**XMM-NEWTON SPECTROSCOPY OF FOUR BRIGHT ULTRALUMINOUS X-RAY SOURCES IN THE ANTENNAE GALAXIES (NGC 4038/4039)**

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Received 2004 February 25; accepted 2004 March 19

**ABSTRACT**

We report the results of spectral fits to four bright ultraluminous X-ray sources (ULXs) in the Antennae galaxies (NGC 4038/4039) observed for 41 ks with XMM-Newton. Although emission regions are not resolved as well as in prior Chandra observations, at least four ULXs (X-11, X-16, X-37, and X-44 in the Zezas and Fabbiano scheme) are sufficiently bright and well separated with XMM-Newton that reliable extractions and spectral analyses are possible. We find that the single-component multicolor disk blackbody models cannot describe any of the spectra. Sources X-11 and X-16 are acceptably fitted with simple power-law models. A thermal bremsstrahlung model provides a better fit to the spectrum of X-44. Including a disk blackbody component to the spectrum of X-37 improves the fit and reveals an apparently cool disk ($kT = 0.13 \pm 0.02$ keV). This would suggest a parallel to cool disks recently found in other very luminous ULXs, which may contain intermediate-mass black holes; however, the complex diffuse emission of the Antennae demands that this finding be regarded cautiously.

**Subject headings:** galaxies: individual (NGC 4038/4039) — X-rays: galaxies

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) are off-nuclear point-like X-ray sources in nearby normal galaxies (Fabbiano & Trinchieri 1987; Fabbiano 1989). The X-ray flux variability observed in many ULXs (see, e.g., La Parola et al. 2001; Kubota et al. 2001) signifies that the class is likely dominated by accreting compact objects. The high luminosities measured from ULXs by definition exceed the Eddington luminosity for a neutron star accreting isotropically; many exceed (sometimes by a factor of 10 or more) the Eddington luminosity expected for a $10^{-5}$ black hole.

Theoretical models for ULXs suggest that these may be stellar-mass sources with relativistically beamed emission (Körding et al. 2002), stellar-mass sources with anisotropic emission (King et al. 2001), or intermediate-mass black holes (IMBHs). Observations with *Chandra* and *XMM-Newton*, and especially multiwavelength observing schemes, are beginning to reveal that no single model for ULXs may describe the entire class. Rather, the class may include examples of each possibility described above (see recent reviews by King 2004, Fabbiano & White 2004, and Miller & Colbert 2004). NGC 5408 X-1 may be an example of a stellar-mass source with relativistically beamed emission (Kaaret et al. 2003); it is also possible that the spectrum can be described in part with a cool disk, which would indicate an IMBH. Many of the ULXs in the Antennae (there are nine sources with $L_x \geq 10^{39}$ erg s$^{-1}$ for a distance of 19 Mpc; Fabbiano et al. 2001) may be stellar-mass sources with anisotropic emission, because their average distances from the nearest star clusters suggest runaway binaries and tend to exclude very massive systems, although capture of a companion from a primordial IMBH cannot be excluded (Zezas et al. 2002). Finally, sources with high luminosities but low disk temperatures may be IMBHs; NGC 1313 X-1 and X-2 (Miller et al. 2003) may be examples.

At present, the anisotropic emission model (King et al. 2001) may be the most compelling description for many ULXs. It is motivated in part by the unusually large number of ULXs resolved in the Antennae with *Chandra* that suggest a link with the actively forming stellar population. This conclusion is supported by the association of large numbers of ULXs with active star-forming galaxies (e.g., NGC 3256, Lira et al. 2002; NGC 4485/90, Roberts et al. 2002; NGC 1068, Smith & Wilson 2003). However, the King et al. (2001) scenario may not be able to describe sources at the highest end of the ULX luminosity distribution (e.g., the sources with cool accretion disks mentioned above; see also Strohmayer & Mushotzky 2003).

In this paper we report the result of *XMM-Newton* observations of the Antennae, which provide for the first time high-quality medium-resolution X-ray spectra of four bright ULXs in this merger system. These data can be used to constrain the emission model, as was done in the case of the discovery of low-temperature components in the NGC 1313 ULXs (Miller et al. 2003). The spatial resolution of *XMM-Newton* is approximately 10 times more coarse than that of *Chandra*, so that robust spectra can only be obtained from the brightest sources in targets with crowded fields such as the Antennae. The procedure used to reduce our data and extract spectra is described in § 2. In § 3, we present the results of fitting simple spectral models to four bright ULXs. Finally, in § 4 we discuss our results and their impact on our understanding of ULXs within the context of models for their nature and anomalous luminosity.

