X-RAY MONITORING OF ULTRALUMINOUS X-RAY SOURCES

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ABSTRACT

X-ray monitoring observations were performed with the Swift observatory of the ultraluminous X-ray sources Holmberg IX X-1, NGC 5408 X-1, and NGC 4395 X-2 and also of the nuclear X-ray source in NGC 4395. Holmberg IX X-1 remains in the hard X-ray spectral state as its flux varies by a factor of 7 up to a (isotropic) luminosity of $2.8 \times 10^{46}$ erg s$^{-1}$. This behavior may suggest an unusually massive compact object. We find excess power at periods near 60 days and 28 days in the X-ray emission from Holmberg IX X-1. Additional monitoring is required to test the significance of these signals. NGC 5408 X-1 and NGC 4395 X-2 appear to remain in the soft spectral state found by Chandra and XMM with little variation in spectral hardness even as the luminosity changes by a factor of 9. We found an outburst from the nuclear source in NGC 4395 reaching an X-ray luminosity of $9 \times 10^{40}$ erg s$^{-1}$, several times higher than any previously reported.

Key words: black hole physics – galaxies: individual (Holmberg IX, NGC 5408, NGC 4395) – galaxies: stellar content – X-rays: binaries – X-rays: galaxies

1. INTRODUCTION

Ultraluminous X-ray sources (ULXs) were originally identified as potential intermediate-mass black holes (IMBHs) on the basis of the high luminosities inferred assuming isotropic emission of X-rays (Colbert & Mushotzky 1999; Makishima et al. 2000; Kaaret et al. 2001). If ULXs are, indeed, radiating isotropically below the Eddington luminosity, then the inferred masses are, in some cases, greater than 500 $M_\odot$. This is larger than the maximum compact object mass which can be formed in the collapse of a single star with metallicity $Z \gtrsim 10^{-3} Z_\odot$ (Bromm & Loeb 2003), and requires a different mechanism for formation. The existence of IMBHs would be of interest for studies ranging from the formation of galaxies and their supermassive black holes to the generation of gravitational waves. However, the physical nature of ULXs is not well understood. The X-rays may be mechanically or relativistically beamed in which case IMBHs are not required.

New information is needed to understand the ULXs. Knowledge of the patterns of evolution of the X-ray emission from Galactic black hole X-ray binaries has been the key to understanding their physical nature (Remillard & McClintock 2006; Belloni et al. 2005). Detailed study of spectral evolution was the key to determining the physical nature of the spectral components contributing to the emitted X-ray flux.

Previously, it has been possible to obtain light curves with more than about a dozen points only for the brightest ULX located in M82 (Kaaret et al. 2006a, 2006b; Kaaret & Feng 2007). The Swift observatory (Gehrels et al. 2004) has a capability, unique among focusing X-ray telescopes, to perform multiple observations of a given target with flexible scheduling. While the effective area of the Swift X-Ray Telescope (XRT) is limited in comparison with the larger X-ray observatories, the brighter ULXs have sufficiently high fluxes to provide reasonable numbers of counts ($\sim 200$) in modest individual observations (less than 2 ks). Thus, Swift provides the unique means to extend our knowledge of ULXs by probing their patterns of spectral evolution with dense temporal coverage.

Here, we report on X-ray monitoring observations performed with the Swift observatory of the ULXs Holmberg IX X-1, NGC 5408 X-1, and NGC 4395 X-2 and also of the nuclear X-ray source NGC4395 X-1. The targets, observations, and data reduction are described in Section 2. The results are discussed in Section 3.

2. TARGETS, OBSERVATIONS, AND DATA ANALYSIS

Holmberg IX X-1 (= NGC 3031 X-9) has an average X-ray luminosity near $10^{40}$ erg s$^{-1}$ and is surrounded by a large and energetic optical nebula (Grisé et al. 2006). This ULX is one of the best on which to perform long-term monitoring with Swift, because it is the brightest ULX with no contaminating sources within the angular resolution of the Swift XRT. The source shows large flux variations across the observations obtained to date by various X-ray instruments (La Parola et al. 2001). Based on XMM-Newton spectra, we estimated a typical count rate for the Swift XRT of 0.14 c/s when retaining events with grades 0–12 in photon-counting mode. Thus, measurements of the source intensity and a hardness ratio are possible with observations of around 1400 s. We obtained 72 observations of Holmberg IX X-1 under Swift program 90008 (PI: Kaaret). In addition, we analyzed one observation obtained under program 25952, nine from program 35335, and 25 from program 90079.

