The rare X-ray flaring activity of the Ultraluminous X-ray source NGC 4559 X7

Fabio Pintore$^{1,2}$, S. Motta$^3$, C. Pinto$^2$, M.G. Bernardini$^3$, G. Rodríguez-Castillo$^{2,4}$, R. Salvaterra$^1$, G. L. Israel$^1$, P. Esposito$^5$, E. Ambrosi$^2$, C. Salvaggio$^{3,6}$, L. Zampieri$^7$, A. Wolter$^3$

$^1$ INAF – IASF Milano, Via E. Bassini 15, 20133 Milano, Italy; $^2$ INAF – IASF Palermo, Via U. La Malfa 153, 90146 Palermo, Italy; $^3$ INAF, Osservatorio Astronomico di Brera, Via Brera 28, 20121 Milano, Italy; $^4$ INAF - Osservatorio astronomico di Roma, Via Frascati 44, I-00040, Monteporzio Catone, Italy; $^5$ Scuola Universitaria Superiore IUSS Pavia, Piazza della Vittoria 15, 27100 Pavia, Italy; $^6$ Dipartimento di Fisica, Università degli Studi di Milano-Bicocca, Piazza della Scienza 3, I-20126 Milano, Italy; $^7$ INAF-Osservatorio Astronomico di Padova, Vicolo dell’Osservatorio 5, I-35122 Padova, Italy

ABSTRACT

Ultraluminous X-ray sources are considered amongst the most extremely accreting objects in the local Universe. The recent discoveries of pulsating neutron stars in ULXs strengthened the scenario of highly super-Eddington accretion mechanisms on stellar mass compact objects. In this work, we present the first long-term light curve of the source NGC 4559 X7 using all the available Swift/XRT, XMM-Newton, Chandra and NuSTAR data. Thanks to the high quality 2019 XMM-Newton and NuSTAR observations, we investigated in an unprecedented way the spectral and temporal properties of NGC 4559 X7. The source displayed flux variations of up to an order of magnitude and an unusual flaring activity. We modelled the spectra from NGC 4559 X7 with a combination of two thermal components, testing also the addition of a further high energy cut-off powerlaw. We observed a spectral hardening associated with a luminosity increase during the flares, and a spectral softening in the epochs far from the flares. Narrow absorption and emission lines were also found in the RGS spectra, suggesting the presence of an outflow. Furthermore, we measured hard and (weak) soft lags with magnitudes of a few hundreds of seconds whose origin is possibly due to the accretion flow. We interpret the source properties in terms of a super-Eddington accretion scenario assuming the compact object is either a light stellar mass black hole or a neutron star.

Key words: accretion, accretion discs - X-rays: binaries - X-Rays: galaxies - X-rays: individual: NGC 4559 X7.

1 INTRODUCTION

Ultraluminous X-ray sources (ULX) are a class of non nuclear accreting compact objects displaying X-ray luminosities higher than $10^{39}$ erg s$^{-1}$ and up to $10^{41}$–$10^{42}$ erg s$^{-1}$ (e.g. Kaaret et al. 2017). The nature of the compact object, in the vast majority of ULXs, is nowadays believed to be of stellar type, i.e. stellar mass black holes (BH; $M_{\text{BH}} = 5$–80 $M_\odot$) or neutron stars (NS). In particular, six accreting ULXs hosting pulsating NSs (PULXs), with spin periods in the range 0.5 s – 20 s have been discovered in recent years (Bachetti et al. 2014; Israel et al. 2017; Carpano et al. 2018; Israel et al. 2017; Koliopanos et al. 2017; Walton et al. 2018, 2020). The assumption that the accretor is a stellar-mass compact object implies super-Eddington accretion, where a certain degree of

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geometrical beaming may be taken into account to explain the observed high X-ray luminosity in ULXs. Magnetohydrodynamical simulations showed that, in case of super-Eddington accretion, strong optically thick outflows in the form of winds can be radiatively ejected by the accretion disc (e.g. Poutanen et al. 2007; Ohsuga & Mineshige 2011; Takeuchi et al. 2014), from radii smaller than the so called spherization radius \( r_{\text{sp}} \propto \dot{m}^{1/2}, \) where \( r_{\text{sp}} \) is the accretion rate in Eddington rate units; e.g. Poutanen et al. 2007). Observational evidence in favour of powerful outflows/winds were identified in some ULXs in which blue-shifted (\( \sim 0.2c \)) absorption lines have been detected (e.g. Pinto et al. 2016, 2017; Kosacev et al. 2018). In addition, such winds are believed to be the main cause of the time lags between soft and hard X-ray photons observed in some ULXs, such as NGC 55 ULX-1 (Pinto et al. 2017), NGC 5408 X-1 (e.g. Heil & Vaughan 2010; De Marco et al. 2013) and NGC 1313 X-1 (Kara et al. 2020). Such lags, conventionally labelled as negative lags (or soft lags, because the soft photons lag the hard ones), are observed at low frequencies (\( \sim 0.1-10 \text{ mHz} \)) with a magnitude of tens to thousands of seconds, and are thought to originate from the propagation of hard photons through a very extended optically thick medium, likely associated with the base of the outflows. Because of the generally low ULX count-rate, time lags appear to be preferentially observed in sources with high short-term variability. The presence of flaring activity was also observed in epochs where lags were found, as in the case of the ULX NGC 1313 X-1 (Kara et al. 2020). However, flares as well as heart-beat variability are not so common in ULXs and only an handful of sources showed them (e.g. NGC 7456 ULX-1, Pinto et al. 2020; NGC 253 ULX-1, Barnard 2010; NGC 6946 ULX-3, Earnshaw et al. 2019; NGC 247 ULX-1, Pinto et al. in prep.; 4XMM J111816.0-324910 in NGC 3621, Motta et al. 2020).

In this work, we report on the source NGC 4559 X7 (also known as RX J123551+2756; X7 hereafter), a ULX in the galaxy NGC 4559, which showed a peculiar flaring activity during X-ray observations taken with XMM-Newton and NuSTAR in 2019. NGC 4559 is a spiral galaxy historically assumed to be at a distance of \( \sim 10 \text{ Mpc} \) (Tully & Fisher 1988; Sanders et al. 2003; although the lower distance limit is \( \sim 7 \text{ Mpc} \), Sorce et al. 2014). The galaxy hosts two ULXs (X7 and X10; e.g. Soria et al. 2004) that have been poorly studied in the past. Only a few short Chandra and XMM-Newton observations of NGC 4559 are available in the archives, during which the two ULXs showed extremely high 0.3–10 keV luminosity (\( > 10^{40} \text{ erg s}^{-1} \)), if a distance to the source of 10 Mpc is assumed. X7 lies in the outskirt of the galaxy (RA = 12h 35m 51.71s, Dec = +27d 56m 04.1s; Swartz et al. 2011), inside a region rich of OB-type stars with low metallicity (0.2 < [Z/Fe] < 0.4), where Soria et al. (2004) identified its possible optical counterpart as a blue supergiant of 20 M\(_{\odot}\) and an age of \( \sim 10 \text{ Myr} \).

