THE XMM-NEWTON LONG LOOK OF NGC 1365: LACK OF A HIGH/SOFT STATE IN ITS ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

Based on our long (~300 ks) 2007 XMM-Newton observation of the Seyfert galaxy NGC 1365, we report here on the spectral and timing behavior of two ultraluminous X-ray sources (ULXs), which had previously reached isotropic X-ray luminosities \( L_X \approx 4 \times 10^{39} \text{ erg s}^{-1} \) (0.3–10 keV band). In 2007, they were in a lower state \( (L_X \approx 5 \times 10^{39} \text{ and } 1.5 \times 10^{39} \text{ erg s}^{-1} \text{ for X1 and X2, respectively}) \). Their X-ray spectra were dominated by power laws with photon indices \( \Gamma \approx 1.8 \) and 1.2, respectively. Thus, their spectra were similar to those at their outburst peaks. Both sources have been seen to vary by a factor of 20 in luminosity over the years, but their spectra are always dominated by a hard power law; unlike most stellar-mass black holes, they have never been found in a canonical high/soft state dominated by a standard disk. The lack of a canonical high/soft state seems to be a common feature of ULXs. We speculate that the different kind of donor star and/or a persistently super-Eddington accretion rate during their outbursts may prevent accretion flows in ULXs from settling into steady standard disks.

Key words: black hole physics – X-rays: binaries – X-rays: individual (NGC 1365)

Online-only material: color figures

1. INTRODUCTION

One of the hallmarks of accretion onto stellar-mass black holes (BHs) is a pattern of state transitions, initially discovered from X-ray spectral studies (starting from Cyg X-1: Tananbaum et al. 1972) and later understood as fundamental changes in the structure of the accretion flow, and recognized also in the radio and optical behavior. The “canonical” scheme of BH accretion (Remillard & McClintock 2006; Fender et al. 2004; Esin et al. 1998) consists of at least three main states: low/ hard, high/soft, and very high. The low/hard state is dominated by a power-law spectrum in the X-ray band, probably produced by inverse Compton scattering of soft seed photons (Sunyaev & Titarchuk 1980). The location and geometry of the scattering region is still unclear: it has been suggested that it could be a hot corona above the cold disk (Haardt & Maraschi 1993; Poutanen & Svensson 1996), an advection-dominated accretion flow (ADAF; Narayan & Yi 1994; Esin et al. 1997), a fast jet or the base-of-the-jet (Fender et al. 2004), or a hot, centrifugally supported boundary layer or postshock region due to sub-Keplerian inflows (Chakraborti & Titarchuk 1995; Chakraborti 1997). The high/soft state is dominated by thermal X-ray emission; most of the accretion power is radiated by an optically thick, geometrically thin disk (Shakura & Sunyaev 1973). The very high state, observed when a source approaches its Eddington luminosity, is still poorly understood: it is again dominated by a power-law component in the X-ray band (usually steeper than in the low/hard state, Remillard & McClintock 2006), together with a thermal disk component that becomes relatively less important as the luminosity increases. The power-law component is thought to be produced by the Comptonization of soft X-ray photons from the inner-disk region (Done & Kubota 2006). The spectrum of the disk component itself may be heavily modified by electron scattering, energy advection, and radiation trapping, in the very high state (slim-disk model: Watarai et al. 2001). In the simplest approximation, an accreting BH is in the radiatively inefficient low/hard state when the mass accretion rate is less than a few percent of the Eddington accretion rate (i.e., the accretion parameter \( \dot{m} \equiv \dot{M}/M_{\text{Edd}} \approx (0.1c^2 \dot{M})/L_{\text{Edd}} \lesssim 0.01 \)). At higher accretion rates (0.01 \( \lesssim \dot{m} \lesssim 0.5 \)), accreting BHs are expected to switch to the radiatively efficient, disk-dominated high/soft state and then to the very high state, until the standard disk becomes unstable (at \( \dot{m} \gtrsim 1 \)). Another fundamental property, revealed by radio observations, is the presence in the low/hard state of a steady jet which may carry most of the outgoing accretion power; the jet is suppressed in the high/soft state (Merloni et al. 2003; Fender et al. 2004); strong X-ray and radio flares are instead observed in the very high state (Remillard & McClintock 2006).

One of the interesting properties of the standard-disk spectrum in the high/soft state is that we expect a simple relation between the disk luminosity, the disk peak temperature, and the BH mass (Makishima et al. 1996, 2000): \( L_{\text{disk}} \approx 4\pi R_g^2 \sigma T_{\text{in}}^4 \approx M_{\text{BH}}^2 T_{\text{in}}^4 \). In this formula, the inner-disk radius \( R_{\text{in}} \approx 6R_g \) for a nonrotating BH, where the gravitational radius \( R_g = M_{\text{BH}} \) in geometric units. This relation has been observationally confirmed for many Galactic BHs, and the BH masses inferred with this method are generally in agreement (within a factor of 2) with direct kinematic measurements. Another useful property of the high/soft state is the simple parameterization of disk luminosity and temperature with the accretion rate: for a fixed BH mass, \( L_{\text{disk}} \approx \dot{m}, T_{\text{in}} \approx \dot{m}^{1/4} \) (Shakura & Sunyaev 1973).

