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SPECTRAL AND TEMPORAL PROPERTIES OF CXOUJ122956.7+075728 (ULX-1), AN ULTRALUMINOUS X-RAY SOURCE IN NGC 4472

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This report presents a comprehensive analysis of the spectral and temporal characteristics of a highly significant Ultraluminous X-ray Source (ULX) designated as CXOUJ122956.7+075728 (ULX-1) situated in the elliptical galaxy NGC 4472 within the Virgo cluster. ULX-1 exhibits a soft spectral state, featuring a cool accretion disk component with $kT_{in} \sim 0.15$ keV, accompanied by a power-law tail displaying a steep power-law photon index, $\Gamma \sim 2.8$. The spectral findings strongly support an estimated black hole mass of approximately 3.30×10^3 $M_\odot$ under an isotropic emission model, and around 1.47×10^3 $M_\odot$ in an extreme beaming scenario. Temporally, ULX-1 displays significant variability on time scales of 0.5, 1, and 2 ks, suggesting the possibility of instabilities within the accretion disk contributing to this behavior. However, despite this temporal variability, the power spectra analysis of this soft ULX reveals no signatures of pulsations, distinguishing it from certain pulsating ULXs (PULXs) typically associated with neutron stars. This absence of pulsations in ULX-1 further underscores its unique spectral and temporal characteristics within the broader context of ULX phenomena.

Keywords: *Accretion, Accretion disks; Galxies: individual (NGC 4472); X-rays: binaries*

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1. INTRODUCTION

Non-nuclear X-ray point sources exibiting isotropic luminosity $\geq 10^{39}$erg s^{-1} in the (0.1 - 10.0) keV energy range are usually termed as Ultraluminous X-ray Sources (ULXs) [1]. Essentially, ULXs are accreting sources with X-ray luminosities surpassing the Eddington limit of a 10$M_\odot$ black hole (BH) [2, 3]. The inferred high luminosity of ULXs have been modelled as due to - sub-Eddington accretion on to the Intermediate Mass Black Holes (IMBHs) [4, 5, 6]. Black Holes with masses in the range $M_{BH} \sim 10^2 - 10^5 M_\odot$ are termed as IMBHs. The formation process of IMBHs presented a challenge until the recent discovery of a binary black hole merger with a total mass of $M_{BH} \sim 150 M_\odot$ [7], providing compelling evidence for the existence of IMBHs. This discovery has significantly contributed to our understanding of the potential formation mechanisms of Intermediate Mass Black Holes. The ULX model involving sub-Eddington accretion onto Intermediate Mass Black Holes (IMBHs) holds significant importance in elucidating the exceptionally high luminosities observed in certain ULXs, particularly those in very soft states such as CXOUJ132943.3+471135 of M51 [8], X-7 of NGC 6946 [9] etc.

In the last few decades advanced satellites like Chandra, XMM-Newton, NuSTAR etc. have enabled to catalogue around 1840 ULXs [10, 11]. Detailed spectral and temporal studies of these ULXs have revealed that majority of the ULXs are super-accretors. In this model, the very high luminosity of ULXs are being modelled as due to super-Eddington accretion on to stellar mass black holes or neutron stars [12, 13, 14, 15, 16, 17]. Example of super-Eddington accretor ULX include ULX NGC 1313 X-1 [18]. Indeed, recent studies have increasingly employed the model of super-Eddington accretion to explain the spectral and temporal properties of ULXs in terms of radiatively driven outflows/winds. Jithesh (2022) [19]extensively explored the physical characteristics of NGC 55 ULX1, an exceptionally super-soft and luminous ULX, by proposing a model based on supercritical radiatively driven outflowing winds to explain its unique features. Pinto et al. (2017) [20] & (2021) [21] has also reported the existence of outflowing wind in some ULXs.

In the past decade, a novel scenario has emerged with the discovery of pulsating ULXs (PULXs)- PULX in M82 [22], NGC 300 ULX-1 [23], NGC 1313 X-2 [24]; M 51 ULX-7 [25], ULX Swift J0243.6+6124 [26], M 81 X-6 [27] etc. PULXs are modeled as accreting systems where the compact object is a neutron star with a mass of approximately 1 - 2 $M_\odot$, accreting at extremely super-Eddington rates. Considering the scenarios above, the mass of compact objects within ULXs remains a topic of significant debate. While it's true that a significant portion of ULXs are categorized as super-accretors, the heterogeneity within this family is striking. ULXs exhibit diversity in terms of the compact objects they host, which can include Neutron Stars (NS), stellar-mass black holes, or even Intermediate Mass Black Holes (IMBHs), depending on the system.