### 2 DATA REDUCTION

**XMM-Newton.** XMM-Newton observed NGC 4559 on 27 May 2003 for \( \sim 42 \text{ ks} \). Then our group obtained a new \( \sim 75 \text{ ks}-\text{long observation}, which was taken on 16 June 2019 (PI: F. Pintore; Table 1). We reduced the two observations with SAS v18.0.0. We used data from both EPIC-pn and EPIC-MOS (1 and 2) cameras; events were selected considering \( \text{PATTERN} \leq 4 \) (i.e. double and single-pixel events) for the PN, and \( \text{PATTERN} \leq 12 \) (i.e. single- and multiple-pixel events) for the MOS. We extracted source and background events from circular regions with radii of 30” and 60”, respectively. The photon times of arrival (ToAs) were converted to the barycenter of the Solar System with the task BARYCEN, using the best Chandra coordinates (RA = 12h 35m 51.71s, Dec = +27d 56m 04.1s; Swartz et al. 2011) of the target.

Both observations were only marginally affected by high background epochs, which were excluded from the analysis. This resulted in a net exposure time of \( \sim 35 \text{ ks} \) and \( \sim 65 \text{ ks} \) for the observations taken in 2003 and 2019, respectively. Source and background spectra were grouped, with the FTOOLS grrppha, in order to accumulate at least 25 counts per energy bin, and we applied the SAS task EPICLCXCORR to all light curves. We also used data from the Reflection Grating Spectrometer (RGS; den Herder et al. 2001) of the 2019 observation, where X7 was at center of the field of view (FoV). The RGS data were reduced with the RGSPROC task, which produces calibrated event files, spectra, response matrices, and 1D images. Following the standard proce-

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**Table 1. Log of the observations used in this work.**
The total exposure time of this observation is ∼XMM-Newton taken about 6.4 h after the 2019 XMM-Newton observation (Obs.ID: 30501004002) was taken about 6.4 h after the 2019 XMM-Newton observation (Table 1). The total exposure time of this observation is ∼95 ks. We processed and reduced the data with the standard NUPI pipeline task of the NuSTAR Data Analysis Software v1.3.0 (NUSTARDAS) in the HEASOFT package version 6.25, adopting standard filtering and corrections. Spectra were extracted from circular regions with radius 60″ for both source and background. Spectra were then rebinned to accumulate at least 25 counts per energy bin.

**Chandra.** We analyzed the Chandra observations of 14 January and 4 June 2001, and 14 March 2002, with exposures of 9.7 ks, 11 ks and 3 ks, respectively (Table 1). We reduced the data with CIAO v4.9 and calibration CALDB v4.7.6. We selected source and background events from circular regions with radii 3″ and 15″, respectively. The source spectra were obtained with the task SPECRECTRACTOR of the CIAO package, which produces appropriate response and auxiliary files. Source and background spectra were grouped with grppha in order to accumulate at least 25 counts per energy bin.

**Swift.** The Neil Gehrels Swift Observatory (hereafter Swift) observed the galaxy NGC 4559 for 56 times between January 2006 and March 2021 (Table 1). Most observations were taken in PC mode with an average exposure time of about 1–2 ks each. We reduced the data with the XRTPipeline tool and we extracted source and background events from circular regions of radii 40″ and 60″ (centered at the source position and in a source-free region of the CCD), respectively. We used the Swift/XRT observations only to construct a long-term light curve, as the data quality is not good enough to allow us to perform high quality spectral analysis of individual or stacked pointing. We estimated the source flux in each observation by fitting an absorbed powerlaw model with photon index and column density fixed at 2 and 1.5 × 10^{21} cm^{-2}, respectively, and letting only the powerlaw normalization to vary. The choice of this reference model was adopted because of the poor quality of the spectra.

Figure 1. Long-term lightcurve of X7 in the 0.3–10 keV energy band obtained from the XMM-Newton, NuSTAR, Chandra and Swift/XRT observations. The luminosities (not corrected for absorption) refer to the average values for all the observations and are calculated assuming a distance of 10 Mpc. The source luminosities in the Swift/XRT observations are estimated by adopting an absorbed powerlaw model (see text for details).

3 **LONG AND SHORT TERM VARIABILITY**

The long-term X-ray light curve shows that X7 varies in flux by up to a factor of ∼5–6. The observed source flux peaked during the 2019 XMM-Newton observation of our X-ray campaign, Swift/XRT and NuSTAR pointed at X7 a few hours later, finding the source at a mean flux a factor of ∼3 lower than during the XMM-Newton observation. This indicates that flux variations in X7 may happen on a few-hours time-scales (Fig. 1).

Remarkably, the 2019 XMM-Newton and NuSTAR observations caught a period of flaring activity of X7, never seen in any of the previous X-ray observations of the source. In particular, we found two flares in the XMM-Newton observation, at MJD ∼ 58651.22 and 58651.33, and at least four (or possibly five) flares in the NuSTAR observation, at MJD ∼ 58652.46, 58652.52, 58652.61 and 58652.99 (Fig. 2). Furthermore, in the last ∼15 ks of the XMM-Newton observation (i.e. from MJD 58651.44), we observed a high flux phase following the flares, which plateaued at a flux level compatible with that at the peak of the flares (see Fig. 2). During the high-flux phase, the source flux increased by more than a factor of ∼4 with respect to the persistent pre-flare emission, implying that the luminosity of X7 can vary by over almost an order of magnitude.

The flares show a variable duration of ∼5–10 ks and, based on the XMM-Newton observation, their shape is mildly energy-dependent (Fig. 2; we stacked the EPIC-pn and MOS1-2 cameras...
to obtain the shown light curve). The first flare in the *XMM-Newton* curve presents a double peak at energies < 2 keV, but appears to be single-peaked at higher energies. Despite the lower signal-to-noise ratio of the *NuSTAR* data, we note that in these data the flares seem to be grouped: at least three flares occurring in fast succession can be identified around MJD 58652.6, and two flares around MJD 58653. The limited count statistics of the data prevents us to perform a more in-depth analysis, although a visual inspection suggests that the flares do not show any obvious repeating pattern.

We also note the existence of “dip”-like events during the high flux epochs in the last 15 ks of the *XMM-Newton* observation. Such features last for ~ 1ks and resemble the dips seen in NGC 55 ULX-1 (Stobbart et al. 2004), as they appear stronger at higher energies. Unfortunately, we cannot determine if they are really ULX-like dips or rather a storm of unresolved flares.

Finally, the *Swift/XRT* observations taken in 2020–2021 seems to show a possible (super-)orbital variability of X7 (see zoom in Fig. 1), which is even more evident in the 1.5–10 keV energy band. We performed a Lomb-Scargle analysis on these data only (i.e. we excluded all the scanty observations taken prior to 2020) and we found a possible best period of ~ 190 d. Unfortunately, the number of covered periods is still poor, which makes not possible yet to confirm robustly such a variability. Further continuous *Swift/XRT* monitoring are needed.

### 4 2019 XMM-NEWTON AND NUSTAR OBSERVATIONS

#### 4.1 Timing

We created three light-curves of X7 by combining events collected with all the EPIC cameras in the energy band 0.3–10 keV. Then we binned the data with 140 s (Nyquist frequency $\delta f \approx 1/T \approx 3 \times 10^{-5}$ Hz), we calculated one single power density spectrum (PDS) from the entire light-curve. The resulting PDS is shown in Fig. 3. The *XMM-NEWTON* power density spectrum appears featureless, characterised by low-amplitude red noise. A low-significance narrow feature appears at frequency $\approx 10^{-4}$ Hz, which can be ascribed to the flares visible in the light curve. We investigate the presence of variability on shorter timescales as well (from a few tens to a few hundreds seconds). The resulting power density spectrum appears completely dominated by the instrumental noise, and no other feature is significantly detected above it.

