Feeding Compact Objects: Accretion on All Scales
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Accretion disk parameters in HLX-1

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Abstract. We estimate the outer radius of the accretion disk in HLX-1 from its optical brightness and from the exponential timescale of the decline in the X-ray lightcurve after an outburst. We find that the disk is an order of magnitude smaller than the semimajor axis of the orbit. If the disk size is determined by the circularization radius near periastron, the eccentricity of the binary system must be $\gtrsim 0.95$. We report on the discovery of Hα emission during the 2012 outburst, with a single-peaked, narrow profile (consistent with a nearly face-on view), and a central velocity displaced by ≈ 490 km s^{-1} from that of the host galaxy.

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

1. Introduction

The X-ray source 2XMM J011028.1$-$460421 (HLX-1) is the strongest intermediate-mass black hole (IMBH) candidate known to date (Farrell *et al.* 2009). It is located at a projected distance of $8'' \approx 3.7$ kpc from the nucleus of the S0 galaxy ESO 243-49 ($z = 0.0224$, $d \approx 95$ Mpc). If the peak X-ray luminosity $\approx 10^{42}$ erg s^{-1} is Eddington limited, the BH mass has to be $\sim 10^4 M_\odot$. A similar value is obtained by modelling the X-ray spectrum with thermal disc emission (Farrell *et al.* 2009, Davis *et al.* 2011, Servillat *et al.* 2011). Its X-ray spectral variability (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. 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, Soria *et al.* 2010). The Hα emission line at a redshift consistent with that of ESO 243-49 (Wiersema *et al.* 2010) is the strongest argument for a true physical association. It is still debated whether the optical/UV continuum is dominated by the irradiated accretion disc, or by a young star cluster around the BH (Soria *et al.* 2012, Farrell *et al.* 2012, Mapelli *et al.* 2013). The X-ray flux shows recurrent outbursts every ≈ 370 d, probably triggered by a sudden increase in the mass trasnfer rate when the donor star is near periastron of a highly eccentric orbit (Lasota *et al.* 2011). In this scenario, we can use the X-ray lightcurve to constrain the system parameters.

2. Disc size

Fits to the *XMM-Newton*, *Chandra*, *Swift* spectra during outbursts have consistently shown that the size of the inner disk (with $kT_{\rm in} \approx 0.2$ keV) is $\sim$ a few 10^9 cm (Farrell *et al.* 2009, Servillat *et al.* 2011, Davis *et al.* 2011, Soria *et al.* 2011, Soria *et al.* 2012, Farrell *et al.* 2012), consistent with an IMBH. Instead, much less is known about the outer disc radius $R_{\rm out}$. If the disc is the dominant optical emitter, the *HST* and VLT studies of Farrell *et al.* (2012) and Soria *et al.* (2012) agree on $R_{\rm out} \lesssim 2 \times 10^{13}$ cm for a face-on disc. A recent reanalysis of the *HST* data (Mapelli *et al.* 2013) suggested $R_{\rm out} \approx 3.5 \times 10^{13}$ cm for a viewing angle $i = 45°$ (a little smaller if face-on).

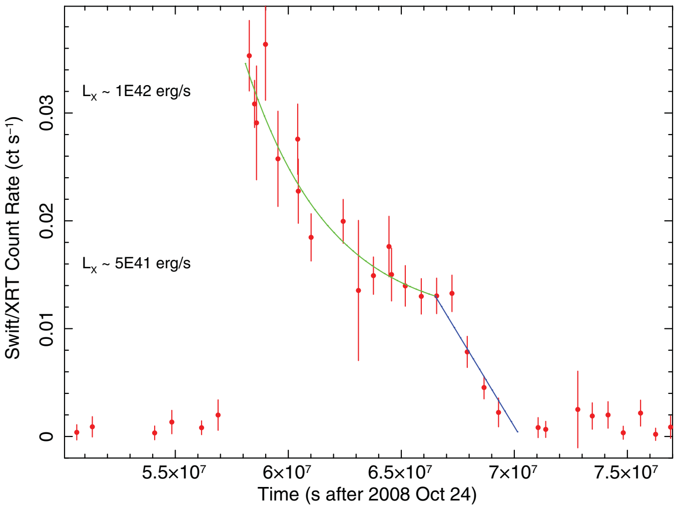

Figure 1. *Swift*/XRT lightcurve of the 2010 outburst, fitted with a standard X-ray transient model (exponential decay, knee, linear decay). It is remarkably similar to those of several transient Galactic X-ray binaries modelled by Powell *et al.* (2007).

