Recurrent Outbursts Revealed in 3XMM J031820.8-663034

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\section*{Abstract}

3XMM J031820.8-663034, first detected by \textit{ROSAT} in NGC 1313, is one of a few known transient ultraluminous X-ray sources (ULXs). In this paper, we present decades of X-ray data of this source from \textit{ROSAT}, XMM-\textit{Newton}, \textit{Chandra}, and the Neil Gehrels Swift Observatory. We find that its X-ray emission experienced four outbursts since 1992, with a typical recurrent time $\sim$1800 days, an outburst duration $\sim$240–300 days, and a nearly constant peak X-ray luminosity $\sim 1.5 \times 10^{39}$ erg s$^{-1}$. The upper limit of X-ray luminosity at the quiescent state is $\sim 5.6 \times 10^{36}$ erg s$^{-1}$, and the total energy radiated during one outburst is $\sim 10^{46}$ erg. The spectra at the high luminosity state can be described with an absorbed disk blackbody, and the disk temperature increases with the X-ray luminosity. We compare its outburst properties with other known transient ULXs including ESO 243-49 HLX-1. As its peak luminosity only marginally puts it in the category of ULXs, we also compare it with normal transient black hole binaries. Our results suggest that the source is powered by an accreting massive stellar-mass black hole, and the outbursts are triggered by the thermal-viscous instability.

\textbf{Key words:} accretion, accretion disks – black hole physics – X-rays: binaries – X-rays: individual (3XMM J031820.8-663034) – X-rays: stars

\section*{1. Introduction}

Galactic low-mass X-ray binaries (LMXBs) spend most of their time in quiescence and enter into outbursts only occasionally, with X-ray luminosity increased by several orders of magnitude (e.g., Chen et al. 1997; Corral-Santana et al. 2016). Black hole LMXBs manifest themselves into five well-known spectral states (see Fender et al. 2004; McClintock & Remillard 2006; Zhang 2013; Yuan & Narayan 2014, for reviews). As luminosity increases, sources leave the “off” state (i.e., the quiescent state, $L_x < 10^{34}$ erg s$^{-1}$), and enter the low-hard state and the high/soft state. The X-ray spectra at the low-hard and the quiescent states are dominated by a power-law component. In contrast, the high/soft state is dominated by thermal emission from the accretion disk with much weaker variabilities. Meanwhile, the very high state and the intermediate state, representing transitions between the low-hard state and the high/soft state (e.g., McClintock & Remillard 2006), have more complex spectral and temporal behaviors. Additionally, a few rare LMXBs could show episodes of super-Eddington accretion, e.g., V4641 Sgr (Revnivtsev et al. 2002) and V404 Cyg (e.g., Motta et al. 2017). The behaviors become sophisticated in these outbursts, and the knowledge on them is rather rudimentary.

It is widely accepted that outbursts of LMXBs result from thermal-viscous instability in accretion disks (e.g., Chen et al. 1997; Dubus et al. 2001). When the mass transfer rate from the donor star onto the compact object is less than a critical value, the inner region of the accretion disk is hot while the temperature of the outer disk drops below 6000 K—somewhere in between, the disk should hence be unstable. This is because the accretion material in this region is partially ionized, and the hydrogen recombination results in a large change in opacity. Consequently, this region could be out of thermal-viscous equilibrium, and the instability would propagate in the disk, triggering an outburst. It has been noticed that such a standard disk instability model (DIM) fails to explain some of the observed properties of the outbursts (e.g., the typical “fast-rise exponential-decay” light curves), and additional irradiation and truncation disk effects should be taken into account (see Lasota 2001, for reviews).

Compared to LMXBs, ultraluminous X-ray sources (ULXs) found in nearby galaxies are more powerful ($L_x > 10^{39}$ erg s$^{-1}$) and more stable in X-ray luminosities (see Feng & Soria 2011; Kaaert et al. 2017, for reviews). In general, the X-ray luminosities of ULXs vary by a factor of $\lesssim 10$. For instance, M33 X-8 exhibits an X-ray variation amplitude of $< 50\%$ since its discovery in 1981 (Weng et al. 2009; La Parola et al. 2015). As their temporal and spectral properties are quite different from those observed in LMXBs, most ULXs are suggested to be massive stellar-mass black holes (MsBHs; $M_{BH} \sim 20–100 M_\odot$) with super-Eddington accretion (Feng & Soria 2011; Weng et al. 2014). In such an system, the mass transfer rate is large enough to keep the whole disk fully ionized (with the aid of powerful irradiation), and therefore, the accretion proceeds stably.

