BRIGHT X-RAY TRANSIENTS IN M31: 2004 JULY XMM-NEWTON OBSERVATIONS

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ABSTRACT

We present the results of X-ray observations of four bright transient sources detected in the 2004 July XMM-Newton observations of the central bulge of M31. Two X-ray sources, XMMU J004315.5+412440 and XMMU J004144.7+411110, were discovered for the first time. Two other sources, CXOM31 J004241.8+411635 and CXOM31 J004309.9+411635, were previously detected by Chandra. The properties of the sources suggest their identification with accreting binary systems in M31. The X-ray spectra and variability of two sources, XMMU J004144.7+411110 and CXOM31 J004241.8+411635, are similar to that of the Galactic black hole transients. The X-ray source XMMU J004315.5+412440 demonstrates a dramatic decline of the X-ray flux on a timescale of three days and a remarkable flaring behavior on a timescale of tens of minutes. The X-ray data on XMMU J004315.5+412440 and CXOM31 J004309.9+412332 suggest that they can be either black hole or neutron star systems. Combining the results of 2000–2004 XMM-Newton observations of M31, we estimate the total rate of the bright transient outbursts in the central region of M31 to be 6–12 yr−1, in agreement with previous studies.

Subject headings: galaxies: individual (M31) — X-rays: binaries — X-rays: stars

1. INTRODUCTION

Bright X-ray transient sources provide a unique opportunity to study the accretion onto stellar-mass compact object in the binary system. The observations of transient sources at X-ray, optical, and other wavelengths can be used to trace evolution of the different parts of the accretion disk during the outburst, study binary system properties, and in some cases, constrain the nature of the compact object. The observations of the Galactic X-ray novae (XRNe) show that they can be either high-mass (HMXB) or low-mass (LMXB) binaries (Tanaka & Shibazaki 1996), but most confirmed black-hole binaries are LMXB (McClintock & Remillard 2006 and references therein).

Until recently, the detailed study of X-ray transient sources has been mostly limited to our Galaxy. The advent of a new generation of X-ray telescopes (Chandra and XMM-Newton) has allowed the study of the spectral and temporal properties of XRNe located in the nearby galaxies and their comparison to Galactic transients (Fabbiano & White 2006 and references therein).

The relative proximity and favorable orientation of M31 make it a prime target for the study of extragalactic XRNe populations. M31 is more massive than other nearby Local Group galaxies and has higher frequency of bright transient events, providing better XRNe statistics. Recent Chandra and XMM-Newton observations of M31 have led to the discovery of several dozen bright transient X-ray sources with luminosities between \(10^{36}\) and \(10^{38}\) erg s\(^{-1}\) (Garcia et al. 2000; Trudolyubov et al. 2001; Kong et al. 2002; Williams et al. 2004, 2006b). The follow-up observations of X-ray transients with the Hubble Space Telescope (HST) ensured the identification and study of optical counterparts to some of these systems (Williams et al. 2004, 2005a, 2005b). Here we present the results of spectral and timing analysis of four bright transient sources detected in 2004 July XMM-Newton observations.

2. OBSERVATIONS AND DATA ANALYSIS

The central region of M31 was observed with XMM-Newton on four occasions during 2004 July (Barnard et al. 2006 and Fig. 1). In the following analysis we use the data from three European Photon Imaging Camera (EPIC) instruments: two EPIC MOS detectors (Turner et al. 2001) and the EPIC pn detector (Strueder et al. 2001). In all observations EPIC instruments were operated in the “full window” mode (30′ FOV) with the medium optical blocking filter.

We reduced EPIC data with the latest version of XMM-Newton Science Analysis System (SAS ver. 6.5.0). Each of the original event files were screened for periods of high background. The remaining exposure times for each observation are listed in Table 1. The 2004 July 17 observation (observation 2 in Table 1) is affected by high background, so we excluded it from our spectral and timing analysis and used it for total flux estimates only.

We generated EPIC pn and MOS images of the central region of M31 (Fig. 1) in the 0.3–7.0 keV energy band and used the SAS standard maximum likelihood (ML) source detection script edetect_chain to detect and localize point sources. We used bright X-ray sources with known optical counterparts from USNO-B (Monet et al. 2003) and 2MASS catalogs (Cutri et al. 2003) to correct EPIC image astrometry. After applying the astrometric correction, we estimate residual systematic error in the source positions to be of the order 0.5″–1″. To identify transient sources, the resulting list of the XMM-Newton sources was compared to the existing catalogs of M31 X-ray sources (Trinchieri & Fabbiano 1991; Primini et al. 1993; Kong et al. 2002; Williams et al. 2004; Pietsch et al. 2005) and transient source lists from the Chandra monitoring campaign (e.g., Williams et al. 2005a, 2005b, 2006a, 2006b).

