SPECTRAL STATE TRANSITIONS OF THE ULTRALUMINOUS X-RAY SOURCES X-1 AND X-2 IN NGC 1313

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ABSTRACT

X-ray spectral state transitions are a key signature of black hole X-ray binaries and follow a well-defined pattern. We examined 12 XMM-Newton observations of the nearby spiral galaxy NGC 1313, which harbors two compact ultraluminous X-ray sources (ULXs), X-1 and X-2, in order to determine if the state transitions in ULXs follow the same pattern. For both sources, the spectra were adequately fitted by an absorbed power law with the addition of a low-temperature \((kT \approx 0.1-0.3 \text{ keV})\) disk blackbody component required in six of the 12 observations. As the X-ray luminosity of X-1 increases to a maximum at \(3 \times 10^{39} \text{ ergs s}^{-1}\), the power-law photon index softens to 2.5–3.0. This behavior is similar to the canonical spectral state transitions in Galactic black hole binaries, but the source never enters the high/soft or thermal-dominant state and instead enters the steep power-law state at high luminosities. X-2 has the opposite behavior and appears to be in the hard state, with a photon index of \(\Gamma = 1.7-2.0\) at high luminosity, but can soften to \(\Gamma = 2.5\) at the lower luminosities.

Subject headings: accretion, accretion disks — black hole physics — X-rays: binaries — X-rays: galaxies — X-rays: individual (NGC 1313 X-1, NGC 1313 X-2)

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are pointlike, nonnuclear X-ray sources with luminosities above the Eddington limit of a 20 \(M_\odot\) black hole \((3 \times 10^{38} \text{ ergs s}^{-1}\); for review see Fabbiano & White 2006). Many ULXs show strong variability and are believed to be black hole binaries. Their X-ray luminosities (Colbert & Mushotzky 1999; Kaaret et al. 2001), thermal disk emissions (Kaaret et al. 2003), variation timescales (Strohmayer & Mushotzky 2003; Dewangan et al. 2006), and surrounding emission-line nebulae (Pakull & Mirioni 2003; Kaaret et al. 2004b) suggest that they might have masses of \(20-10^3 M_\odot\), falling into the class of intermediate-mass black holes (IMBHs). However, if the emission is beamed (King et al. 2001; Körding et al. 2002) or exceeds the Eddington limit (Begelman 2002; Ebisawa et al. 2003), some or all ULXs may be stellar-mass black holes.

A comparison of the properties of ULXs with the well-known phenomenology of stellar-mass black hole X-ray binaries should help us reveal the nature of ULXs. Spectral state transitions are essential characteristics of black hole binaries (for a review see McClintock & Remillard 2006). Most X-ray binaries have been observed in both the hard and high/soft states. Typically, the intrinsic energy spectrum in the hard state is described as a power law with a photon index \(\Gamma = 1.5-2.1\). The energy spectrum in the high/soft consists of a thermal disk component and a power law with a photon index \(\Gamma = 2.1-4.8\). Some sources also show the steep power-law state with \(\Gamma > 2.4\). The steep power-law state differs from the high/soft state in that the disk is the dominant spectral component in the high/soft state while the power-law component is dominant in the steep power-law state. The luminosity and spectral shape are correlated with higher luminosities corresponding to softer photon indexes, e.g., in Cyg X-1 (Wilms et al. 2006) and XTE J1550–564 (Kubota & Makishima 2004), and to higher disk temperatures, e.g., in XTE J1550–564 (Kubota & Makishima 2004) and 4U 1630–47 (Tomsett et al. 2005). However, in the steep power-law state, the disk luminosity remains constant or decreases while the disk temperature increases (Tomsett et al. 2005; McClintock & Remillard 2006).

If ULXs are binary systems similar to Galactic black hole binaries, then they should exhibit similar spectral states, unless they are super-Eddington sources, in which case the spectral state(s) may differ from the standard ones. State transitions following the canonical high/soft versus hard pattern have been reported for two ULXs in IC 342 (Kubota et al. 2001) and Holmberg IX X-1 (La Parola et al. 2001). However, the temporal coverage for IC 342 was poor, only two observations, while the coverage for Holmberg IX X-1 was poor and had to be stitched together from several different observatories. Multiple high-quality XMM-Newton spectra have been obtained only for a few sources: two very similar spectra for Holmberg IX X-1 (Wang et al. 2004) and three observations of Holmberg II X-1, with one showing an unusual low/soft state (Dewangan et al. 2004). Repeated Chandra observations of the Antennae revealed state transitions of several ULXs (Fabbiano et al. 2003), but the photon counts were insufficient to permit spectral modeling, and the source spectra were studied using hardness ratios—which are insufficient to disentangle different spectral components.

