Spectral variability in NGC 1042 ULX1

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ABSTRACT
We report X-ray spectral variability in an ultraluminous X-ray source NGC 1042 ULX1, using archival XMM-Newton and recent NuSTAR observations. In long-term evolution, the source has shown a trend of variation in spectral hardness. The variability in different XMM-Newton observations is prominent above ~ 1 keV. Cool thermal disk component with a characteristic temperature of ~ 0.2 keV manifests that the spectral state of NGC 1042 ULX1 in all epochs is similar to that of the ultraluminous state sources. An apparent anti-correlation between luminosity and powerlaw index demonstrates that the source becomes spectrally harder when it is in a brighter state. That is conceivably related to variation in accretion rate, strength of comptonization, wind/outflow in the system or a manifestation of varying disk occultation. Typical hard ultraluminous type spectra indicate that NGC 1042 ULX1 is a low inclination system in general. Spectral properties suggest that, like many other ULXs which show spectral curvature around ~ 6 – 10 keV, NGC 1042 ULX1 could be another stellar-mass super-Eddington accreter.

Key words: accretion, accretion discs – X-rays: binaries – X-rays: individual (NGC 1042 ULX1)

1 INTRODUCTION
Ultraluminous X-ray sources (ULXs) are point-like off nuclear sources, X-ray luminosity of which is greater than the Eddington limit of a 10 M_sol black hole; L_X > 10^{39} erg s^{-1} (see Kaaret et al. 2017 for a recent review). Initially, these sources were considered to be the population of intermediate-mass black holes (IMBHs) accreting in sub-Eddington accretion rate (Colbert & Mushotzky 1999). However, unique spectral properties like curvature ≤ 10 keV and presence of soft excess ≤ 0.4 keV, characterize these sources as distinct from the sub-Eddington sources (e.g., Stobbart et al. 2006; Gladstone et al. 2009; Sutton et al. 2013). Especially, recent studies with broadband X-ray data strongly indicate that most of these sources are stellar-mass super-Eddington accretors (e.g., Bachetti et al. 2013; Walton et al. 2013, 2014, 2015a,b; Mukherjee et al. 2015; Rana et al. 2015). The discovery of a few neutron stars in these extra-galactic ULX populations further confirmed that super-Eddington accretion is a feasible scenario in some ULXs (Bachetti et al. 2014; Fürst et al. 2016; Israel et al. 2017a,b; Brightman et al. 2018; Carpano et al. 2018; Rodríguez Castillo et al. 2020; Sathyaprakash et al. 2019). However, some ULXs have luminosities more than 10^{41} erg s^{-1}. They are known as hyperluminous X-ray sources (HLXs) and possible candidates for IMBH hosts (e.g., Brightman et al. 2016; Webb et al. 2010).

ULXs are broadly classified into different states based on spectral components and hardness (see Kaaret et al. 2017; Sutton et al. 2013). ULXs with a cool accretion disk and a powerlaw tail are classified as the ultraluminous state. Depending on the hardness of the source, they can be hard ultraluminous (HUL) or soft ultraluminous (SUL) regimes, as defined by Sutton et al. 2013. A correlated classification of these two regimes is hard intermediate and soft bright states, respectively, as defined in Gürpide et al. 2021a,b. Typically, soft bright states are found in a higher luminosity regime than the hard intermediate state, which directly relates to the physical scenario of photons being down scattered by the dense medium of clumpy winds when the rate of accretion flow is high. The other states are broadened disk (BD) state and the super-soft ultraluminous (SSUL) state. The spectra of the former are dominated by thermal emission from a geometrically modified accretion disk. The SSUL spectra on the other hand, are dominated by single component cool blackbody emission. However, it is essential to understand that the distinction between these classifications is not always aseure, and many ULXs show spectral transition among these different states/regimes (e.g., Sutton et al. 2013; Walton et al. 2020; Gürpide et al. 2021a,b; D’Aì et al. 2021). These changes are due to variations in accretion rate, disk occultation, wind outflow strength, and several other physical parameters.