However, a number of ULXs show more dramatic luminosity variations, manifesting themselves as transients (e.g., Zezas et al. 2006; Grimm et al. 2007; Crivellari et al. 2009). These sources may provide a bridge between LMXBs and luminosity ULXs. Due to the lack of observations, only a few transient ULXs have been studied in detail (e.g., Kaur et al. 2012; Middleton et al. 2012). It is yet unclear whether the outbursts in transient ULXs are driven by the DIM. 3XMM J031820.8-663034 (R.A. = 03:18:20.8, decl. = $-66:30:35$) is 0'8 away from the center of NGC 1313. It was first detected by \textit{ROSAT} with a maximum X-ray luminosity of $L_x \sim 1.2 \times 10^{39}$ erg s$^{-1}$ (Liu & Bregman 2005) by assuming a distance of $d = 4.61$ Mpc (Gao et al. 2015). Investigating a set of XMM-\textit{Newton} data, Lin et al. (2014) found that the source was only detected in 2 out of 14
observations, revealing the transient nature of this source. Because there are two persistent ULXs (i.e., NGC 1313 X-1 and NGC 1313 X-2; Petre et al. 1994; Makishima et al. 2000; Bachetti et al. 2013; Weng et al. 2014; Pinto et al. 2016; Kosec et al. 2018), and one bright supernova (SN 1978K: Ryder et al. 1993; Zhao et al. 2017) in this region, numerous X-ray observations have been devoted to explore the spectral evolution of these sources. In this paper, we analyze all available X-ray data of 3XMM J031820.8-663034, collected by ROSAT, Chandra, XMM-Newton, and the Neil Gehrels Swift Observatory, and report its recurrent activities. The data reduction and results are described in Section 2. Because its peak luminosity marginally puts it in the category of ULXs, we compare in Section 3 its outburst properties with those of both known transient ULXs and normal LMXBs. We also discuss the origin of the outbursts and determine the black hole mass in 3XMM J031820.8-663034 according to the spectral investigation (Section 3).

2. Data Reduction and Results

2.1. XMM-Newton Data

A total of 21 XMM-Newton observations covering 3XMM J031820.8-663034 were made from 2000 October and 2016 March (Table 1). We reduce all data collected from the EPIC camera (Strüder et al. 2001; Turner et al. 2001) using the Science Analysis System software (SAS) version 14.0.0, and the intervals contaminated by flaring particle background are discarded. Other than the detections during two observations reported in Lin et al. (2014), the source also turned up on MJD 5684. For the first two observations, only the EPIC-pn data are analyzed because the source fell in CCD gaps of MOS1/MOS2. For the same reason, we only use MOS1/ MOS2 data for the observation on MJD 56844. Circular regions with radii of 15″ and 30″ are adopted for the source and background (nearby source free region), respectively. The spectral response files are generated by the SAS tasks rmfgen and arfgen, and the spectra are grouped to have at least 15 counts per bin with the task specgroup to enable the use of chi-square statistics.

Both an absorbed steep power law ($\Gamma \sim 2.2$–2.5) and a disk blackbody ($tbabs+diskbb$ in XSPEC, Arnaud 1996) provide adequate fits to the first two observations (Figure 1 and Table 2). The derived parameters are consistent with those reported by (Lin et al. 2014, Table 3 in their paper). The spectrum obtained on MJD 56844, however, is poorly fitted by an absorbed power law ($\chi^2$/dof $\sim 1.68$, Table 2 and Figure 1), corresponding to a null hypothesis probability of $1.2 \times 10^{-6}$. Contrarily, the data can be well described by a disk blackbody ($\chi^2$/dof $\sim 1.10$), and an additional power-law component is statistically not required ($<99\%$ according to F-test). As shown in Figure 2, the disk temperature ($kT$) increases with the unabsorbed X-ray luminosity in 0.5–10 keV. We fit the $L_X$–$kT$ relation with a power-law function and take the error of $kT$ into account. The best fitted power-law index $n = 2.9 \pm 1.3$ is roughly consistent with $L_X \propto kT^n$ (as predicted by the standard disk model with a constant inner radius, i.e., the innermost stable circular orbit).

3XMM J031820.8-663034 was not detected in the other 18 XMM-Newton observations, and 2$\sigma$ upper limits to the source count rates are estimated with the SAS task eregionanalyse (Table 1).

2.2. Swift Observations

In this work, we analyze all 371 Swift (Gehrels et al. 2004) observations made before 2017 July. Two episodic outbursts of 3XMM J031820.8-663034 have been caught by the Swift dense observations, and Swift monitored the second entire outburst (Figure 3). The exposure time of individual Swift observations ranges from 138 s to 7.75 ks, with a mean value of 1.3 ks. We extract the source counts in 0.3–10 keV band from a circle aperture with a radius of 6 pixels centered at the source position and the background from nearby source free regions. The telescope vignetting and point-spread function corrections are applied by running the Swift script xrtlcicorr.

Due to the limited photons in individual pointings, we stack all observations during each of the two outbursts. As only 137 photon counts were collected during the outburst in MID 55050–55200, we rebin the spectrum to have at least five counts per bin and employ the C-statistic (Cash 1979) in spectral fitting. During the second outburst, a total of 396 counts were detected. We group the spectrum to have at least 15 counts per bin and the common $\chi^2$ statistic is applied. The spectral modeling confirms that the X-ray spectra during the outbursts are very soft and can be fitted by either an absorbed steep power law ($\Gamma \sim 2$–2.4) or a disk blackbody (Table 2). During other Swift observations, 3XMM J031820.8-663034 remains undetected. We estimate an upper limit of count rate $\sim 2.6 \times 10^{-4}$ cts s$^{-1}$ (or an upper limit of $L_X \sim 2.8 \times 10^{37}$ erg s$^{-1}$) by summing all observations in the off state (with total exposure of $\sim 365$ ks from 285 snapshots).