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Another important aspect to understand the physical nature of ULXs is its variability. The variability of Ultra-Luminous X-ray Sources (ULXs) spans a wide range of timescales, from kilo-seconds to weeks, and even extending to years. Notably, Krauss et al. (2005) [28] studied M74 X-1, an extremely variable ULX, displaying variations on very short timescales of approximately 1000 seconds, reminiscent of the behavior observed in the Galactic black hole system GRS 1915+105. Large amplitude variability on kilo-second timescales has been reported in many ULXs, potentially linked to spectral state transitions. The exploration of such variability in ULXs, whether on short or longer timescales, provides valuable insights into their dynamic behavior. These studies contribute to our understanding of the underlying processes governing ULXs and may unveil key features of their nature and evolution.

In this paper we present the detail spectral and temporal analysis of a very significant Ultraluminous X-ray source (ULX) named here as CXOUJ122956.7+075728 (ULX-1) in the elliptical galaxy NGC 4472 in the Virgo cluster. NGC 4472 is well known as a galaxy with hosting more than 200 X-ray sources, including even a good number ($\sim$ 80) of Low mass X-ray binaries (LMXBs) in Globular cluster [29]. Joseph et al. 2017 [29] has classified ULX-1 as a non Globular Cluster (GC) source. Here we adopt the distance to the galaxy NGC 4472 as 16 Mpc [30].

2. OBSERVATION AND DATA ANALYSIS

NGC 4472 have been observed by *Chandra* ACIS detector 17 times over a span of approximately 21 years, from 2000 to 2021. Notably, the source of interest, CXOUJ122956.7+075728 (referred to as ULX-1 hereafter), was prominently detected only during the year 2011 observation with Observation ID 12888, featuring an approximate exposure time of 160 ks. In the remaining observations, the positioning of the detectors did not provide proper coverage of ULX-1 in the field of view.. Consequently, the entirety of the presented work is based on the *Chandra* observation with ObsID 12888.

The reduction and analysis of the data were carried out by using Chandra Interactive Analysis of Observations (CIAO-4.16), along with its calibration data (CALDB 4.11.0) and Heasoft-6.32.1. Specific to the observation considered, the identification of problematic pixels was accomplished by configuring observation-specific bad pixel lists within the ardlib parameter file using the *acis_set_ardlib* tool.
The CIAO source detection tool, *Wavdetect*, was employed to identify X-ray sources from the level 2 event lists. The process involves two stages - *Wtransform* and *Wrecon*. In the first stage, *Wtransform*, putative source pixels were detected within the dataset using iterative correlation with "Mexican Hat" wavelet functions at different scales (1.0, 2.0, 4.0, 6.0, 8.0, and 16.0 pixels). Source pixels were identified based on the default value of the "sigthresh" parameter, set at approximately 10^{-6}. The second stage, *Wrecon*, utilized information obtained from *Wtransform* at each wavelet scale to generate a list of sources. In the source list, specifically, CXOUJ122956.7+075728 (ULX-1) was detected at RA $12^h29^m56.74^s$ and Dec. $+07°57'27.77''$ with a total source count of $\sim$ 556. ULX-1 is found to be located at an off-nuclear distance $\approx 3.55'$. The source region is taken as a circular region with a radius of approximately 0.05 arcminutes, effectively encircling the source. The corresponding background region is choosen as a nearby source-free circular region. Using the CIAO tool *specextract* along with calibration data, the source and background spectra were extracted. The spectra were then grouped using the default setting of 15 counts per bin in specextract. Moreover, it is ensured that the source is not affected by pileup effects, given its count rate of approximately 2.96×10^{-03} counts s^{-1}. Also, for temporal analysis, using the CIAO tool *dmextract*, we have generated the background subtracted light curve of ULX-1 binned at 0.5, 1 and 2 ks.