Kajava & Poutanen (2009) studied a sample of ULXs which showed distinctive luminosity-spectral photon index (L_X – Γ) correlation and anti-correlation. Such correlation studies indicate dissimilitude in ULX accretion scenarios in different epochs. Nevertheless, some important factors need to be considered before concluding such correlations. The absorption component and soft continuum like cool accretion disk can degenerate with a powerlaw model (e.g., Feng & Kaaret 2009; Kajava & Poutanen 2009; Pinto et al. 2017) since the powerlaw component extends to the low energy without any bound. Thus, luminosity from the soft spectral counterparts is often mis-interpreted. Hence, to understand whether such correlations come from real physical property, it is crucial to investigate and mitigate these “artefacts”.

NGC 1042 ULX1 (2XMM J024025.6-082428) is an extreme ULX, peak X-ray luminosity of which reaches L_X ~ 5×10^{40} erg s^{-1} (Sutton et al. 2012). The host galaxy is a SAB(s)cd type galaxy with a distance of ~ 18.9 Mpc. Sutton et al. (2012) studied a sample of
extreme ULXs using X-ray data from XMM-Newton and Chandra observatories. NGC 1042 ULX1 is one of the extremely luminous ULX in that sample. We study ULX1 in this work utilizing seven XMM-Newton observations and one NuSTAR observation. Three of these seven XMM-Newton observations (0093630101, 0306230101, 0553300401) were studied by Sutton et al. (2012) in detail. We primarily focus on the spectral properties and variability of ULX1 in different XMM-Newton observations and how different spectral parameters vary during these epochs. The data from NuSTAR indicate a typical spectral curvature of NGC 1042 ULX1, which is not revealed in any XMM-Newton observations.

The data reduction and analysis procedure are discussed in section 2. The timing and spectral analysis results of ULX1 are described in section 3. Section 4 contains a comprehensive discussion of the results.

2 DATA REDUCTION AND ANALYSIS

We study NGC 1042 ULX1 by utilizing archival XMM-Newton (Jansen et al. 2001) data and new NuSTAR (Harrison et al. 2013) observation. The observation log is given in table 1. The archival XMM-Newton observations targeted other sources like NGC 1052 galaxy and SDSSJ024052-082827. Hence, in most of the observations, ULX1 is highly off-axis. Thus, it is not always simultaneously detected by all three EPIC cameras. The new NuSTAR observation was a part of NICER+NuSTAR joint venture. However, the NICER spectra are dominated by background. Hence, we utilize NuSTAR data for scientific purposes.

The XMM-Newton data are extracted using standard XMM-Newton SAS software v20.0.0.1. The EPIC data are reprocessed with emproc and emproc tasks for pn and MOS respectively. The data are cleaned from background and proton flare by eliminating the time intervals strongly affected by flaring activities by identifying those intervals in the single event high energy light curves. Thus, while cleaning the data for all observations, we create good time intervals for each camera. After background filtering, the cleaned events are utilized to extract spectra and light curves with the emselect tool. The filtering expressions include PATTERN<= 4 for pn, which takes single and double events, and PATTERN<= 12 for both MOS, which take single, double, triple, and quadruple events. For spectral analysis, we use a strict filtering constraint of FLTFLAG= 0 for both pn and MOS. For timing analysis, we perform barycentric corrections on the events using the barycen tool. The background-corrected source light curves are created by epiclccorr task, which considers various effects like vignetting, quantum efficiency, bad pixels, and PSF variations. For most of the XMM-Newton observations, as stated earlier, the source ULX1 (RA:02 40 25.6 DEC:-08 24 30.0 ; Sutton et al. 2012) is highly off-axis. However, a 30 arcsec radius circle covers the whole source in all cases. Hence, we treat ULX1 as a point source in all observations. We extract source photons from a 30 arcsec circle around the source, and corresponding background photons are selected from a nearby source-free 60 arcsec circle in the same chip. The spectra are grouped using the task specgroup to have a minimum of 20 counts per energy bin and ensure that the minimum width of a group is 1/3 of the corresponding energy resolution (in full-width half maxima). RMFs and ARFs are created using rmfgen and arfgen tasks respectively.

The NuSTAR data are reprocessed and science events are extracted using HEASOFT (v6.29) routine nupipeline and nuproducts. The background subtraction of light curves for both FPMA and FPMB modules is done by the lcmath tool, and the spectra are grouped to have a minimum of 20 counts per energy bin. The source region is selected with a 30 arcsec circle around the source and the background of a 60 arcsec radius circle from a nearby source-free region.