2. DATA REDUCTION AND ANALYSIS

The Antennae (NGC 4038/4039) were observed with *XMM-Newton* for 40.9 ks on 2002 January 8, starting at 22:03:37 (UT). We used only the EPIC data for this analysis. The EPIC MOS-1 and MOS-2 cameras were operated in...
“prime full window” mode and the EPIC-pn camera was operated in “prime full window extended” mode. The “medium” optical blocking filter was used for all three cameras.

The XMM-Newton reduction and analysis suite SAS version 5.3.3 was used to filter the standard pipeline event lists, detect sources within the field, and make spectra and responses. After filtering against soft proton flares, the net “good time” for each camera was 22.6, 25.6, and 25.7 ks for the pn, MOS-1, and MOS-2 cameras, respectively.

The ULX population in the Antennae is concentrated near the center of the interacting galaxies, which is a region with a dense source population. By relying on the Chandra source detections, we determined that many sources are blended or too close to other bright sources to reliably extract a spectrum. Fortunately, at least four ULXs are well separated from others and/or bright enough that counts within a reasonable extraction region should be strongly dominated by the bright source. These sources are X-11, X-16, X-37, and X-44 (as numbered and identified by Zezas et al. 2002) and are shown in Figure 1.

We used circular regions centered on the known Chandra positions to extract source counts for these ULXs. The recipes described in the MPE “cookbook” were used to filter the event lists. These parameters were chosen as follows: we set FLAG = 0 to reject events from bad pixels and events too close to the CCD chip edges; patterns 0–4 were selected for the pn camera, and patterns 0–12 for the MOS-1 and MOS-2 cameras; finally, the pn spectral channels were grouped by a factor of 5 and the MOS-1 and MOS-2 channels by a factor of 15.

For X-11, X-16, and X-44, source counts were extracted within a 12″ radius; because of the proximity of a nearby source a 9″ extraction radius was used for X-37. Flux from source X-13, a transient soft source (Fabbiano et al. 2003b), might contaminate the flux extracted from X-11. However, no soft emission component is required to describe the spectra of X-11 (see § 3), so it is likely that X-13 was in a low-flux state. Background spectra were not extracted for two reasons. First, for XMM-Newton approximately 40% of the on-axis point source encircled energy lies between radii of 15″ and 50″. Extracting a background spectrum in an annulus for subtraction from the source spectrum would primarily act to subtract source counts. Second, the central region of the Antennae galaxies is a crowded field; adjacent regions may include emission from point sources that are weaker than the brightest ULXs and prevent measurement of a true (diffuse) background.

Fig. 1.—EPIC/MOS-1 0.3–10.0 keV image of the central regions of the Antennae galaxies, shown on a linear scale. The source spectra considered in this work were extracted using the circular regions shown, which are centered on previously measured Chandra source positions.
Observations with Chandra suggest that the diffuse background near to the brightest ULXs should be less than 1% of the source counts, however, and so not significantly affect fits to the source spectra. Moreover, sources resolved with Chandra that are nearby to the four brightest ULXs considered in this work were previously found to generally be 1–2 orders of magnitude fainter than the ULXs (Zezas et al. 2002). Given the falloff in encircled energy noted above, flux from nearby point sources is likely to be less than 5% of the flux in the ULX extraction regions. See § 3, however, for a brief discussion of the observed local background, which is more complex than these simple estimates would indicate. Response files were generated for each spectrum from each camera using the SAS tools rmfgen and arfgen. Prior to fitting, the spectra were grouped to require at least 10 counts per bin to ensure the validity of $\chi^2$ statistics. Grouping to require more counts per bin did not significantly change the fitted results.

The ULX light curves (in the 0.3–10.0 keV band, with 1.0 ks bins) are well described by a constant flux level. We therefore considered only the time-averaged spectra from each ULX. Model spectra were fitted to the data using XSPEC version 11.2 (Arnaud 1996). The pn, MOS-1, and MOS-2 spectra of each source were fitted jointly, allowing an overall normalizing constant to account for small differences in the broadband flux calibration of the cameras. Values obtained for the constant indicate that at the time of observation, the pn and MOS-1 flux calibrations differ by less than 5%. The MOS-2 flux calibration differed by less than 5% from the MOS-1 camera but may have differed from the pn at the 10% level. Systematic errors were not added to the spectra prior to fitting. Models were fitted to the EPIC spectra in the 0.3–10.0 keV band. Errors quoted in this work are at the 90% confidence level for one interesting parameter. Using the SAS tool epatplot and the HEASARC tool PIMMS, we found that the effects of photon pileup were negligible in this observation.