3. SPECTRAL PROPERTIES OF CXOUJ122956.7+075728 (ULX-1)

In most cases, *Chandra* ULX spectra, due to low source count, are basically explained with simple empirical models such as powerlaw and multi-color disk blackbody. ULX-1, with a total source count $\sim$ 556, can be classified as possessing an averagely detailed *Chandra* spectrum. So, we first tried fitting the spectra of ULX-1 with simple models - an absorbed powerlaw model and then with an absorbed disk blackbody model separately. The XSPEC multiplicative model *phabs* was used as the absorption component. The spectra is all fitted in the energy range 0.3 - 8.0 keV. However neither of the two models could give a very good fit, as shown by the spectral parameters in Table 1. In both the cases, the fitting statistics were very poor with χ^2/degrees of freedom (dof) $\approx$ 36.45/24 for powerlaw model and 42.89/24 for the absorbed disk blackbody model. So, neither of these two simple models (powerlaw or diskbb) could sufficiently represent the spectra of ULX-1.

Next, we tried the phenomenological two-component model i.e. the multi-color disk blackbody (*diskbb* in XSPEC) component added with a powerlaw (*pow* in XSPEC) component. This two-component model is frequently used to characterize the thermal emission originating from the accretion disc and the Comptonized emission emerging from either the hot corona or the inner accretion flow. *Phabs* was used as the absorption component and the hydrogen column density (n_H) was set free to vary while fitting. Table 1 shows the model fitted spectral parameters. It is seen that this two-component model provides an improved fit as compared to the simple powerlaw or the disk blackbody. Rather, it gives a very good fit with $\chi^2/dof \approx 22.71/22$. The fitted spectra with this two component (diskbb + pow) model is shown in Figure 1.

Table 1. Spectral Properties of CXOUJ122956.7+075728 (ULX-1)

parameter	units	value
	diskb blackbody (diskbb) model	
n_H	$(10^{22} cm^{-2})$	$0.13^{+0.11}_{-0.08}$
kT_{in}	(keV)	$0.29^{+0.06}_{-0.06}$
$\log(L_{bol})$	(erg s^{-1})	$39.38^{+0.30}_{-0.19}$
$\chi 2/dof$		42.89/24
	powerlaw (pow) model	
n_H	$(10^{22} cm^{-2})$	$0.45^{+0.18}_{-0.13}$
Γ		$4.76^{+1.14}_{-0.76}$
$\log(L_X)$	(erg s^{-1})	$40.05^{+0.68}_{-0.44}$
$\chi 2/dof$		36.45/24
	diskbb+pow model	
n_H	$(10^{22} cm^{-2})$	0.43 ± 0.17
kT_{in}	(keV)	0.15 ± 0.04
Γ		2.82 ± 0.89
$\log(L_X)$	(erg s^{-1})	$39.84^{+0.10}_{-0.06}$
$\chi 2/dof$		22.71/22

Consequently, we can accept that the spectra of ULX-1 can be well explained by this two-component model. It is found that ULX-1 have a soft component emission from the accretion disk with an inner disk temperature, kT$_{in}$ $\sim$ 0.15 keV, besides the spectra of ULX-1 is complimented with a powerlaw tail emission which might have arrise due to inverse comptonization of soft seed photons in the hot corona near the inner accretion disk. Using the *cflux* model in XSPEC, we derived the unabsorbed flux. Then, using the distance to the source, D $\sim$ 16 Mpc [30], we computed the unabsorbed luminosity (L$_X$) in the 0.3 - 8.0 keV range.

Analyzing the spectral parameters of ULX-1 in Table 1, it is evident that neither the single absorbed disk blackbody model nor the powerlaw model adequately explains the ULX-1 spectra. However, a preliminary examination of the parameters suggests that ULX-1 may indeed be in a soft spectral state, characterized by an inner disk temperature kT_{in} definitely less less than 0.5 keV and a steep powerlaw photon index ($\Gamma \sim 4$). Additionally, individual estimations using these models indicate that ULX-1 is an exceptionally bright source, with an X-ray luminosity exceeding $10^{39} erg\ s^{-1}$, firmly placing it in the high-soft state. This spectral state of ULX-1 is indeed confirmed from a more nuanced analysis employing a two-component model: a multicolor disk blackbody component combined with a powerlaw component. This model yields a robust fit, confirming that ULX-1 indeed exhibits a high-soft spectral state. The X-ray luminosity (L$_X$) is approximated to be $\sim\ 6.99 \times 10^{39}\ erg\ \ s^{-1}$, and the spectral components include a cool disk with $kT_{in} \sim 0.15$ keV and a powerlaw tail characterized by a photon index $\Gamma \sim 2.82$. In analogy to the high-soft state of X-ray binaries, the presence of a low-temperature disk blackbody component in the ULX-1 spectra may be due to radiation from an accretion disk. In this scenario, the observed luminosity may be primarily attributed to emissions from a standard thin disk, extending up to the last innermost stable circular orbit (ISCO). Consequently, an