The canonical state classification has also been applied to active galactic nuclei (AGNs), justified by the self-similar nature of many physical processes near a BH horizon, provided that characteristic sizes, timescales and disk temperatures are properly rescaled by the BH mass (Maccarone et al. 2003; Merloni et al. 2003; Jester 2005; Markowitz & Uttley 2005). In
this scheme, low-luminosity AGNs and LINERs may represent the low/hard state, typical AGNs and Seyferts may be in the high/soft state, and the most powerful quasars and FR II radio galaxies may be in the very high state.

Ultraluminous X-ray sources (ULXs) are accreting BHs with observed fluxes corresponding to isotropic X-ray luminosities up to approximately a few $10^{40}$ erg s$^{-1}$, well above the Eddington limit for the kind of stellar BHs known in our Local Group (Roberts 2007 for a recent review). It is still widely debated whether this is due to extremely heavy stellar BHs, with masses $\sim 30–70$ $M_\odot$ (Pakull & Mirioni 2002), or intermediate-mass BHs (Miller & Colbert 2004), or collimation of the outgoing radiation (King et al. 2001; King 2008), or super-Eddington luminosity (Begelman 2002, 2006; Ohsuga & Mineshige 2007); or perhaps a combination of some of those factors. In other words, it is still unclear whether ULXs represent a different physical class of accreting BHs (perhaps with their own sequence of canonical states), or a different accretion state of “ordinary” stellar-mass BHs.

In the absence of direct kinematic measurements of BH masses in ULXs (mainly because of the faintness of their optical counterparts, at typical distances $\gtrsim$ a few Mpc), X-ray spectroscopy could in principle provide strong constraints, by analogy with the properties of canonical spectral states in stellar-mass BHs. For example, if we observe a ULX in different spectral states over time, we could estimate its luminosity at the transition between low/hard and high/soft states, or the maximum luminosity in the low/hard state, and the fitted disk luminosity and temperature in the high/soft state. Such arguments were used for example by Winter et al. (2006) and Miller & Colbert (2004), in support of BHs with masses $\gtrsim 10^3$ $M_\odot$. However, this method relies on the assumption that ULXs follow the same pattern of canonical spectral states; specifically, that they will switch from the low/hard to the high/soft state at a luminosity approximately a few percent of $L_{\text{Edd}}$, and that they are dominated by a standard disk in the high/soft state.

Until now, it has been difficult to test these assumptions. The main reason why we still know very little about spectral-states transitions in ULXs is that none of these sources has had the kind of daily or weekly X-ray monitoring that is possible for Galactic BHs. Even the brightest ULXs are usually observed only sporadically, every few months or years. This makes it difficult for us to understand the sequence and timescale of their spectral-state transitions. Nonetheless, for a few ULXs there are now enough data points over the years, so that we can try and compare their behavior with those of transient Galactic BHs.

NGC 1365 X1 is one of such rare sources, detected by ROSAT, ASCA, Chandra, Swift, and XMM-Newton at various levels of activity between 1993 and 2007 (Komossa & Schulz 1998; Soria et al. 2007; Strateva & Komossa 2008), with peak luminosities $\approx 3–4 \times 10^{40}$ erg s$^{-1}$ in 1995 and 2006 (Soria et al. 2007). The nearby transient ULX X2 also reached a luminosity $\approx 4 \times 10^{40}$ erg s$^{-1}$ in 2006 (Strateva & Komossa 2008), but was much fainter or undetected during the earlier observations. Their host galaxy is the most luminous spiral in the Fornax Cluster (type SBb(s)I, Sandage & Tammann 1981) with a total gas mass $\approx 3 \times 10^{10}$ $M_\odot$, a kinematic mass $\approx 3.6 \times 10^{11}$ $M_\odot$, and a star formation rate $\approx 10 M_\odot$ yr$^{-1}$ (Lindblad 1999; Roussel et al. 2001). The Cepheid distance to NGC 1365 is 19 ± 1 Mpc (Ferrarese et al. 2000); at that distance, 1" = 92 pc. In this paper, we report the results of our $\approx 300$ ks XMM-Newton observation, split over three orbits between 2007 June 30 and 2007 July 05 (Table 1 and Section 2 for details). We interpret the X-ray properties of the two ULXs (in particular, their hard power-law spectra) in the context of their long-term behavior.

### 2. OBSERVATIONS AND DATA ANALYSIS

The XMM-Newton observed NGC 1365 on 2007 June 30–July 5 (PI: G. Risaliti; Table 1). The prime instrument was the European Photon Imaging Camera (EPIC), in the full window mode, medium filter. See Figure 1 for a true-color image of the combined MOS data set. The primary target was the highly variable Seyfert nucleus, on which we report elsewhere (Risaliti et al. 2009). We used the XMM-Newton Science Analysis System (SAS) version 7.1.0 to process and filter the event files and extract light curves and spectra. Several background flares occurred during the three observations. We tried various rejection thresholds to increase the signal-to-noise for the nonnuclear sources; in particular, to improve the

| Revolution | Obs ID   | Instrument | Start Time          | End Time          | Live Time (ks) | Clean GTI (ks) |
|------------|----------|------------|---------------------|-------------------|----------------|----------------|
| 1384       | 0505140201 | MOS        | 2007 Jun 30 at 07:08:45 | 2007 Jul 1 at 18:51:55 | 126.7          | 96.6           |
| 1385       | 0505140401 | MOS        | 2007 Jun 30 at 07:31:03 | 2007 Jul 1 at 18:48:52 | 110.8          | 78.4           |
| 1386       | 0505140501 | MOS        | 2007 Jul 2 at 07:07:24 | 2007 Jul 3 at 18:23:52 | 124.7          | 123.3          |

