Spectral and Temporal Properties of the Ultraluminous X-Ray Source ULX-1 in NGC 4088 (Postprint)

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Abstract

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Full Text

Preamble

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Abstract

We present the results of a multi-epoch, detailed spectral and temporal analysis of the ultraluminous X-ray source (ULX), ULX-1, in the galaxy NGC 4088 using XMM-Newton, Chandra, and Swift observations. The presence of a hard power-law spectral slope supports the interpretation of ULX-1 as a hard ULX. The observed inner disk temperature of $kT_{in} > 1.5$ keV is inconsistent with the presence of an intermediate mass black hole, but favors the super-Eddington accretion state. Moreover, the physically acceptable value of the parameter controlling the radial temperature profile of the disk (p) derived from fitting the first XMM-Newton observation with the slim disk model further points toward the possible presence of a broadened disk, indicating the super-Eddington accretion nature. Slight overall long-term flux variability is evident for this ULX, and a hint toward a positive correlation between flux and the power-law photon index is also observed when the relatively better data of XMM-Newton and Chandra are considered. The L–T relationship is observed to follow a positive trend, with the L–T profile consistent with either relation ($L \quad T^4$ or $L \quad T^2$) in both cases. The source exhibits no significant short-term variability at different time binnings of the light curve as indicated by the chi-square probability of constancy and fractional RMS variability values. The power density spectrum created shows no evidence of intrinsic variability of the source above the white noise. Further, no sign of pulsation was detected for this source. Assuming this ULX to be powered by an accreting black hole and using the slim disk geometry, the upper limit of the black hole mass was estimated and found to be less than 100 M_ .

Key words: accretion, accretion disks — X-rays: binaries — Galaxy: abun-

dances

1. Introduction

Ultraluminous X-ray sources (ULXs) are among the most intriguing yet least understood phenomena in the realm of X-ray astronomy. They are bright, point-like, non-nuclear X-ray sources with an isotropic X-ray luminosity, L_X > 10^{39} erg s^-1, exceeding the isotropic Eddington luminosity for an accreting stellar-mass black hole (BH) of M_{BH} 10 M_ (Kaaret et al. 2017; King et al. 2023). Since their first discovery with Einstein Observatory (Fabbiano 1989), they have been the subject of extensive research and study specifically because of their high inferred luminosity in contrast to the well-studied Galactic X-ray binary sources. Extensive and in-depth studies of X-ray spectral and variability properties of these sources suggest that they are accreting objects (Miller et al. 2004). Moreover, recent studies using high-quality data show that ULXs exhibit a variety of long-term variability behaviors (Gúrpide et al. 2021; Earnshaw et al. 2024). Statistical study of a large sample of ULX sources reveals that they are located preferentially in spiral galaxies and galaxies with higher star formation rates (Tranin et al. 2024).

It still remains unclear and a part of an open ongoing debate about what actually powers such high luminosity in these sources. Various models proposed in this regard to explain this unique phenomenon include sub-Eddington accretion onto intermediate mass black holes (IMBHs), with a proposed mass range of $10^{2–10}$5 M_ (Colbert & Mushotzky 1999; Miller et al. 2004), super-Eddington accretion onto stellar mass BHs (Gladstone et al. 2009; Sutton et al. 2013), highly relativistically beamed emission (Freeland et al. 2006), or geometrically beamed emission (King et al. 2001). In addition, there are other models proposing ULXs as supernova remnants (Mezcua & Lobanov 2011) or white dwarfs. However, detailed extensive studies of the high-quality data from satellites like XMM-Newton, Chandra, and NuSTAR in the last couple of decades favor the mechanism of super-Eddington accretion onto stellar mass BHs to explain the ULX phenomenon (Bachetti et al. 2013; Middleton et al. 2015; Rana et al. 2015). Moreover, the recent discovery of pulsation from several ULXs confirms the presence of neutron stars (NS) as compact objects in the ULX population (Bachetti et al. 2014; Sathyaprakash et al. 2019; Castillo et al. 2020), thereby further supporting the super-Eddington emission mechanism in the ULX population.