3. RESULTS

An examination of the individual spectra did not reveal compelling evidence for emission or absorption lines, where a possible feature is seen in one spectrum (pn, MOS-1, or MOS-2), in each case there is no feature evident in the other spectra. This strongly suggests that any narrow deviations from a continuum spectrum are statistical fluctuations. We therefore restricted our modeling to continuum components. For each model, the phabs model in XSPEC was used to describe the equivalent neutral hydrogen column density along our line of sight. We fixed the lower bound of the equivalent neutral hydrogen column density to the Galactic value ($N_H = 4.0 \times 10^{20} \text{ cm}^{-2}$;Dickey & Lockman 1990). The results of fits with a number of simple models are listed in Table 1, and the results are described in detail below.

Prior fits to a number of ULX spectra (not sources within the Antennae) obtained with ASCA with the multicolor disk (MCD) blackbody model (Mitsuda et al. 1984) suggested that hot accretion disks may be a fundamental accretion flow structure in ULXs (Makishima et al. 2000). Fits to X-11, X-16, X-37, and X-44 yielded high disk color temperatures ($1.0 \text{ keV} < kT < 1.7 \text{ keV}$), similar to prior ASCA results. However, this model does not yield an acceptable fit to any of the spectra. Other single- and two-component models are strongly preferred statistically (see below). This may suggest that X-11, X-16, X-37, and X-44 may be different from ULXs such as Dwingeloo X-1 (see Makishima et al. 2000). It is possible, however, that the apparent differences are partially due to the better sensitivity of XMM-Newton.

Significantly better fits are obtained when the spectra are fitted with either a power-law or thermal Bremsstrahlung model. In systems accreting at high rates, most of the flux phenomenologically described as a power law likely arises from the Compton-upscattering of relatively cool disk photons in an optically thin corona (see, e.g., Titarchuk 1994). A thermal Bremsstrahlung spectrum is consistent with expectations for an optically thick, geometrically thick disk that may have a significant advective component (see, e.g., Ebisuzaki et al. 2001; Begelman 2002). Statistically acceptable fits to the spectra of X-11 and X-16 are obtained with either continuum model (see Table 1). The spectra of X-37 are not acceptably described with either model. A bremsstrahlung model is a better description of the spectra from X-44 than a power-law model. The fits to X-11, X-16, X-37, and X-44 with a power-law model and associated data/model ratios are shown in Figures 2–5. The best-fit models for the spectra from each ULX are shown in Figure 6.

The addition of a simple blackbody component to a power law yielded cool temperatures and marginal statistical improvements to the fits. However, disk temperatures certainly fall off with radius (see, e.g., Frank et al. 2002) and are more properly modeled as a series of blackbody annuli as approximated by the MCD model. A single blackbody component might reasonably approximate a neutron star surface; however, the luminosities inferred in these sources are 2 orders of magnitude above the Eddington limit for a neutron star, which is the basis for the often-made assumption that ULXs harbor accreting black holes.

Similarly, the addition of a low-temperature diffuse thermal emission component (e.g., a MEKAL plasma) to a power law gives marginal statistical improvement when fitting the ULX spectra. However, this model is likely not justified. Observations of black hole binaries in the Milky Way and Magellanic Clouds do not reveal evidence of optically thin thermal emission local to the systems through plasma emission line spectra. It is particularly interesting to note that such spectra have not been revealed even in systems with high-mass (O or B type) companions, given the emerging links between ULXs and star formation (for reviews, see Fabbiano & White 2004 and Miller & Colbert 2004). Observations of Cygnus X-1 (O9.7 Iab companion; Gies & Bolton 1982) with the Chandra High Energy Transmission Grating Spectrometer (HETGS) have revealed a rich absorption spectrum in all states (Schulz et al. 2002; Marshall et al. 2001; Miller et al. 2004; Feng et al. 2003). LMC X-1 (O7 III companion; Cowley et al. 1995) is often observed at luminosities exceeding $10^{39} \text{ ergs s}^{-1}$ (Wilm et al. 2001), but even Chandra/HETGS spectra have failed to reveal emission lines from an optically thin plasma (Cui et al. 2002). Moreover, the diffuse emission in the Antennae that can be described in terms of optically thin thermal models (Fabbiano et al. 2003a) is expected to be 2 orders of magnitude less than the flux from a ULX.