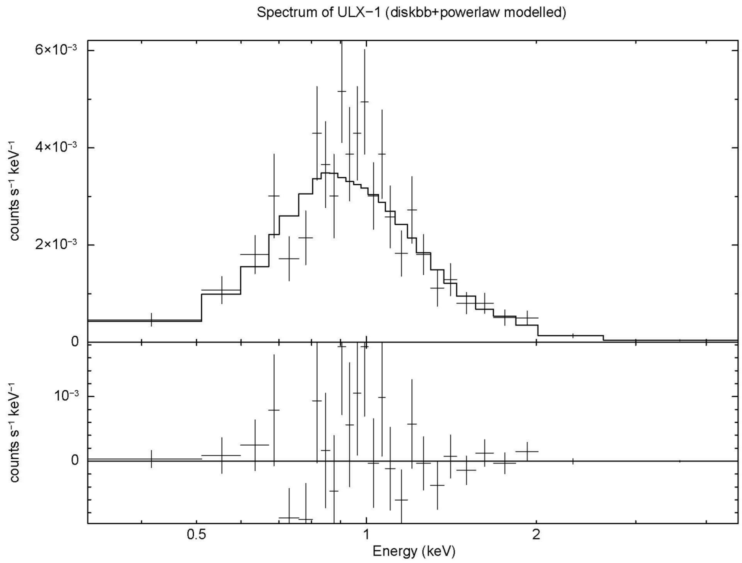

Figure 1. *Chandra* spectra of ULX-1 fitted with an absorbed (disk blackbody + powerlaw) model.

indirect estimation of the mass of the central compact object in ULXs can be derived from the disk blackbody component.

For the disk blackbody component, the inner disk radius from where the observed X-rays are emitted, is given by $R_{in} = (\sqrt{Normalisation} \times Distance_{10kpc})/\sqrt{\cos\theta}$ km, where θ represents the viewing angle. Utilizing the normalization value obtained from the fit, the distance to the source, D $\approx$ 16 Mpc and and considering a viewing angle of $cos\theta$=0.5 [31], we can approximate the mass of the compact object. This estimation assumes that the inner disk radius R_{in} is situated at approximately 5 times the Schwarzschild radius ($R_{Sch} = 2\ GM/c^2$, where G is the Universal Gravitational Constant, M is the mass of the object, c is the speed of light in vacuum). Thus, for ULX-1 it is found that the mass of the central compact object is $\approx 3.30 \times 10^3$ $M_\odot$, which indeed correspond to the intermediate mass black hole range accreting at around 0.01 times the Eddington limit i.e $L/L_{Edd} = 0.01$. Referring to the work of King et al. (2001) [32], if we consider the emission to be anisotropic and beamed by a factor η, then R_{in} would be overestimated by a factor of $\eta^{1/2}$. Consequently, assuming maximum beaming with $\eta \sim$5, as suggested by Misra and Sriram (2003) [33], the estimated black hole mass for ULX-1 is approximately $1.47 \times 10^3 M_\odot$; also falling within the range of intermediate mass black holes. Therefore, there is a high probability that ULX-1 in NGC 4472 is powered by an accreting intermediate mass black hole.

4. TEMPORAL PROPERTIES OF CXOUJ122956.7+075728 (ULX-1)

Ultra-Luminous X-ray Sources (ULXs) exhibit variability across a broad spectrum of time scales, ranging from a few kilo-seconds to weeks, and extending to periods spanning years. To examine the temporal variability of ULX-1 at the kilo-second time scale, we generated background-subtracted light curves for this source. These light curves were systematically binned over intervals of 0.5, 1 and 2 kilo-seconds, allowing for a detailed analysis of the source's temporal behavior over these specific time intervals. Figure 2 shows the light curve of ULX-1 in the specified time bins. The probability of a constant count rate during the observation is exceptionally low, with values less than 1.1×10^{-8} for 500 ks, 1.9×10^{-23} for 1000 ks, and 9.4×10^{-26} for 2000 ks binned light curves. Consequently, the likelihood of significant variability in the source exceeds 99% across all these time bins. This suggests that ULX-1 exhibits substantial amplitude variability on a kilo-second time scale. While the precise nature of such variability in Ultra-Luminous X-ray sources (ULXs) remains unclear, existing studies have explored various hypotheses, including potential beaming effects from a jet closely aligned with our line of sight [28] and large-scale instabilities within accretion disks.