As shown explicitly in Figure 3, 3MM J031820.8-663034 has almost the same peak luminosity during two outbursts. Coincidentally, when the source reached the peak of the second outburst, the XMM-Newton observation recorded an X-ray luminosity of $L_X \sim 1.5 \times 10^{39}$ erg s$^{-1}$ (Section 1). Using the XMM-Newton spectral fitting model, we convert count rates (and upper limits) from different instruments into those expected from Swift/XRT and plot them in Figures 3 and 4 for comparison.

2.3. ROSAT and Chandra Archival Data

We employ the XIMAGE software to measure the count rate in all nine ROSAT/HRI and two ROSAT/PSPC images (Truemper 1982; Pfeffermann et al. 1987). 3XMM J031820.8-663034 was detected in two images ($>2\sigma$), and a maximum count rate ($5.63 \times 10^{-3}$ cts s$^{-1}$) was obtained on MJD 49527 (see Table 1). Assuming a power law with photon index of 1.7, we run the tool WebPIMMS and estimate an unabsorbed luminosity of $\sim 1.3 \times 10^{39}$ erg s$^{-1}$ (0.5–10 keV), which is consistent with the value reported in Liu & Bregman (2005).

From 2002 September to 2012 December, Chandra (Weisskopf et al. 2000) visited the source region nine times. However, the 3XMM J031820.8-663034 was in quiescence state and was not detected in any observation. We estimate the flux upper limit with the tasks srcflux/aprates in the CIAO software (version 4.6.7). The deepest observation

5 https://heasarc.gsfc.nasa.gov/cgi-bin/Tools/w3pimms/w3pimms.pl
6 http://cxc.harvard.edu/ciao/threads/upperlimit/
7 http://asc.harvard.edu/ciao/
Table 1
X-Ray Observations Log

| Instrument     | ObsID       | Date      | MJD      | Energy (keV) | Net Exposure (ks) | Count Rate (cts s⁻¹) | Flux (erg cm⁻² s⁻¹) |
|----------------|-------------|-----------|----------|--------------|-------------------|----------------------|---------------------|
| XMM-Newton/pxM | 0106860101  | 2000 Oct 17 | 51834    | 0.5–10       | 22.3              | <3.0 × 10⁻³          | <1.0 × 10⁻¹4        |
| XMM-Newton/pxT | 0150280101  | 2003 Nov 25 | 52968    | 0.5–10       | 1.2               | <1.1 × 10⁻²          | <3.8 × 10⁻¹4        |
| XMM-Newton/pxT | 0150280301  | 2003 Dec 21 | 52994    | 0.5–10       | 8.6               | <4.1 × 10⁻³          | <1.4 × 10⁻¹4        |
| XMM-Newton/pxT | 0150284001  | 2003 Dec 23 | 52996    | 0.5–10       | 4.1               | <3.8 × 10⁻³          | <1.3 × 10⁻¹4        |
| XMM-Newton/pxT | 0150285001  | 2003 Dec 25 | 52998    | 0.5–10       | 6.0               | <8.5 × 10⁻³          | <2.9 × 10⁻¹4        |
| XMM-Newton/pxT | 0150280601  | 2004 Jan 08 | 53012    | 0.5–10       | 10.2              | <4.1 × 10⁻³          | <1.4 × 10⁻¹4        |
| XMM-Newton/pxT | 0150281101  | 2004 Jan 16 | 53020    | 0.5–10       | 5.9               | <6.1 × 10⁻³          | <2.1 × 10⁻¹4        |
| XMM-Newton/pxT | 0205230201  | 2004 May 01 | 53126    | 0.5–10       | 0.7               | <1.0 × 10⁻²          | <3.5 × 10⁻¹4        |
| XMM-Newton/pxT | 0205230301  | 2004 Jun 05 | 53161    | 0.5–10       | 10.0              | <6.7 × 10⁻³          | <2.2 × 10⁻¹4        |
| XMM-Newton/pxT | 0205230401  | 2004 Aug 23 | 53240    | 0.5–10       | 10.1              | <4.4 × 10⁻³          | <1.4 × 10⁻¹4        |
| XMM-Newton/pxT | 0205230501  | 2004 Nov 23 | 53322    | 0.5–10       | 12.5              | (2.2 ± 0.1) × 10⁻²  | (2.0 ± 0.1) × 10⁻¹³ |
| XMM-Newton/pxT | 0205230601  | 2005 Feb 07 | 53408    | 0.5–10       | 9.8               | (6.2 ± 0.2) × 10⁻²  | (2.5 ± 0.1) × 10⁻¹³ |
| XMM-Newton/pxM | 0301860101  | 2006 Mar 06 | 53800    | 0.5–10       | 19.9              | <8.5 × 10⁻³          | <2.9 × 10⁻¹4        |
| XMM-Newton/pxM | 0405090101  | 2006 Oct 15 | 54023    | 0.5–10       | 98.8              | <4.3 × 10⁻³          | <1.5 × 10⁻¹4        |
| XMM-Newton/pxM | 0693850501  | 2012 Dec 16 | 56277    | 0.5–10       | 110.7             | <6.3 × 10⁻³          | <2.1 × 10⁻¹4        |
| XMM-Newton/pxM | 0693851201  | 2012 Dec 22 | 56283    | 0.5–10       | 114.8             | <6.2 × 10⁻³          | <2.1 × 10⁻¹4        |
| XMM-Newton/pxM | 0722650101  | 2013 Jan 08 | 56451    | 0.5–10       | 22.3              | <5.3 × 10⁻³          | <1.8 × 10⁻¹4        |
| XMM-Newton/MOSM | 0742590301  | 2014 Jul 05 | 56844    | 0.5–10       | 61.0/60.1         | (4.7 ± 0.1) × 10⁻²  | (5.9 ± 0.2) × 10⁻¹³ |
| XMM-Newton/pxM | 0742490101  | 2015 Mar 30 | 57111    | 0.5–10       | 94.8              | <4.2 × 10⁻³          | <1.4 × 10⁻¹4        |
| XMM-Newton/pxM | 0764770101  | 2015 Dec 05 | 57361    | 0.5–10       | 65.3              | <3.2 × 10⁻³          | <1.1 × 10⁻¹4        |
| XMM-Newton/pxM | 0764770401  | 2016 Mar 23 | 57470    | 0.5–10       | 21.9              | <3.4 × 10⁻³          | <1.2 × 10⁻¹4        |