To generate light curves and spectra of X-ray sources, we used elliptical extraction regions with semiaxis sizes of \(15″–50″\) (depending on the distance of the source from the telescope axis and neighboring sources) and subtracted as background the spectrum of adjacent source-free regions, with subsequent normalization by ratio of the detector areas. For spectral analysis, we used...
data in the 0.3–7 keV energy band. All fluxes and luminosities derived from spectral analysis apply to this band. We used spectral response files generated by XMM-Newton SAS tasks. Spectra were grouped to contain a minimum of 20 counts per spectral bin in order to allow 2 statistics and fit to analytic models using the XSPEC version 116 fitting package (Arnaud 1996). EPIC pn, MOS1, and MOS2 data were fitted simultaneously, but with normalizations varying independently. The energy spectra of the sources were fitted by two standard X-ray binary spectral models (DISKBB). To estimate upper limits on the quiescent source luminosities, the EPIC count rates were grouped to contain a minimum of 20 counts per spectral bin. All fluxes and luminosities were converted into energy fluxes in the 0.3–7 keV energy band.

3. RESULTS AND DISCUSSION

3.1. XMMU J004144.7+411110

A new X-ray source, XMMU J004144.7+411110, has been discovered in the data of 2004 July 16 XMM-Newton observations of M31. In addition, our analysis of the archival Chandra data (2004 July 17 observation 4719) revealed the presence of a bright X-ray source at the position consistent with XMMU J004144.7+411110. Combining the data of XMM-Newton and Chandra observations, we measure the position of XMMU J004144.7+411110 to be \( \alpha = 00^h41^m44.70^s, \delta = 41^\circ11'10''' \) (J2000.0 equinox) with an uncertainty of \( \pm 1'' \). The projected galactocentric distance of XMMU J004144.7+411110 is \( \sim 12'' \) (2.7 kpc), corresponding to the outskirts of the M31 bulge or inner disk. The search for the optical counterparts using the images from Local Group Survey (LGS; Massey et al. 2001) did not yield any object brighter than \( m_V \sim 21 \) within the error circle of XMMU J004144.7+411110. Using the data of archival XMM-Newton observations of the central region of M31, we estimate the upper limit (2 \( \sigma \)) on the source quiescent luminosity to be \( \sim 2 \times 10^{35} \) erg s\(^{-1}\) in the 0.3–7 keV energy band, 100 times lower than maximum measured outburst luminosity (Table 2).

The energy spectra of XMMU J004144.7+411110 are soft and can be well fitted by an absorbed DISKBB model with color temperatures \( \sim 0.6–0.8 \) keV or absorbed power-law model with photon index of \( \sim 2.8–3.3 \) (Table 2; Fig. 2). The corresponding estimated luminosities of the source have been found to be in the range of \( \sim (2.3–3.0) \times 10^{37} \) ergs s\(^{-1}\). For two observations (1 and 3), the energy spectrum shows clear signs of high-energy cutoff: the DISKBB model approximates it better than a simple power law, as indicated by fit statistics (Table 2).

The X-ray spectrum, transient behavior, and extreme faintness of the optical counterpart indicate that XMMU J004144.7+411110 is not a Galactic foreground object and probably is an accreting binary system in M31. The spectral model fits require absorbing columns well in excess the Galactic foreground value of \( 7 \times 10^{20} \) cm\(^{-2}\) (Table 2), this could be consistent with the source located inside or behind the M31 disk (Trudolyubov & Priedhorsky 2004).

The observed spectrum and luminosity of XMMU J004144.7+411110 bear clear resemblance to the Galactic black-hole transients in the high-“thermal-dominant” state during the flux decline that precedes the transition to the low/hard state (Tomsick & Kaaret 2000; McClintock & Remillard 2006). It should also be noted that the 0.3–7 keV spectrum of the source is significantly softer than observed in the neutron star systems at similar luminosities. In the following analysis we assume an M31 distance of 760 kpc (van den Bergh 2000). All parameter errors quoted are 68% (1 \( \sigma \)) confidence limits.