3 RESULTS

3.1 Spectral Analysis

We utilize XSPEC v12.12.0 (Arnaud 1996) for spectral analysis of the ULX1 data. The neutral absorption component is modelled by TBABS with updated abundances (Wilms et al. 2000) and cross-sections (Verner et al. 1996). The uncertainties on the measured spectral parameter are quoted with a 90% confidence interval unless mentioned otherwise. We have utilized cflux model to estimate fluxes throughout the paper.

First, we plot the unfolded spectra from the observations we utilize in this paper to inspect the source spectral properties visually (see figure 1). The unfolded spectra are generated using a power-law model with zero photon index, i.e., essentially a constant model. An apparent variability above ~ 1 keV in different epoch spectra is clear. On the other hand, below ~ 1 keV, the spectra remain mostly overlapping. Signal to noise ratio (S/N) decreases significantly after 8.0 keV for XMM-Newton spectra and 20.0 keV for NuSTAR spectra. Hence analysis of XMM-Newton spectra are restricted to 0.3 – 8.0 keV energy range and for NuSTAR spectra 3.0 – 20.0 keV energy range is utilized.

We start analyzing data from individual XMM-Newton epochs by simultaneously fitting them with a simple absorbed powerlaw model and observing how spectral parameters change during these epochs. Parameters from all cameras for each observation are linked except for a constant parameter that is allowed to vary to consider the cross-calibration effects. Nevertheless, the parameters for each epoch are free to vary and are not linked to other epochs. The evolution of the parameters NH and Γ and their correlation are plotted in figure 2. We find that the NH component remains mostly consistent within error among these different epochs of observation (see figure 2 - left). However, the source shows a significant variation in spectral photon index (Γ) which ranges between ~ 1.4 – 2.7 (see figure 2 - middle). The NH – Γ relation is shown in figure 2 - right panel. It shows that NH does not play a significant role in the large variation of photon indices in different epochs.

To see how the NH influences the spectral hardness and flux, we also simultaneously fit all XMM-Newton epochs spectra by keeping NH free to vary globally but linking between different epochs. Keeping NH linked does not significantly change the fit in terms of χ^2/d.o.f from 631/534 to 642/540, which is expected because NH in all epochs are statistically similar. Nevertheless, more importantly, this comes with a prize of better constraints on the other spectral parameters. Our goal is to quantify the spectral variability for different epochs by measuring the continuum spectral parameters. Hence, we keep this NH linked for further analysis of XMM-Newton data. Linking NH ensures that the apparent variability is not artificial (see section 4 for details).

As stated earlier, we invoke the simplest model widely used to fit X-ray binaries and ULX spectra, an absorbed powerlaw. While

1 https://www.cosmos.esa.int/web/xmm-newton/sas-threads
2 https://www.cosmos.esa.int/web/xmm-newton/sas-thread-epic-filterbackground
3 https://heasarc.gsfc.nasa.gov/docs/software/heasoft/
keeping the $N_H$ linked between different epochs, the best fit value of $N_H$ is $0.18 \pm 0.02 \times 10^{22}$ cm$^{-2}$. The wide range variation of $\Gamma$ still holds in this case, too (see table 2). Both absorbed and unabsorbed luminosities are measured, which show variation in different epochs. The highest absorbed luminosity is $\sim 3$ times more than the lowest absorbed luminosity of the source.

We find that a single component multi color disk model (diskbb in XSPEC) is not a good description for the simultaneous spectral absorbed luminosity of the source. The highest absorbed luminosity is $\sim 3$ times more than the lowest absorbed luminosity of the source.

We find that a single component model following the work by Stobbart et al. (2006). We find that the $\Delta \chi^2$ values are significant compared to a single component powerlaw fit. We also find that the temperature of the disk component remains statistically the same (within 90% confidence) in all epochs; hence we link this parameter for different epochs and let it vary globally. We find that compared to the single component powerlaw model, the diskbb+powerlaw model gives much better statistical fit ($\Delta \chi^2 \approx -68$ for 8 less degrees of freedom). The variation in photon indices still prevails even though the cool disk component significantly contributes to the softer regime of the spectra (see the model components in figure 3). We also see a trend that for XM2 and XM4 epochs, which have shown hard spectra, have comparatively more ratio of the powerlaw flux and disk flux ($\frac{F_{\text{pl}}}{F_{\text{disk}}}$) than the epochs which have softer spectra (see table 3).