We also produced an average PDS from the *NuSTAR* observation. A typical *NuSTAR* observation features a large number of data segments separated by orbital gaps, which prevent from exploring via Fourier analysis the presence of long-term variability on timescales longer than the typical data segment (≈ 1000s). Furthermore, the count rate of X7 as seen by *NuSTAR* is low (between 0.05 and 0.25 counts s$^{-1}$). Therefore, for both the FMPA and FMPB instruments on-board *NuSTAR*, we only explored the short timescales by producing PDS over data stretches of variable length (between 130s and 1050s), which we averaged into one final PDS to increase the signal-to-noise ratio. Similarly to the *XMM-NEWTON* case, the resulting PDS are dominated by instrumental noise, and no significant feature is detected.
**4.2 Search for pulsations**

We searched for coherent signals in the 2019 XMM-Newton/EPIC-pn light curves of X7 in the 0.3–10 keV energy range (about 72000 counts) by adopting the recipe outlined in Israel & Stella (1996). We firstly considered the effects of signal smearing introduced by the possible presence of a strong first period derivative component $\dot{P}$, as seen in many PULXs (as an example see Israel et al. 2017). We corrected the photon arrival times by a factor $\frac{1}{2} \dot{P} P^2$ for a grid of about 2000 points in the range $4 \times 10^{-6} < |\dot{P} (s^{-1})| < 5 \times 10^{-12}$ (see Rodríguez Castillo et al. 2019 for details). No significant peak was found and 3σ upper limits to the pulsed fraction (PF), defined as the semi-amplitude of the sinusoid divided by the average count rate, were derived for the source. In the best cases, we obtained upper limits around 5%–8% in the 150 ms–150 s range. We then searched for pulsations applying orbital corrections for orbits with periods in the range $\sim 2$ h – 10 d, and composed by a NS and a companion star mass ranging from $\sim 0.01$ up to 100 $M_\odot$. No convincing pulsations were detected, but only a marginal detection of a signal at $\sim 1.7$ s, with PF $\sim 8\%$ and significance $\sim 3\sigma$, for an orbital period of about 2.8 h and a companion star of mass $\sim 0.2 M_\odot$. However, we note that such a companion mass value would be in contrast with the blue supergiant counterpart identified by Soria et al. (2004).

To investigate the 1.7 s candidate signal, we used its orbital parameters and all the available observations with enough statistics to reveal a $\sim 8\%$ PF signal. We searched in the 2003 XMM-Newton observation and in our NuSTAR (see Table 1) observation, which are the only two observations that could at least marginally detect such a low PF signal. We applied the corrections corresponding to the orbital parameters, but the 1.7 s signal candidate could not be confirmed. We do report on this candidate signal in future observations, with better counting statistics, which could allow us to convert its marginal significance to a robust detection.

**4.3 Time lags**

The appearance of flaring activity in X7 prompted us to search for time-lags between different energy bands, similar to those observed in the ULXs NGC 5408 X-1, NGC 55 ULX1 and NGC 1313 X-1 (De Marco et al. 2013; Pinto et al. 2017; Kara et al. 2020). We performed the analysis focusing only on the EPIC-pn data of the 2019 XMM-Newton observation, to avoid stacking data from different instruments that may introduce fake variability. In order to do so, we created background-subtracted light curves in the 0.3–2 keV and 2–10 keV energy bands, where the source counting statistics are comparable.

We first performed a cross-correlation between the two light
curves in the time domain by using a non-mean subtracted discrete cross-correlation function (CCF, Band 1997). We used light-curves binned to a time resolution of $\Delta T = 20s$ (in order to exclude all the white noise at high frequencies) and choose the 2–10 keV range as reference energy band. We calculated the CCF value for a series of time delays $k\Delta T$ and we defined the lag as the time delay that corresponds to the global maximum of the circular CCF versus time delay, located by fitting an asymmetric Gaussian model to the CCF versus time delay. The uncertainties on the CCF have been derived by applying a flux-randomization method (Peterson et al. 1998).

versus time delay. The uncertainties on the CCF have been derived by applying a flux-randomization method (Peterson et al. 1998).

We found marginal indications of a positive lag (hard lag) of 94 ± 4.1s (1σ uncertainty), which, according to our convention, implies that the hard photons lag the soft photons.

Further investigated how the hard lag depends on the frequency. Following the recipe described in Uttley et al. (2014), we calculated the Fast Fourier transform of the light curves in the 0.3–2 keV and 2–10 keV energy bands, binned with $\Delta T = 100s$, and we calculated the CCF. The latter was then averaged over 5 intervals, each of them containing segments of 128 time bins. Lags were then grouped in equally spatially logarithmic bins of frequency.

High coherence $^{1}$ between the two bands are observed for frequencies lower than $\sim 10^{-3}$ Hz, while above this threshold the coherence dramatically drops to values consistent with zero (Fig. 4 top-left). A hard lag in the frequency range (0.7 – 1.6) × $10^{-4}$ Hz is seen, in a frequency region where the coherence is also high. The global significance of the lag (estimated by summing the significance of each lag point) in the (0.7 – 1.6) × $10^{-4}$ Hz frequency range is higher than 5σ. This result still confirms that, on long time-scales, the hard band lags the soft one for a weighted average value of 335 ± 89s, compatible within uncertainties with the value derived from the CCF. The frequency range at which the lag is found is compatible with the time interval between the two observed flares, which implies that the lag is likely mainly driven by such temporal features.

We verified the robustness of the positive time lag by performing a Monte Carlo simulation of 1000 light-curves having the same variability observed in the EPIC-pn 0.3–10 keV energy band, rescaled to the mean count-rate found in the 0.3–2.0 keV and 2.0–10 keV energy bands. For each couple of simulated 0.3–2.0 keV and 2.0–10 keV light curves, we estimated the frequency-dependent lags and we inferred that a hard lag in the range (0.7 – 1.6) × $10^{-4}$ Hz can be observed with a significance higher than 5σ only 3 times over a total of 1000, i.e. a probability of 0.007 (hence $> 3\sigma$), that the observed lags in the 2019 XMM-Newton observation are not due to chance coincidence.

We then extracted the lag-energy spectrum of the observed data in the frequency range (0.7 – 1.6) × $10^{-4}$ Hz. For each energy bin, we calculated the lag using the 0.3–10 keV band as reference, from which we removed each band of interest. This is shown in Fig. 4 top-right. The coherence clearly increases towards higher energies. At energies below 2 keV the lags are quite unconstrained although they suggest a soft lag, while above this energy the lags are significantly positive.

Besides the hard lag, we also note the hint (1σ significance) of a soft lag at frequencies around 2 × $10^{-4}$ Hz. However, when using the energy bands 0.3–1.0 keV and 2–10 keV, we found that the detection of the soft lag increases ($\sim 2.5\sigma$ significance). The lag energy spectrum at these frequencies is shown in Fig. 4 bottom.

### 4.4 Spectral analysis

The hardness ratio between the energy bands 0.3–2.0 keV and 2.0–10 keV of the 2019 XMM-Newton observation clearly indicates a marked spectral variability along the observation, which in particular shows evidence of a hardening during the flaring activity (Fig. 2 bottom panel). We investigated the spectral variability in both the XMM-Newton and NuSTAR 2019 observations, extracting a persistent and flare spectrum from both the XMM-Newton and the NuSTAR observations.

