, the semimajor axis a of the binary is

$$a = 1.50 \times 10^{13} m^{1/3} (1+q)^{1/3} P_{\rm yr}^{2/3}\ {\rm cm} \qquad (22)$$

(Newton 1687), where $q = M_2/M_{\rm BH}$ and $m \equiv (M_{\rm BH} + M_2)/{\rm M}_\odot \equiv M/{\rm M}_\odot$. Typical values for HLX-1 in the intermediate-mass BH scenario are $q \sim 10^{-3}$ and $m^{1/3} \sim 10$–20. Therefore, in the most accepted scenario, the semimajor axis is at least 10, and possibly up to 100 times larger than the disc radius. This mismatch clearly suggests an eccentric orbit (Lasota et al. 2011), in which the characteristic disc size is determined by the periastron separation $R_{\rm per} = (1-e)a$, with eccentricity $e \gtrsim 0.9$.

The amount of mass transferred to the BH in each outburst suggests that the donor star overflows its instantaneous Roche lobe every time it passes at periastron. In Roche lobe mass transfer systems, the outer edge of the accretion disc is generally identified with the largest stable non-intersecting orbit (tidal truncation radius $R_{\rm T}$). For mass ratios $M_2/M_1 \ll 1$, $R_{\rm T} \approx 0.48a$ (Paczynski 1977; Papaloizou & Pringle 1977; Whitehurst 1988; Warner 1995). If unstable orbits are also allowed, the disc may expand up to $R_{\rm T} \approx 0.60a/(1+q)$ (Warner 1995, and references therein). If we take the periastron distance as the instantaneous binary separation during the phase of Roche lobe overflow, this corresponds to an expected disc size $R_{\rm out} \approx 0.6(1-e)a$. For an observed disc size $R_{\rm out} = 10^{13}$ cm, the tidal radius condition would require an eccentricity $e \approx 0.89$ for a BH mass $=1000\,{\rm M}_\odot$, and $e \approx 0.95$ for a BH mass $=10^4\,{\rm M}_\odot$. If we take the lower bound to our observed disc size $R_{\rm out} = 10^{12}$ cm, we need $e \approx 0.989$ or 0.995, respectively.

We can argue that the tidal truncation constraint is not relevant to the case of HLX-1, where mass transfer may occur impulsively near periastron, and the time-scale for the disc to expand to its tidal truncation radius is similar to the time-scale for the disc matter to be accreted and for the binary orbit to expand after periastron. In other words, in HLX-1 the disc may look small because it did not have time to grow to its tidal truncation radius. Instead, the circularization radius provides a stronger lower limit to the predicted disc size, and is applicable to any system where mass transfer occurs through the Lagrangian point L_1.

The circularization radius $R_{\rm cir}$ is defined via the conservation of angular momentum equation

$$v_\phi\,(R_{\rm cir})\,R_{\rm cir} = (X_{\rm L1} R_{\rm per})^2 \Omega\left(R_{\rm per}\right), \qquad (23)$$

Table 1. Distance $X_{\rm L1}$ between the BH and the L_1 point, in the parameter range of interest for HLX-1, from equation (24).

	$e = 0.80$	$e = 0.90$	$e = 0.95$	$e = 0.99$
		$f = 0$		
$q = 10^{-1}$		0.695		
$q = 10^{-2}$		0.843		
$q = 10^{-3}$		0.924		
$q = 10^{-4}$		0.964		
		$f = 1$		
$q = 10^{-1}$	0.732	0.734	0.735	0.735
$q = 10^{-2}$	0.868	0.869	0.869	0.869
$q = 10^{-3}$	0.937	0.938	0.938	0.938
$q = 10^{-3}$	0.970	0.971	0.971	0.971

where v_ϕ is the orbital velocity of the accretion stream around the BH, $X_{\rm L1}\ R_{\rm per}$ is the distance between the BH and the Lagrangian point L_1 and $\Omega(R_{\rm per})$ is the angular velocity of the donor star at periastron. Here, we must be careful not to use the well-known fitting formula for $X_{\rm L1} \approx 0.500$–$0.227 \log q$ (Frank et al. 2002), because it applies only for $q > 0.1$ and for circular orbits. Instead, we need to compute $X_{\rm L1}$ from equation (A13) of Sepinsky et al. (2007) valid for eccentric orbits:

$$\frac{q}{(1-X_{\rm L1})^2} - \frac{1}{X_{\rm L1}^2} - f^2\,(1-X_{\rm L1})\,(1+q)(1+e) + 1 = 0. \qquad (24)$$