Figure 1. EPIC-MOS true-color image of the central region of NGC 1365. Red = 0.3–1 keV; green = 1–2 keV; blue = 2–10 keV. The two ULXs discussed in this paper are marked as “1” and “2.” (A color version of this figure is available in the online journal.)
signal-to-noise of X1 and X2 at photon energies $\gtrsim 5$ keV (the two sources have similar fluxes in that energy range). Instead, the nucleus is brighter, and therefore much less affected by the flares, except for a particularly strong, short one at the end of the second observation. In the end, for our spectral analysis we chose to retain good time intervals of 78.4, 107.9, and 55.9 ks for the EPIC-MOS (Table 1). For the timing analysis, we used the whole live exposure time, although of course the intervals with high or flaring background give lower signal-to-noise bins in the light curve.

The extraction of spectra and light curves for X1 was made difficult by the unfortunate location of the source on a chip gap in the pn, leading to a loss of about half the counts in every exposure. The ancillary response function is supposed to take into account the reduced effective area of the source region; however, because the point-spread functions of hard and soft photons are slightly different, a chip gap may in principle introduce a change in the spectral shape. Fortunately, X1 is not on a chip gap in the MOS images. We fitted separately and compared the MOS and pn spectra, and verified that they are consistent with each other. Thus, we conclude that the chip gap may have decreased the signal-to-noise achievable in principle, but has not significantly affected the spectral results.

The radius of the source extraction regions was 20′′ for X1 (the brightest nonnuclear source), and only 8′′ for X2, to reduce contamination from a nearby source of similar brightness (X2 was much fainter than in 2006). Background extraction regions were chosen around the source regions, in a suitable way to avoid contamination. After building response and ancillary response files with rmfgen and arfgen we used XSPEC (Arnaud 1996) for spectral analysis. To improve the signal-to-noise ratio (S/N), we used the whole live exposure time, although of course the intervals with high or flaring background give lower signal-to-noise bins in the light curve.

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3. MAIN RESULTS

3.1. Time Variability of X1

We extracted background-subtracted MOS and pn light curves of X1 in the three observations, and analyzed them with standard FTOOLS tasks, with various choices of binning. We did not find any significant variability between the three observations, nor within a single observation. For example, for the 2007 July 2–3 EPIC pn observation (Rev. 1385), which has the highest signal to noise, we find a $\chi^2$ probability of constancy $>0.9$ (Figure 2). We do not find any significant features in the power density spectra, either.

Over the past 14 years, X1 has shown strong variability, with two major outbursts detected by ASCA in 1995 and Chandra in 2006 (Figure 3). In addition to the luminosity data points already summarized in Soria et al. (2007), we have also analyzed a series of short Swift monitoring observations, carried out on 2006 July 21–24 (three months after the Chandra observation), for a total exposure time of 19.4 ks. We detect 23 net counts with the X-ray Telescope (count rate $\approx 0.0012$ count s$^{-1}$), corresponding to an emitted luminosity $\approx (2.3 \pm 0.5) \times 10^{39}$ erg s$^{-1}$ in the 0.3–10 keV band (Figure 3), assuming a power-law model with photon index 1.8 and $N_H = 5 \times 10^{20}$ cm$^{-2}$.

3.2. Spectral Analysis: X1 is a Power-law ULX

First, we fitted and compared the MOS spectra of X1 from each XMM-Newton observation during the three consecutive revolutions of 2007 June 30–July 5. We find that the three spectra are consistent with each other with regard to observed flux, absorbing column density and spectral shape (Figure 4). All three spectra are well fitted by an absorbed power-law model with total absorbing column density $\approx 5 \times 10^{20}$ cm$^{-2}$ and power-law photon indices $\approx 1.7$–1.8, consistent within the 90% confidence limit of each data set. Hence, we are justified in adding the EPIC spectral data from all three observations to increase the (S/N).

The combined XMM-Newton/EPIC spectrum is well fitted ($\chi^2 = 1.03 (156.2/152)$) by a simple power-law model (see the top panel of Figure 5, and Table 2 for the best-fitting parameters). From this fit, we estimate an unabsorbed, isotropic luminosity $L_X \approx 5.3 \times 10^{39}$ erg s$^{-1}$ in the 0.3–10 keV band. Some ULXs often show a curvature in their X-ray spectra (see Section 4), to the point that it is sometimes difficult to distinguish between a power law, a cutoff power law and a disk-blackbody
The best-fitting disk-blackbody model in the bottom panel of Figure 5 (A color version of this figure is available in the online journal.)