Finally, we considered a model consisting of MCD and power-law components. This simple model is often applied to stellar-mass black hole binaries in the Milky Way and Magellanic Clouds. Moreover, as noted above it has a stronger physical motivation than simple blackbody plus power law models or optically thin thermal emission plus power-law models. The MCD plus power-law model permits an interesting comparison to recent ULX spectral results in which MCD color temperatures 5–10 times lower than commonly
Results of fitting simple models to the EPIC spectra of four bright ULXs in the Antennae galaxies. The XSPEC model *phabs* was used to measure the equivalent neutral hydrogen column density along the line of sight.

- The measured flux.
- The absorption-corrected or “unabsorbed” flux.
- The source luminosity in the 0.3–10.0 keV band for a distance of 19 Mpc.

### TABLE 1
**Spectral Fit Parameters**

| Parameter | X-11 | X-16 | X-37 | X-44 |
|-----------|------|------|------|------|
| **Power-Law Model** | | | | |
| \(N_H (10^{21} \text{ cm}^{-2})\) | 1.0 ± 0.2 | 0.4 ± 0.2 | 2.0 ± 0.3 | 1.3 ± 0.3 |
| \(\Gamma\) | 1.9 ± 0.1 | 1.48 ± 0.07 | 2.06 ± 0.09 | 2.2 ± 0.2 |
| Norm. \((10^{-5})\) | 5.5 ± 0.7 | 3.6 ± 0.3 | 5.3 ± 0.9 | 5 ± 1 |
| \(F_{0.3-10} \times 10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ yr}^{-1}\) | 3.3 ± 0.4 | 2.9 ± 0.2 | 2.5 ± 0.4 | 2.3 ± 0.5 |
| \(\chi^2/\text{dof}\) | 162.6/160 | 140.0/164 | 163.0/129 | 162.6/139 |

| **MCD Model** | | | | |
| \(N_H (10^{21} \text{ cm}^{-2})\) | 0.4 ± 0.1 | 0.40 ± 0.02 | 0.4 ± 0.1 | 0.40 ± 0.03 |
| \(kT (\text{keV})\) | 1.1 ± 0.1 | 1.5\(^{+0.2}_{-0.1}\) | 1.2 ± 0.1 | 1.0 ± 0.1 |
| Norm. \((10^{-5})\) | 7.0 ± 1.2 | 2.2 ± 0.7 | 4.5\(^{+1.2}_{-0.7}\) | 9\(^{+0.4}_{-1}\) |
| \(\chi^2/\text{dof}\) | 245.8/160 | 258.8/164 | 220.2/129 | 194.8/139 |

| **Bremsstrahlung Model** | | | | |
| \(N_H (10^{21} \text{ cm}^{-2})\) | 0.4 ± 0.1 | <0.4 | 1.1 ± 0.2 | 0.5\(^{+0.2}_{-0.2}\) |
| \(kT (\text{keV})\) | 5.1 ± 0.8 | 12\(^{+6}_{-2}\) | 4.5 ± 0.8 | 3.7 ± 0.5 |
| Norm. \((10^{-5})\) | 6.0 ± 0.6 | 5.2 ± 0.4 | 5.1 ± 0.6 | 4.9\(^{+0.7}_{-0.3}\) |
| \(\chi^2/\text{dof}\) | 164.1/160 | 152.1/164 | 178.7/129 | 149.4/139 |