We also explore another two component model widely used for ULX spectral fits, i.e. diskbb+diskbb (e.g., Gürpide et al. 2021a; Koliopanos et al. 2017) which comprises of two temperature disk blackbody components. However, we find that when we fit two diskbb components, in some cases the uncertainties in hotter disk component is unphysically high, this could be partly due to the degeneracy between different parameters. Hence, we do not explore this model in detail for the current data. Certainly, we should mention that future on-axis and long exposure observations of this source might be able to adequately constrain such model.

With the current limitation of data, we consider that the two-component model diskbb+powerlaw provides a good statistical fit of ULX1 spectra in all epochs, and we consider this combination of the model as the best fit model for NGC 1042 ULX1. The residuals and unfolded spectra for all XMM-Newton epochs, along with the additive model components for this best fit model combination, are shown in figure 3. The spectral parameters are noted in table 2 and 3 for powerlaw and diskbb+powerlaw models.

Apart from analyzing the archival XMM-Newton observations, we analyze the new NuSTAR data to understand the spectral nature of ULX1 in the hard energy band. Unfortunately, the simultaneous soft counterpart of NICER observation of ULX1 is completely background-dominated. Hence, we cannot use the NICER data for any meaningful scientific analysis. Since the soft counterpart is unavailable, the NuSTAR spectra are fitted with absorption $N_H$ fixed to the best fit values taken from XMM-Newton fits. First, we fit an absorbed powerlaw model with $N_H$ fixed to 0.18 $\times 10^{22}$ cm$^{-2}$ and find that $\chi^2/d.o.f = 32/34$ with $\Gamma = 2.74^{+0.21}_{-0.20}$, which is a statistically acceptable fit suggesting that the current NuSTAR data are broadly consistent with a simple powerlaw model. However, if we include an exponential cutoff powerlaw model (cutoffpl) instead of powerlaw, the fit provides a lower $\chi^2$ value ($\chi^2/d.o.f = 21/33$). However, due to the limited S/N of the data, the photon index has a large error bar ($\Gamma = 0.14^{+1.39}_{-1.65}$), including a negative value in the lower error and an unconstrained normalization ($< 15.64 \times 10^{-5}$) with a folding energy value of $E_{\text{fold}} = 2.45^{+0.86}_{-0.98}$ keV. Hence, we freeze the photon index of cutoffpl model to 0.59, which is typical value for pulsar ULXs (see Walton et al. 2020). The fit remains statistically similar to a free photon index. The $\chi^2/d.o.f = 21/34$ with folding energy at $E_{\text{fold}} = 2.96^{+0.39}_{-0.33}$ keV. This folding energy value has to be treated with caution when compared with other ULXs. Due to the unavailability of simultaneous soft counterpart data, the cutoffpl parameters, including the photon index, are not well determined. Nevertheless, the turnover in the NuSTAR spectra is apparent from figure 1. The archival XMM-Newton data could not detect the cutoff in any observation when fitted with cutoffpl model (i.e., unconstrained folding energy with no statistical improvement compared to simple powerlaw fit), whereas, the new NuSTAR data detect the cutoff, although at the low energy threshold of XMM-Newton. The unabsorbed flux in $3.0 - 20.0$ keV energy range is $(2.49^{+0.39}_{-0.29}) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and corresponding luminosity is $(1.06^{+0.13}_{-0.12}) \times 10^{40}$ erg s$^{-1}$. The NuSTAR spectra are plotted in figure 3 (last panel). In order to provide statistical justification for the observed spectral turnover, we further fit the NuSTAR data with a broken powerlaw model following the work by Stobbart et al. (2006). We find that the $\chi^2/d.o.f = 19/32$ and the break energy is $E_{\text{break}} = 6.64^{+1.98}_{-1.24}$ keV.
with power law photon index for $E < E_{\text{break}}$ is $1.98_{-0.60}^{+0.49}$ and for $E > E_{\text{break}}$ is $4.0_{-0.7}^{+2.49}$. This indeed statistically validate the observed spectral break in the NuSTAR data.