Detailed studies of high-quality XMM-Newton spectra of ULXs have revealed two main components: a soft excess and a high-energy curvature (Stobbart et al. 2006; Gladstone et al. 2009; Sutton et al. 2013). The hard emission may originate either from the innermost regions of the accretion flow or from inverse Compton scattering of seed photons from the inner disk in a hot corona (Roberts 2007; Middleton et al. 2015; Mukherjee et al. 2015; Jithesh et al. 2017). The soft component is typically interpreted either as thermal emission from an outflowing wind (Poutanen et al. 2007; Middleton et al. 2015) or as emission from the accretion disk itself (Miller et al. 2013). The presence of the high-energy curvature at around 2–10 keV in several ULXs (Bachetti et al. 2013; Kaaret et al. 2017) signifies a unique feature of ULXs, which is quite different from the Galactic XRBs, where such curvature occurs at significantly higher energies.

Detailed studies of several ULXs show the preference of the slim disk model over the Keplerian thin disk model as has been exemplified by the cases of M33 X-8 (Middleton et al. 2011), NGC 5408 X-1 (Pinto et al. 2017), Ho II X-1 (Gladstone et al. 2009), NGC 1313 X-1 (Vierdayanti et al. 2008), etc. Under super-Eddington emission, there is the elevation of the scale height of the innermost region of the accretion disk owing to forming a funnel-shaped structure from the outward radiation pressure, creating a "slim" disk structure (West et al. 2018).

NGC 4088 is an asymmetrical spiral galaxy situated at a distance of 13 Mpc and having a redshift of 0.002524 (Verheijen & Sancisi 2001), harboring a ULX, ULX-1. It is located about 32 from the nucleus. This ULX was first discovered with the ROSAT satellite by Liu & Bregman (2005), reporting an X-ray luminosity of $L_{0.3-8.0\ \mathrm{keV}}$ 6×10^{39} erg s^{-1}. The ULX is situated within the spiral arm of NGC 4088 and is possibly associated with an H II region (Sánchez-Sutil et al. 2006). The first Chandra and Swift X-ray study of the galaxy, NGC 4088, and its ULX, ULX-1, was done by Mezcua et al. (2014).

In this paper, we present a multi-epoch, detailed spectral and timing study of the ULX, ULX-1 in NGC 4088 using multi-satellite observations from XMM-Newton, Chandra, and Swift. Here, the main focus of the study is on the relatively better data from XMM-Newton while the data from Chandra and Swift were primarily used to study long-term spectral and flux variability. The paper is structured as follows. Observation and data reduction processes are provided in Section 2, while the analysis and results are presented in Section 3. Finally, the discussions and conclusions are listed in Section 4.

2. Observation and Data Reduction

We used the X-ray data of ULX-1 from XMM-Newton (Jansen et al. 2001), Chandra (Weisskopf et al. 2002), and Neil Gehrels Swift Observatory (Gehrels et al. 2004). The observations used in the work are shown in Table 1 .

2.1. XMM-Newton

The galaxy NGC 4088 was observed three times by XMM-Newton in 2022. For the present work, only two observations were used as ULX-1 was not found in the other observation. For the analysis, the data from the XMM-Newton European Photon Imaging Camera (EPIC) PN (Strüder et al. 2001) and Metal Oxide Semiconductor (MOS; Turner et al. 2001) instruments were used. The data reduction process was carried out using the XMM-Newton Science Analysis System (SAS; version 20.0). We produced the calibrated event lists of EPIC-PN and EPIC-MOS detectors using the SAS standard tools EPPROC and EMPROC, respectively. High particle full field background flaring was removed using the source background light curve extracted from the EPIC camera in the 10–12 keV energy band and creating a Good Time Interval (GTI) file for each observation. Standard filter expressions #XMMEA_{EP}, PATTERN $\leq$ 4, FLAG == 0 for PN data and #XMMEA_{EM}, PATTERN $\leq$ 12 for MOS data were applied.