We also searched the Swift archive for series of multiple observations of other relatively bright ULXs. We found 78 observations of the ULX NGC 5408 X-1 under program 90041 and 24 under program 90218 (both PI: Strohmayer). This ULX has exhibited quasiperiodic oscillations at relatively low frequencies (Strohmayer et al. 2007) and is surrounded by a powerful radio nebula (Kaaret et al. 2003; Soria et al. 2006; Lang et al. 2007) and a photoionized optical nebula (Kaaret & Corbel 2009). NGC 5408 X-1 is one of the best IMBH candidates among the ULXs. However, NGC 5408 X-1 is dimmer than Holmberg IX X-1.

We also found 59 observations of the nearby active galaxy NGC 4395 obtained under program 90053 (PI: Uttley).
NGC 4395 contains an X-ray source at a position near R.A. = 12h26m02s and decl. = 33°31′34″ (J2000), NGC 4395 X-2 in Lira et al. (2000), and source E in Moran et al. (1999), that during the ROSAT-era appeared brighter than nuclear X-ray source, reaching a luminosity near $3 \times 10^{39}$ erg s$^{-1}$. We examined this source. We also examined the nuclear X-ray source in NGC 4395, NGC 4395 X-1 in Lira et al. (2000), and source A in Moran et al. (1999), for comparison with the ULXs.

We retrieved level 2 event files with observations of these targets made in photon counting and pointed mode. These event files have data screening already applied as described in the XRT User’s Guide. Each observation is divided up into one or more good time intervals (GTIs). We analyzed each GTI separately, retaining only those GTIs with durations of 100 s or longer. We extracted source counts from a region with a radius of 25″ and background counts from an annulus with an inner radius of 50″ and an outer radius of 100″. This extraction radius captures 82% of the total photon flux (Moretti et al. 2006), and we correct for this when calculating source fluxes. There are bad pixels in the XRT CCD that can lead to a loss of photons. For each GTI, we calculated the displacement of the center of gravity of the recorded photons from the nearest bad pixel and rejected the GTI if the displacement was less than 12.5″. This removes GTIs that have one or more bad pixels near the core of the source point-spread function. About 20% of the GTIs were rejected due to bad pixels. Using the measured point-spread function (Moretti et al. 2006) and making the conservative assumption that the nearest bad pixel is at the edge of a half-plane of bad pixels, we estimate that the maximum loss of counts for the unrejected GTIs is less than 6%. We performed our analysis using the Pulse Invariant data, which are corrected for gain variations with time, temperature, and charge transfer inefficiency. For each observation interval, we calculated the net count rate in the 0.3–8 keV band and in the 1–8 keV band. We calculated a hardness ratio equal to the rate in the hard band (1–8 keV) divided by the rate in the full band (0.3–8 keV).

### 3. RESULTS

The X-ray light curves of the four targets in the 0.3–8 keV band are shown in Figure 1. Significant variability is seen in all of the light curves. We calculated periodograms for the data shown in each light curve using the method of Horne & Baliunas (1986) with the power normalized by the total variance of the data for periods in the range of 4–130 days. The maximum power is 18.1 near a period of 115 days for NGC 5408 X-1 and 12.3 at a period near 28 days for NGC 4395 X-2; neither is a significant signal. The periodogram for Holmberg IX X-1 is shown in Figure 2. There are two peaks: one with a power of 35.0 at a period near 60 days and other with a power of 31.6 at a period near 28 days. The fine structure of the peaks is due to aliasing of nearby periods due to the large gap in time between the different epochs of Swift observations. We note that a significant part of the power comes from the flare near MJD 54020 in observations taken before the start of the monitoring. Excluding the data from MJD 54000 to 54100, the strongest signal has a power of 23.1 at a period near 56 days. Thus, we do not interpret the signal as a true periodicity at this time. However, the observed signal is strong motivation to continue periodic monitoring of Holmberg IX X-1 with Swift.

Hardness/intensity diagrams for the four targets are shown in Figure 3. The intensity is the count rate in the 0.3–8 keV band and the hardness is the ratio of the rate in the hard band (1–8 keV) divided by the rate in the full band (0.3–8 keV). The individual GTIs were generally too short to adequately constrain the hardness ratio, particularly for the dimmer sources. However, the hardness values for a given source at a given count rate appeared consistent. Thus, we chose to bin the data by count rate and calculate the average hardness for all of the observations within each count rate bin. The behavior of all three ULXs is consistent with no significant spectral evolution as a function of intensity. The average hardness and the $\chi^2$ for a model where the hardness is taken as equal to the average hardness/intensity are consistent with no significant evolution.
are shown in Table 1. For comparison, we show the results of a fit of an absorbed power-law model to XMM-Newton data of an absorbed power-law model, and the expected hardness calculated using the average hardness found from the Swift data. For Holmberg IX X-1, the column density and photon index measured from fits to XMM-Newton data are shown in Table 1. For comparison, we show the results of a fit of an absorbed power-law model to XMM-Newton data of a constant model is $\chi^2$/DoF = 5.8/7. Thus, the data remain consistent with the constant hardness even if the points with large errors are excluded.