3.2 Timing Analysis

NGC 1042 ULX1 shows steady nature in the time series of all XMM-Newton and NuSTAR observations. The background-subtracted source light curve for FPMA is plotted in figure 4. We utilize the pn data of four XMM-Newton observations to search for pulsation using HENDRICS v7.0.2 software (Bachetti 2018; Huppenkothen et al. 2019) implementing the HENzsearch tool with the fast folding algorithm, which searches for the first spin derivative. We have restricted the search to the frequency range of 0.1 ~ 6.8 Hz and the energy range of 0.3 ~ 8.0 keV. No pulsation is detected in any observation. We obtain the upper limits of pulsed amplitude for all four epochs, which range between ~ 20 ~ 40% (90% confidence interval). We also utilize the new NuSTAR data for timing analysis and search for pulsation with a similar method within the 0.1 ~ 10.0 Hz frequency range and 3.0 ~ 20.0 keV energy range. However, the S/N of NuSTAR data is low. Hence, we do not detect any pulsation here either. The upper limit of pulsed amplitude is ~ 40%.

4 DISCUSSIONS

This paper aims to study a luminous and variable ULX source, NGC 1042 ULX1. Sutton et al. (2012) studied a sample of extremely bright ULX sources; NGC 1042 ULX1 was one of them. Both possibilities of sub-Eddington accretion onto the intermediate-mass black hole and super-Eddington stellar-mass accretors scenario are discussed in that paper, which analyzed three archival XMM-Newton observations and one Chandra observation of ULX1. However, the absence of apparent soft excess and characteristic spectral cutoff in XMM-Newton data favoured the IMBH scenario. The spectral curvature of NGC 1042 ULX1, which is not constrained by any of the XMM-Newton observations, can be due to the low quality of the data (see the discussion of Sutton et al. 2012). Nevertheless, the current analysis of XMM-Newton and NuSTAR data provides more insight into the source, thoroughly discussed in this section.

4.1 Accretion states of ULX1

It is important to compare the accretion state of any individual ULX with the known ULX spectral states (e.g., Sutton et al. 2013; Kaaret et al. 2017; Gürpide et al. 2021a,b). Based on the definition followed by Sutton et al. 2013 for different ULX states and interpreting the relative contribution of soft and hard components for NGC 1042 ULX1 indicates similarity with the ultraluminous state. The spectral hardness mostly indicates the source resembles HUL regime, although, in some observations, the error on the photon index extends to the SUL regime. Due to the limited quality of XMM-Newton data, it would be difficult to rule out the degeneracy between the soft thermal disk component and hard powerlaw component, which is manifested by the somewhat large measurement uncertainties in the spectral parameters. Nevertheless, the changes in spectral profile are evident from figure 1, figure 3 and the quantified results noted in table 2 and 3.

Another critical point to note is that the spectral differences are more prominent beyond ~ 1 keV. Such an interesting behavior has also been reported in other ULXs, like NGC 1313 X1, NGC 55 ULX1, Holmberg IX X1, M51 ULX8, NGC 4395 ULX1 (Sutton et al. 2013; Middleton et al. 2015; Walton et al. 2020; Gürpide et al. 2021a; Ghosh et al. 2022). In general, it can be understood as a scenario where the cool emission component does not vary in different observations, but the hot counterpart exhibits variability. Typically for ULXs, it is understood that the cool disk blackbody component is the manifestation of optically thick wind which is launched near the spherization radius when the accretion rate reaches the Eddington limit and the powerlaw component approximates a hotter inner accretion flow modified by a Comptonization process, which is a dominant radiative mechanism in many ULXs (see e.g., Urquhart & Soria 2016; Pinto et al. 2017; Walton et al. 2020). Current data do not allow us to constrain a theoretical Comptonization model like comptt. Since the spectral hardness for a Comptonization process directly depends on how much photons are up-scattered from the seed photons of the disk, the powerlaw model as an approximation indicates that there is a variation in the up-scattered photon fraction in different epochs of XMM-Newton if the hard spectrum is indeed dominated by Comptonization process. It is also important to note that the temperature of the soft disk blackbody component for ULX1 remains similar within the ~ 90% confidence interval, again suggesting that the spectral variability originates from the hard component i.e., either variability in inner accretion flow or contribution from Comptonization process.