Bottom panel: the same spectrum cannot be well fitted by a disk-blackbody model, which highlights the lack of spectral curvature. Including those three channels does not change the best-fitting parameters. Odd behavior of those three channels, but we suspect they are related to the EPIC pn behavior at the edge of the chip gap (they are not discrepant in the MOS). Including those three channels does not change the best-fitting parameters. Table 2: Best-fitting Parameters for the Combined 2007 XMM-Newton/EPIC Spectrum of X1, Compared with the 2006 Peak Outburst Spectrum from Chandra Data. Spectral Model: phabs*phabs*power-law. Errors are 90% Confidence Levels for 1 Interesting Parameter (Δχ² = 2.7)

| Parameter | 2006 Chandra Value | 2007 XMM-Newton Value |
|-----------|---------------------|-----------------------|
| N_{H,GAU} | 1.3 × 10^{20}       | 1.3 × 10^{20}         |
| N_{H}     | 1.5^{+0.4}_{-0.3} × 10^{21} | 4.3^{+1.5}_{-1.2} × 10^{20} |
| r        | 1.74^{+0.12}_{-0.11} | 1.80^{+0.04}_{-0.05}  |
| N_{BB}   | 9.8^{+1.3}_{-1.1} × 10^{-5} | 1.9^{+0.1}_{-0.05} × 10^{-5} |
| Δχ²/dof  | 0.93 (85,4/92)      | 1.03 (156,2/152)      |

Notes:

a From Kalberla et al. (2005). Units of cm⁻².
b Photon index.
c Units of photons keV⁻¹ cm⁻² s⁻¹, at 1 keV.
d Observed flux in the 0.3–10 keV band; units of erg cm⁻² s⁻¹.
e Unabsorbed luminosity in the 0.3–10 keV band; units of erg s⁻¹.

Figure 4. Individual EPIC-MOS spectra of X1 during the three observations in 2007, and respective χ² residuals, for absorbed power-law fits. Black data points and residuals are for Rev. 1384; red ones for Rev. 1385; green ones for Rev. 1386. The three spectra are statistically identical in flux normalization and spectral slope. (A color version of this figure is available in the online journal.)

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Figure 5. Top panel: combined 2007 XMM-Newton/EPIC spectrum of X1, and χ² residuals. The model is an absorbed power law. The best-fitting parameters are listed in Table 2. We have not included in the fit three “bad” channels (at ≈0.6, 0.8, and 2 keV) that were clearly very discrepant from any fitting model, leading to an additional Δχ² ≈ 30; we are unable to pin down the reason for the odd behavior of those three channels, but we suspect they are related to the EPIC pn behavior at the edge of the chip gap (they are not discrepant in the MOS). Including those three channels does not change the best-fitting parameters. Bottom panel: the same spectrum cannot be well fitted by a disk-blackbody model, which highlights the lack of spectral curvature. (A color version of this figure is available in the online journal.)

model. It is clearly not the case here: we show the best-fitting disk-blackbody model in the bottom panel of Figure 5 (χ² > 2), as a graphic evidence of the lack of spectral curvature. For the same reason, even a bremsstrahlung model, although slightly less curved than a disk-blackbody, does not fit the data well; the best-fitting model has χ² = 1.13(172.3/152), for kT e = (5.6 ± 0.6) keV.

A power law is the best-fitting one-component phenomenological model, and it makes no assumptions on the underlying physical process. It is of course possible to fit the same spectrum equally well with other, more complex physical models, provided that they look exactly like a power law in the observed band. For example, we tried the Comptonization model comp making assumptions on the underlying physical process. Because of this, we tried the Comptonization model comp and found that we could get equally good fits by fixing the seed-photon temperature at any value kT e ≲ 0.1 keV, if the coronal temperature kTe ≳ 2 keV and the optical depth τ ≳ 0.5. The best-fitting comp model has χ² = 1.03(155.2/151) for kT e ≈ 2.9 keV and τ ≈ 0.2 (warm, optically thick corona). But we also get a statistically equivalent fit (χ² = 1.04(157.8/152)), for example, for kT e ≳ 50 keV and τ ≳ 0.5 (hot, optically thin corona). Both models are indistinguishable from a power law, with the available data.

We then tried adding a diskbb component (soft excess) to the power law: the best-fitting model has χ² = 1.02(153.2/150) for kT a = 0.35^{+0.17}_{-0.13} keV and photon index Γ = 1.66^{+0.11}_{-0.15}, but this is not a statistically significant improvement with respect to the simple power-law model. From the upper limit to the diskbb normalization, we find that, if there is an additional disk-blackbody component, it does not contribute more than ≈3.6 × 10^{38} erg⁻¹ in the 0.3–10 keV band (≈5.4 × 10^{38} erg⁻¹ bolometric), that is, <7% of the power-law contribution.

Finally, we looked for a possible break or cutoff in the power law at high energies. An exponential cutoff does not improve the fit, because it introduces excessive curvature in the model. A break at the energy E_b = 7.5 ± 0.9 keV gives χ² = 1.00(150.3/150), which is, formally, a marginally significant improvement from a simple power-law fit, and confirms the
visual impression of a spectral downturn (Figure 5, top panel). However, given the low signal-to-noise level at those channel energies, and the uncertainties in the background subtraction (contaminated by the strong AGN emission above \( \approx 6 \) keV), we cannot attribute any physical meaning to this possible break. Nonetheless, we recall that there was also marginal evidence of a break at \( \approx 6 \) keV in one of the XMM-Newton observations of 2004 (Soria et al. 2007).