In the case of ULX-1 in NGC 4472, its very soft spectra featuring a cool accretion disk component (kT_{in} $\sim$ 0.15 keV) make it improbable for the variability to result from beaming effects associated with sub-Eddington accretors. Moreover, its likelihood of being powered by an Intermediate-Mass Black Hole (IMBH) with a mass around $10^3 M_\odot$ further diminishes this possibility. Therefore, it is suggested that the observed variability in ULX-1 may be attributed to substantial large-scale instabilities within the accretion disk, particularly within the detected time scales. However, it is essential to note that confirmation of any specific accretion disk instability model is pending further investigation.

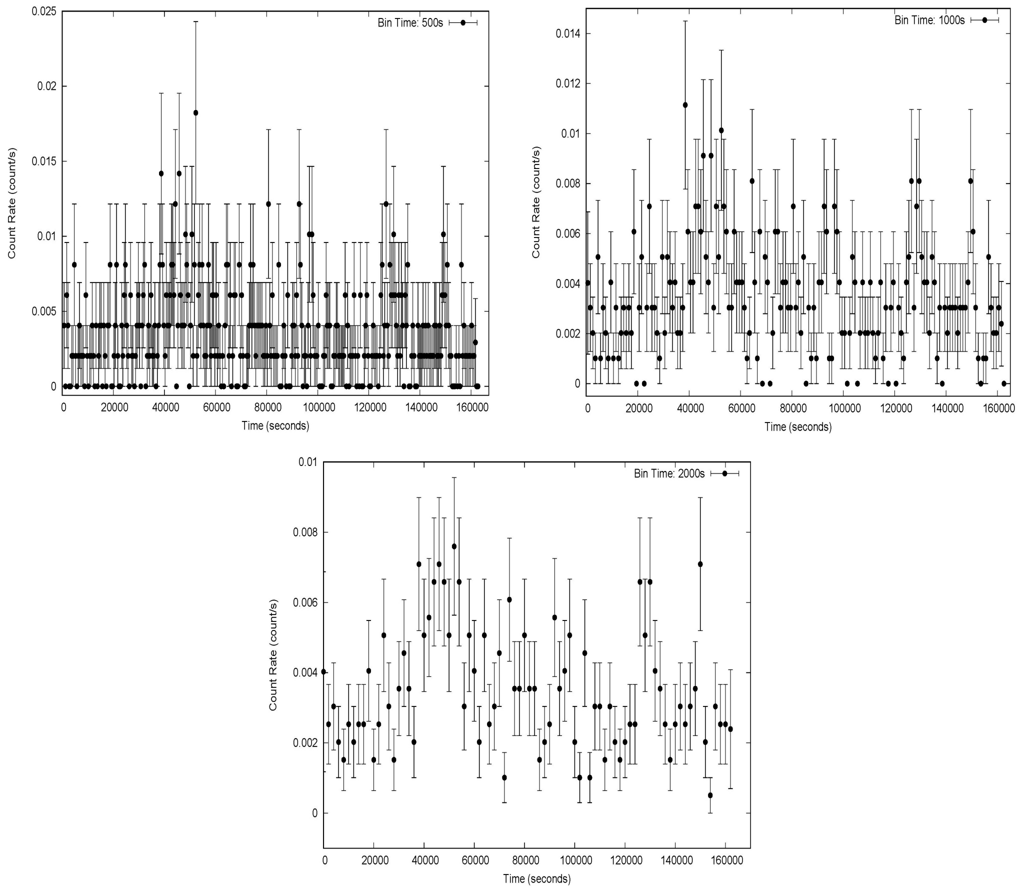

Figure 2. Lightcurve of ULX-1 binned at 0.5 ks, 1.0 ks & 2.0 ks

Again, to examine potential pulsations from the source, power spectra were generated using the FTOOL *powspec* within the 0.001 - 10 Hz frequency range. No pulsation signal was identified in the power spectra, diminishing the likelihood of ULX-1 being powered by a pulsating neutron star. It's crucial to note, however, that the limited timing capabilities of many sensitive X-ray instruments aboard satellites may have hindered the detection of the transient nature of pulsations in numerous variable sources. As a result, a more comprehensive future study, utilizing higher-quality data from alternative missions, could provide a clearer understanding of the genuine physical nature of this soft ULX, CXOUJ122956.7+075728 (ULX-1). Future observations and a detailed temporal study of this source are anticipated to contribute significantly to our understanding of the nature of this soft ULX.