We checked for pileup using the EPATPLOT task of SAS but none of the observations were found to be affected by pileup. The source spectrum was extracted from a circular region (R.A. = 12:05:32.33, centered decl. = 50:32:45.9, equinox J2000; Mezcua et al. 2014) while for the background spectrum, a source-free region in the same CCD, close to the source, was used. For both observations, the source radius was 25 (near the chip gap) for PN data while it was 30 for the MOS data. The radius of the background region taken was the same as that of the source in the same chip in the source-free region. The redistribution matrix file (RMF) and ancillary response file (ARF) for the sources were generated using the SAS tasks rmfgen and arfgen, respectively.

The spectra were grouped to have a minimum count of 20 per energy bin. For the timing analysis, only the PN data were used as they have higher counts and better timing resolution as compared to the MOS data. The source and background light curves were extracted from the same regions used for the spectral analysis using the evselect task. Background correction of the light curves was done using the EPICLCCORR task. The presence of any short-term variability was checked using the chi-square probability of constancy and RMS fractional variability values produced using the LCSTATS tool of HEASOFT at different time binnings of the light curve at 0.01 ks, 0.1 ks, 0.5 ks, 1 ks, and 2 ks. Moreover, we also searched for pulsations by generating the power density spectrum (PDS) from the background-corrected light curves using the powspec tool at different time binnings of 0.1 s, 1 s, 10 s, 100 s, 500 s, 1000 s, and 2000 s.

2.2. Chandra

NGC 4088 was observed only once in 2012 by the Chandra X-ray Observatory. It was performed using the Advanced CCD Imaging Spectrometer detector. Data reduction and analysis were done using Heasoft 6.29 and Chandra Interactive Analysis of Observations (CIAO) version 4.13. A combination of CIAO tools and calibration data (CalDB 4.10.2) was used to extract the source and background spectra. We extracted the source spectrum using the specextract script, selecting a circular region of 10 around the target source, and for the background, a circular region of the same radius as that of the source was used in the source-free region. The spectrum was grouped and binned at 20 counts per energy bin. Spectral analysis was done by using the spectral fitting package XSPEC version 12.12.0. ^2 statistics were used to fit the observed spectrum with the model parameters.

2.3. Swift

NGC 4088 was observed 48 times over a period of 16 yr between 2009 and 2025 by the Swift Observatory. Here, in this study, we used only 34 observations out of the total of 48 observations, primarily to examine long-term flux and spectral variability. For eight of the observations (Obs ID-00031401002, 00031401020, 00045814002, 00045814003, 00045814014, 00045814015, 00045814018, and 00045814021), the counts in the source region were found to be too low, up to a maximum of 1 or 2 counts, so that their spectra could not be fitted, while for two observations (Obs ID-00045814011 and 00045814012), the data of the photon counting mode were not found, and finally for four observations (ID-00357498000, 00362817000, 00362818000, and 00362917000), the XRT exposures were found to be zero. The XRT data were processed, filtered, and screened with the XRTPIPELINE tool (part of FTOOL) using the standard criteria. The photon-counting (PC) mode data from the observations were used for the analysis. We extracted the source and background spectra from circular regions with radii of 47 and 94 , respectively, using the XSELECT tool. Standard calibration database (CALDB) spectral redistribution matrices were used while the ARFs were generated with XRTMKARF accounting for different extraction regions, vignetting, and point-spread function (PSF) corrections.

Due to the low count statistics of Swift XRT spectra, Cash Statistics (Cash 1979) were used for the analysis. Here, we used the Swift data only for long-term flux and spectral variability studies. The spectra were analyzed in the 0.3–10.0 keV energy range.