The availability of 14 archival XMM-Newton observations offers us an opportunity to investigate state transitions of ULXs in NGC 1313, which is a spiral galaxy at a distance of \(4.13 \pm 0.11 \text{ Mpc}\) (Méndez et al. 2002). Besides the supernova remnant SN 1978K, two ULXs, X-1 and X-2, are associated with NGC 1313. Both sources exhibit disk emission with temperatures lower than those found in stellar-mass black holes (Miller et al. 2003), suggesting they could be IMBHs. In the luminosity versus temperature \(\left(L, kT\right)\) diagram of bright ULXs in nearby galaxies (Feng & Kaaret 2005), they appear in the low-temperature, high-luminosity class, which contains sources most likely to be IMBH candidates. Ramsey et al. (2006) find a unique optical counterpart to X-2 in the Hubble Space Telescope images and suggest that the companion star is a B1–B2 giant. NGC 1313 X-2 resides in an optical nebular supershell (Pakull & Mirioni 2003), whose kinetic energy is much larger than a typical supernova explosion. The shell is either a hypernova remnant or a continually powered nebula—possibly by an outflow from the ULX. These two ULXs are interesting IMBH candidates. In the following, we present the observations, our analysis, and results on the spectral variation in § 2, and we discuss the nature of the spectral states of these two ULXs in § 3.
2. DATA REDUCTION

We analyzed 12 XMM-Newton observations of NGC 1313 from 2000 October to 2005 February (Table 1). There are another two observations made on 2003 September 9 and December 27 that are not included because of high background contamination. We reduced the observation data files to event files with SAS 6.5.0 and calibration files current as of 2006 May. Data were selected from good time intervals, where there were no back- ground flares, with the best quality data (FLAG = 0) and screened with PATTERN ≤ 12 for MOS and PATTERN ≤ 4 for PN. Source spectra were extracted in 32° radius circular regions. Background regions were selected at the same CCD chip as the source and at a similar distance from the readout node. We combined all available PN and MOS data from each individual observation for the spectral analysis, unless the source was located on or near a CCD gap in one or more of the instruments.

Spectra were fitted with XSPEC 11.3.2. First, we tried to fit data with an absorbed power-law model (wabs*powerlaw in XSPEC), and then we added a multicolor disk blackbody model [wabs(diskbb + powerlaw) in XSPEC] to see if that improved the fitting. If the disk blackbody component had a significance level above 99% as evaluated using an F-test, we accepted the second model as the best-fit model, otherwise we adopted the single-power-law model. All the best-fit parameters and their errors at the 90% confidence level are shown in Table 1 with the luminosity in the 0.3–10 keV band after correction for absorption. For observations best fitted with a single-power-law model, we also tried to add a disk blackbody component, but that did not change the power-law index or luminosity significantly. We attempted to use a single absorption column density to fit all the observations of each source, but we found that adequate fits could not be obtained in several cases. Thus, the absorption was allowed to vary. We found that the normalizations for all three detectors were consistent within errors.

Other models, such as a hot disk blackbody plus a soft power law, a soft blackbody plus a hot disk blackbody, and/or a soft disk blackbody plus a hard Compton corona, have been used to fit ULX spectra (Roberts et al. 2005; Stobbart et al. 2006). The motivation for such models is spectral curvature at high energies. We find no evidence of high-energy spectral curvature for NGC 1313 X-1 or X-2. Stobbart et al. (2006) report a break near 5 keV in X-1 in an analysis of only the high-energy portion of the spectrum; however, this break is not reflected in their modeling of the broadband spectrum. Furthermore, the hot disk blackbody plus soft power-law model is unphysical (Stobbart et al. 2006), while the soft blackbody plus hot disk blackbody model would require a very strong super-Eddington source for X-1 or X-2. We note that in our model of choice, the power-law component is a reasonable approximation to a more physical model such as a Compton corona if the optical depth is low. Applying a Comptonization model, Stobbart et al. (2006) find a low optical depth for X-1 and that the power-law model gives as good a fit as the Comptonization model for X-2, indicating a low optical depth. Since we find no strong evidence of spectral curvature at high energies, use of a Comptonization model is not justified. Use of a soft disk blackbody plus power-law model provides the closest analogy to the spectral model commonly used for the classification of spectral states in Galactic black holes (McClintock & Remillard 2006).