| **MCD + Power Law** | | | | |
| \(N_H (10^{21} \text{ cm}^{-2})\) | 3.0\(^{+0.8}_{-1.8}\) | 1.5 ± 1.0 | 5.6 ± 1.5 | 1.4\(^{+1.9}_{-1.0}\) |
| \(kT (\text{keV})\) | 0.15 ± 0.02 | 0.19 ± 0.05 | 0.13 ± 0.02 | 0.15\(^{+0.02}_{-0.01}\) |
| Norm. \((10^{-5})\) | 50\(^{+10}_{-10}\) | 5\(^{+1}_{-1}\) | 250 ± 150 | 1\(^{+0.7}_{-0.7}\) |
| \(\Gamma\) | 1.9 ± 0.2 | 1.4 ± 0.2 | 2.0 ± 0.2 | 2\(^{+0.4}_{-0.4}\) |
| Norm. \((10^{-5})\) | 5.5\(^{+1.7}_{-1.6}\) | 3.2\(^{+0.8}_{-0.7}\) | 5.4 ± 1.5 | 5.0 ± 1.0 |
| \(\chi^2/\text{dof}\) | 153.2/158 | 131.5/162 | 143.8/127 | 162.2/137 |
| \(F (10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ yr}^{-1})\) | 2.5\(^{+0.7}_{-1.3}\) | 2.9\(^{+0.7}_{-0.8}\) | 1.9\(^{+0.7}_{-0.7}\) | 1.8\(^{+0.4}_{-0.3}\) |
| \(F (10^{-13} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ yr}^{-1})\) | 4.9\(^{+1.1}_{-1.4}\) | 3.8\(^{+0.9}_{-0.9}\) | 7.9\(^{+3.9}_{-3.8}\) | 2.3\(^{+1.0}_{-0.9}\) |
| \(F_{\text{power law}}/F_{\text{total}}\) | 0.61 | 0.33 | 0.33 | 0.72 |
| \(L_{0.3-10} (10^{39} \text{ ergs s}^{-1})\) | 2.1\(^{+0.7}_{-1.1}\) | 1.6\(^{+0.4}_{-1.0}\) | 3.4\(^{+1.7}_{-1.2}\) | 1.0\(^{+1.3}_{-0.2}\) |

Notes:—Results of fitting simple models to the EPIC spectra of four bright ULXs in the Antennae galaxies. The XSPEC model *phabs* was used to measure the equivalent neutral hydrogen column density along the line of sight.
measured in stellar-mass black holes may imply IMBHs, since \( T \sim M_{\text{BH}}^{1/4} \) in the MCD model (Miller et al. 2003; see also Kaaret et al. 2003). While this model is not required to describe the spectra of X-11 or X-16, it provides a marginally better fit and represents a statistically better fit to X-37 at the 3.5 \( \sigma \) level of confidence based on an \( F \)-test. However, this two-component model provides no improvement for X-44. In each case, the color temperature obtained is consistent with a cool disk (the range of temperatures obtained is 0.11 keV < \( kT < 0.21 \) keV). The power-law component represents a significant fraction of the 0.3–10.0 keV flux in this model. This may suggest that the gas in any optically thin accretion flow geometry is very hot; if so, it is unlikely that the potentially cool thermal emission we have characterized with a disk model is actually due to local illumination of diffuse gas. This two-component model is the best description of the spectra of X-37; for this source we measure \( kT = 0.13 \pm 0.02 \) keV.

If color temperatures of \( kT \sim 0.5–1.0 \) keV may be taken as typical of stellar-mass black holes near to or above \( L_X/L_{Edd} \sim 0.1 \), then color temperatures in the \( kT \sim 0.11–0.21 \) keV range may indicate black holes with masses in the range of \( 30 M_\odot \leq M_{\text{BH}} \leq 6800 M_\odot \) in these ULXs. The two-component MCD plus power-law model provides the best fit to X-37; for this source, black hole masses in the range \( 120 M_\odot \leq M_{\text{BH}} \leq 7000 M_\odot \) (90\% confidence, including uncertainties in \( kT \) and stellar-mass black hole disk color temperatures in the range \( 0.5 \) keV ≤ \( kT \) ≤ 1.0 keV) may be suggested. It is worth noting, however, that the model used represents only a 3.5 \( \sigma \) improvement to the spectra of X-37, far less than the 8 \( \sigma \) improvement over single-component fits to NGC 1313 X-1 (\( kT_{\text{NGC 1313 X-1}} = 0.15^{+0.02}_{-0.04} \) keV; Miller et al. 2003).

Given the impact that cool soft components can have on models for the nature of a given ULX, it is worth carefully reexamining the question of local background contamination. The Antennae are known to have a complex, spatially variable diffuse emission component (Fabbiano et al. 2004). To investigate this more fully and to test our assumptions regarding background contamination (see § 2), we extracted a number of local background regions inside of, along, and outside of the core ring of emission seen in Figure 1. Outside of this ring and in some locations within the ring, the total background (in counts per area) is only 3\%–8\% of the flux in our source extraction regions. In other locations, particularly at points along the inner edge of the ring, the background can be as high as 20\%–30\% of flux in our source extraction regions. The intensity and spectrum of the local background varies considerably, consistent with Fabbiano et al. (2004). In view of the complex diffuse background, the possibility of a cool disk component in X-37 must be regarded more cautiously than in cases such as NGC 1313 X-1 and X-2.