### Table 1

| Observation | UT Date | UT Time | Obs. ID | R.A.| Decl. | Exposure |
|-------------|---------|---------|--------|-----|-------|----------|
| 1           | 2004 Jul 16 | 16:17:05 | 0202230201 | 42 12.42 | 16 | 16 |
| 2           | 2004 Jul 17 | 12:07:53 | 0202230301 | 42 12.40 | 16 | 16 |
| 3           | 2004 Jul 18-19 | 23:49:30 | 0202230401 | 42 12.42 | 16 | 16 |
| 4           | 2004 Jul 19 | 12:48:23 | 0202230501 | 42 12.42 | 16 | 16 |

Notes:
- Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
- Coordinates of the center of the field of view.
- EPIC pn instrument exposure used in the analysis.
- Observation affected by high background.
luminosity levels both in the Galaxy (Christian & Swank 1997) and in M31 globular clusters (Trudolyubov & Priedhorsky 2004).

3.2. XMMU J004315.5+412440

XMM-Newton observations from 2004 July revealed another previously undetected X-ray source, located at \( \alpha = 0^h 0^m 43^s 15^m 51^s, \delta = 41^\circ 24' 40" \pm 15', \sim 10' \) from the center of M31. The inspection of the LGS images showed no optical sources brighter than \( m_v \sim 21 \) in the XMM-Newton error circle of XMMU J004315.5+412440. Using the data of previous XMM-Newton observations, we estimated the quiescent luminosity of the source to be \( \lesssim 10^{35} \text{ergs s}^{-1} \) in the \( 0.3-7 \text{keV} \) energy band.

The X-ray source XMMU J004315.5+412440 demonstrates a remarkable variability on timescales ranging from minutes to several days (Fig. 3). The source flux in the \( 0.3-7 \text{keV} \) band changed dramatically in the course of four 2004 July XMM-Newton observations, dropping from \( \sim 10^{37} \text{ergs s}^{-1} \) on July 16 to \( \sim 1.5 \times 10^{14} \text{ergs s}^{-1} \) in four days (Fig. 3a). The source XMMU J004315.5+412440 also shows a high level of variability during July 16 observation (observation 1; Fig. 3b). In addition to the irregular flux variations, the source produced an intense flare at \( \sim 13,700 \text{ s} \) (Fig. 3b), lasting for \( \sim 1000 \text{ s} \). The time evolution of the source flux during the flare is characterized by fast rise (\(< 200 \text{ s}\)) to a maximum level followed by quasi-exponential decay with estimated e-folding time of \( \sim 500 \pm 200 \text{ s} \). The peak intensity of the flare was \( \sim 4 \) times higher than the average source intensity, corresponding to an absorbed luminosity of \( \gtrsim 3 \times 10^{37} \text{ergs s}^{-1} \) in the \( 0.3-7 \text{keV} \) energy band. The estimated total energy emitted during the flare is \( \sim 10^{40} \text{ergs} \). Unfortunately, the sensitivity of our observations does not allow us to make a reliable conclusion about the evolution of the source spectrum during this flare.

The X-ray spectrum of XMMU J004315.5+412440 during the July 16 observation (observation 1) is soft, and can be well approximated by an absorbed power-law model with photon index of \( \sim 3.8 \) or by DISKBB model with color temperature of \( \sim 0.3 \text{keV} \) (Table 2). The corresponding absorbed luminosity of the source was \( \sim 7 \times 10^{36} \text{ergs s}^{-1} \). The power-law model provides a better fit to the observational data than a DISKBB model, as seen from Table 2. The power-law model fit requires a high level of low-energy absorption \( \sim 5 \times 10^{21} \text{cm}^{-2} \), while the DISKBB model requires an absorbing column consistent with Galactic foreground value in the direction of M31 (Table 2). We did not detect a statistically significant change in the shape of the source spectrum during the overall flux decline, as seen from power-law model fits (Table 2).

The X-ray properties of XMMU J004315.5+412440, along with the constraints on the optical counterpart, support its identification as an accreting binary system in M31. A combination of strong long- and short-term variability of X-ray flux makes XMMU J004315.5+412440 especially interesting.

