On the origin of the HLX-1 outbursts

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ABSTRACT
HLX-1, currently the best intermediate-mass black hole candidate, has undergone seven violent outbursts, each with a peak X-ray luminosity of $L_{\text{peak},X} \sim 10^{42}$ erg s$^{-1}$. Interestingly, the properties of the HLX-1 outbursts evolve with time. In this work, we aim to constrain the physical parameters of the central engine of the HLX-1 outbursts in the framework of the black hole accretion. We find that the physical properties of the HLX-1 outbursts are consistent with being driven by the radiation pressure instability. This scenario can explain the evolution of the recurrent timescales of the HLX-1 outbursts as a function of the durations.

Key words: accretion, accretion disks – instabilities – X-rays: binaries

1 INTRODUCTION
HLX-1, a hyper-luminous X-ray source in galaxy ESO 243-49 ($z = 0.0224$), is currently the best intermediate-mass black hole (IMBH) candidate (Farrell et al. 2009; Davis et al. 2011; Servillat et al. 2011). Since its identification, HLX-1 has undergone seven recurrent violent X-ray outbursts, each with a peak X-ray luminosity of $L_{\text{peak},X} \sim 10^{42}$ erg s$^{-1}$. The recurrent timescale is roughly one year (Lasota et al. 2011; Godet et al. 2014). A detailed analysis by Yan et al. (2015) indicates that various properties of the HLX-1 outbursts evolve with time while $L_{\text{peak},X}$ is roughly a constant (see Table 1 for more details†).

The hydrogen ionization instability, which is believed to drive the outbursts in many Galactic black hole X-ray binaries (BHXRBs), is unlikely to trigger the outbursts of HLX-1. This is simply due to the fact that the hydrogen ionization instability is triggered only in the region of partial ionization of the hydrogen. The corresponding viscous timescale is $\sim 100$ years (Lasota et al. 2011) which is too long for HLX-1. In addition, Yan et al. (2015) systematically quantified the outburst properties of HLX-1, and compared their results with those of BHXRBs. They conclude that HLX-1 does not follow the correlations that are defined by BHXRBs (Yan & Yu 2015). These results indicate that, if the HLX-1 outbursts are driven by instabilities in the accretion disk, and the typical unstable radius is much smaller than that of the region of partial ionization of the hydrogen.

Several new mechanisms are proposed to explain the timescales. For instance, Lasota et al. (2011) attribute the one-year recurrent timescale as the orbital period of the donor star. That is, the outbursts are triggered as the donor star passes the periapse of a highly eccentric orbit and overfills the Roche lobe. However, as pointed out by Miller et al. (2014), this model may not be able to explain the fact that both $E_{\text{rad}}$ and $t_{\text{daw}}$ decrease with time (see Table 1). Miller et al. (2014) therefore favor the wind accretion instead of the Roche lobe overflow. The evolution in the properties of HLX-1 outbursts is ascribed to the variability of wind velocity. In a word, our understanding of the HLX-1 outbursts is far from clear.

In this work, we aim to recover the physical properties of the central engine that drives the HLX-1 outbursts. Our methodology is introduced in Section 2. In Section 3, we apply our model to HLX-1. We found that the HLX-1 outbursts are consistent with being driven by the radiation pressure instability. Discussions are made in Section 4.

2 OUR MODEL
As pointed out by previous work (e.g., Davis et al. 2011), the central engine of HLX-1 is most likely to be an IMBH surrounded by a cool and thin accretion disk. In this

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† As $t_{\text{sec}}$ is properly measured only for the last five outbursts, we will focus on these outbursts in this work.
work, we adopted the standard Shakura-Sunyaev model (Shakura & Sunyaev 1973) to describe the structure of the accretion disk. In this model, the viscosity stress scales as the total pressure (i.e., $\propto \alpha \rho c^2$, where $\alpha$ is the dimensionless viscous parameter). As a first order of approximation, we relate the properties of each outburst with a steady time-independent disk model.

The dimensionless accretion rate of an outburst ($\dot{m}_{\text{bar}}$, i.e., the ratio of the absolute accretion rate to the Eddington accretion rate, $M_{\text{Edd}} = 1.4 \times 10^{18} M_{\odot} \, \text{g s}^{-1}$) can be roughly estimated as

$$\dot{m}_{\text{bar}} = \frac{k E_{\text{rad}}}{t_{\text{dur}} \eta c^2 M_{\text{Edd}}}$$  

where $E_{\text{rad}}$, $\eta$, $k$ and $c$ are the total radiated energy in 0.3–10 keV per each outburst (i.e., the integration of the X-ray luminosity over $t_{\text{dur}}$), the radiative efficiency, the bolometric correction factor, and the speed of light, respectively.

We then calculated the radial structure of the Shakura-Sunyaev disk for each $\dot{m}_{\text{bar}}$ (estimated from Eq. 1) and obtained the corresponding radial velocity $v_{R,\text{bar}}$ as a function of radius. The viscous timescale at a typical radius $R_c$ is simply $R_c / v_{R,\text{bar}}$. This viscous timescale controls the duration of each outburst, i.e.,

$$t_{\text{dur}} \equiv R_c / v_{R,\text{bar}}$$

In principle, we can estimate $R_c$ from $t_{\text{dur}}$.