4. DISCUSSION

We have analyzed the XMM-Newton/EPIC spectra of four bright ULX sources (X-11, X-16, X-37, and X-44; as numbered by Zezas et al. 2002). The spectra of two sources (X-16, X-11) can be well described by a single power law (\( \Gamma_\text{x-11} = 1.48 \), \( \Gamma_\text{x-16} = 1.9 \)). One of the other sources (X-44) is best described by a thermal bremsstrahlung model (\( kT = 3.7 \) keV), while the fourth source (X-37) may require two spectral components: a power-law (\( \Gamma_\text{x-37} = 2.0 \)) and an MCD model (\( kT_{\text{x-37}} = 0.13 \) keV). Here we comment on the implications of these results for the nature of these sources and the general ULX population.

The co-added spectrum of the ULXs detected in the first Chandra observations of the Antennae was well represented by a composite MCD/power-law model with a temperature of...
1.13 keV (Zezas et al. 2002), while similar fits of the XMM-Newton spectra give temperatures in the 0.1–0.2 keV range. This difference is most probably due to the fact that the Chandra results are for the co-added spectra of 18 sources, while here we study the detailed spectra of individual sources. In fact, a comparison with the individual Chandra spectral fits for these sources (Zezas et al. 2002) shows that the photon indices from the Chandra power-law fits are slightly flatter but consistent within the 2 $\sigma$ level with those derived from the XMM-Newton fits. Similarly, the values of $N_H$ from the Chandra fits are slightly higher than those derived from the XMM-Newton fits but again are consistent within the 2 $\sigma$ level. The discrepancy in $N_H$ may be due to the fact that the degradation of the Chandra/ACIS quantum efficiency was not taken into account by Zezas et al. (2002). We note that no flux variability above the 3 $\sigma$ level has been detected between the two observations.

The thermal bremsstrahlung model that best describes the spectrum of X-44 is broadly consistent with expectations for a “slim” disk around a stellar-mass black hole (Watarai et al. 2001), or perhaps a thin disk radiating above the Eddington limit because of photon bubble instabilities (Begelman 2002). Additional sensitive observations of X-44 may be able to confirm or reject these disk models by determining whether the spectrum we have measured is typical.

The spectra of the other ULXs are even more difficult to parse. The power-law indices measured from X-11, X-16, and X-37 are well within the range commonly observed in Galactic stellar-mass black holes (for reviews, see McClintock & Remillard 2004). If these sources were “microblazars” (e.g., Körding et al. 2002), in which a jet axis coinciding with the line of sight might boost the flux through beaming, the same beaming should act to create a significantly harder power-law spectrum. In addition, beaming should tend to create strong short-timescale flux variations, which are also not seen in these sources. While very sensitive optical and radio limits are needed to more definitively rule out a microblazar interpretation (this is complicated greatly by the distance of the Antennae galaxies), the X-ray properties of these sources are certainly inconsistent with a microblazar scenario.

Another possibility is that X-11, X-16, and X-37 are stellar-mass black holes in the “very high” state (see the reviews mentioned previously; see also Kubota et al. 2002). Certainly, if ULXs behave similarly to Galactic stellar-mass black holes, it is reasonable to expect that this state holds at the luminosities observed. Whereas Cygnus X-1 gets softer when it brightens in the soft X-ray band (below 10 keV), X-11 and X-16 have been observed to get harder when they get brighter (Fabbiano et al. 2003b); this is sometimes referred to as microquasar-like variability since the very high state is spectrally harder than the high/soft state. However, at high accretion rates a hot disk component ($kT \approx 1$ keV or higher) is always important, even in cases where the power-law component appears to dominate (e.g., Zycki et al. 1999). The spectra of X-11, X-16, and X-37 cannot be described by fits consisting only of hot MCD components. Moreover, as noted previously, when MCD plus power law models are fitted to the spectra, the temperatures of cool disks are measured. Identifying X-11, X-16, and X-37 as stellar-mass black holes in a very high state similar to that defined in Galactic systems is therefore very problematic.