In XMM, the persistent spectrum was extracted over the first part of the observation, where no flares were detectable ($\sim 28$ ks). The flare spectrum was extracted by considering only the times when the count-rate was higher than 1.1 cts s$^{-1}$ in the 0.3–10 keV EPIC-pn lightcurve, which resulted in a net exposure of 18 ks. In NuSTAR, we instead selected the persistent and flare epoch manually. The flare spectrum was extracted by choosing the latter as time intervals where the count-rate was significantly higher than the average one. Even though we adopted a different approach for XMM-Newton and NuSTAR, we highlight that the flare and persistent spectra obtained with the two satellites are well over-imposed above the 3 keV.

We simultaneously analyzed the XMM-Newton+NuSTAR spectra of the two epochs in the range 0.3–30 keV, using XSPEC v.12.10.1. We adopted TBABS to model the absorption, assuming no variations of the absorption column density along the line of sight during the two epochs (i.e. we linked the parameter between the spectra). As typically found for ULXs, the X7 spectra cannot be described by simple models such as an absorbed single POWLAW or a DISKBB ($\chi^2 > 3$). The data are well-modelled by either

| Model | Component | No flare | Flare |
|-------|-----------|---------|-------|
| TBABS | nH (10$^{22}$) | 0.11$^{+0.04}_{-0.06}$ | - |
| NTHCOMP | kT$_{\text{reed}}$ (keV) | 0.13$^{+0.04}_{-0.02}$ | - |
| | $\Gamma$ | 2.4$^{+0.04}_{-0.03}$ | 1.7$^{+0.02}_{-0.04}$ |
| | E$_{\text{cut}}$ | 3.7$^{+0.04}_{-0.03}$ | 2.0$^{+0.04}_{-0.03}$ |
| | norm (10$^{-4}$) | 7.0$^{+0.2}_{-0.2}$ | 9.4$^{+0.4}_{-0.2}$ |
| $\chi^2$/dof | 1752.03/1804 |
| DISKBB | Tin (keV) | 0.15$^{+0.04}_{-0.03}$ | - |
| | norm | 3.3$^{+0.4}_{-0.3}$ | 20$^{+10}_{-6}$ |
| DISKBB | p | 0.09$^{+0.03}_{-0.03}$ | 0.54$^{+0.04}_{-0.03}$ |
| | norm (10$^{-3}$) | 1.1$^{+0.3}_{-0.3}$ | 0.9$^{+0.4}_{-0.2}$ |

Table 2. Best-fit spectral parameters. Errors at 90% uncertainty for each parameter of interest.
Flaring activity in NGC 4559 X7

Figure 5. Unfolded persistent EPIC-pn (black points) + NuSTAR (red, dark cyan points) spectrum, and flare EPIC-pn (blue points)+ NuSTAR (purple and cyan points) spectrum. Black, red and green solid lines indicate the DISKBB, DISKPBB and CUTOFFPL best-fit models, respectively, for the persistent spectrum, while the brown solid line is the total model; we use the same color coding for the dashed lines, which refer to best-fit models of the flare spectrum. Middle panel: residuals of the fit with an absorbed DISKBB+DISKPBB model. Bottom panel: residuals of the best-fit with an absorbed DISKBB+DISKPBB+CUTOFFPL model. Spectra have been rebinned for display purposes only.

a single Comptonization model (NTHCOMP in XSPEC, Zdziarski et al. 1996; $\chi^2 = 0.97/1804$) or a combination of thermal models. A model in the form \( \text{TBABS} \times (\text{DISKBB} + \text{DISKPBB}) \) provides a statistically acceptable fit, with ($\chi^2 = 0.99/1803$). Comparing the flare and persistent spectra, the low-energy DISKBB component is consistent with being constant within 90% uncertainties, therefore we linked its temperature and normalization to a common value across the spectra.

Even though the resulting best fit is statistically acceptable ($\chi^2 = 0.99/1803$), we note the presence of a hard excess in the form of structured residuals above 10 keV (see Fig. 5, center panel), as in many other PULXs and ULXs observed with NuSTAR (e.g. Bachetti et al. 2013; Walton et al. 2020). To take into account the high energy excess, we added a cut-off power law component (CUTOFFPL in XSPEC), which has been found previously to be representative of the high energy emission in PULXs. Such a component is usually interpreted as due to the presence of an accretion column above the NS and it appears to be present also in ULXs where the nature of the compact object could not be determined yet (Walton et al. 2018). The simple inclusion of a cut-off power-law to the best fit model causes a number of spectral parameters to become unconstrained. Hence, we fixed the spectral parameters of the cut-off power-law to the average values found for the PULXs spectra, i.e. $\Gamma = 0.59$ and $E_{\text{cut}} = 7.1$ keV, and left only the model normalization amongst the spectra free to vary. The final model \( \text{TBABS(DISKBB+DISKPBB+CUTOFFPL)} \) provided a very good fit ($\chi^2 = 0.97/1801$; Fig. 5-top and bottom panel), which suggests that during the flaring activity both the DISKPBB and the CUTOFFPL contributed to the high energy flux increase. All the results are reported in Table 2. The measured absorbed 0.3–30 keV fluxes are $(2.08 \pm 0.03) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ and $(5.16 \pm 0.07) \times 10^{-12}$ erg cm$^{-2}$ s$^{-1}$ for the persistent and flare spectra, respectively, corresponding to luminosities of $(2.48 \pm 0.04) \times 10^{40}$ erg s$^{-1}$ and $(6.15 \pm 0.09) \times 10^{40}$ erg s$^{-1}$ (for a distance of 10 Mpc).

4.5 Covariance spectra

We extracted the covariance spectrum (see Uttley et al. 2014) from the EPIC-pn data in the frequency range $(0.7–1.6) \times 10^{-4}$ Hz. The covariance spectrum measures the spectral behaviour of the short-term variability correlated with a given reference band. It allows to investigate the spectral components that are responsible of the variability. We compared the EPIC-pn covariance spectrum with those of the persistent and flare spectra, in order to allow us to investigate the correlated spectral variability (Fig. 6). At a first glance, the spectral shape of the covariance spectrum is quite similar with the flare one.

We fitted the covariance spectrum with the best-fit model \( \text{TBABS(DISKBB+DISKPBB+CUTOFFPL)} \) of the flare spectrum. First, we multiplied it by a constant, which was left as the only free parameter, to account for an overall flux variation. We found that the model does not reproduce the covariance spectral shape correctly. Then, we removed the constant, and left the normalizations of the three spectral components (i.e. DISKBB, DISKPBB and CUTOFFPL) free to vary independently. This approach provided a statistically acceptable result ($\chi^2/dof = 14.62/9$): we found that the CUTOFFPL model contributes the most to describe the spectrum (normalization of $(4.6 \pm 0.4) \times 10^{-5}$). Instead, the DISKPBB normalization was almost two orders of magnitude lower.

The radial dependence of the disc temperature of the DISKPBB goes as $r^{-p}$, with $p = 0.75$ for a standard disc and $p = 0.5$ for a slim disc.

\footnote{The radial dependence of the disc temperature of the DISKPBB goes as $r^{-p}$, with $p = 0.75$ for a standard disc and $p = 0.5$ for a slim disc.}
The RGS spectra cover a limited energy band, which means that an additional broadband spectrum has to be used in order to constrain the continuum shape, and to avoid systematics in the search for narrow spectral features. Therefore, we simultaneously fitted the RGS and pn spectra because the latter, amongst the XMM-Newton detectors, features the highest effective area all the way up to 10 keV. Here we do not use the MOS 1 and 2 spectra for two reasons: 1) their effective area in the Fe-K band is significantly lower than the pn’s; 2) their high count rate in the soft band of the RGS (together with that of pn) would wash away the statistical weight from the RGS data, which makes hard to detect the features.