The disk component was only detected in observations 1, 6,
8, 10, 11, and 12 for X-1, with a fractional contribution of 0.27, 0.20, 0.32, 0.41, 0.20, and 0.27, respectively, to the total intrinsic luminosity in the 0.3–10 keV band. Disk emission from X-2 was detected in observations 1, 3, 9, 10, 11, and 12 with a fractional flux of 0.21, 0.23, 0.40, 0.31, 0.24, and 0.63, respectively. The disk fractional flux was calculated by setting the column density and power-law normalization to zero and finding the ratio of the resulting flux in the 0.3–10 keV band to the total unabsorbed flux in the same band. The fractional fluxes in the 0.1–10, 0.2–10, and 0.4–4 keV bands are similar.

We note that the disk luminosity obtained from the fitting is correlated with the absorption column depth: high disk luminosities tend to occur for high \( n_H \) values. We consider the disk luminosity values to be good upper bounds, but caution is required in their interpretation.

X-ray light curves for NGC 1313 X-1 and X-2 are presented in Figure 1. X-1 is variable by a factor of about 3, while X-2 is variable by a factor of about 10.

A strong correlation was found between \( \log L_x \) and photon index (\( \Gamma \)) for X-1 (see Fig. 2), with higher luminosities found for softer spectra. Including all 12 observations, the correlation coefficient is 0.82 with a chance probability of occurrence of \( 1.1 \times 10^{-3} \). Excluding the rightmost point (observation 10) where the luminosity appears to saturate, the correlation coefficient is 0.91, and the chance probability is \( 8.8 \times 10^{-5} \). We note that if we use a power-law–only model to fit all the observations, then this correlation is essentially unchanged. X-2 follows the opposite trend, with lower luminosities found for softer spectra. With the power-law–only model, the points move into two clusters, one at high luminosity and hard photon index and the other at low luminosity and soft photon index.

We found some evidence of a correlation between the total (\( L_{\text{total}} \)) and the disk (\( L_{\text{disk}} \)) luminosity for X-2. However, the uncertainty in the disk luminosity warrants caution in its interpretation. No other significant correlations were found.

We searched for time variability for both sources in every observation. Power spectra were calculated from continuous good time intervals, avoiding data gaps and background flares. No significant variability was found. However, nonconstant light curves with a significance level above 3 \( \sigma \) were found with a Kolmogorov-Smirnov test in observations 3 and 9 for X-1 and observation 3 for X-2, respectively in good time intervals of 4.45, 7.23, and 4.45 ks. We note that the XMM EPIC CCD timing gaps have timescales from several to hundreds of seconds, which can result in strong instrumental signals in the frequency range from millihertz to hertz. These instrumental effects can appear as artificial quasi-periodic oscillations or broken power-law features if adequate care is not taken in dealing with data gaps and background flares. High-quality temporal diagnostics, which could confirm the state identification, is absent with these XMM data.

3. DISCUSSION

The strong correlation between X-ray luminosity (\( \log L_x \)) and power-law photon index (\( \Gamma \)) for NGC 1313 X-1 is similar to the behavior found in Galactic black hole binaries, e.g., Cyg X-1 (Wilms et al. 2006), and suggests that ULX NGC 1313 X-1 is a black hole X-ray binary. The disk temperature in X-1 is constant within the uncertainties. However, this is consistent with the behavior of stellar-mass black hole binaries because the luminosity variation is small.

In Galactic black hole X-ray binaries, over 75% of the total flux in the 2–20 keV band in the high/soft state arises from the disk emission component—the high/soft state is a thermal-dominant state (McClintock & Remillard 2006). To compare the disk versus power-law luminosity ratios for ULXs, we choose to use the 0.3–10 keV band rather than the 2–20 keV band, because the disk temperature in ULXs is a factor of 5–10 smaller than that in stellar-mass black holes. We also compared the luminosity ratios in the 0.1–10 and 0.4–4 keV bands and found that they were similar.