The $kT = 0.13 \pm 0.02$ keV disk component in the spectrum of X-37 (if due to a standard disk around an IMBH) implies a mass in the 120–7000 $M_\odot$ range. Similar temperatures have been measured in the spectra of NGC 1313 X-1, NGC 1313 X-2 (Miller et al. 2003), and NGC 5408 X-1 (Kaares et al. 2003). As noted in § 3, however, it is possible that the complex, spatially variable diffuse emission in the Antennae has contaminated the spectrum of X-37; part of the soft component may be background flux. The spatial resolution afforded by XMM-Newton makes it unlikely that future observations with XMM-Newton will determine the nature of the apparent soft component in X-37 with greater certainty. Analysis of new, long Chandra observations, or future Chandra observations, may be able to make such a determination.

A comparison of the Chandra position of X-37 and the positions of its nearby star clusters shows that there are no star clusters down to $m_V = 23$ mag within a radius of 1.7 pc (Zezas et al. 2002), which translates to a physical distance of 156 pc ($d = 19.0$ Mpc). Following Zezas et al. (2002), if this separation is due to a supernova kick to the system, and assuming (1) conservation of momentum, (2) that the same mechanism imparting kicks to neutron star systems is active here, and (3) that the X-ray binary becomes active in the end of the donor’s main-sequence lifetime, we can set an upper limit to its mass of $\sim 6 M_\odot$ if the compact object has a mass of $120 M_\odot$; this corresponds to a star of spectral type B5 or later. However, the large mass ratio between the putative IMBH and the donor makes this type of system prone to transient behavior. Therefore, if this object is an IMBH then there may be a large population of such systems throughout the Antennae (relatively few may be observed at any given moment, depending on their duty cycles).

King & Pounds (2003) have proposed a model wherein the cool thermal emission revealed in some ULXs may be due to an optically thick, quasi-spherical outflow originating approximately 100 Schwarzschild radii from a stellar-mass black hole accreting at a rate close to the Eddington limit. As noted previously, when stellar-mass black holes are near peak luminosity, they are found in the very high state. A number of hallmark features of the very high state clearly reveal the inner disk and are plainly inconsistent with an optically thick outflow obscuring the innermost accretion environment (for a recent review, see McClintock & Remillard 2004). First, a hot thermal accretion disk component ($kT \approx 1$ keV or above) is always observed in the very high state. Second, high-frequency (a few $\times$ 100 Hz) quasi-periodic oscillations (QPOs), which are connected to the Keplerian orbital frequency in the inner disk, to resonances in the inner disk in a Kerr spacetime, or both, are preferentially found in the very high state (some are also found in the intermediate state, which is likely a lower flux version of the very high state). Third, broad relativistic Fe Kα emission lines due to hard X-ray emission irradiating the inner disk are preferentially revealed in the very high state. The model suggested by King & Pounds (2003) also requires that any hard X-ray emission originate in shocks outside of the optically thick outflow. This is again inconsistent with observations. High-frequency QPOs (and lower frequency QPOs) are a higher fraction of the rms noise at higher energy, suggesting a fundamental connection between inner disk frequencies and the hard X-ray–emitting region. Relativistic Fe Kα emission lines also require the source of hard X-ray emission to be very central in the accretion flow. Fourth, the photon index of the power-law components often observed in bright ULXs is harder than is generally found in the very high state of Galactic black holes (where $\Gamma \approx 2.4$ is common;
McClintock & Remillard 2004; Roberts et al. 2004). Finally, high-inclination “dipping” X-ray binaries clearly require that the hard component in these systems be fairly compact and central. Clearly, if the King & Pounds (2003) model is to hold, the source state required cannot be similar to those already observed in Galactic black holes in their highest flux phases.

In summary, the spectra we have obtained do not allow for definitive conclusions regarding the nature of the four brightest ULXs in the Antennae galaxies. However, the spectra are of sufficient quality to imply that the ULXs in the Antennae may not all have a common nature. These results provide further evidence that models for the ULX phenomenon based on a single source population may not be sufficient to describe the entire class.

J. M. M. acknowledges support from the NSF through its Astronomy and Astrophysics Fellowship Program. We thank the anonymous referee for helpful suggestions. This work is based on observations obtained with XMM-Newton, an ESA mission with instruments and contributions directly funded by ESA Member States and the US (NASA). This work made use of the High Energy Astrophysics Archive Research Center (HEASARC), operated for NASA by GSFC.

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