The simultaneous spectral analysis of the RGS and EPIC-pn data is performed using a minimal binning of 1/3 of the line spread function in order to avoid a loss in spectral resolution. We used the SPEX software\(^3\) (Kaastra et al. 1996) to carry out the spectral analysis and we adopted the C-statistics (Cash 1979). We analyzed the EPIC-pn spectrum between 0.3–10 keV and the RGS 1 and 2 spectra between 6–30 Å (∼ 0.4 – 2 keV). While in principle the RGS spectra could extend down to 0.3 keV, we note that the background already dominates the X-ray emission below 0.5 keV.

As shown in Section 4.4 and in Table 2, a simple model consisting of an absorbed Comptonisation component is able to reproduce both the XMM-Newton and NuSTAR spectra. Therefore, as we have used NTHCOMP in the XSPEC modelling, we use the corresponding COMT model in SPEX to describe the EPIC-pn and RGS spectra in both the time-averaged and flared-resolved approaches. Of course, the SPEX / COMT parameters are consistent within the uncertainties with those estimated for XSPEC / NTHCOMP. Unsurprisingly, the column density of the absorbing interstellar medium is also consistent with the values derived within XSPEC. The SPEX spectral continuum model for the averaged spectra and the corresponding residuals are shown in Fig. 7.

There are positive residuals in both RGS and pn at 1 keV and negative residuals on both edges of the energy range, which are similar to those found in many other ULX spectra from XMM-Newton, Chandra, and Suzaku. Such residuals have been interpreted as the evidence for the presence of winds (see, e.g., Middleton et al. 2015b) and they are often resolved with RGS in rest-frame emission and blue-shifted absorption lines from ionised atomic species (Pinto et al. 2016; Kosec et al. 2018). We performed a Gaussian line scan over the whole XMM-Newton energy band in order

\(^3\) http://www.sron.nl/spx

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4.6 RGS spectra

The primary goal of the RGS is to resolve and constrain the properties of narrow features that are detected with higher statistics (albeit at lower resolution) in the EPIC spectra in the soft (< 2 keV) X-ray band. To be consistent with the extraction of the EPIC spectra, we extracted the first-order RGS spectra in a cross-dispersion region of width 1′, centred at the emission peak. We extracted the background spectra by selecting photons beyond the 98% of the source point-spread-function and we checked for consistency by comparing the resulting spectrum with the background spectra from blank field data. We stacked the RGS 1 and 2 spectra for plotting purposes with the rgscombine task. The time-averaged stacked RGS spectrum is shown in Fig. 7 along with the EPIC-pn spectrum. In order to search for any changes in the narrow spectral features during the source flare events, we extracted flare-resolved spectra from the RGS 1 and 2 by running the rgsproc task and using the GTIs that were used to produce the flare EPIC-pn spectrum.

The RGS spectra cover a limited energy band, which means that an additional broadband spectrum has to be used in order to constrain the continuum shape, and to avoid systematics in the search for narrow spectral features. Therefore, we simultaneously fitted the RGS and pn spectra because the latter, amongst the XMM-Newton detectors, features the highest effective area all the way up to 10 keV. Here we do not use the MOS 1 and 2 spectra for two reasons: 1) their effective area in the Fe-K band is significantly lower than the pn’s; 2) their high count rate in the soft band of the RGS (together with that of pn) would wash away the statistical weight from the RGS data, which makes hard to detect the features.

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There are positive residuals in both RGS and pn at 1 keV and negative residuals on both edges of the energy range, which are similar to those found in many other ULX spectra from XMM-Newton, Chandra, and Suzaku. Such residuals have been interpreted as the evidence for the presence of winds (see, e.g., Middleton et al. 2015b) and they are often resolved with RGS in rest-frame emission and blue-shifted absorption lines from ionised atomic species (Pinto et al. 2016; Kosec et al. 2018). We performed a Gaussian line scan over the whole XMM-Newton energy band in order...
to search for the energy centroids of the strongest features. We decided to keep the pn spectrum in the range 0.3–2 keV (avoiding to fit the RGS spectrum alone), in order to minimise systematic effects of the RGS instrumental features although EPIC spectra have a lower spectral resolution. In fact, Kosec et al. (2018) have shown that exposures larger than 120 ks of bright ULXs are typically required to detect significant features in the RGS spectra alone.

Following the approach used in Pinto et al. (2016), we searched for narrow spectral features by scanning the RGS and the pn spectra with Gaussian lines, adopting a logarithmic energy grid with energy steps comparable to the RGS and pn resolving power in the 0.5–2 keV and 2–10 keV energy ranges, respectively. We adopted a line width of 500 km s$^{-1}$ FWHM (i.e., comparable with the RGS spectral resolution). At each energy bin, we express the single trial significance as the square root of the Gaussian normalisation (middle panel) to distinguish between emission (positive flux) and absorption (negative flux) lines. The rest-frame energies of the strongest K and L transitions in the X-ray band are labelled.

In order to constrain better the line significance, we performed line scan of 1000 EPIC-pn + RGS spectra, simulated with a Monte Carlo approach by adopting the best-fit continuum model of the average spectrum, and we searched for fake lines in the same way as we did for the observed EPIC-pn+RGS spectrum. To address the significance of the three main features, we checked the probability of having two (fake) spectral features yielding $\Delta C$-stat (DC) equal to or above that of the two emission lines found in the real data. This gave a probability of 99% (i.e. $\sim 2.6\sigma$) and this was determined by combining the $p$-values of the individual probabilities. A comparable confidence level was obtained by searching simulated spectra for at least 1 spectral feature with DC stronger than that of our most relevant absorption feature at 0.74 keV. The probability of finding individual fake features around 0.5 – 0.6 keV and 0.9 – 1.1 keV with DC equal or above 10 was even smaller. We therefore believe the real significance of the observed lines to be between 2.6$\sigma$ – 3.0$\sigma$ each. Ideally one should perform an ad-hoc, time consuming, physical models automatic grid search (e.g. Pinto et al. 2020; Kosec et al. 2018) but this is not the focus of this work and it will be left for a forthcoming paper.

5 ARCHIVAL CHANDRA AND XMM-NEWTON OBSERVATIONS

Finally, we analyzed the source spectra of the previous XMM-Newton and Chandra observations. As a first step, we unfolded the spectra with a power-law of photon-index 0 and we compared them with the 2019 persistent and flare spectra (Fig. 9). We found that the 2003 XMM-Newton and Chandra spectra are all compatible, with only subtle changes at soft energies, and in general consistent at energies above $\sim 5$ keV with the 2019 persistent spectrum.

We fitted the 2013 XMM-Newton and Chandra spectra simultaneously, adopting an absorbed $\text{DISKBB} + \text{DISKPB}$ model and a common absorption column. The fit gave a quite reasonable description of the data ($\chi^2 = 492.3/465$), with a mean 0.3–10 keV absorbed flux of $\sim 8 \times 10^{-13}$ erg cm$^{-2}$ s$^{-1}$, corresponding to a luminosity of $9.5 \times 10^{39}$ erg s$^{-1}$. Results are reported in Table 2.

6 DISCUSSION

We present the first long-term light curve of X7, by using all the available Swift/XRT, XMM-Newton, Chandra and NuSTAR observations taken between 2001 and 2020. Thanks to new high quality XMM-Newton and NuSTAR observations taken in 2019, we could...
investigate the source short-term temporal and spectral variability, and we characterized them in great detail.