The fraction of total flux arising from the disk for X-1 is always below 50%, even allowing for the uncertainties in the measurement of the disk luminosity. Therefore, X-1 appears to never enter the high/soft state and is in either the hard state or the steep power-law state. McClintock & Remillard (2006) define the steep power-law state by the presence of a power-law component with a photon index larger than 2.4. In Figure 2, observation 10 with \( \Gamma = 3.08 \) and a disk component of 41% fractional flux, showing up as the rightmost point in Figure 2, is fully consistent with the steep power-law state, and there are observations (3, 4, 7, and 9) with a single–power-law spectrum and

![Fig. 1.—Light curves of NGC 1313 X-1 (top) and X-2 (bottom). The first point is shifted 1000 days later to fit on the plot. Luminosities are taken from best-fit models. Open circles: Disk blackbody plus power law. Open triangles: Single power law.](image1)

![Fig. 2.—Total X-ray luminosity in the 0.3–10 keV band vs. power-law photon index for NGC 1313 X-1 (top) and X-2 (bottom). For the panels on the left, the photon index and luminosity are calculated from the best-fitting model, either a disk blackbody plus power law (open circles) or a single power law (open triangles). For the panels on the right, the photon index and luminosity are calculated from an absorbed power-law model for all observations.](image2)
The same behavior of state transitions in X-1 as in stellar-mass black holes indicates that the emission is from the accretion flow and not a relativistic jet. The mechanical beaming model needs a near- or super-critical accretion rate in the binary system. Whether or not such a system can produce a spectral state transition as observed in normal black hole binaries is unclear. Other models involving super-Eddington accretion rates, like the advection-dominated optically thick disk (Ebisawa et al. 2003) or the radiation-dominated accretion disk (Ebisawa, Zywki, Kubota, Mitsu, T., & Watarai, K., 2003, ApJ, 597, 780) must also address the spectral state transition behavior. The transition to the hard state at luminosities only a factor of 3 below the maximum observed luminosity, as well as a maximum luminosity that exceeds the Eddington limit of a 20 $M_\odot$ black hole by a factor of 10, may be difficult to explain in such scenarios.

The main physical distinction between the steep power-law state and the high/soft state (in most models) is the presence of a highly energized corona in the former. The absence of the high/soft state may suggest that NGC 1313 X-1 always has an energetically important corona. Goad et al. (2006) and Stobbart et al. (2006) have suggested that ULXs have optical thick coronae, but the data for X-1 suggest an optically thin corona. Merloni (2003) proposed a coupled magnetic disk-corona solution, in which the disk is stable when it is corona-dominated at high accretion rates. Most bright ULXs have spectra dominated by a soft power-law component (Feng & Kaaret 2005) and are thought to be accreting from high-mass companion stars via Roche lobe overflow (Lu et al. 2004; Kaaret et al. 2004a; Ramsey et al. 2006; Kaaret et al. 2006a, 2006b). Detailed modeling of accretion flows that produce powerful coronae at high accretion rates should be important for understanding ULXs and also for determining if super-Eddington accretion occurs (Merloni 2003). We note that, based on the spectral properties alone, we identify the state of Holmberg II X-1 reported by Goad et al. (2006) as the steep power-law state since the photon index is 2.6 and since less than 15% of the flux arises from the disk. The low level of timing noise is consistent with the state definitions of McClintock & Remillard (2006).

At luminosities above $6 \times 10^{39}$ ergs s$^{-1}$, NGC 1313 X-2 appears to be in the hard state, with a photon index of $\Gamma = 1.7-2.0$ (see the bottom panels of Fig. 2). At lower luminosities, the photon index can reach much softer values. When fitting with the simple-power-law model, the points from two clusters with high luminosity are associated with a hard photon index, and those with low luminosity are associated with a soft photon index. The high/hard versus low/soft behavior of X-2 is unlike that of typical Galactic black hole binaries, but a similar, unusual, low/soft state has been observed from GRS 1758–258 (Smith et al. 2001). Galactic black holes in the hard state typically produce compact radio jets. Scaling using the radio–X-ray flux ratio of GX 339–4 (Corbel et al. 2003), the predicted radio flux density would be $\sim 5 \mu$Jy at 8.6 GHz and would be difficult to detect. However, such a jet could power the optical nebula surrounding X-2.