Gürpide et al. 2021a,b studied spectral variability in a sample of ULX sources and predicted physical scenarios which could generate such variabilities in these sources. One crucial understanding is that, for super-Eddington stellar-mass accretors, a strong radiatively driven outflow is generated near the spherization radius due to the high accretion rate in the system. The outflow can be optically thin or thick depending on whether the inclination angle of the system is low or high, respectively (Gürpide et al. 2021a; Poutanen et al. 2007). Thus, a low inclination of the disk would enhance the probability of hard photons dominating the line of sight emission. On the contrary, for a higher inclination angle, the hot part of the disk would be obscured, and most of the hard photons would be down-scattered by the optically thick wind, and thus soft emission would dominate the spectrum. Thus, changes in inclination would imply the variation in
occultation of the inner region of the disk which would imprint the variability in hardness of the observed spectrum.

NGC 1042 ULX1 shows a negative correlation between spectral photon index and luminosity (see figure 5 and section 4.3), which means a higher luminosity state is harder. One of the possible explanations for such a behavior is that the hard photons are aligned to the line of sight through the optically thin tunnel, and with a higher accretion rate (which means higher luminosity) in the inner region of the accretion disk, hot (hard) photons can reach us. This would imply that, in general, NGC 1042 ULX1 is a low inclination system where the outflow is optically thin. Hence, an increase in accretion rate does not ensure that the hard photons would be down-scattered and move out of the line of sight. Moreover, geometrical beaming would play a crucial role to explain that the higher luminosity state is spectrally

Table 2. Parameter table for {\textit{powerlaw}} model in seven epochs of \textit{XMM-Newton} observation of NGC 1042 ULX1 for linked $N_H$. We list the observed (absorbed) fluxes and luminosities in 0.3-8.0 keV energy range. The intrinsic (unabsorbed) fluxes are typically ~ 1.2-1.6 times of the observed flux.

| Parameters | Unit            | XM1          | XM2          | XM3          | XM4          | XM5          | XM6          | XM7          |
|------------|-----------------|--------------|--------------|--------------|--------------|--------------|--------------|--------------|
| $N_H$      | $10^{22} \text{cm}^{-2}$ | 0.18 ± 0.02  | 0.18 ± 0.02  | 0.18 ± 0.02  | 0.18 ± 0.02  | 0.18 ± 0.02  | 0.18 ± 0.02  | 0.18 ± 0.02  |
| $\Gamma$   |                 | 2.00 ± 0.14  | 2.11 ± 0.10  | 2.11 ± 0.10  | 2.11 ± 0.10  | 2.11 ± 0.10  | 2.11 ± 0.10  | 2.11 ± 0.10  |
| $N_{pl}$   | $10^{-4}$       | 1.59 ± 0.19  | 1.19 ± 0.08  | 1.01 ± 0.08  | 1.46 ± 0.10  | 1.18 ± 0.10  | 0.98 ± 0.10  | 1.20 ± 0.13  |
| $\chi^2$/d.o.f |            | 642/540      | 642/540      | 642/540      | 642/540      | 642/540      | 642/540      | 642/540      |
| $F_{\text{obs}}$ | $10^{-12} \text{erg s}^{-1} \text{cm}^{-2}$ | 5.72 ± 0.11  | 6.96 ± 0.44  | 3.54 ± 0.26  | 8.77 ± 0.53  | 3.55 ± 0.31  | 3.28 ± 0.32  | 5.26 ± 0.50  |
| $L_{\text{obs}}$ | $10^{42} \text{erg s}^{-1}$ | 2.44 ± 0.35  | 2.98 ± 0.19  | 1.51 ± 0.12  | 3.75 ± 0.22  | 1.52 ± 0.13  | 1.40 ± 0.14  | 2.25 ± 0.25  |

Table 3. Parameter table for {\textit{diskbb+powerlaw}} model in seven epochs of \textit{XMM-Newton} observation of NGC 1042 ULX1. We list the observed (absorbed) fluxes and luminosities in 0.3-8.0 keV energy range. We also note the individual intrinsic flux of additive components in the same energy range.