During the quiescent state (i.e., the state between the current outburst and the previous one), the gas supplying rate to the central IMBH (again in units of $M_{\text{Edd}}$) can be estimated as follows,

$$(1 - f) \dot{m}_{\text{fill}} t_{\text{dur}} = \dot{m}_{\text{bar}} t_{\text{dur}}$$

where $f$ parameterize the fraction of gas lost in e.g., outflows during each outburst. The radial structure of the accretion disk (i.e., temperature, density, pressure, the radiation-to-gas pressure ratio, the radial velocity, and other physical properties as a function of radius) during this state was also calculated for each $\dot{m}_{\text{fill}}$.

3 APPLYING OUR MODEL TO HLX-1

We now estimate $R_c$ for each HLX-1 outburst. To convert the X-ray luminosity and energy to the bolometric ones, we assume a bolometric correction factor of $k = 2$. We adopt $\eta = 0.1$. The mass of the IMBH in HLX-1 is assumed to be $M_{\text{BH}} = 3 \times 10^6 M_{\odot}$ (i.e., the “average” value in Davis et al. 2011). For the viscosity, we consider two cases: $\alpha = 0.01$ and $\alpha = 0.1$. For the parameter $f$ (see Section 2), we present the results for $f = 0$ (i.e., no outflows) and $f = 0.5$ (i.e., the outflow rate equals $\dot{m}_{\text{bar}}$). For the purpose of exploring the impact of the assumed $M_{\text{BH}}$ on our results, we also considered $M_{\text{BH}} = 10^4 M_{\odot}$ for the case $\alpha = 0.1$ and $f = 0$.

For each HLX-1 outburst, we estimated $R_c$ via Eqs. 1 and 2. Let us take $\alpha = 0.1$ and $f = 0$ as an example, the expected $R_c$ for the five HLX-1 outbursts are 69.8 $R_s$, 67.7 $R_s$, 61.9 $R_s$, 59.9 $R_s$ and 57.6 $R_s$, where $R_s$ is the Schwarzschild radius. We then calculated the radiation-to-gas pressure ratio at $R_c$ during each quiescent state. We found that this ratio is generally greater than 1. We therefore speculate that the HLX-1 outbursts are triggered within the radiation-pressure-dominated accretion disk. If so, it would be very interesting to connect $t_{\text{rec}}$ with the viscous timescale at $R_c$ in the quiescent state, $t_{\text{vis,fill}}$. The corresponding viscous timescale can be estimated as $t_{\text{vis,fill}} = R_c / v_{R,\text{fill}}$, where $v_{R,\text{fill}}$ is the radial velocity of the accretion disk during the quiescent state, and the corresponding accretion rate is calculated from Eq. 3.

In Figure 1, we plot the observed time evolution of $t_{\text{rec}}$. For comparison, we also show the expected $t_{\text{vis,fill}}$. It is clear that, for a wide range of $\alpha$, $t_{\text{rec}}$ is roughly consistent with the expected viscous timescale of the radiation-pressure-dominated region. It is also important to note that $t_{\text{vis,fill}}$ decreases with increasing $t_{\text{dur}}$ in a way similar to that

3 The X-ray spectral analyses of Yan et al. (2015) indicate that, during the luminous state, the ratio of the integrated luminosity of the disk black body component to $L_{\text{peak, X}}$ is $\sim 2$ (the exact value depends on the inclination angle). Therefore, we adopted $k = 2$. We also performed our calculation for $k = 5$. Very similar conclusions were obtained.

\begin{table}
\centering
\caption{Properties of the HLX-1 outbursts$^a$}
\begin{tabular}{|c|c|c|c|c|}
\hline
Year of outburst & $L_{\text{peak, X}} (10^{24} \text{ erg s}^{-1})$ & $t_{\text{dur}}$ (days) & $t_{\text{rec}}$ (days) & $E_{\text{rad}}$ (10^{46} \text{ erg}) \\
\hline
2011 & 1.3$\pm$0.2 & 128 & 320 & 6.6$\pm$0.4 \\
2012 & 1.4$\pm$0.4 & 110 & 334 & 5.9$\pm$0.2 \\
2013 & 1.2$\pm$0.2 & 96 & 360 & 4.8$\pm$0.2 \\
2014 & 1.0$\pm$0.1 & 84 & 392 & 4.3$\pm$0.1 \\
2015 & 1.4$\pm$0.8 & 69 & 455 & 3.7$\pm$0.1 \\
\hline
\end{tabular}
\end{table}
of $t_{\text{sec}}$. This is due to the fact that $\dot{m}_{\text{fill}}$ and therefore the radial velocity decrease with time.