| Swift/XRT | … | Quiescence | … | 0.3–10 | 365 | <2.6 × 10⁻⁴ | <1.1 × 10⁻¹⁴ |

**Note.** Energy: energy band used to estimate the photon counts from each instrument. pxM: medium filter was used. pxT: thin filter was used. Quiescence: the summed image in 0.3–10 keV is generated for all Swift/XRT in the quiescence state (see the text). Count rate: the 95.45% confidence upper limit in the corresponding energy band is given when the source is undetected. Flux: the unabsorbed flux (or its 2σ upper limit) in 0.5–10 keV is estimated by assuming a power-law model ($\nu F(\nu) \propto \nu^\Gamma$).

(0bsID = 2950) yields the strongest upper limit to its X-ray luminosity ($\sim 5.6 \times 10^{36}$ erg s⁻¹), which is more than two orders of magnitude fainter than its maximum luminosity during the outbursts.

### 2.4. Outburst Parameters

*Swift* monitored the entire outburst from MJD ~56800 to 57100, suggesting a fast-rise slow-decay light-curve profile, an outburst duration of ~240–300 days, and a total energy radiated during the outburst of ~$10^{46}$ erg s⁻¹. However, we are unable to determine the light-curve profile precisely, including the rise and decay timescales owing to the large uncertainties of *Swift* data. The maximum fluxes recorded in *ROSAT*, *Swift*, and *XMM-Newton* data indicate that the peak luminosity remains constant ($\sim 1.5 \times 10^{38}$ erg s⁻¹) during different outbursts. The strongest upper limit for the quiescence state comes from the deepest *Chandra* pointing, indicating a variation amplitude of >270.

We plot X-ray count rates (and upper limits) from all observations in Figure 4. All count rates from instruments other
than Swift/XRT are converted into (with WebPIMMS) XRT count rates for comparison. For three XMM detections, the best-fit spectral models were adopted for the conversion. For ROSAT observations and all other upper limits, as accurate spectral modeling is unavailable, we assume a typical low/hard state spectrum for conversion, i.e., a hard power-law model \((nH = 6 \times 10^{20} \text{ cm}^{-2} \text{ and } \Gamma = 1.7)\).

It seems that the source enters into outburst regularly with a recurrent time of \(\sim 1800\) days. We calculate the Lomb–Scargle periodogram (Horne & Baliunas 1986) in a timescale range from 10 days to 5000 days with 50000 independent frequencies. As the source was nondetected during most observations, omitting these nondetections would yield too sparse a sampling, and no periodical signal emerges in the periodogram. Here, we take all data into account, and 2\(\sigma\) upper limits to the count rates are adopted for those nondetections. As can be seen in Figure 5, the signal at \(\sim 1750\) days and its second/third harmonic frequencies (\(P \sim 815/580\) days) are higher than 99.9% white noise confidence level. Because the structured window function might lead to aliasing of signals in the data (e.g., VanderPlas 2017), we examine the window power spectrum and do not find any significant feature. We further model the periodogram in the range of 1500–2000 days with a Gaussian, yielding a best-fit period of 1744 days with a FWHM of \(\sim 418\) days. The recurrent time of \(\sim 1800\) days is also verified with the folded light curve (Figure 6). However, we would like to caution that the periodic signal can not be robustly confirmed for the following reasons: (1) The source was not detected in many observations, and upper limits used in the test may introduce large uncertainty. (2) The confidence level of signals would be lower than the 99.9% with different assumptions of the noise (e.g., red noise). Future monitoring data are required to check the recurrence period.