| Parameters | Unit            | XM1            | XM2            | XM3            | XM4            | XM5            | XM6            | XM7            |
|------------|-----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| $N_H$      | $10^{22} \text{cm}^{-2}$ | 0.23 ± 0.04   | 0.23 ± 0.04   | 0.23 ± 0.04   | 0.23 ± 0.04   | 0.23 ± 0.04   | 0.23 ± 0.04   | 0.23 ± 0.04   |
| $T_{\text{in}}$ | keV            | 2.82 ± 0.45   | 3.67 ± 0.24   | 2.45 ± 0.60   | 6.46 ± 0.50   | 2.70 ± 0.66   | 6.38 ± 0.91   | 6.38 ± 0.91   |
| $N_{\text{disk}}$ |                 | 1.39 ± 0.13   | 1.81 ± 0.28   | 1.45 ± 0.11   | 1.71 ± 0.26   | 2.01 ± 0.21   | 1.10 ± 0.24   | 1.10 ± 0.24   |
| $N_{pl}$   | $10^{-4}$       | 0.90 ± 0.15   | 0.72 ± 0.23   | 1.33 ± 0.16   | 0.60 ± 0.37   | 0.79 ± 0.26   | 0.58 ± 0.15   | 0.58 ± 0.15   |
| $\chi^2$/d.o.f |            | 574/532       | 574/532       | 574/532       | 574/532       | 574/532       | 574/532       | 574/532       |

Figure 2. The variation of $N_H$ and $\Gamma$ over different \textit{XMM-Newton} observation epochs are shown in left and middle panels. The relation between $N_H$ and $\Gamma$ are shown in right panel. For these parameter estimates, we utilize an absorbed powerlaw model with $N_H$ parameter being allowed to vary for different epochs of observation.
Figure 3. The spectra and residuals for `diskbb+powerlaw` model of XMM-Newton observations and `cutoffpl` model of NuSTAR observation. The black, red and green colors correspond to MOS1, MOS2 and pn, while blue and light blue colors correspond to FPMA and FPMB data respectively. Corresponding additive models are also shown in top panels of each figure.
4.2 Nature of the accretor

The acceleration search in the Fourier space of time series does not confirm any pulsation candidates, hence we cannot confirm whether ULX1 hosts a neutron star or black hole. An interesting comparison of NGC 1042 ULX1 and its hard spectra would be with the spectra of pulsar ULXs and the sources which resemble pulsar-like spectra (see, e.g., Pintore et al. 2017; King 2009; Middleton et al. 2015; Luangtip et al. 2016).

While discussing the Comptonization process, one should consider both black hole and neutron star scenarios of ULXs. This Comptonization can be either an external Comptonization in the Corona region due to inverse-scattering, or it can be a magnetized Comptonization due to shock formation in the polar region of a neutron star. The hard sources are often perceived to be strongly magnetized neutron star systems where the emission is directly coming from the accretion column (Gürpide et al. 2021a).

4.3 Anti-correlation between $\Gamma - L_X$

The correlation between $\Gamma$ and $L_X$ is widely studied for X-ray binaries (e.g., Yang et al. 2015) and ULXs (e.g., Kajava & Poutanen 2009). They are excellent probes in understanding the physical accretion processes in these sources. We carry out a similar study for NGC 1042 ULX1 and plot the correlation between luminosity and spectral photon index in figure 5. We discuss the theoretical notion of negative correlation found for ULX1. Before that, we need to discuss possible “artefacts” which can arise from absorption and low-energy thermal components.