The power-law photon index \( \Gamma \approx 1.8 \) (Table 2) is consistent with the indices fitted to the Chandra spectra during the 2006 April outburst (see Table 2 for the best-fitting parameters of the combined 2006 April 12–15 spectrum), and also with the April outburst (see Table 2 for the best-fitting parameters of a break at \( \approx 6 \) keV contributing about 25\%–30\% of the X-ray luminosity, in addition to a dominant (and harder) power-law component with a high-energy break. At that time, the unabsorbed luminosity was \( \approx 10^{39} \) erg s\(^{-1} \) (Soria et al. 2007).

The column density in the 2007 spectrum is consistent with the values previously fitted to the XMM-Newton spectra when X1 had X-ray luminosities \( \approx 10^{39} \) erg s\(^{-1} \). The neutral column density was instead a few times higher during the 2006 outburst, when a single-component power-law model was used (Soria et al. 2007). As a further check that the decrease in column density between 2006 and 2007 is real and not due to the appearance of an underlying soft component, we fitted the 2007 spectrum with an additional diskbb component (leaving its temperature and normalization as free parameters) and \( N_{\text{H}} \) fixed at the 2006 value. We obtain \( \chi^2 = 1.15(173.9/151) \) which is significantly worse than the low-column best fit. Besides, there was also strong ionized absorption at the peak of the 2006 outburst (Soria et al. 2007), which is absent from the 2007 spectra.

We also reexamined the 2006 data to test the opposite scenario: the possibility that the column density in 2006 was as low as in 2007 or at any other epoch. We started from the best-fitting model (\( \chi^2 = 0.72(105.5/146) \)) to the 2006 outburst summarized in Table 7 of Soria et al. (2007), but this time we imposed \( N_{\text{H}} = 4.5 \times 10^{20} \) cm\(^{-2} \). A single power-law model is no longer acceptable (\( \chi^2 = 1.06(155.5/147) \)), because it does not reproduce the low-energy downturn. A low-\( N_{\text{H}} \) disk-blackbody model is statistically worse than the best-fitting model (\( \chi^2 = 0.76(113.2/146) \)): it can reproduce the low-energy downturn but, in that case, it overpredicts high-energy curvature; the best-fitting \( kT_{\text{in}} \approx 1.4 \) keV (a characteristic temperature that makes it difficult for Chandra/ACIS to distinguish between an absorbed power-law and a disk-blackbody model, because of its limited spectral coverage). On the other hand, low-\( N_{\text{H}} \) Comptonization models provide statistically equivalent fits to the high-\( N_{\text{H}} \) power-law model, if the seed-photon temperature \( \approx 0.3 \) keV. For example, using the Comptonization model bmc, we obtain \( \chi^2 = 0.72(104.5/145) \) with the best-fitting seed-photon temperature \( kT_{\text{B}} = 0.27^{+0.03}_{-0.04} \) keV. The same Comptonization models applied to the 2007 spectra require a lower seed-photon temperature, \( \lesssim 0.1 \) keV. As for the ionized absorption component seen at the peak of the 2006 outburst (Soria et al. 2007), we have not found it possible to eliminate it or replace it with any other simple spectral component.

3.3. X2: A Transient, Hard Power-law ULX

The transient ULX X2 (Figure 1) was serendipitously discovered during the 2006 Chandra observations (Strateva &...
power-law model). But the best-fitting temperature $kT_{\text{in}} = 3.48^{+0.66}_{-0.69} \text{ keV}$ is unphysically high for a standard disk, and the normalization corresponds to an unphysically small inner radius $r_{\text{in}}(\cos \theta)^{0.5} \approx 7 \text{ km}$. A bremsstrahlung model provides a formally acceptable fit ($\chi^2 = 1.14(112.6/99)$) for $kT \gtrsim 48 \text{ keV}$. The Comptonization model comppt with seed-photon temperature fixed at $kT_{\text{b}} \equiv 0.1 \text{ keV}$ and optically thin corona ($\tau \equiv 0.5$) gives an equivalent fit ($\chi^2 = 1.12(111.3/99)$) for $kT_{\text{b}} \gtrsim 250 \text{ keV}$. For an optically thick corona ($\tau \equiv 10$), the best-fitting model has $kT_{\text{b}} = 2.73^{+0.66}_{-0.50} \text{ keV} (\chi^2 = 1.11(109.7/99))$. An exponential cutoff does not improve the power-law fit ($\chi^2 = 1.12(110.8/99)$), and the cutoff is constrained to be at energies $\gtrsim 5.8 \text{ keV}$. A break does not improve the power-law fit, either. Adding a soft disk-blackbody component to the power law does not improve the fit: the best-fitting model has a null normalization for diskbb, and an upper limit of $\lesssim 25\%$ for the disk-blackbody contribution. In short, as was the case for X1, also X2 can be fitted by various physical models, as long as they look exactly like a hard power law in the observed band. We then fixed the absorbing column density to the 2006 value (Table 3) and verified that it is not consistent with the 2007 data, even with the addition of an unconstrained disk-blackbody component to compensate for that. The best-fitting high-absorption model has $\chi^2 = 1.25(122.5/98)$. Finally, we reexamined the 2006 data, and tried fitting them with the same low absorption as in 2007. As for the case of X1, we find that Comptonization models with low absorption but high seed-photon blackbody temperature ($kT_{\text{b}} \approx 0.9 \text{ keV}$) give fits that are only slightly worse than the high-absorption models. However, such scenario is too contrived, and unseen in any other accreting source. Hence, we conclude that the decrease in absorption at lower luminosities is physically significant for X2.