![Figure 1. Upper panel: XMM-Newton MOS1 (black) and MOS2 (red) spectra observed on 2014 July 5–6 (ObsID = 074290301), and the best-fit absorbed diskbb model. Middle and lower panels: the fitting residuals to an absorbed power-law model and an absorbed diskbb model, respectively. The XMM pn spectra observed on MJD 53332 and 53408 are also plotted in the upper panel (gray and light-blue) for comparison.](image)

3. Discussion and Conclusions

In this work, we investigate the wealth of X-ray data collected on 3XMM J031820.8-663034 and reveal four periods of activity, making it a transient ULX. The outburst properties are summarized as follows: (1) The outbursts likely occur regularly; (2) One outburst with sufficiently dense sampling exhibits a fast-rise slow-decay profile; (3) The peak X-ray luminosity \(L_{\text{peak}} \sim 1.5 \times 10^{39} \text{ erg s}^{-1}\) does not change much among different outbursts; (4) The source occupies the thermal state at the high luminosity; and (5) The deepest Chandra observation provides a luminosity upper limit of \(\sim 5.6 \times 10^{36} \text{ erg s}^{-1}\) for the quiescent state.

The evolving soft X-ray spectra from 3XMM J031820.8-663034 imply its accretion nature and the accreting object could be a black hole. High-mass X-ray binaries commonly consist of a neutron star and a young massive star, and they have very hard X-ray spectra (e.g., Fabbiano 2006; Walter et al. 2015; Wang et al. 2016a). Thereby, the scenario of a canonical high-mass X-ray binary is disfavored for 3XMM J031820.8-663034. Because its peak luminosity marginally puts the source in the category of ULXs, below we compare its outburst properties with normal transient black hole binaries and other known transient ULXs, including the intermediate-mass black hole candidate ESO 243-49 HLX-1.

3.1. Association with NGC 1313

Before discussing the nature of outbursts, we need to determine whether 3XMM J031820.8-663034 is associated with NGC 1313 or a foreground/background object. The high Galactic latitude \((l = 283^\circ3634 \text{ and } b = -44^\circ6295)\) indicates that the source is unlikely a foreground star. Moreover, if the source is at a distance of less than 10 kpc, its peak X-ray luminosity during the outbursts would be less than \(10^{34} \text{ erg s}^{-1}\). The X-ray spectrum of such a very faint X-ray transient should be dominated by a nonthermal component (e.g., McClintock & Remillard 2006; Weng & Zhang 2015; Wijnands et al. 2015), contradicting the XMM-Newton and Swift observations, which are in favor of the thermal dominated spectra. We can therefore exclude the possibility of a Galactic counterpart.

Alternatively, we estimate the probability of a background QSO/AGN using X-ray log \(N–\log S\) (e.g., Wang et al. 2016b). According to the new XMM-Newton detection, the source has an absorbed flux in 0.5–2\(\text{keV}\) of \(2.3 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}\). We would expect \(\sim 0.5\) contaminating source per square degree with the same or higher flux based on the Lockman Hole log \(N–\log S\) relation (Hasinger et al. 1998; Mushotzky et al. 2000; Moretti et al. 2003; Wang et al. 2016b). Meanwhile, the \(D_{25}\) isophote of NGC 1313 is about \(\sim 9^\prime 1\) (Liu & Bregman 2005), and the distance between 3XMM J031820.8-663034 and the center of NGC 1313 is \(\sim 0^\prime 9\). Therefore, the number of expected background sources within the D25 of NGC 1313 (or in \(0^\prime 8\)) is only \(\sim 0.01\) (or \(9 \times 10^{-5}\)). Furthermore, the chance that a background source has similar dramatic variations is even lower. We thus conclude the association of 3XMM J031820.8-663034 with NGC 1313 is convincing.

3.2. Repeated Outbursts

A straightforward explanation for the regular outbursts is that the mass transfer rate is significantly enhanced during the periastron passage of the donor star bounded to the black hole.

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in an eccentric orbit. However, the formation of a black hole binary with such long period (~1800 days) could be challenging. To our knowledge, GRS 1915+105 has the longest orbital period (~33.5 days, Greiner et al. 2001) among LMXBs (Liu et al. 2007). Meanwhile, very few high-mass X-ray binaries have periods longer than 10^3 days (Liu et al. 2006; Reig 2011), e.g., PSR B1259-63 (~3.4 years, Johnston et al. 1994) and PSR J0332+4127 (~25–50 years, Lyne et al. 2015; Ho et al. 2017), both of which are faint in X-ray (L_X < 10^{38} erg s^{-1}). On the other hand, during the early observations, HLX-1 displayed regular outbursts at an interval of ~1 year (Farrell et al. 2009b; Webb et al. 2012). However, the initial hypothesis that the recurrence time corresponded to the binary period became controversial due to the increase of the detected recurrence time (Godet et al. 2014; Weng & Feng 2018).