Based on our results, we argue that the origin of the HLX-1 outbursts can be pictured as follows (see also Figure 2). The gas supplying rate to fill the empty region with a typical radius of $R_e$ is relatively high, and this viscous filling timescale controls the quiescent timescale between two adjacent outbursts. As the filling gas approaches close enough to the central IMBH, there would be no stable standard thin disk solution as this part is radiation-dominated instead of gas pressure dominated (e.g., Shakura & Sunyaev 1973; Lightman & Eardley 1974; Czerny et al. 2009). Small temperature perturbations can result in a catastrophic growth of $\dot{m}_{\text{out}}$ (i.e., $\dot{m}_{\text{fill}}$) in this radiation-pressure-dominated region. Therefore, a dramatic increase of $L_\lambda$ is observed. As the gas fuel in this region is consumed, the central IMBH accretion switch off, and leaves a new nearly empty region around. This full cycle determines the properties of each HLX-1 outburst.

4 DISCUSSION

We argued that the HLX-1 outbursts are driven by the radiation pressure instability in the accretion disk. Such a possibility is also briefly mentioned by Lasota et al. (2011) although they do not perform a detailed analysis. This could be partially due to the fact that the radiation pressure instability itself is under debate.

Indeed, although the radiation pressure instability is analytically well expected for $L \sim 0.06 L_{\text{Edd}}$ (e.g., Shakura & Sunyaev 1973; Lightman & Eardley 1974; Li et al. 2007; Czerny et al. 2009; Xue et al. 2011; Zheng et al. 2011), its observational evidence is surprisingly lacking as most BHXRBs remain stable for $L \sim 0.5 L_{\text{Edd}}$ (Gierliński & Done 2004). This discrepancy has been speculated due to the over-simplified description of the viscosity law (e.g., Nayakshin et al. 2000; Lin et al. 2011; Zheng et al. 2011). Some early magnetohydrodynamic shearing box numerical simulations (e.g., Hirose et al. 2009), which intend to model the viscosity self-consistently also find that radiation-dominated disks are thermally stable. However, recent new magnetohydrodynamic simulations with increased shearing box and more accurate radiation transfer algorithm suggest that the thermal runaway behavior actually exists (e.g., Jiang et al. 2013).

Although most BHXRBs are stable against the radiation pressure instability, there is a notable exception, i.e., GRS 1915+105. The “heartbeat” like variability in GRS 1915+105 is likely driven by the radiation pressure instability (e.g., Belloni et al. 1997). Recently, similar “heartbeat” light curve is also discovered in IGR J17091-3624. This similarity indicates that IGR J17091-3624 could plausibly be a second BHXB that suffering the radiation pressure instability (Altamirano et al. 2011).

In our opinion, HLX-1 could be a third one but with an IMBH. 4 As the critical accretion rate to trigger the radiation pressure instability $\propto M_{\text{BH}}^{-1/8}$ (e.g., Section 3.2.3 of Kato et al. 2008), such instability might be more easily observed for IMBHs. Note that the recurrent timescales are not expected to scale linearly with $M_{\text{BH}}$. The physical reason are as follows. First, the radial velocity around $R_e$ is inversely proportional to $M_{\text{BH}}$. Second, the outer boundary of the radiation pressure region (in units of $R_\oplus$) scales positively with $M_{\text{BH}}$ (see Section 3.2.3 of Kato et al. 2008). Indeed, $R_e/R_\oplus$ we obtained for HLX-1 each outburst is larger than that of GRS 1915+105 (Belloni et al. 1997) by roughly one order of magnitude. Therefore, even the IMBH in HLX-1 is only $\sim 3000$ times larger than the BH in GRS 1915+105, the recurrent timescales of the HLX-1 outbursts could be $10^5$ times longer than those of the GRS 1915+105 outbursts.

On even larger scale, the radiation pressure instability might also play a role in some active galactic nuclei (AGNs), e.g., some young compact radio sources (Czerny et al. 2009; Wu 2009). It would be interesting to reveal any possible scaling relations among these systems (Wu et al. 2016).

5 SUMMARY

In this work, we adopted the standard Shakura-Sunyaev model to constrain the physical properties of the central engine of HLX-1. We determined the typical size of the disk ($R_e$) during the outbursts. We found that, even in the quiescent state, the radiation-to-gas pressure ratio at $R_e$ is usually greater than 1. We therefore proposed that the HLX-1 outbursts are driven by the radiation pressure instability. This scenario can explain the evolution of the recurrent timescales of the HLX-1 outbursts as a function of the durations.

ACKNOWLEDGEMENTS

We thank Wenfei Yu for helpful discussions. This work was supported by the National Basic Research Program of China (973 Program) under grants 2014CB845800 and 2015CB857004, the National Natural Science Foundation
of China under grants 11573023, 11573009, 11473022, 11403074, 11333004, 11223328, 11133005, and U1331101, the Knowledge Innovation Program of the Chinese Academy of Sciences, the CAS Open Research Program of Key Laboratory for the Structure and Evolution of Celestial Objects under grant OP201503, and the Fundamental Research Funds for the Central Universities under grants 20720140532 and 20720160024.

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