In previous years, X2 was not seen by ASCA. It was claimed (Strateva & Komossa 2008) that it may have been marginally detected by ROSAT/HRI in 1995, at a count rate corresponding to a 0.3–10 keV luminosity $\approx 4 \times 10^{39} \text{ erg s}^{-1}$, if we assume the spectral parameters of the 2007 XMM-Newton spectrum; however, this detection is doubtful, because of likely source confusion. X2 was also in a low state ($L_X \lesssim 3 \times 10^{38} \text{ erg s}^{-1}$) during the 2002 Chandra observation. It may be marginally detected (but confused with nearby, brighter sources) in the 2004 XMM-Newton observations, at a luminosity approximately a few $10^{38} \text{ erg s}^{-1}$. It is not detected ($L_X \lesssim 10^{39} \text{ erg s}^{-1}$) in the Swift observations of 2006 July.

4. DISCUSSION AND SPECULATIONS

4.1. Power-law Versus Thermal Disk Spectra

The strongly star-forming spiral galaxy NGC 1365 contains many X-ray sources that have exceeded the ULX threshold at some stage in the past few years. Here, we have focused on two sources that showed recent outbursts and great changes in flux; for one of them (X1) there is a long sequence of X-ray observations dating back to 1993. The X-ray spectra of X1 and X2 appear always dominated by broad, power-law-like components with photon indices $\Gamma \approx 1.8 \pm 0.1$ and $1.2 \pm 0.1$, respectively, both in their higher and lower states (even though their luminosities varied by a factor of 20). For X1, sometimes (XMM-Newton observations from 2004, Soria et al. 2007) there is also a cool, thermal soft component in addition to the dominant, hard power-law component. For both sources, a significant difference in the 0.3–10 keV band between spectra taken at higher and lower luminosity is the higher intrinsic column density in the higher state. We do not have enough elements to determine whether this is directly related to a higher mass inflow or outflow rate, or both.

Based on their phenomenological spectral appearance, one may be tempted to classify both ULXs in the power-law dominated low/hard state, using the canonical definition of BH spectral states. Several other luminous ULXs (with $L_X \lesssim 3 \times 10^{39} \text{ erg s}^{-1}$) are well fitted by a single power law of photon index $1 \lesssim \Gamma \lesssim 2$ (Berghera et al. 2008): such slopes are consistent with and sometimes even harder than those measured in the low/hard state of Galactic BHs. However, the first hint that the accretion state of X1 and X2 may not be the canonical low/hard state comes from their long-term variability: both sources remained in the same hard state over the years, despite their luminosity changes. This is different from the behavior observed in most stellar-mass Galactic BHs, which recurrently switch between the low/hard and high/soft states. In particular, in most Galactic soft X-ray transients, outbursts tend to start in the hard state, but rapidly switch to the soft state (on a timescale of few days, during which the disk builds up); then, such sources spend the majority of their bright time (a few weeks or months) in the high/soft state, dominated by standard disk-blackbody emission with $\sim L_{\text{disk}}$ and $0.1 \lesssim L \lesssim L_{\text{Edd}}$.

This does not appear to be the case for ULXs: none of the most luminous or best studied sources has ever been unequivocally found in a canonical high/soft state. Some ULXs do have a convex spectrum (Makishima et al. 2000; Feng & Kaaret 2005; Stobbart et al. 2006; Tsunoda et al. 2007; Mizuno et al. 2007; Makishima 2007; Miyawaki et al. 2009), with various degrees of curvature between a straight power law and a disk-blackbody. But if they are formally fitted with a disk-blackbody model, their peak color temperature ($kT_{\text{b}} \sim 1.5–2.5 \text{ keV}$) is much higher than expected for a standard disk, and implies a luminosity $L \gg L_{\text{Edd}}$ inconsistent with the standard-disk model. One possible interpretation is that the emission is from a hot, super-Eddington slim disk (Watarai et al. 2001; Makishima 2007). Another interpretation is that it is Comptonized emission from a warm, optically thick corona covering the inner part of the disk (Roberts 2007). A second subgroup of ULXs (including NGC 1365 X1 in 2004) sometimes show a thermal soft excess ($kT_{\text{b}} \approx 0.15 \text{ keV}$) in addition to the power-law component; but the soft excess contributes only $\lesssim 30\%$ of the luminosity (Stobbart et al. 2006). Again, this is not evidence of a canonical high/soft state, which is by definition dominated by the disk. In fact, it is not uncommon also for Galactic BHs in the low/hard state to have a nondominant soft excess from the truncated outer disk in addition to the hard power-law component (Remillard & McClintock 2006). In summary, although there are two subgroups of ULXs with possible evidence of thermal components in their X-ray spectra, neither case corresponds to the canonical high/soft state.

4.2. A Different Accretion State or a Different Class of BHs?

Based on the previous arguments, we sketch three possible scenarios to explain the spectral state of hard power-law ULXs such as X1 and X2, and their variability (or lack of) between states.