3. Analysis and Results

3.1. Temporal Analysis

For the temporal analysis, only the EPIC-PN background-corrected light curves were considered and used as PN data have higher counts and better timing resolution as compared to the MOS data. For the first observation having Obs ID-0882480301, the time-averaged count rate of the PN data is 0.06 counts s^-1, while in the later observation with Obs ID-0882480701, it becomes 0.03 counts s^-1. So, there is a slight decrease in the average count rate between the two observations. For analyzing any short-term variability of the source, we calculated the chi-square probability of constancy (p) and the RMS fractional variability values using the LCSTATS tool of HEASOFT at different time binnings of the light curve at 0.01 ks, 0.1 ks, 0.5 ks, 1 ks, and 2 ks. The obtained values of chi-square probability of constancy values (p) and RMS fractional variability values at different time binnings are listed in Table 2 .

From the obtained chi-square probability of constancy values (p) of the source at different time binnings of the light curve, we have observed that, in most of the cases, the null hypothesis of a constant flux cannot be rejected, except for the second observation at the 0.1 ks timescale, for which it can be rejected at the 99% confidence level, although with a 0.41 upper limit on the RMS fractional variability (F_{var}). So, taken together, there is no strong evidence for significant short-term variability of the source. Moreover, the PDS presented in Figure 1 [Figure 1: see original paper] shows no evidence of any intrinsic variability of the source above the white noise. As the PDSs from the various observations are similar, the PDS from the earlier observation (Obs ID-0882480301) is shown as a representative example.

Further, to check for any pulsations in the source, the PDSs of the source for all the observations were generated at different time binnings of the light curve at 0.1 s, 1 s, 10 s, 100 s, 500 s, 1000 s, and 2000 s. However, no sign of pulsation was detected for this source.

3.2. Spectral Analysis

For the detailed spectral analysis, we used the spectral fitting package XSPEC version 12.12.0. The tbabs model with updated solar abundances (Wilms et al. 2000) and photoionization cross-section (Verner et al. 1996) was employed to model for the absorption effects due to neutral absorbers. $\hat{}2$ statistics were employed for fitting the spectral models. During the spectrum fitting process, the hydrogen column density (N_H) was typically allowed to vary freely, but in instances where the estimated N_H was significantly lower than the average Galactic value, it was fixed to that corresponding Galactic value (Bekhti et al. 2016). The simultaneous fitting of the EPIC-PN and MOS spectra was done to obtain the best-fitting values of spectral model parameters. The analysis was carried out in the energy range 0.3–10.0 keV.

The spectral parameter values obtained for different models are shown in Table 3 . As mentioned earlier, we have focused mainly on the XMM-Newton data, but for the Chandra data, we have shown the parameter values for simple models only as the data quality does not allow us to try complex models. First, we tried to fit the observed spectrum with simple models—absorbed power-law and absorbed multicolor diskbb model. From the obtained spectral parameters listed in Table 3, we observed that both models produce a statistically good fit for the first XMM-Newton observation (Obs ID-0882480301), yielding a hard spectrum with the power-law photon index Γ 0.21 and inner disk temperature kT_{in} 0.30 keV. A slight signature of spectral hardening is observed in the later observation (Obs ID-0882480701) with the power-law photon index Γ 0.28 and inner disk temperature kT_{in} 0.50 keV. However, when the error limits are taken into account, the power-law photon index values of the two observations are more or less consistent with each other.

For the Chandra observation also, it was observed that both the power-law and diskbb models provide an acceptable statistical fit with the power-law photon index Γ 0.60 and inner disk temperature kT_{in} 3.90 keV, indicative of a hard spectrum. The hard power-law spectral slope obtained in both observations is consistent with the classification of this ULX, ULX-1, as a hard ULX (Soria 2011; Sutton et al. 2013).