6.1 Flaring activity

The source long-term flux evolution shows that X7 appears to be persistent (i.e. it is detected in each observation) and exhibits a flux variability of up to a factor of \( \sim 6 \) (from a luminosity of \( \sim 7 \times 10^{40} \) erg s\(^{-1} \) to \( \sim 4 \times 10^{40} \) erg s\(^{-1} \), assuming a reference distance of 10 Mpc) over about 20 years of observations. We also report on a possible (super-)orbital variability with period of \( \sim 190 \) d, to be confirmed by new continuous monitoring of the source. We note that super-orbital variabilities are seen in several ULXs with periods of tens of a few hundreds days (e.g. Walton et al. 2016a; Weng & Feng 2018; Fürst et al. 2018; Vasilopoulos et al. 2020), therefore the X7 periodicity would be in line with those. In addition, we remark that the possible X7 periodicity is better seen at high energies, for which disc precession effect may be stronger.

On ks time-scales, X7 is even more variable and shows clear flaring activity, which we observed for the first time in our most recent observations (2019). The flaring activity manifests itself only when the source is at its highest observed luminosities. At the peak of the flares, the luminosity was a factor of \( \sim 1 \times 10^7 \) (e.g. Walton et al. 2020) and we found that the flare recurrency was identified, as opposed to the quasi-periodic heart-beat of the ULX 4XMM J111816.0-324910 in the galaxy NGC 3621 (Motta et al. 2020). This may indicate that the flares in ULXs cannot be explained with only one mechanisms and, furthermore, whatever process that generates flares might or not generate periodic events. In fact, generally speaking the presence of flares does not appear to be clearly related to a specific spectral state or luminosity level (the range spanned by these source is very broad), although it seems that many ULXs preferentially flare during their brightest states. If we consider the spectral state of a given source, we remark they are quite different, which suggests that the high short-term activity can appear in both soft ultraluminous, broadened disc and hard ultraluminous states (where we adopted the spectral classification of Sutton et al. 2015).

6.2 Spectral evolution

The spectral properties of X7 varied over the years, passing through a soft-ultraluminous state, with luminosities \( < 3 \times 10^{40} \) erg s\(^{-1} \), to a hard-ultraluminous state characterised by flares. X7 is one of the best example of a ULX switching across two extreme ULX states. The general behaviour of the ULX population shows that sources can transit from soft-ultraluminous to broadened disc states, or from hard-ultraluminous to broadened disc states, or viceversa, but it is not often observed the transition from a soft-ultraluminous to a hard-ultraluminous state (see, for example, the hardness-intensity/color-color diagrams in e.g. Sutton et al. 2013; Pintore et al. 2017). We have shown that the X7 spectra can be modelled with the combination of at least two thermal components, i.e. a standard multicolour blackbody disc (\text{DISKBB}) at low energies and a “modified” one (\text{DISKRPB}) at high energies. Such phenomenological model was proven to be a good representation of the spectra of a large sample of ULXs containing both PULXs and sources with compact objects of unknown nature (e.g. Stobbart et al. 2006; Pintore et al. 2015; Koliopanos et al. 2017; Walton et al. 2020). Based on our results it appears that, in X7, the behavior of the two disk components correlates with the luminosity (see Fig. 5).

In particular, at low luminosity, the soft \text{DISKBB} component, which describes a standard Shakura-Sunyaev disk (Shakura & Sunyaev 1973), shows a temperature of \( \sim 0.2 \) keV and an inner radius of \( 4.5 \times 10^7 \) \( \sqrt{T/\cos(i)} \) km (where \( i \) is the inclination angle of the system). The hard disk component, i.e. the \text{DISKRPB}, is likely to be ascribed to an advection dominated accretion flow (as suggested by the \( p \) parameter, which assumes a value of \( \sim 0.5 \)), and its apparent temperature converged at \( \sim 2 \) keV. Such a compo-

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can be obtained from $R_d = \sqrt{K (\xi D f_{\text{col}})^2 / \cos(i)}$ (where $K$ is the disc normalization, $D$ is the source distance): for the disc normalization values found in our spectral analysis, we calculated $R_{\text{in,disks}} \sim 3000\,\text{km}$ and $R_{\text{in,disks}} \sim 16\,\text{km}$, further strengthening that the compact object is likely of stellar origin (although its mass cannot be constrained yet in an obvious way).

At higher luminosity, in epochs of the light-curve far from the flares, the spectra present an increase of the flux for energies below $\sim 5\,\text{keV}$, while at higher energies the source flux did not change significantly with respect to the lower flux spectra. A similar behaviour was identified in NGC 1313 X-1 and Holmberg IX X-1 (Walton et al. 2016b, 2020; Gürpide et al. 2021), which are both relatively hard sources and both present a high-energy tail that dominates the spectrum above $10\,\text{keV}$. The origin of such a stable high energy tail has been explained in a super-Eddington accretion scenario, where the matter in the accretion flow is removed in an disk-fed outflow and this dampens most of the accretion rate variability at large radii, which leaves only low variability in the inner regions (Middleton et al. 2015a) that therefore appear more stable. At super-Eddington rates, the outflows are expected to form a funnel, which is responsible for the geometric beaming of the high energy emission. Such a scenario is one of the most likely explanation of the properties and behavior of the Galactic X-ray binary SS 433, which is believed to be an edge-on Galactic ULX (Begelman et al. 2006). When the accretion rate increases further, the outflow opening angle can narrow (e.g. King 2009) even further, thus exacerbating the geometrical beaming of the high energy emission. Hence, in the sources with a hard-tail, the stability of the high energy component may indicate that, even though the flux is rising (i.e. the accretion rate is increasing), the emission of the wind is increasing as well, but the changes in accretion rate are not prominent enough to significantly affect the geometrical beaming. Alternatively, the increase of the accretion rate does not affect the aperture of the cone of the outflows, but rather it only increases the size of the apparent outflow emitting radius, i.e. the smallest disc radius at which outflows are ejected. In this last case the beam may present a radial dependency, which implies that only the emission produced within a characteristic radius can be beamed (see e.g. Lasota et al. 2016; Walton et al. 2020). In the case of X7, at least the first interpretation we described (i.e. a not changing geometrical beaming) may hold as the flux and spectral variability is mainly observed at low-middle energies, where the contribution of the outflow emission is thought to be dominant.

Instead, during the flares and at the highest source fluxes, X7 undergoes an abrupt spectral change with respect to the pre-flare state (see Fig. 2). While the flare and pre-flare spectra are consistent at energies below $1\,\text{keV}$, a clear increase in flux is observed above $1\,\text{keV}$ during the flares. In addition, a third non-thermal spectral components may pop-up at energies $> 10\,\text{keV}$. Such a component is being detected in an increasing number of sources when high-quality and broadband data are available, and it is generally well-modelled by a cut-off power-law. Remarkably, this component tends to be stronger in PULxs (see e.g. Walton et al. 2018) and for this reason it is generally interpreted as the presence of the accretion column on the top of the NS in these sources. Our spectral modeling during the highest flux epochs and during the flares shows that the softer thermal component does not vary appreciably in flux with respect to the pre-flare epochs. This has a temperature of $\sim 0.2\,\text{keV}$ and its corresponding emitting radius is $3.6^{+2.0}_{-0.6} \times 10^{7} \sqrt{1/\cos(i)}\,\text{km}$, consistent with the value derived for same component when observed at lower flux epochs. In contrast, the hard disc component shows an apparent inner radius of $(80^{+40}_{-20} \times \sqrt{1/\cos(i)})\,\text{km}$, which is larger than what we found at lower fluxes, although its temperature does not change significantly.