Remillard & McClintock (2006) have identified three main spectral/stiming states of accreting stellar-mass black holes: the steep power-law state, the thermal dominant state, and the hard state. The hard state is defined as having a photon index $1.4 < \Gamma < 2.1$. The Swift data show that Holmberg IX X-1 remains in the hard state, with $\Gamma$ near 1.9, as the flux varies over a factor of $\sim 7$. The highest counting rate observed with Swift corresponds to a flux of $1.8 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 0.3–10 keV band using the spectral model in Table 1 and a luminosity of $2.8 \times 10^{40}$ erg s$^{-1}$ at the distance of 3.6 Mpc to Holmberg IX assuming isotropic emission. Correcting for absorption increases this luminosity by 50%.

### Table 1

| Quantity     | Holm IX X-1 | N5408 X-1 | N4395 X-2 |
|--------------|-------------|-----------|-----------|
| Hardness     | 0.80 ± 0.01 | 0.43 ± 0.01 | 0.35 ± 0.02 |
| $\chi^2$/DoF | 7.9/10     | 4.0/9     | 6.1/4     |
| $N_H$ (cm$^{-2}$) | $2.0 \times 10^{20}$ | $1.4 \times 10^{20}$ | $2.4 \times 10^{21}$ |
| $\Gamma$     | 1.88        | 3.06      | 4.12      |
| Hardness     | 0.79        | 0.47      | 0.39      |

The spectra of NGC 5408 X-1 and NGC 4395 X-2 are softer than found in the hard state. These sources appear to be in the steep power-law state, defined as a photon index $\Gamma > 2.4$. The Swift observations find these sources at luminosities $\lesssim 1 \times 10^{40}$ erg s$^{-1}$. There are several other ULXs that appear in the steep power-law state at similar luminosities (Feng & Kaaret 2005). The steep power-law state tends to occur at the highest luminosities seen from accreting stellar-mass black holes. These
ULXs may represent a high luminosity extension of the steep power-law state.

NGC 4395 has been referred to as the least luminous type 1 Seyfert galaxy (Moran et al. 1999) due to measurements of very low luminosities with ROSAT. Most recent observations covering a broader energy band suggest an average luminosity near $9 \times 10^{39}$ erg s$^{-1}$ in the 0.5–10 keV band (Moran et al. 2005), within the range seen from ULXs. The light curve of the nucleus of NGC 4395 shows a strong flare near MJD 54624. We use a simple absorbed power-law model to convert the Swift count rates to fluxes. Following Moran et al. (1999), we adopt an absorption column density $N_H = 1.6 \times 10^{20}$ cm$^{-2}$. We use a photon index $\Gamma = 1.5$, which produces a hardness of 0.7, in reasonable agreement with the measured values. The true X-ray spectrum of NGC 4395 X-1 is more complex than this, but this approximation should be sufficient to produce rough flux estimates. The peak counting rate observed is 0.84 c/s and corresponds to a flux of $4.5 \times 10^{-11}$ erg cm$^{-2}$ s$^{-1}$ in the 0.5–10 keV band and a luminosity of $9.1 \times 10^{40}$ erg s$^{-1}$ at the distance of 4.1 Mpc. This is several times higher than any flux previously reported from NGC 4395 X-1.

The spectral evolution of the nuclear X-ray source in NGC 4395 is inconsistent with being constant. The $\chi^2$/DoF for a model of constant hardness is 27.9/6 corresponding to a probability of occurrence of $1.0 \times 10^{-4}$. The spectrum appears to harden at the lowest flux levels observed. O’Neill et al. (2006) found a similar trend comparing two Chandra observations of NGC 4395 and suggested that the cause is a variable absorption. NGC 4395 is known to exhibit dramatic long-term spectral variability on timescales of several years. Such dramatic variability is not apparent in the Swift data, but this may be because the Swift data cover only 1 year.

The monitoring programs described here demonstrate that Swift can be used to measure the flux and spectral evolution of ULXs and active galactic nucleus on timescales of months to years. For the nuclear source in NGC 4395, the trend for harder spectra at lower fluxes seen in two Chandra observations (O’Neill et al. 2006) is confirmed with a sample of more than 100 observations; and the highest X-ray luminosity ever seen, $9 \times 10^{40}$ erg s$^{-1}$, was recorded. The three ULXs monitored do not show significant changes in spectral state over months to years. Two of the ULXs, NGC 5408 X-1 and NGC 4395 X-1, remain in a soft spectral state, equivalent to a photon index softer than 2.6, as their flux varies by factors of $\sim 9$. The other ULX, Holmberg IX X-1, remains in a hard spectral state, equivalent to a photon index near 1.9, as its flux varies by a factor of 7 in observations spread over several years and with (isotropic) luminosities up to $2.8 \times 10^{40}$ erg s$^{-1}$. This behavior may suggest an unusually massive compact object.

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