There is an alternative way to estimate the outer disc size, based on the X-ray outburst decline timescale. Following King & Ritter (1998) and Frank *et al.* (2002), we assume that the outbursting disc is approximately in a steady state with surface density $\Sigma \equiv \rho H \approx \dot{M}_{\rm BH}/(3\pi\nu)$, where $\dot{M}_{\rm BH}$ is the central accretion rate and ν the kinematic viscosity. When the whole disc from $R_{\rm in}$ to $R_{\rm out}$ is in a hot, high-viscosity state, its total mass

$$M_{\rm disc} = 2\pi \int_0^{R_{\rm out}} \Sigma R\, dR \approx \frac{\dot{M}_{\rm BH} R_{\rm out}^2}{3\nu} = \frac{-\dot{M}_{\rm disc} R_{\rm out}^2}{3\nu}, \tag{2.1}$$

where ν is the kinematic viscosity near the outer edge of the disc (King & Ritter 1998). Integrating Eq.(2.1) gives an exponential decline for the disc mass, the accretion rate, and the outburst luminosity $L \sim L_{\rm X} \sim 0.1\dot{M}_{\rm BH}c^2$. We expect to see a luminosity

$$L_{\rm X} \approx L_{\rm X,0} \exp(-3\nu t/R_{\rm out}^2), \tag{2.2}$$

where $L_{\rm X,0}$ is the value at the outburst peak, declining on a timescale $\tau_{\rm e} \approx R_{\rm out}^2/(3\nu)$, 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, we take the usual parameterization $\nu = \alpha c_{\rm s} H$ (Shakura & Sunyaev 1973), where α is the viscosity coefficient in the hot state, $c_{\rm s}$ is the sound speed, and H the vertical scaleheight. In the Shakura-Sunyaev disc solution (Shakura & Sunyaev 1973, Frank *et al.* 2002), with Kramers opacity, after some algebra we obtain (Soria 2013):

$$R_{12} \approx \left(\frac{\tau_{\rm e}}{5.2 \times 10^6}\right)^{4/5} \alpha^{16/25} \dot{M}_{22}^{6/25} m_3^{-1/5}, \tag{2.3}$$

where $\dot{M}_{22}$ is the accretion rate in units of 10^{22} g s^{-1}, m_3 is the BH mass in units of $10^3 M_\odot$, $R_{12} \equiv R_{\rm out}/(10^{12}{\rm cm})$.

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 central accretion rate declines linearly (King & Ritter 1998), with a slope such that $t_{\rm end} - t_1 = \tau_{\rm e}$, where $t_{\rm end}$ is the (extrapolated) time in which the accretion rate and luminosity go to zero. Finally, if there is ongoing mass transfer $\dot{M}_2$ from the donor star

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during the outburst, the lightcurve has a characteristic "knee" at the point where it switches from an exponential to a linear decline (Powell *et al.* 2007).

Soria (2013) fitted the *Swift* X-ray lightcurve of the 2010 outburst (Fig. 1) to obtain two independent estimates of the viscous timescale $\tau_{\rm e}$, from the exponential and the linear regime, and used them to constrain $R_{\rm out}$. For the exponential part, $\tau_{\rm e} = R^2_{\rm out}/(3\nu) = 3.7^{+5.0}_{-1.5} \times 10^6$ s (90% confidence limit). For the linear part, $\tau_{\rm e} = 3.5^{+1.0}_{-0.8} \times 10^6$ s. Assuming a peak accretion rate $\dot{M} \approx 2 \times 10^{22}$ g s^{-1} and a viscosity parameter $\alpha \lesssim 1$, and more likely $\alpha \sim 0.3$ (Frank *et al.* 2002), both decline timescales give $R_{\rm out} \sim 10^{12}$ cm. We also determined e-folding decline timescales $\approx 5 \times 10^6$ s and $\approx 3 \times 10^6$ s for the 2009 and 2011 outbursts, respectively, both consistent with an outer radius $\sim 10^{12}$ cm, in the standard disc approximation. Those values are an order of magnitude smaller than what is estimated by assuming that most of the continuum emission comes from the hot disc; and the latter is already a small size compared with the semi-major axis.