Based on our finding, and on the comparison between our results and what has been observed in other ULXs, we argue that each spectral component can be interpreted in the context of a super-Eddington accretion scenario, where the accretion flow is formed by: an outer disc; an advection dominated disc (or thick disc), which is covered by an optically thick outflow; and an inner accretion flow. The inner accretion flow could be a “naked” (i.e. without outflows) advection dominated disc or an optically thick corona covering the inner disc regions and the compact object. Alternatively it may be an optically thick boundary layer, should the compact object be a NS (Mushnikov et al. 2015, see). We associate i) the outer disk to the softer thermal component (DISKB), which we expect to be in a standard regime (e.g. Shakura & Sunyaev 1973); ii) the thick-disc/outflows to the high-energy DISKPB component; and iii) the cut-off power-law to the inner disc or the boundary layer.

### 6.3 Evidences of outflows

According to our spectral analysis, the soft disc component does not vary significantly in neither flux or temperature, which suggests that the size of its inner radius was constant even though the total flux increased by about an order of magnitude. Because the data points are limited, we cannot claim any relation between the disc luminosity and its temperature. More high quality observations at different fluxes will allow us to investigate if the outer disc properties can be firmly associated to a standard disc. Similar considerations can be done for the high-energy disc component, which we associated to the photosphere of outflows ejected by the accretion disc. An analysis of the high-quality 2019 XMNM2Newton/RGS spectra allowed us to detect blue-shifted absorption and emission features. The former are probably due to O VII-VIII, while the latter are likely associated to Ne X or Fe L transitions. The significance of such spectral features is limited by the short exposure we had to employ, but the strict similarity with features reported in previous work (see, e.g., Pinto et al. 2016, 2017; Kosec et al. 2018; Wang et al. 2019) provides support for the presence of optically-thin plasma and, likely, optically thick winds in X7. Given the likely presence of the winds, we note that the DISKPB is a phenomenological model that can only mimic the more complex spectral emission of the outflows. We found that the flux evolution of this component is consistent with the photosphere of a wind increasing in size (the apparent emitting radius evolved from $\sim 25\,\text{km}$ to $\sim 80\,\text{km}$) and decreasing in temperature because of the expansion. Our results indicate that the existence of outflows in X7 strengthens even more the compact object stellar origin, which we claimed to be likely a NS or a stellar-mass BH. Indeed, should the compact object being an IMBH, for the observed luminosity we would expect sub-Eddington or Eddington accretion rates, for which we do not expect powerful optically thick winds, nor an emission that spectrally bends below $10\,\text{keV}$.

Our results seem to indicate that X7 is seen from a small inclination angle, i.e. our line of sight intersects the cone produced by the wall of the optically thick outflow. In this scenario, the flares originate from a large increment of the accretion rate, which is able to significantly modify the geometrical structure of the outflows, in particular closing the aperture angle of the wind cone, favouring a stronger geometrical beaming of the high-energy inner emission of the accretion flow. This results in a larger high energy flux, and
thus in an hardening of the spectra during the flaring activity (see the sketch in Fig. 10).

6.4 Short-term temporal properties

The lags discovered in X7 can be explained in the super-Eddington framework as well. The hard lag is such that the high energy emission lags the soft one by \( \sim 300 \) s, on timescales of \( \sim 10^{-3} \) Hz. Hard lags are observed at low frequencies in a variety of Galactic X-ray binaries (Miyamoto et al. 1988; Arévalo & Uttley 2006) and active galactic nuclei (AGN; e.g. De Marco et al. 2013; Alston et al. 2013; Uttley et al. 2014; Kara et al. 2014, 2016). Hard lags are commonly believed to be caused by the inward propagation of fluctuations in the accretion flow, for which the outer regions of the flow (responsible for the soft photons’ emission) respond earlier than the inner regions where high-energy photons are produced (Kotov et al. 2001; Arévalo & Uttley 2006). X7 is the first ULX where low-frequency hard lags have been observed, with an average value of \( 334 \pm 89 \) s. We can explain such lags in terms of the inward propagation of mass accretion rate fluctuations which is also responsible for the flares.

An alternative scenario may instead relate the low-frequency range of the lag to the temporal length between the flares: in such a case, a scattering of soft photons from a very extended optically thin corona or a jet may be likely. The corona can be supported by the RGS spectroscopic analysis, which showed the existence of emission possibly produced in an optically thin plasma. Should the hard lag simply be the crossing time of the soft photons into a hot and optically thin medium, it implies a size of \( \sim 10^{13} \) cm, which may be too large and unfeasible. Hence, the inward propagating fluctuations remain the best explanation for the source hard lag.

In addition, we also remark the existence of a weak soft lag at frequencies \( \sim (2 - 4) \times 10^{-4} \) Hz with a weighted average value of \( 395 \pm 167 \) s. Soft lags were reported for the sources NGC 55 ULX-1 (Pinto et al. 2017), NGC 1313 X-1 (Kara et al. 2020) and NGC 5408 X-1 (De Marco et al. 2013), with magnitudes from tens to thousands of ks. Soft lags are commonly associated with delays due to the crossing time and down-scattering of hard photons passing through the optically thick outflows. The interpretation of the soft lags in these sources then points towards a quite high inclination angle of the systems. However, the phenomenology of X7 seems instead to point towards a quite low inclination of the system. Should the soft lag in X7 be real, this would be in line with the magnitudes observed in the other ULXs, but it may be interpreted as reflection of the hard photons from a lower temperature region.

Assuming that the Compton scattering is the dominant process, the radius of the scattering region can be estimated as \( R = \frac{c t}{\sigma_T n_e} \), where \( c \) is the speed of light, \( t \) is the soft lag in seconds, \( \sigma_T \) is the Thompson cross-scattering and \( n_e \) is the electron density. Assuming a disc/wind electron density of \( n_e \sim 10^{20} \) cm\(^{-3}\) (e.g. Shakura & Sunyaev 1973; Takeuchi et al. 2013) and a single scattering, the size of the scattering medium would then be \( < 10^7 - 10^8 \) cm, i.e. larger than the characteristic inner disc radii estimated from the spectral analysis, and instead consistent with the outer regions of the accretion flow or with the base of the outflow. We note that the estimated size could be smaller if we allow for multi-scatterings of the hard photons into the medium.

Finally, although we analyzed the highest quality available data of the source, which shed light on the geometry and structure of the accretion flow, the exact nature of the compact object in X7 remains dubious. The timing analysis did not provide any strong indication on the existence of pulsations, but only some hints of pulsations when orbital corrections are applied, the statistical significance of which is very low. More high quality data are needed to confirm or refute such a tentative pulsation detection. The large flux variation on long timescale, the hard spectra during the flares and the small size of the inner disc during the low flux epochs can favour X7 hosting a NS. We note that, should the compact object be a magnetic NS able to truncate the inner accretion flow at radii of tens of km, as suggested by our spectral analysis, by assuming a beaming factor of 0.1, we derive a dipolar magnetic field of magnitude \( 10^{10} - 10^{11} \) G.
7 CONCLUSIONS

We analyzed all the available X-ray observations of the ULX X7 taken with XMM-Newton, NuSTAR, Chandra and Swift/XRT. Its long-term variability features changes in flux of up to an order of magnitude, with extreme luminosity reaching an observed maximum of \( \sim 6 \times 10^{40} \text{ erg s}^{-1} \) during flare activity. The spectral analysis of the high quality XMM-Newton and NuSTAR observations allowed us to characterize the properties of the source, which we modelled with two thermal disc-like components. We interpret the source spectral and temporal evolution within the framework of super-Eddington accretion and we associated the soft disc component to an outer, standard razor-thin accretion disc, while the high-energy disc to the photosphere of a powerful optically thick outflow above the disc. Confirmation on the existence of a wind comes from the detection of blue-shifted absorption and emission features in the RGS data, which indicate also the presence of an optically thin plasma. We also note that during the flare, a third spectral component could be exhibited by X7. Comparing it with the ones observed in a number of ULXs, we may associate it to either an accretion column density if the compact object is a NS or a boundary layer/optically thick corona in case of a BH accretor. We propose that the source evolution can be explained with variations of the accretion rate that can affect the geometrical cone of the outflow, enhancing the degree of beaming of the inner regions responsible for the high-energy emission.