We find anti-correlation between $\Gamma$ and $L_X$ for powerlaw fit in both cases when the absorption parameter is kept free for all epochs and linked between different epochs. In both cases, unabsorbed and absorbed luminosities are negatively correlated with $\Gamma$. The overall nature of this negative correlation is not significantly influenced by the absorption parameter, as shown in figure 2-right. However, a reader would be cautious when interpreting the correlation between $\Gamma$ and $N_H$, where a slightly lower $N_H$ trend is seen when the spectra are harder. The Pearson r-coefficient is $\sim 0.77$ with p-value $\sim 0.04$ and the Spearman correlation coefficient is $\sim 0.73$ with p-value $\sim 0.06$. The p-values suggest the probability of having the same correlation measurement from an uncorrelated system. In other words, typically, if $p > 0.05$, then the correlation might have occurred by chance and cannot be considered statistically significant. Although this correlation between $N_H$ and $\Gamma$ is not statistically significant, we would discuss two possibilities for such a trend. First, the powerlaw model extends to lower energy arbitrarily, degenerating with softer spectral components. This could give rise to such a correlation. Another possibility is that the $N_H - \Gamma$ correlation is indeed physical. A higher accretion rate would increase the luminosity and we see a trend of increasing hardness in the system. Due to low inclination, the hard photons pass through the optically thin tunnel and reach us. Hence, the neutral $N_H$ component appears to be less dominant with the harder spectral state. In either case, the anti-correlation between $\Gamma$ and $L_X$ is prominent and can be understood as real. When the absorption parameter is linked, we measure the correlation coefficients between $\Gamma$ and $L_X$. For absorbed luminosity, the Pearson r-coefficient is $\sim -0.921$ with p-value $\sim 0.003$ and the Spearman correlation coefficient is $\sim -0.857$ with p-value $\sim 0.014$. For unabsorbed luminosity, the Pearson r-coefficient is $\sim -0.857$ with p-value $\sim 0.014$ and the Spearman correlation coefficient is $\sim -0.857$ with p-value $\sim 0.014$ (see figure 5 - left).

To remove any “artefact” from soft energy regime apart from the neutral absorption, we also study the correlation trend between $2.0 - 8.0$ keV $\Gamma$ and intrinsic $L_X$ (figure 5 - right). This would minimize any artificial boost in luminosity in the soft energy part and predict the correlation only in the high energy spectrum. For this purpose, we fit the data with an absorbed powerlaw model in the $2.0 - 8.0$ keV range by fixing the $N_H$ to the best-fit value from $0.3 - 8.0$ keV fit. The negative correlation still holds although the measurement uncertainties are large due to lower count statistics. Observation XM1 has very low counts in $2.0 - 8.0$ keV; hence, the measurement errors are very high. Hence, we do not consider this observation in figure 5 - right. In this figure, the Pearson r-coefficient is $\sim -0.922$ and p-value is $\sim 0.009$. The Spearman correlation coefficient, on the other hand, for the same data points, is $\sim -0.771$, and the p-value is $\sim 0.072$. We would also mention that the measurement of the Pearson and Spearman correlation coefficients need to be treated with caution because of the low sample space and also these measurements do not consider the errors in the parameters.

It is important to understand the underlying theoretical interpr-
Figure 5. $\Gamma - L_X$ negative correlation for different XMM-Newton epochs for 0.3 – 8.0 keV energy range (Left). Same quantities are plotted on the right side also but for 2.0-8.0 keV energy range.

The negative correlation between $\Gamma$ and $L_X$ can be interpreted as geometric beaming of hard photons directly to the line of sight as explained in section 4.1. Also, the hard spectrum is often explained by the emission from the strong accretion column (e.g., Pintore et al. 2017; Walton et al. 2018; Gürpide et al. 2021a). Relative contribution of change in accretion rate and magnetic field strength would determine the scale of magnetospheric radius $R_M$ and spherization radius $R_S$. If $R_M$ truncates the disk close to the $R_S$, the spectral contribution from accretion column would be stronger (see Walton et al. 2018), hence making the spectra harder. That would mean the increasing luminosity is directly coming from the hard emission from the accretion column. This is also supported by the observed trend in table 3, where harder spectral epochs like XM2 and XM4 are seen to have increased flux in powerlaw component.

To summarize, NGC 1042 ULX1 is a bright ULX whose luminosity reaches a few times $\sim 10^{40}$ erg s$^{-1}$. The spectral properties suggest that the source is a stellar mass super-Eddington accretor. Due to variations in accretion rate, disk occultation, or strength of Compton scattering, the source exhibit a change in luminosity and spectral hardness. Future monitoring broadband observations can decipher the energy-dependent variability in the source beyond $\sim 10$ keV and help in understanding the accretion state of the source in a more comprehensive form.

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DATA AVAILABILITY

The XMM-Newton data utilized in this work are available for download in the High Energy Astrophysics Science Archive Research Center (HEASARC) archive (https://heasarc.gsfc.nasa.gov/db_perl/W3Browse/w3browse.pl). The NuSTAR data used in this work were acquired from the joint NICER+NuSTAR proposal and will become available in the HEASARC archive from December 2022.

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