The profile of the X-ray flare detected in the July 16 observation of XMMU J004315.5+412440 is somewhat similar to that of the typical thermonuclear X-ray bursts detected from the

| Observation | Model  | \( N_H \) (10^{22} \text{cm}^{-2}) | \( kT \) (keV) | \( R_{in} \) (cos \( i \)) \( \times 10^3 \) (km) | Photon Index | Fluxb | \( \chi^2 \) (dof) | \( L_x^c \) | \( L_x^d \) | Instrument |
|-------------|--------|-----------------|-------------|-----------------|-------------|-------|-----------------|------------|------------|-------------|
| XMMU J004144.7+411110 |
| 1........... | PL     | 51 ± 5          | ...         | 3.16 ± 0.15     | 4.38 ± 0.16 | 56.6 (53) | 30.3          | 160.9      | pn+M1+M2   |
| 3........... | PL     | 40 ± 18         | ...         | 2.72 ± 0.14     | 3.59 ± 0.16 | 64.8 (53) | 24.8          | 77.0       | pn+M1+M2   |
| 4........... | PL     | 55 ± 7          | ...         | 3.31 ± 0.15     | 3.68 ± 0.20 | 54.9 (44) | 26.9          | 192.9      | pn+M2      |

| XMMU J004315.5+412440 |
| 1........... | PL     | 29 ± 5          | ...         | 3.81 ± 0.44     | 1.07 ± 0.06 | 33.9 (22) | 7.39          | 47.0       | pn         |
| 3........... | PL     | 18 ± 18         | ...         | 4.10 ± 1.18     | 0.20 ± 0.03 | 4.1 (5)   | 1.38          | 5.75       | pn         |

| CXOM31 J004241.8+41635 |
| 1........... | PL     | 23 ± 2          | ...         | 2.54 ± 0.05     | 7.26 ± 0.13 | 220.8 (209)| 50.2         | 107.9      | pn+M1+M2   |
| 3........... | DISKBB | 3 ± 2           | ...         | 2.36 ± 0.04     | 8.07 ± 0.12 | 295.8 (233)| 55.8         | 109.6      | pn+M1+M2   |
| 4........... | PL     | 22 ± 1          | ...         | 2.33 ± 0.04     | 9.65 ± 0.21 | 300.8 (242)| 66.7         | 122.3      | pn+M1+M2   |

| CXOM31 J004309.9+412332 |
| 1........... | PL     | 11 ± 2          | ...         | 2.80 ± 0.50     | 0.38 ± 0.05 | 11.9 (8)  | 2.63          | 4.93       | pn         |
| 3........... | DISKBB | 4 ± 1           | ...         | 0.33 ± 0.11     | 33 ± 4     | 19.8 (8)  | 1.94          | 2.44       | pn         |
| 4........... | DISKBB | 31 ± 12         | ...         | 4 ± 0.36        | 0.44 ± 0.05 | 13.4 (11)| 3.04          | 25.9       | pn         |

* Effective inner disk radius, where \( i \) is the inclination angle of the disk.
* Absorbed model flux in the 0.3–7 keV energy range in units of \( 10^{-13} \text{ergs s}^{-1} \).
* Absorbed luminosity in the 0.3–7 keV energy range in units of \( 10^{36} \text{ergs s}^{-1} \).
* Estimated absorption-corrected model luminosity in the 0.3–7 keV energy range in units of \( 10^{36} \text{ergs s}^{-1} \).
Galactic neutron stars (Strohmayer & Bildsten 2006 and references therein). The flare lasted \( \frac{C_2}{2} \)–3 times longer than typical long type I X-ray bursts with decay times of several minutes (Strohmayer & Bildsten 2006), although it could be similar to the two atypical long X-ray bursts recorded from Aquila X-1 (Czerny et al. 1987). In the type I burst interpretation, the longer duration of the flare could be partially explained by the softer energy band used in our observations (0.3–3 keV), since the burst profiles are typically shorter at higher energies, due to cooling of the neutron star surface with time. The peak flux and the overall energetics of the flare are comparable to the observed for type I X-ray bursts. The estimated absorbed peak luminosity of the flare is \( \approx 3 \times 10^{37} \) ergs s\(^{-1}\) in the 0.3–7 keV energy band (assuming the same spectral shape as the persistent emission), while the absorption-corrected luminosity could be \( \approx 1.5 \)–6 times higher, depending on the spectral model (Table 2). Despite aforementioned similarities between the X-ray flare from XMMU J004315.5+412440 and type I X-ray bursts, which are understood to be thermonuclear flashes in the envelopes of neutron stars, the results of spectral analysis do not fully support the neutron star interpretation. The energy spectrum of the persistent emission from XMMU J004315.5+412440 is much softer than the observed spectra of the burst sources at similar luminosity levels in the 0.3–7 keV energy band (Christian & Swank 1997; Strohmayer & Bildsten 2006).