Here, f is the ratio of the rotational angular velocity of the donor star to its orbital angular velocity, at periastron. It parametrizes the degree of tidal locking; a star with $f = 1$ is rotating synchronously with the orbit, at periastron. A list of $X_{\rm L1}$ solutions for characteristic values of q and e is given in Table 1. The orbital velocity of the accretion stream around the BH is

$$v_\phi \approx \left(\frac{GM_{\rm BH}}{R_{\rm cir}}\right)^{1/2}, \qquad (25)$$

and the orbital angular velocity at periastron is

$$\Omega\left(R_{\rm per}\right) = \frac{(1+e)^{1/2}}{(1-e)^{3/2}}\left[\frac{G\,(M_{\rm BH}+M_2)}{a^3}\right]^{1/2}. \qquad (26)$$

For the sake of our numerical estimate, we take $X_{\rm L1} = 0.95$, a typical value in the range of parameters thought to be relevant for HLX-1 (Table 1). Then, substituting into equation (23), we have

$$\begin{aligned} R_{\rm cir} &\approx \frac{\left(0.95 R_{\rm per}\right)^4}{GM_{\rm BH}}\,\frac{(1+e)}{(1-e)^3}\,\frac{G\,(M_{\rm BH}+M_2)}{a^3} \\ &\approx 0.81(1-e^2)(1+q)a \\ &\approx 1.2 \times 10^{14} m_3^{1/3} (1-e^2)(1+q)^{4/3} P_{\rm yr}^{2/3}\ {\rm cm}. \qquad (27) \end{aligned}$$

Assuming that the BH mass is in the range of $\sim 10^3$–$10^4\,{\rm M}_\odot$, equation (27) gives us a strong constraint on e, by imposing that the circularization radius is smaller than the observed outer disc size. For example, assuming $M_{\rm BH} = 5 \times 10^3\,{\rm M}_\odot$, a circularization radius $R_{\rm cir} = 10^{13}$ cm (at the upper end of our disc size estimates) requires $e \approx 0.97$; for $R_{\rm cir} = 10^{12}$ cm (at the lower end of our disc size estimates), $e \approx 0.997$. The corresponding periastron distances[3]

[3] Note that for $e \gtrsim 0.2$, the periastron distance between the two stars is always smaller than the circularization radius around the accreting primary. This is because the angular momentum of the secondary at periastron, and of the matter transiting through the L_1 point, is larger than the angular

$R_{\rm per} = (1-e)a \approx 6 \times 10^{12}$ cm for $e = 0.97$, and $R_{\rm per} \approx 6 \times 10^{11}$ cm for $e = 0.997$.

The distance between L_1 and the centre of the donor star places an upper limit on its radius; characteristic values of its instantaneous volume-averaged Roche lobe radius at periastron can be obtained from Eggleton (1983). For typical values $q \sim 10^{-4}$ to 10^{-3}, the secondary gets squeezed to a radius of $\approx(0.02–0.05)R_{\rm per}$. Since we have assumed that the secondary fills the Roche lobe and dumps mass into the BH only near periastron, this radius must also be similar to the size of the donor star. For example, if $q = 2 \times 10^{-4}$ and $e = 0.97$, the donor star must have a radius $\approx 4\,{\rm R}_{\odot}$, consistent with main sequence and subgiant stars.

The values of e estimated here from disc size arguments are much more extreme than what was suggested in Lasota et al. (2011). They may seem implausible, knowing that tidal forces tend to circularize orbits in X-ray binaries. However, Sepinsky et al. (2007, 2009) showed that in the case of a donor star that transfers mass impulsively only at periastron, with $q \lesssim 1 - 0.4e + 0.18e^2$, the secular evolution of the orbit leads to an increase of both eccentricity and semimajor axis, even when the opposite effect of tidal forces is taken into account. If tidal circularization is neglected, the eccentricity increases as

$$\langle \dot{e} \rangle = \frac{1}{\pi} \frac{\langle \dot{M}_2 \rangle}{M_2} (1-e^2)^{1/2}(1-e)(q-1), \tag{28}$$

and the semimajor axis (and hence the binary period) as

$$\langle \dot{a} \rangle = \frac{a}{\pi} \frac{\langle \dot{M}_2 \rangle}{M_2} (1-e^2)^{1/2}(q-1). \tag{29}$$

It is then easy to show from equations (28) and (29) that the periastron distance $R_{\rm per} = (1-e)a$, and therefore also the size of the secondary's Roche lobe at periastron, remains unchanged.