In addition, super-orbital periods have been reported in tens of X-ray binaries (Sood et al. 2007; Farrell et al. 2009a), and some of them could be more than 10^3 days (e.g., ~1667 days for LS I +61° 303, Li et al. 2012), similar to the recurrent time of 3XMM J031820.8-663034. However, the amplitude of super-orbital modulation (e.g., Smith et al. 2002; Corbet & Krimm 2013) is significantly smaller than that of 3XMM J031820.8-663034 (>270). Thus, whether the outbursts of 3XMM J031820.8-663034 are some kind of super-orbital modulation is still questionable.

Note that a small number of LMXBs, e.g., 4U 1630-47 (Parmar et al. 1995; Capitanio et al. 2015) and H1743-322 (Yan et al. 2015), exhibited some successive (not all) outbursts equally spaced in time. The light-curve profiles of these outbursts could be complicated but are not always the typical “fast-rise-exponential-decay”. It was suggested that the periodicity resulted from the DIM or sometimes with additional perturbation from the companion star mass transfer (Capitanio et al. 2015). Here, as only four outbursts are recorded for 3XMM J031820.8-663034 and the observation cadence is incomplete, we suggest that additional monitoring data are required to check whether the quasi-periodic behaviors are temporary or if they represent some process in physics. As further discussed below, all available data at the current stage can be interpreted with the DIM.

### 3.3. Outburst Mechanism

There are two transient ULXs detected in M31, i.e., CXOM31 J004253.1+411422 (Kaur et al. 2012; Middleton et al. 2012) and XMMU J004243.61+412519 (Middleton et al. 2013). Middleton et al. (2012) found the X-ray luminosity of CXOM31 J004253.1+411422 steadily declined from 5 × 10^{39} erg s^{-1} to 6 × 10^{38} erg s^{-1} over 1.5 month (see also Kaur et al. 2012). XMMU J004243.61+412519 entered an outburst in 2012 January, reached a peak X-ray luminosity of ~1.26 × 10^{39} erg s^{-1} within a few days, and then decayed slowly (Middleton et al. 2013). Their outburst parameters resemble those found in Galactic LMXBs, indicating a DIM origin for these two sources as well (e.g., Yan & Yu 2015). However, only one outburst had been observed for each source; thus, the recurrence timescale is unavailable.

It is worth noting that the recurrence outbursts of the best-studied transient ULX, HLX-1, are analogous to the outbursts of 3XMM J031820.8-663034 in many aspects. Meanwhile, the outbursts of HLX-1 have significantly higher luminosity at both active and quiescent states, and smaller amplitude of luminosity variation. The total energy radiated during an outburst is about two to three orders of magnitude larger than the averaged value observed in 3XMM J031820.8-663034 (Table 3). Yan et al. (2015) argued that HLX-1 and LMXBs follow the same linear relationship between the hard-to-soft state transition luminosity and the peak luminosity, but the data of HLX-1 deviate the correlation between the X-ray fluence and peak luminosity observed in LMXBs (Figure 7). The minimum observed X-ray luminosity of HLX-1 is up to ~3 × 10^{40} erg s^{-1}, indicating that the thin disk within a very large radius (~10^{13} cm) is fully ionized because of large

| Observatory | MJD | nH (10^{21} cm^{-2}) | Γ | χ²/df | nH (10^{21} cm^{-2}) | kT (keV) | Norm (×10^{-3}) | χ²/df | Flux |
|-------------|-----|----------------------|---|--------|----------------------|---------|-----------------|--------|------|
| XMM-Newton  | 53332 | 2.5^{+2.3}_{-1.9} | 2.2^{+1.0}_{-0.8} | 9.8/12 | 0.9^{+1.4}_{-0.7} | 0.77^{+0.65}_{-0.24} | 30.0^{+1.0}_{-1.3} | 11.0/12 | 2.0^{+0.8}_{-0.4} |
| XMM-Newton  | 53408 | 2.7^{+1.1}_{-1.0} | 2.4^{+0.4}_{-0.4} | 21.3/28 | 0.6^{+0.6}_{-0.5} | 0.88^{+0.19}_{-0.15} | 22.4^{+2.62}_{-1.21} | 25.1/28 | 2.5^{+0.3}_{-0.0} |
| XMM-Newton  | 56844 | 3.3^{+0.3}_{-0.3} | 2.3^{+0.1}_{-0.1} | 229.7/137 | 0.5^{+0.1}_{-0.1} | 1.16^{+0.05}_{-0.05} | 17.1^{+3.0}_{-2.4} | 151.4/137 | 5.9^{+0.2}_{-0.2} |

Note. Flux: 0.5–10.0 keV absorbed flux calculated with the disk blackbody model in units of 10^{-13} erg cm^{-2} s^{-1}. All errors are in the 90% confidence level (1.645 σ). a The C-statistic is adopted for the spectral fitting.