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DATA AVAILABILITY

All of the data underlying this article are already publically available from ESA’s XMM-Newton Science Archive (https://www.cosmos.esa.int/web/xmm-newton/xsa), NASA’s HEASARC archive (https://heasarc.gsfc.nasa.gov/), and the Chandra Data Archive (https://cxc.harvard.edu/cda/).

REFERENCES

Alston W. N., Vaughan S., Uttley P., 2013, MNRAS, 435, 1511
Arévalo P., Uttley P., 2006, MNRAS, 367, 801
Bachetti M., Harrison F. A., Walton D. J., Greffnestrte B. W., Chakrabarty D., Fürst F., Barret et al. 2014, Nature, 514, 202
Bachetti M., Rana V., Walton D. J., Barret D., Harrison F. A., et al. 2013, ApJ, 778, 163
Band D. L., 1997, ApJ, 486, 928
Barnard R., 2010, MNRAS, 404, 42
Belgeman M. C., King A. R., Pringle J. E., 2006, MNRAS, 370, 399
Belloni T., Klein-Wolt M., Méndez M., van der Klis M., van Paradijs J., 1996, ApJ, 464, 291
Begelman M. C., King A. R., Pringle J. E., 2006, MNRAS, 370, 399
Barnard R., 2010, MNRAS, 404, 42
Carpino S., Haberl F., Maitra C., Vasilopoulos G., 2018, MNRAS
Cash W., 1979, ApJ, 228, 939
De Marco B., Ponti G., Miniutti G., Belloni T., Cappi M., Dadina M., Muñoz-Darias T., 2013, MNRAS, 436, 3782
den Herder J. W., Brinkman A. C., Kahn S. M., et al., 2001, A&A, 365, L7
Earnshaw H. M., Roberts T. P., Heil L. M., Mezcua M., Walton D. J., Done C., Harrison F. A., Lansbury G. B., Middleton M. J., Sutton A. D., 2016, MNRAS, 456, 3840
Earnshaw H. P., Greffnestrte B. W., Brightman M., Walton D. J., Barret D., Fürst F., Harrison F. A., Heida M., Pike S. N., Stern D., Webb N. A., 2019, ApJ, 881, 38
Earnshaw H. P., Roberts T. P., Sathyaprakash R., 2018, MNRAS, 476, 4272
Fürst F., Walton D. J., Heida M., Harrison F. A., Barret D., Brightman M., Fabian A. C., Middleton M. J., Pinto C., Rana V., Trumper F., Webb N., Kretschmar P., 2018, A&A, 616, A186
Gürpide A., Godet O., Koliopanos F., Webb N., Olive J.-F., 2021, arXiv e-prints, p. arXiv:2102.11159
Heil L. M., Vaughan S., 2010, MNRAS, 405, L86
Israel G. L., Belfiore A., Stella L., Esposito F., Nature, 2017, Science, 355, 817
Israel G. L., Papitto A., Esposito F., Stella L., 2017, MNRAS, 466, L48
Israel G. L., Stella L., 1996, ApJ, 468, 369
Kaaret P., Ferg H., Roberts T. P., 2017, ARA&A, 55, 303
Kaastra J. S., Mewe R., Nieuwenhuijzen H., 1996, in K. Yama shuta & T. Watanabe ed. UV and X-ray Spectroscopy of Astrophysical and Laboratory Plasmas: SPECTRE: a new code for spectral analysis of X & UV spectra, p. 411
Kara E., Alston W. N., Fabian A. C., Cackett E. M., Uttley P., Reynolds C. S., Zoghibi A., 2016, MNRAS, 462, 511
Kara E., Fabian A. C., Marinucci A., Matt G., Parker M. L., Alston W., Brenneman L. W., Cackett E. M., Miniutti G., 2014, MNRAS, 445, 56
Kara E., Pinto C., Walton D. J., Alston W. N., Bachetti M., Barret D., Brightman M., Canizares C. R., Earnshaw H. P., Fabian A. C., Fürst F., Kosec P., Middleton M. J., Roberts T. P., Soria R., Tao L., Webb N. A., 2020, MNRAS, 491, 5172
King A., Lasota J.-P., 2020, MNRAS, 494, 3611
King A. R., 2009, MNRAS, 393, L41
Koliopanos F., Vasilopoulos G., Godet O., Bachetti M., Webb N. A., Barret D., 2017, A&A, 608, A47
Kosec P., Pinto C., Fabian A. C., Walton D. J., 2018, MNRAS, 473, 5680
Kosec P., Pinto C., Walton D. J., Fabian A. C., Bachetti M., Brightman M., Fürst F., Greffnestrte B. W., 2018, MNRAS, 479, 3978
Kotov O., Churazov E., Gilfanov M., 2001, MNRAS, 327, 799
Kubota A., Tanaka Y., Makishima K., Ueda Y., Dotani T., Inoue H., Yamaoka K., 1998, PASJ, 50, 667
Lasota J. P., Vieira R. S. S., Sadowski A., Narayan R., Abramowicz M. A., 2016, A&A, 587, A13
Middleton M. J., Brightman M., Pintore F., Bachetti M., Fabian A. C., Fürst F., Walton D. J., 2019, MNRAS, 486, 2
Middleton M. J., Heil L., Pintore F., Walton D. J., Roberts T. P., 2015a, MNRAS, 447, 3243
Middleton M. J., King A., 2017, MNRAS, 470, L69
Middleton M. J., Walton D. J., Fabian A., Roberts T. P., Heil L., Pinto C., Anderson G., Sutton A., 2015b, MNRAS, 454, 3134
Miyamoto S., Kitamoto S., Mitsuda K., Dotani T., 1988, Nature, 336, 450
Motta S. E., Marelli M., Pintore F., Esposito F., Salvaterra R., De Luca A., Israel G. L., Tiengo A., Castillo G. A. R., 2020, ApJ, 898, 174
Mushtukov A. A., Suleimanov V., Tsygankov S. S., Poutanen J., 2015, ApJ, 811, 115
Nakajima K., Mineshige S., 2011, ApJ, 736, 115
Ohsuga K., Mineshige S., 2011, ApJ, 736, 115
Peterson B. M., Wanders I., Horne K., Collier S., Alexander T., Kaspi S., Maoz D., 1998, PASP, 110, 660
Pintore F., Alston W. N., Fabian A. C., Walton D. J., Sutton A. D., 2017, Nature, 544, 2539
Pintore F., Marelli M., Salvaterra R., Israel G. L., et al. 2020, ApJ, 890, 166

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