Although there is still no clear physical interpretation of hard ULXs, possible scenarios include an IMBH in a low/hard state as described in Winter et al. (2006) or a possible variety of super-Eddington accretion onto a stellar-mass compact object (Gladstone et al. 2009; Soria 2011; Sutton et al. 2013). However, the observed inner disk temperature >1.5 keV in all the observations is inconsistent with the presence of an IMBH, as the temperature of the accretion disk surrounding a BH is expected to decrease with the increase in BH mass as predicted by the standard accretion disk relation, T_{in} $M_{BH}^{(-1/4)}$ (Shakura & Sunyaev 1973), implying softer spectra ($kT_{in} < 0.5$ keV) for an IMBH, as exemplified by the case of ESO 243–49 HLX-1, which shows a thermal component of around 0.26 keV in its high state (Servillat et al. 2011). This shows the possibility of the super-Eddington accretion regime for this ULX.

Further, the observed inner-disk temperature of >1.5 keV for this ULX is too high for a typical standard thin accretion disk (Remillard & McClintock 2006). High disk temperatures have been observed in many ULXs (Stobbart et al. 2006; Roberts 2007), which are explained in two possible ways. The first scenario involves the standard thin Keplerian disk evolving into a slim disk as the accretion rate reaches a critical threshold and the luminosity approaches or slightly surpasses the Eddington limit (Watarai et al. 2000; Mizuno et al. 2001; Isobe et al. 2012). A key property that differentiates a slim disk from a standard thin disk is its flatter radial temperature profile, where $T(r)$ $r^{(-p)}$ with $p = 0.75$ in the case of a standard thin disk. The other scenario includes the non-negligible emission from inside the innermost stable circular orbit (ISCO, Watarai et al. 2000; Mizuno et al. 2001).

Considering the above conditions, we have tried modeling the spectrum with the diskpbb model (slim disk model), which represents super-Eddington accretion, to the two sets of XMM-Newton data. It gives a statistically good fit in the first XMM-Newton observation (Obs ID-0882480301) with a physically acceptable p value of 0.03, favoring a slim disk geometry over the standard thin disk with a value of $p = 0.75$. However, in the later observation (Obs ID-0882480701), although the fit is acceptable, we got a value of $p > 0.75$ in the upper limit, which could represent a truncated disk (Walton et al. 2018). So, for this observation, given the large uncertainties for the value of $p = 1.3$, a possible scenario of the standard thin disk with the value of $p = 0.75$ cannot be ruled out. Here, given the quality of data that we have, we are not able to distinguish between the models statistically, and hence not in a position to provide a clear picture about the nature of this ULX. However, the p value of 0.03 obtained when fitting the first XMM-Newton observation with the slim disk model provides tentative evidence of a broadened disk spectrum, indicating possible super-Eddington accretion. But its exact nature could be evident with the availability of more high-quality data in the future. The unfolded spectrum of this ULX for the XMM-Newton observation (Obs ID-0882480301) simultaneously fitted with the different models is shown in Figure 2 [Figure 2: see original paper].

3.3. Temperature-Luminosity Relation

In order to draw more information about the nature of the accretion disk and to gain more insights about the environment of the compact object harbored by this ULX, we plotted the luminosity–temperature (L–T) relation for both the thin disk and slim disk models. As stated earlier, for these plots, we used the data from XMM-Newton, Chandra, and Swift. For Swift, we used only the relatively better data (higher exposures) out of all the observations taken between 2009 and 2025. The L–T plots for both the thin disk and slim disk models are shown in Figures 3 and 4, respectively.

From the L–T plots, we have observed that ULX-1 exhibits a positive L–T relation in both the thin disk and slim disk models, similar to the behavior shown by the ULX, NGC 4190 ULX-1 (Ghosh & Rana 2021). It is seen that in both cases, the observed data points could be consistent with either relation (L T^4 or L T^2). However, for the case of the slim disk model, it is noteworthy to state that the low counts of the Swift data restrict its ability to effectively constrain the model parameter values as shown in Figure 4 [Figure 4: see original paper]. So, considering the relatively better data of XMM-Newton and Chandra, it seems to prefer the advection-dominated slim disk model.