3. Orbital parameters

We can now compare the size of the disc estimated from optical and X-ray flux measurements (10^{12} cm $\lesssim R_{\rm out} \lesssim 3 \times 10^{13}$ cm) with the characteristic size of the binary system. The semimajor axis a of the binary is

$$a = 1.50 \times 10^{13} m^{1/3} (1+q)^{1/3} P_{\rm yr}^{2/3} \text{ cm}, \tag{3.1}$$

where $q = M_2/M_{\rm BH}$ and $m \equiv (M_{\rm BH} + M_2)/M_\odot \equiv M/M_\odot$. Typical values for HLX-1 in the IMBH scenario are $q \sim 10^{-3}$ and $m^{1/3} \sim 10$–20. Therefore, the semimajor axis is at least 5, 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 $R_{\rm per} = (1-e)a$ and the tidal truncation radius $R_{\rm out} \approx 0.6(1-e)a$ (Warner 1995). For $R_{\rm out} = 10^{13}$ cm, the tidal radius condition requires an eccentricity $e \approx 0.89$ for $M_{\rm BH} = 1000 M_\odot$, and $e \approx 0.95$ for $M_{\rm BH} = 10^4 M_\odot$.

We can argue that the tidal truncation constraint is not relevant here, if mass transfer occurs impulsively only near periastron: the disc may be small because it does not have time to grow to its tidal truncation radius before being accreted. 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 $v_\phi\,(R_{\rm cir})\,R_{\rm cir} = X^2_{\rm L1}\Omega\,(R_{\rm per})$, where v_ϕ is the orbital velocity of the accretion stream around the BH, $X_{\rm L1}$ the distance between the BH and L_1, and $\Omega\,(R_{\rm per})$ the angular velocity of the donor star at periastron. We computed $X_{\rm L1}$ from Eq. (A13) of Sepinsky *et al.* (2007), valid for eccentric orbits, and found (Soria 2013) $X_{\rm L1} \sim 0.95 R_{\rm per}$ for the expected mass ratio and period. For $M_{\rm BH} = 5 \times 10^3 M_\odot$, a circularization radius $R_{\rm cir} = 10^{13}$ cm requires $e \approx 0.97$. This eccentricity is much more extreme than what was suggested in Lasota *et al.* (2011). It 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.

We also assessed whether the donor stars can avoid tidal disruption for such a small periastron distance. Comparing this distance to the tidal disruption radius (Rees 1988), we find that the star survives if $M_2 \gtrsim 4.6 \times 10^{-5} M_{\rm BH}$, easily satisfied in the likely mass range of HLX-1. The small periastron distance sets an upper limit to the radius of the donor star: $R_2 \lesssim$ a few $R_\odot$, ruling out supergiants, red giants and AGB stars. Possible donors are main sequence (B type or later) or subgiants.

There is at least one class of stellar objects where eccentricities $\gtrsim 0.95$ are common: S stars observed on highly eccentric orbits within 0.01 pc of the Galactic nuclear BH (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, hyper-velocity star, and a more tightly bound star on a very eccentric orbit.

4. Hα emission line

Galactic BHs in outburst usually show optical emission lines (*eg*, Hα, Hβ, HeII 4686) from the irradiated outer disk, often with a double-peaked profile. The peak separation or full-width-half-maximum (FWHM) provides an estimate of the projected velocity of the outer disk (where such lines are mostly emitted), and therefore constrains $R_{\rm out}$. We observed HLX-1 with VLT/FORS on 2012 Aug 27–28, and Sep 11, near outburst peak. We will present a full discussion of the results in a paper currently in preparation.

Our main preliminary result is that we found a strongly significant Hα emission line on all three nights, strengthening the findings of Wiersema *et al.* (2010). The central wavelength of the line (averaged over all 3 nights) is $\lambda \approx 6720.45$ Å, that is a velocity of 7205 km s^{-1}, redshifted by ≈ 490 km s^{-1} with respect to the central velocity of ESO243-49. For an S0 galaxy of similar size, we expect a maximum stellar rotational velocity ~ 250–350 km s^{-1}, from the Tully-Fisher relation (Blanton & Moustakas 2009). If HLX1 is the remnant of an accreted satellite dwarf (Mapelli *et al.* 2012), it must be moving on an eccentric orbit. The Hα line profile is remarkably narrow and single peaked, with a Gaussian FWHM ≈ 10.5 Å ≈ 480 km s^{-1}. The rotational velocity of a Keplerian orbit around the BH at $R = 10^{13}$ cm is $v_\phi \approx 1140\, m_3^{1/2}$ km s^{-1}; therefore, a disk line should have a FWHM $\approx (2300\, m_3^{1/2} \sin i)$ km s^{-1}. This suggests that either the disk is seen face on ($i \lesssim 10°$), or the line is not from a rotating thin disk but from an extended envelope.

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