REFERENCES

Begelman, M. C. 2002, ApJ, 568, L97
Colbert, E. J. M., & Mushotzky, R. F. 1999, ApJ, 519, 89
Corbel, S., Nowak, M. A., Fender, R. P., Tzioumis, A. K., & Markoff, S. 2003, A&A, 400, 1007
Dewangan, G. C., Miyaji, T., Griffiths, R. E., & Lehmann, I. 2004, ApJ, 608, L57
Dewangan, G. C., Titarchuk, L., & Griffiths, R. E. 2006, ApJ, 637, L21
Ebisawa, K., Zywki, P., Kubota, A., Mizuno, T., & Watarai, K.-Y. 2003, ApJ, 597, 780
Fabbiano, G., & White, N. E. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0307077)
Fabbiano, G., Zezas, A., King, A. R., Ponman, T. J., Rots, A., & Schweizer, F. 2003, ApJ, 584, L5
Fender, R. P., Belloni, T. M., & Gallo, E. 2004, MNRAS, 355, 1105
Feng, H., & Kaaret, P. 2005, ApJ, 633, 1052
Goad, M. R., Roberts, T. P., Reeves, J. N., & Uttley, P. 2006, MNRAS, 365, 191
Homan, J., & Belloni, T. 2005, ApSS, 300, 107
Kaaret, P., Alonso-Herrero, A., Gallagher, J. S., III, Fabbiano, G., Zezas, A., & Rieke, M. J. 2004a, MNRAS, 348, L28
Kaaret, P., Corbel, S., Prestwich, A. H., & Zezas, A. 2003, Science, 299, 365
Kaaret, P., Simet, M. G., & Lang, C. C. 2006a, Science, 311, 491
Kaaret, P., et al. 2006b, ApJ, 646, 174
Kaaret, P., Ward, M. J., & Zezas, A. 2004b, MNRAS, 351, L83
Kaaret, P., et al. 2001, MNRAS, 321, L29
King, A. R., et al. 2001, ApJ, 552, L109
Körding, E., et al. 2002, A&A, 382, L13
Kubota, A., & Makishima, K. 2004, ApJ, 601, 428
Kubota, A., Mizuno, T., Makishima, K., Fukazawa, Y., Kotoku, J., Ohnishi, T., & Tashiro, M. 2001, ApJ, 547, L119
Liu, J.-F., Bregman, J. N., & Setizier, P. 2004, ApJ, 602, 249
McClintock, J. E., & Remillard, R. A. 2006, in Compact Stellar X-Ray Sources, ed. W. H. G. Lewin & M. van der Klis (Cambridge: Cambridge Univ. Press), in press (astro-ph/0306213)
Méndez, B., Davis, M., Moustakas, J., Newman, J., Madore, B. F., & Freedman, W. L. 2002, AJ, 124, 213
Merloni, A. 2003, MNRAS, 341, 1051
Miller, J. M., Fabbiano, G., Miller, M. C., & Fabian, A. C. 2003, ApJ, 585, L37
Pakull, M. W., & Mirioni, L. 2003, Rev. Mex. AA Ser. Conf., 15, 197
Roberts, T. P., Warwick, R. S., Ward, M. J., Goad, M. R., & Jenkins, L. P. 2005, MNRAS, 357, 1363
Smith, D. M., Heindl, W. A., Markwardt, C. B., & Swank, J. H. 2001, ApJ, 544, L41
Stobbart, A.-M., Roberts, T. P., & Wilms, J. 2006, MNRAS, 368, 397
Strohmayer, T. E., & Mushotzky, R. F. 2003, ApJ, 586, L61
Tomick, J. A., Corbel, S., Goldwurm, A., & Kaaret, P. 2005, ApJ, 630, 413
Wang, Q. D., Yao, Y., Fukui, W., Zhang, S. N., & Williams, R. 2004, ApJ, 609, 113
Wilms, J., Nowak, M. A., Pottschmidt, K., Pooley, G. G., & Fritz, S. 2006, A&A, 447, 245