1. Intermediate-mass BHs in the low/hard state. In this scenario, the hard power-law spectra are attributed to a true low/hard state. If low/hard to high/soft state transitions (that is, between a nonthermal, radiatively inefficient and a thermal, radiatively efficient accretion mode) must always
occurs for all accreting BHs at $L_X \sim$ a few percent of $L_{\text{Edd}}$, this scenario implies that ULXs with a hard ($\Gamma \lesssim 2$) power-law spectrum and luminosities $\sim 10^{39}$ erg s$^{-1}$ must be powered by intermediate-mass BHs with masses $\gtrsim 10^3 M_\odot$ (Winter et al. 2006). In this scenario, ULXs represent a different physical class of BHs; the reason they never switch to the high/soft state is that the accretion rate from the donor star is never high enough. However, there is still little supporting evidence or theoretical justification for such intermediate-mass BHs. Hence, we argue that this is the least likely interpretation, at this stage.

2. **Stellar-mass BHs in the super-Eddington state(s).** In this scenario, power-law ULXs (with or without soft excess) and convex-spectra ULXs are all varieties of the very high state or super-Eddington regime, characterized by a mix of Compton scattering, photon trapping, slim-disk energy advection, and massive radiation-driven outflows (with possible transitions between states, as seen for example in IC 342 X1, Kubota et al. 2001). This implies BH masses $\sim 10^6 M_\odot$, isotropic X-ray luminosities between $\sim 1 - 30 L_{\text{Edd}}$, and mass accretion rates $\dot{m}$ a few to $\sim 1000$. In this scenario, ULXs represent a different accretion state of normal stellar-mass BHs; their canonical high/soft state is not observed because their accretion rate is always above Eddington, and so is their luminosity.

3. **Massive stellar BHs without a high/soft state.** In this scenario (somewhat intermediate between the other two), BHs in ULXs have masses $\sim 30 - 100 M_\odot$ (at the upper end of the high-mass X-ray binary distribution), and isotropic luminosities $L_X \sim 0.1$ to a few $L_{\text{Edd}}$. The main observational motivation for this massive stellar BH scenario comes from the observed downturn in the ULX luminosity distribution at $L_X \approx 2 \times 10^{40}$ erg s$^{-1}$ (Grimm et al. 2003; Swartz et al. 2004), which can be interpreted as approximately the characteristic Eddington luminosity for the ULX population. This implies that the isotropic luminosity of most ULXs is below Eddington. In turn, this means that ULXs must follow a different canonical sequence of state transitions than Galactic BHs, because they are always dominated by Comptonized emission at luminosities below, near, and slightly above Eddington, without a “naked-disk” high/soft state in between. If there is a direct disk component, it is always less important than the Comptonized component, or it may be a slim-disk component for the most luminous sources. Following this interpretation, there is no longer a gap between low/hard and very high state, just a continuous range of coronal optical depths (getting thicker at higher $\dot{m}$) and temperatures (getting cooler); one “state” can morph directly into the other.

### 4.3. Two-component Accretion Flows?

We argue that the scenario (3) above is the most consistent with multiband observations, although there may also be some ULXs in the highly super-Eddington state of scenario (2). One issue that can differentiate the two scenarios is the relative change in $\dot{m}$ necessary to produce a change in luminosity. For scenario (3), changes in luminosity between $\sim 0.1$ and $\sim 1 L_{\text{Edd}}$ can correspond to similar relative changes in the accretion rate. For scenario (2), the radiative luminosity is strongly saturated above Eddington: $L \sim (1 + \ln \dot{m})$; changes in luminosity between $\sim 1$ and $\sim 10 L_{\text{Edd}}$ require an increase in $\dot{m}$ by several orders of magnitude, which may severely constrain the mechanism responsible for the transition, and may have stronger detectable effects on the optical counterpart, or outflow density.

Why would ULXs lack a canonical high/soft state? Their BHs would be a few times, or perhaps even an order of magnitude more massive than Galactic BHs—but this should not directly affect their state-transition properties. We suggest that the type of donor stars and the mechanism of mass transfer can cause a different spectral-state behavior in Galactic BHs and ULXs. The canonical spectral-state classification is based mostly on the appearance of Galactic BHs in low-mass X-ray binaries, also known as soft X-ray transients. Instead, the most luminous ULXs are thought to have OB donors, with masses $\gtrsim 10 M_\odot$, based on theoretical and observational considerations. Stellar evolution models (Rappaport et al. 2005) show that OB stars can provide the required mass transfer rates $\gtrsim 10^{-6} M_\odot$ yr$^{-1}$ over their nuclear timescale $\sim 10^6$ years, with a peak as the donor evolves to the blue-supergiant stage. And optical observations of ULX counterparts show that they are indeed predominantly located in OB associations or regions of recent star formation, even though it is always difficult to identify the donor star, and separate the optical contribution of the donor star from that of the irradiated accretion disk (Ramsey et al. 2006; Griisé et al. 2008). A typical ULX donor star is also likely to be filling its Roche lobe, because the fraction of gas captured by the BH from wind accretion alone may not be sufficient to produce the observed X-ray luminosity. We speculate that ULX donor stars may provide both high angular momentum gas, feeding the disk through Roche-lobe overflow, and low angular momentum gas, feeding the Comptonizing medium and jet through a sub-Keplerian wind, perhaps enhanced by the X-ray irradiation of the secondary. This would be analogous to the two-flow scenario proposed for some Galactic BHs with massive donors (Smith et al. 2002). In fact, it may not be a coincidence that Cyg X-1, perhaps the closest Galactic analog to a ULX in terms of accretion geometry and donor star, has only rarely been seen in a true high/soft state (Dotani et al. 1997); instead, most of its state transitions are between the low/hard state (where it spends the majority of its time) and what should be properly labeled as very high state, with radio activity and an X-ray spectrum consisting of a strong power law plus thermal component (Remillard & McClintock 2006; Feng et al. 2003; Zhang et al. 1997a, 1997b). We note as another possible analogy that the accretion mode of radio galaxies (as indicated by their emission-line type and radio power) may depend on their source of gas (Bondi accretion of the hot gas and/or disk accretion of cold gas), not simply on the total accretion rate (Hardcastle et al. 2007).