3.4. Variability

For studying the long-term flux variability of ULX-1, the data from the Swift observations (even though having low exposure) in addition to the XMM-Newton and Chandra observations were included. We considered the absorbed flux and luminosity in the 0.3–10.0 keV energy range. Overall, this ULX appears to exhibit slight long-term flux variability, as illustrated in Figure 5 [Figure 5: see original paper]. Further, it is observed that among all the observations, the Swift observation with Obs ID-00045814001 exhibits the highest flux while the lowest flux is observed for the Chandra observation with Obs ID-14442. So, it can be said that the source exhibits a slight overall long-term flux variability by a factor of 2 between the highest and lowest flux observed over a span of 15 months between the two observations.

In addition, we have also studied the spectral hardness variability of ULX-1 by analyzing the variation of observed flux in the energy range 0.3–10.0 keV with the power-law photon index, Γ. Here, since the Swift-XRT data give relatively large errors due to low exposures (low signal-to-noise ratio), the spectral parameters could not be strictly constrained. So, the power-law photon index Γ versus flux variation of only the XMM-Newton and Chandra spectra was considered and plotted as displayed in Figure 6 [Figure 6: see original paper]. From the plots, it is observed that there is no significant change in the spectral hardness of the source. All the power-law photon index values are more or less consistent within the error limits, except for the slight change in Γ value between the two XMM-Newton observations. So, here, all we can say is that there seems to be a possible hint toward a positive relation between the flux and power-law photon index, Γ, which is observed in many ULXs like NGC 1313 ULX-1, Holmberg II ULX-1, and NGC 5204 ULX-1 (Kajava & Poutanen 2009). However, all these interpretations need to be ascertained and verified with the availability of more high-quality data in the future.

3.5. Mass Estimation

From the spectral analysis of ULX-1, although we are not in a situation to make a concrete statement about the accretion nature of this ULX with the available data in hand, but taken together, we can at least say that the data appear to be consistent with a super-Eddington accreting source, although we cannot rule out the other possibilities. So, to get some additional idea in this regard, we have done a mass estimation of this ULX using the normalization value from the diskpbb model for the XMM-Newton observation (Obs ID-0882480301), but as for the other XMM-Newton data, the normalization value could not be constrained.

Assuming the central compact object of this ULX to be a BH accretor, we estimated the BH mass using the slim disk normalization value as R_{in} $^{\{\{2N\}\}}$\{(1/2)(cos)\}\}^(-1/2)D (Ghosh & Rana 2021), where R_{in} is the physical inner radius, r_{in} is the apparent innermost radius; is the hardening factor (the ratio of the color temperature T_{col} and effective temperature T_{eff}), and is the geometric factor (which depends on the proximity of the disk's peak temperature, T_{in}, to the ISCO R_{in}) (Soria et al. 2015). Here R_{in} is expressed in km, D is the distance of the ULX in units of 10 kpc, and is the disk inclination angle.

From this value of R_{in}, the mass of the BH harbored by ULX-1 was estimated using the relation $R_{in} = 3\beta R_g$ (R_{in} will be the ISCO and β is a parameter which depends on the BH spin) (Vierdayanti et al. 2008), where $R_g = 2GM/c^2$ is the Schwarzschild radius, G is the universal gravitational constant, M is the mass of the BH, and c is the speed of light in vacuum.