![Figure 2](image-url)
accretion rate and the additional heating by the strong irradiation (Dubus et al. 2001; Soria et al. 2017). In this case, the local thermal-viscous instability should be ignited (if existed) at an even larger physical radius (not the black hole mass scaled radius). Such instability would take at least 100 years to reach the innermost accretion disk, which however contradicts the observed value of \(\sim 100\) days (Lasota et al. 2011). Therefore, the HLX-1 outbursts are unlikely due to thermal-viscous instability (i.e., DIM) but might be attributed to the radiation pressure instability (Lasota et al. 2011; Sun et al. 2016) or other instabilities (Miller et al. 2014; Lasota 2015).

Investigating the optical/UV and X-ray data, Soria et al. (2017) proposed an oscillating wind scenario for HLX-1: currently, its accretion rate is, on average, a few percent Eddington and its accretion disk is quite large (\(\sim 10^{13}\) cm); but only the inner region (\(<10^{12}\) cm) of the inflow is modulated by the wind instability (Begelman et al. 1983; Shields et al. 1986), which drives the outbursts at a timescale of \(\sim 1\) year. Such a model might also work for V404 Cyg (Muñoz-Darias et al. 2016). Due to the limited data, we do not know whether the strong wind can be launched from 3XMM J031820.8-663034 or whether the wind instability model is applicable to its repeated outbursts. The model is presented here as an option. Alternatively, we argue that the outburst properties of 3XMM J031820.8-663034 reported in this paper can be understood in the framework of DIM.

The X-ray luminosity at the quiescent state of 3XMM J031820.8-663034 (\(<5.6 \times 10^{38} \text{erg s}^{-1}\)) indicates that the disk is cool due to a low accretion rate and weak irradiation. The partial hydrogen ionization instability (i.e., thermal-viscous instability) thus emerges at a much smaller radius and allows the DIM to work. Additionally, we point out that most of the outbursts properties are consistent with the expectation of DIM: (1) The light curve shows a fast-rise slow-decay profile; and (2) It falls on the same relation between the outburst fluence and the peak luminosity that was found for LMXBs (Yan & Yu 2015). Such correlation is expected in DIM, as the outburst peak increases with the mass of accretion disk (e.g., Dubus et al. 2001). Assuming a constant radiative efficiency, the mass of the accretion disk and the peak accretion rate can be estimated from the fluence and the \(L_{\text{peak}}\) respectively. (3) Taking the truncation and irradiation effects into account, theoretical DIM models yield a recurrence time of \(1 \sim 180\) years (Dubus et al. 2001; Lasota 2001), conforming to that of 3XMM J031820.8-663034 (\(\sim 1800\) days).

In addition to X-rays, the nature of the outbursts can be explored with multi-wavelength data. The optical/UV data could provide key information on the companion star and the X-ray irradiated accretion disk (e.g., Rykoff et al. 2007; Weng & Zhang 2015; Soria et al. 2017). Furthermore, the connections between accretion flows and the radio jet have been widely studied (e.g., Fender et al. 2004; Zhang et al. 2014). A stable jet is commonly detected in the low/hard state, while the discrete ejection events are found to be associated with the transitions between the low/hard and the high/soft states. We search the radio images in the literature and the SkyView\(^8\), but do not find the point-like source at the position of 3XMM J031820.8-663034 in the 1.4 GHz radio continuum map (Ryder et al. 1993) nor the SUMSS 843 MHz image. A detailed analysis on these data is beyond the scope of this paper.

### 3.4. Accretion State and Black Hole Mass

Most Galactic LMXBs are in the regime of sub-Eddington accretion with variable X-ray emission. Although different state classifications have been proposed by different authors (e.g., McClintock & Remillard 2006; Zhang 2013; Yuan & Narayan 2014), the low/hard and the high/soft states are normally undisputed. The low/hard state is characterized by a hard spectrum and strong rapid variations. In contrast, the high/soft state is dominated by a thermal disk component and has a low level of variability. Meanwhile, several Galactic LMXBs can occasionally be brighter than \(10^{39} \text{erg s}^{-1}\), e.g., GRS 1915+105 (e.g., Belloni et al. 2000; Yan et al. 2017), V4641 Sgr (Revnivtsev et al. 2002), and V404 Cyg (e.g., Motta et al. 2017, and references therein). These three sources are highly variable on timescales of minutes to hours during the outbursts. In particular, during the 2015 outburst, V404 Cyg showed violent variations in both X-ray and optical bands (Kimura et al. 2016) and the nonthermal dominated X-ray emission (e.g., Motta et al. 2017; Sánchez-Fernández et al. 2017). The source did not enter into the canonical high/soft state classiﬁcation.