5. SUMMARY AND CONCLUSION

We present the results of spectral and temporal analysis of the ULX - CXOUJ122956.7+075728 (ULX-1) in the elliptical galaxy NGC 4472 which is considered to be at a distance of around 16 Mpc. Even though *Chandra* has observed NGC 4472 many times in the last 21 years, the source of interest ULX-1 was significantly detected only in its observation of the year 2011 observation with Observation ID 12888. In this *Chandra* observation, ULX-l was detected with an averagely detailed spectra with a source count ~ 556. Initially, attempts were made to interpret ULX-1's spectrum using simple models, such as a single absorbed power-law or a single absorbed disk blackbody. However, both models yielded poor fit statistics. Subsequently, a two-component model, combining a standard thin disk model with a power-law component (diskbb + pow) in XSPEC, significantly improved the fit with $\chi^2/dof \approx 22.71/22$. This indicates that ULX-1's spectra are well-described by this two-component model, portraying a high-soft spectral state.

The derived spectral parameters reveal an X-ray luminosity (L_X) of approximately $6.99 \times 10^{39} erg\ s^{-1}$, comprising a cool disk with $kT_{in} \sim 0.15$ keV and a power-law tail characterized by a photon index $\Gamma \sim 2.82$. The super soft spectra and the high luminosity suggests the presence of an Intermediate-Mass Black Hole (IMBH) with a mass estimate of $M_{BH} \sim 3.30 \times 10^3 M_\odot$ accreting at ~ 0.01 Eddington limit. Even in an extreme beaming scenario with a factor of $\eta \sim 5$, the estimated black hole mass remains relatively high at $M_{BH} \sim 1.47 \times 10^3 M_\odot$, supporting the likelihood of an IMBH rather than a stellar-mass black hole.

Additionally, investigations into the power spectra of ULX-1 ruled out pulsating neutron stars as a power source, and the observed significant variability in kilo-second time scales suggests potential instabilities in the accretion disk. However, a proper model of such accretion disk instability to explain the variability is pending further investigation. A comprehensive future study, leveraging higher-quality data from alternative missions, is needed for a deeper understanding of ULX-1's physical nature. Furthermore, ongoing observations and detailed temporal studies are expected to contribute significantly to unraveling the mysteries surrounding this soft ULX, CXOUJ122956.7+075728 (ULX-1).

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СПЕКТРАЛЬНІ ТА ЧАСОВІ ВЛАСТИВОСТІ CXOUJ122956.7+075728 (ULX-1), НАДЯСКРАВОГО РЕНТГЕНІВСЬКОГО ДЖЕРЕЛА В NGC 4472

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У цьому дослідженні представлено комплексний аналіз спектральних і часових характеристик надзвичайно важливого надяскравого рентгенівського джерела (ULX), позначеного як CXOUJ122956.7+075728 (ULX-1), розташованого в еліптичній галактиці NGC 4472 у скупченні Діви. ULX-1 демонструє м'який спектральний стан із прохолодною компонентою акреційного диска з $kT_{in} \sim 0,15$ кеВ, що супроводжується хвостом степеневого закону, що відображає крутий степеневий фотонний індекс, $\Gamma \sim 2{,}8$. Спектральні результати переконливо підтверджують розрахункову масу чорної діри приблизно $3,30 \times 10^3$ $M_\odot$ за моделлю ізотропного випромінювання та близько $1,47 \times 10^3$ $M_\odot$ за сценарієм екстремального випромінювання. У часі ULX-1 демонструє значну мінливість на часових шкалах 0,5, 1 і 2 кс, що свідчить про можливість нестабільності всередині акреційного диска, що сприяє такій поведінці. Однак, незважаючи на таку часову мінливість, аналіз спектрів потужності цього м'якого ULX не виявляє ознак пульсацій, що відрізняє його від певних пульсуючих ULX (PULX), які зазвичай асоціюються з нейтронними зірками. Ця відсутність пульсацій в ULX-1 ще більше підкреслює його унікальні спектральні та часові характеристики в ширшому контексті явищ ULX.

Ключові слова: *акреція, акреційні диски; галактики: індивідуальні (NGC 4472); рентгенівські промені: бінарні*