For the case of the slim disk regime, since the accretion rate is high, the hardening factor increases as compared to that of the standard thin disk. So, we adopted the hardening factor as has been used in Soria et al. (2015), by taking 3 for the BH mass estimation. For the case of geometric factor, we assumed 0.353 in line with Vierdayanti et al. (2008). In this way, the physical inner radius R_{in} was estimated assuming a face-on disk geometry (cos = 1). Moreover, for a slim disk, as the inner radius extends slightly inside the ISCO, the true mass can be estimated using the relation M_{BH} 1.2 M (Vierdayanti et al. 2008). Here, given the hard spectrum of this ULX, it is reasonable to assume a face-on geometry (a low value of) for the disk, as at low inclination angles, it is possible to have a direct unobscured view of the innermost region of the accretion flow down the optically thin funnel formed by radiatively driven winds of the super-Eddington accretion regime, leading to the detection of a harder X-ray spectrum (Middleton et al. 2015). So, by assuming a face-on disk inclination and taking the case of a simple Schwarzschild BH ($\beta = 1$) (Vierdayanti et al. 2008), the estimated mass comes out to be M_{BH}   17^(+3) M_ . On the other hand, considering the scenario of maximum possible spin achievable by an astrophysical BH ($\beta = 1/2.4$) (Thorne 1974), the upper limit of the BH mass was estimated to be M_{BH}   87^(+17) M_ , which indeed is less than 100 M_ , within the error limits. So, this supports the possibility of super-Eddington accretion onto a stellar-mass BH in ULX-1.

4. Discussion and Conclusion

From the detailed spectral and temporal analysis of ULX-1 in NGC 4088, we can at least say that there is a tentative hint toward the possibility of this ULX being powered by a stellar-mass compact object in the super-Eddington accretion state, although the other possibilities about the nature of this ULX cannot be ruled out.

The hard power-law spectral slope obtained when fitting the spectrum with the absorbed power-law model supports ULX-1 as a hard ULX. The observed inner disk temperature of kT_{in} > 1.5 keV, while fitting the spectrum with the multicolor disk blackbody model, is inconsistent with the presence of an IMBH but favors the scenario of super-Eddington accretion nature in this ULX. Moreover, the observed presence of a statistically significant spectral break at around 5 keV for this ULX, as described in Mezcua et al. (2014), further weakens the possibility of an IMBH and aligns toward the direction of the super-Eddington nature of ULX-1. Further, the observed inner disk temperature exceeding 1.5 keV is too high for a typical standard thin accretion disk. In addition, the best-fitting value of "p" (0.03) obtained while fitting the relatively better spectrum of XMM-Newton (Obs ID-0882480301) with the diskpbb model hints at the possibility of slim disk geometry, thereby leaning toward the possible scenario of the super-Eddington nature of this ULX. But all these interpretations require further evidence to be ascertained and verified with the availability of more higher-quality data in the future.

ULX-1 exhibits a positive L–T relation for both the thin disk and slim disk models, with the data consistent with either relation in both cases. However, considering the relatively better data of XMM-Newton and Chandra, a slight preference toward the L   T^2 relation is observed for the slim disk case. The slim disk L–T relation, L   T^2, characterized by energy advection through radiation trapping and outflow, is expected in the super-Eddington accretion regime. The ULX appears to show an overall slight long-term flux variation. A slight tentative hint toward a positive relation between the observed X-ray flux and spectral hardness is observed for this source.

The detailed timing studies of this ULX reveal the absence of any significant short-term variability. The PDS created shows no evidence of intrinsic variability of the source above the white noise. Moreover, no signs of pulsation were detected at different time binnings of the background-corrected light curves of this source. Again, assuming a BH as the compact object and using the slim disk geometry, the upper limit of the BH mass was estimated to be M_{BH} 17^(+3) M_ for the case of a simple Schwarzschild BH and M_{BH} 87^(+17) M_ for the case of a BH having the maximum possible achievable spin. So, in both cases, the BH mass estimated is found to be less than 100 M_ .

Hence, it seems to be probable that this ULX is powered by super-Eddington accretion onto a stellar-mass compact object; however, the exact nature of this ULX needs to be confirmed with a study with better quality data in the future.

So, from the above study, although we are in a position to make a statement about the possibility of the super-Eddington accretion nature of this ULX, ULX-1 in NGC 4088, other possibilities about the nature of this source cannot be ruled out due to the limited statistics of available data. So, a comprehensive and holistic analysis of this source with higher quality data, or even incorporating multiwavelength bands in the future, will be the way forward to unveil a better picture of this ULX.

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Note: Figure translations are in progress. See original paper for figures.