The arguments above may at least qualitatively explain why ULXs can retain a hard power-law spectrum even at X-ray luminosities $\sim 0.1 - 1 L_{\text{Edd}}$. The other factor that may determine the ULX state behavior is their high accretion rate, as mentioned earlier. BH transients can switch to a soft, disk-dominated state during an outburst only if $\dot{m} \lesssim 1$; in that case, the accretion flow can settle into a quasi-steady standard-disk configuration. But this cannot occur if the accretion rate during their outbursts stays persistently above Eddington (the inner part of the disk cannot survive at $\dot{m} > 1$). We suggest that some transient ULXs may switch directly from the low/hard state (at low accretion rates) to the slim-disk state (which produces a convex X-ray spectrum), or to the Compton-scattering-dominated very high state (which produces a cutoff power-law spectrum). The standard disk may only survive or be directly visible at large radii, and may produce the cool soft excess (Roberts 2007). In this scenario, the reason why ULXs have long-lasting phases of super-Eddington mass
transfer rate may be due to the different mass or evolutionary stage of their donor stars, compared with the typical donor stars of Galactic BH transients.

4.4. Thresholds for the Low/High State

To make progress on these issues, we need to understand more about the threshold luminosity and accretion rate at which BHs (including Galactic X-ray binaries) switch from the low/hard to the high/soft state, and to determine whether, in some cases, a system can remain in a hard state up to luminosities \( \sim 0.1 - 1 L_{\text{Edd}} \), and then evolve directly towards the very high state. The scenario of a universal threshold between low/hard and high/soft states at \( m_{\text{in}} \sim 0.01 \) works if the low/hard state consists of a radiatively inefficient, advection-dominated flow (Esin et al. 1997). Such flow is not expected to survive at higher accretion rates, when radiative cooling becomes more efficient. However, other accretion models may explain the persistence of a hard state up to higher luminosities: for example, a “luminous hot accretion flow” (Yuan & Zdziarski 2004) may be consistent with high-state luminosities up to at least \( 0.1 L_{\text{Edd}} \). Further investigations should determine whether the hard state in ULXs (and perhaps in some classes of AGNs) can extend to even higher luminosities, if the dominant power-law component is produced by a magnetized corona or a jet, perhaps favored by sub-Keplerian accretion flows. Observationally, low/hard to high/soft transitions during several outbursts of the Galactic BHs GX 339-4 and XTE J1550–564 have been seen at different X-ray luminosities, sometimes as high as \( \sim 0.1 L_{\text{Edd}} \) (Yu et al. 2007). The existence of a linear relation between the peak luminosity in the low/hard and high/soft states, and the properties of the time delay between the two states, have been interpreted (Yu et al. 2007) as possible evidence of the two-flow accretion geometry (sub-Keplerian flow responsible for the low/hard state, and Keplerian flow feeding the disk). Hard-state luminosities \( \geq 10^{38} \text{erg s}^{-1} \) have also been seen in the Galactic BH candidate Cyg X-3 (Hjalmarsdotter et al. 2008), which is a Wolf-Rayet donor with a strong wind. Finally, there is a group of at least eight Galactic BHs (Brocksopp et al. 2004) that remain in the low/hard state throughout their outbursts. Understanding why those BHs never switch to the high/soft state will also provide a useful comparison for the ULX behavior.

If our suggestion that ULXs lack a canonical high/soft state is correct, we should gain further insight by studying their radio behavior. Accreting BHs have a steady jet (flat-spectrum radio-core emission) in the low/hard state; instead, they are radio-quiet in the high/soft state, when the jet is quenched (Fender et al. 2004), and radio-flaring in the very high state. If some BHs never switch to the high/soft state, it will be interesting to determine whether they always have a jet, which may carry out a substantial fraction of the accretion power; perhaps the only transition is between a steady jet at lower luminosities and a flaring jet at higher luminosities. So far, radio observations have not yet been sensitive enough to detect point-like radio-core emission in ULXs, and monitor their short-term variability in relation to their X-ray state. Only the much brighter, persistent, extended lobe emission (optically thin synchrotron nebulae) has been identified in some ULXs (Miller et al. 2005; Lang et al. 2007).

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