\(^{8}\) https://skyview.gsfc.nasa.gov/current/cgi/query.pl
state, but it might be accreting at a super-Eddington accretion rate. Its evolution pattern is distinct from other typical LMXBs. The new XMM-Newton detection of 3XMM J031820.8-663034 performed at the peak of an outburst indicates that its spectrum is dominated by a thermal disk component, and no significant variation is detected within the XMM exposure. The X-ray properties are consistent with the definition of the high/soft state, that is, the source reaches a luminosity of \((0.1-1) L_{\text{Edd}}\) during the outbursts. Compared to those Galactic LMXBs at the high/soft state, 3XMM J031820.8-663034 has a higher peak X-ray luminosity \((\sim 1.5 \times 10^{39} \text{erg s}^{-1})\), which might indicate a heavier black hole (tens of solar masses) hosted in the system. The MsBH scenario is also supported by the fitted disk blackbody normalization \((\sim 0.02-0.03, \text{Arnaud 1996})\), which corresponds to a radius of \(\sim 300 \text{km}\) with an inclination angle of 60° and a spectral hardening factor of 1.7, adopted. If the accretion disk extends to the innermost stable circular orbit, the derived radius corresponds to

\[ \frac{T_{\text{recurrent}}}{\text{years}} \approx 1800 \text{ days} \quad \frac{\text{Duration}}{\text{days}} \approx 240-300 \quad \frac{L_{\text{peak}}}{\text{erg s}^{-1}} \approx 1.5 \times 10^{39} \quad \text{Fluence} \approx 10^{46} \text{ erg} \quad \text{Amplitude} \geq 270 \]

Notes.

a Averaged values are listed for HLX-1 (Godet et al. 2014; Yan et al. 2015).

b Fluence is referred to the total energy radiated during one outburst.

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**Figure 4.** X-ray light curve of 3XMM J031820.8-663034. Count rates and upper limits from other instruments were converted into Swift/XRT count rates. The blue horizontal line marks the Swift/XRT threshold of 2σ detection with an exposure time of 1000 s. The blue vertical lines spaced by 1800 days are plotted to better illustrate the quasi-periodic outbursts.

**Figure 5.** Lomb–Scargle periodogram for 3XMM J031820.8-663034. The dashed line indicates 99.9% significance.

**Figure 6.** Folding the light curve in Figure 4 over a period of 1800 days.

**Figure 7.** Total energy radiated during the outburst vs. peak X-ray luminosity. The filled circles correspond to the outbursts of LMXBs adopted from Yan & Yu (2015). The blue lines indicate the best-fit result with a linear model in a logarithmic scale (solid) and the 3σ confidence intervals (dashed). The red pentagram and the green square mark 3XMM J031820.8-663034 and HLX-1, respectively.
~30–200 $M_\odot$ for a Schwarzschild and a maximally rotating black hole, respectively.

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Facilities: ROSAT, XMM-Newton, Chandra, Swift.
Software: SAS, HEASOFT, CIAO.

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References

Arnaud, K. A. 1996, in ASP Conf. Ser. 101, Astronomical Data Analysis Software and Systems V, ed. G. H. Jacoby & J. Barnes (ASP: San Francisco, CA), 17
Bachetti, M., Rana, V., Walton, D. J., et al. 2013, ApJ, 788, 163
Begelman, M. C., McKee, C. F., & Shields, G. A. 1983, ApJ, 271, 70
Belloni, T., Klein-Wolt, M., Méndez, M., van der Klis, M., & van Paradijs, J. 2000, A&A, 355, 271
Capitanio, F., Campana, R., De Cesare, G., & Ferrigno, C. 2015, MNRAS, 450, 3840
Cash, W. 1979, ApJ, 228, 939
Chen, W., Shrader, C. R., & Livio, M. 1997, ApJ, 491, 312
Corbet, R. H. D., & Krimm, H. A. 2013, ApJ, 778, 45
Corral-Santana, J. M., Casares, J., Muñoz-Darias, T., et al. 2016, A&A, 587, 61
Crivellari, E., Wolter, A., & Trinchieri, G. 2009, A&A, 501, 445
Dubus, G., Hameury, J. M., & Lasota, J. P. 2001, A&A, 373, 251
Fabbiano, G. 2006, ARA&A, 44, 323
Farrell, S. A., Barret, D., & Skinner, G. K. 2009, A&A, 501, 445
Fabbiano, G. 2000, A&A, 355, 271
Fabbiano, G. 2006, ARA&A, 44, 323
Ferrigno, C., De Cesare, G., Capitanio, F., & Ferrigno, C. 2015, MNRAS, 450, 3840
Lasota, J. P. 2000, NewAR, 45, 449
Lasota, J.-P., Alexander, T., Dubus, G., et al. 2011, ApJ, 735, 89
Lasota, J.-P., King, A. R., & Dubus, G. 2015, ApJ, 801, L4
Li, J., Torres, D. F., Zhang, S., et al. 2012, ApJ, 744, L13
Lin, D., Webb, N. A., & Barret, D. 2014, ApJ, 780, 39
Liu, J.-F., & Bregman, J. N. 2005, ApJS, 157, 59
Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2006, A&A, 455, 1165
Liu, Q. Z., van Paradijs, J., & van den Heuvel, E. P. J. 2007, A&A, 469, 807
Lyne, A. G., Stappers, B. W., Keith, M. J., et al. 2015, MNRAS, 451, 581
Makishima, K., Kubota, A., Mizuno, T., et al. 2000, ApJ, 535, 632
McClintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press)
Middleton, M. J., Miller-Jones, J. C. A., Markoff, S., et al. 2013, Natur, 493, 187
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Software: SAS, HEASOFT, CIAO.

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