Finally, we need to assess what donor stars can survive on such eccentric orbits with small periastron distance, avoiding tidal disruption. The condition for survival is that the periastron distance $R_{\rm per}$ is larger than the tidal disruption radius (Rees 1988)

$$R_{\rm td} \approx 5 \times 10^{11} m_3^{1/3} \left(R_2/{\rm R}_{\odot}\right) \left(M_2/{\rm M}_{\odot}\right)^{-1/3} \text{ cm}. \tag{30}$$

By substituting $R_2 \lesssim 0.05 R_{\rm per}$ into equation (31), we can recast the tidal survival condition as

$$M_2 \gtrsim 4.6 \times 10^{-5} M_{\rm BH}, \tag{31}$$

easily satisfied in the likely mass range of HLX-1.

4 CONCLUSIONS

We compared the estimates of the disc size from the optical continuum flux ($R_{\rm out} \lesssim 10^{13}$ cm) with those obtained by fitting the X-ray luminosity decline after an outburst. We found that, at least for the 2010 outburst, the decline displays the standard sequence of exponential phase, knee, linear phase often seen in Galactic X-ray binaries; this strengthens the interpretation that the thermal X-ray emission in HLX-1 comes from a disc, and the decline time-scale corresponds to its viscous time-scale. For all three outbursts observed to-date, the time-scale is very short, $\sim$4–8 weeks. This is similar or only slightly longer than what is typically observed in Galactic X-ray transients, despite the fact that both the orbital period and the BH mass (and, hence, the semimajor axis) of HLX-1 are $\gtrsim$100 times larger. The outer disc radius estimated from the viscous time-scale is $R_{\rm out} \sim 10^{12}$ cm, if the viscosity parameter is similar to the values usually estimated for Galactic BH transients in a high state. We cannot rule out that the fast accretion of the disc matter in HLX-1 may be partly due to an effective viscosity $\alpha_{\rm eff} \gtrsim 1$, higher than in the Shakura–Sunyaev prescription. But we argue that even if we assume the upper disc size estimate $R_{\rm out} \approx 10^{13}$ cm, a highly eccentric orbit is required to explain the small disc size.

To quantify the eccentricity, we calculated the characteristic length-scales of the binary system, as a function of BH mass and eccentricity. If the disc extends at least as far as the circularization radius (as is usually the case in X-ray binaries with Roche lobe mass transfer), we obtain that $R_{\rm cir} \sim (1-e^2)a$, and therefore $e \gtrsim 0.95$ for a BH mass $\gtrsim 10^3\,{\rm M}_{\odot}$. We argued that X-ray binaries with such extreme values of e are the most likely evolutionary endpoint of systems with $q \ll 1$ and a moderately eccentric initial orbit, such that Roche lobe overflow mass transfer occurs only impulsively near periastron. Secular evolution will tend to make the orbit more and more eccentric, by increasing the semimajor axis and the binary period, at constant periastron distance.

The small periastron distance required to explain the HLX-1 observations sets an upper limit to the current radius of the donor star $R \lesssim$ a few ${\rm R}_{\odot}$, ruling out supergiants, red giants and AGB stars. Possible donors are main sequence (B type or later) or subgiants. The compactness of the donor star, and the fact that secular orbital evolution due to mass transfer will not change the periastron distance, implies that the companion star in HLX-1 is not at immediate risk of tidal disruption, and will not be in the near future. In other words, we are not observing HLX-1 in a peculiar moment of its evolution, immediately prior to tidal break-up of the donor star. HLX-1 appears to be a stable system, with a lifetime for X-ray outbursts determined primarily by the mass transfer time-scale from the donor; at a rate $\sim 10^{-5}\,{\rm M}_{\odot}\,{\rm yr}^{-1}$ (averaged over the binary period), it may last for another $\sim 10^5$–10^6 yr, during which its semimajor axis and binary period (and, hence, interval between outbursts) will continue to increase.

Eccentricities $\gtrsim$0.95 may seem implausibly extreme, but there is at least one class of stellar objects where they are the norm: S stars observed on highly eccentric orbits within 0.01 pc of the Galactic nuclear BH (Alexander 2005; Gillessen et al. 2009). A possible scenario for the origin of Galactic S stars is the tidal disruption of a stellar binary system near the BH, which produces an escaping, hypervelocity star, and a more tightly bound star on a very eccentric orbit, theoretically as high as $e \approx 0.99$ (Löckmann, Baumgardt & Kroupa 2008). Observationally, the most eccentric, bound S star for which orbital parameters have been reliably determined has $e \approx 0.96$ (Gillessen et al. 2009). We speculate that intermediate-mass BHs in star clusters may also capture stellar companions on very eccentric orbits through a similar process.

momentum of a circular orbit with the same binary separation. It is not a problem, because by the time the accretion stream has completed a full orbit around the BH and formed a ring, the secondary has moved away from periastron and the primary's Roche lobe has widened.

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