The other possibility is that the flare from XMMU J004315.5+412440 is caused by spasmodic accretion onto the compact object (either a black hole or a neutron star) as a result of accretion instability. The thermal-viscous instabilities in the inner part of the accretion disk (Lightman & Eardley 1974), used to explain variability of black hole candidates (Belloni et al. 1997) and type II X-ray bursts (Taam & Lin 1984; Lewin et al. 1995), can be responsible for the flaring behavior of XMMU J004315.5+412440.

3.3. CXOM31 J004241.8+411635

The X-ray source CXOM31 J004241.8+411635, \( \approx 0.7 \) offset from the center of M31, was first detected in the 2004 July 17 Chandra observation and remained detectable in the 2004 September 2 and October 4 Chandra observations (Williams et al. 2006a). The source was previously detected in 1979 Einstein observations Trinchieri & Fabbiano 1991, which makes it a probable recurrent transient candidate with duty cycle of 0.02–0.06 (Williams et al. 2006a). In addition, the follow-up observations of the source with HST resulted in a determination that the
3.4. CXOM31 J004309.9+412332

The X-ray source CXOM31 J004241.8+411635 was first detected in the 2004 May 23 Chandra observation (Williams et al. 2005b). The projected galactocentric distance of CXOM31 J004241.8+411635 (~9/1.9 kpc) is consistent with source location in the outer bulge or disk of M31. Regular Chandra monitoring of the source revealed a complex X-ray light curve with at least two peaks separated by ~130 days and reaching the maximum 0.3–7 keV luminosity of ~10^{37} ergs s^{-1}. On the basis of the results of Chandra and HST observations, CXOM31 J004309.9+412332 has been classified as a low-mass X-ray binary system (Williams et al. 2005b).

The XMM-Newton spectra of CXOM31 J004241.8+411635 during 2004 July XMM-Newton observations can be approximated by a steep absorbed power law with a photon index of ~2.8–4.0 or by a DISKBB model with $kT_{\text{in}} \sim 0.33–0.36$ keV (Table 2). The corresponding absorbed luminosity of the source is in the range of ~(2–3) × 10^{36} ergs s^{-1}. The spectra of CXOM31 J004241.8+411635 measured with XMM-Newton correspond to the decline of the first outburst, and they appear to be significantly softer than measured during the 2004 May 23 and September 2 Chandra observations (coincident with two outburst peaks; Williams et al. 2005b). The anticorrelation of the spectral hardness and X-ray flux of CXOM31 J004241.8+411635 could be similar to that observed in some Galactic low-mass X-ray binaries (both neutron star and black hole binary systems) and in globular cluster sources in M31 (Trudolyubov & Priedhorsky 2004). The available data on CXOM31 J004241.8+411635 suggest that it could be either a black hole or a neutron star.

4. CONCLUSIONS

Using the data from the 2004 July XMM-Newton EPIC observations of M31, we study the X-ray properties of four bright transient sources. Two X-ray sources, XMMU J004315.5+412440 and XMMU J004144.7+411110, were discovered for the first time. Two other sources, CXOM31 J004309.9+412332 and CXOM31 J004241.8+411635, were previously detected by Chandra. The properties of the sources along with the information on optical counterparts suggest their identification with accreting binary systems belonging to M31. The luminosities, energy spectra, and variability of the two sources, XMMU J004144.7+411110 and CXOM31 J004241.8+411635, are reminiscent of the Galactic black hole X-ray novae, which makes them a good black hole candidates. The X-ray source XMMU J004315.5+412440 demonstrates a dramatic decline of the X-ray flux on a timescale of three days, and a remarkable flaring behavior during the first XMM-Newton observation. The available data on this source and the other transient source CXOM31 J004309.9+412332 are consistent with either black hole or a neutron star interpretation.

A total of 10 transient sources with 0.3–7 keV luminosities higher that 10^{36} ergs s^{-1} have been detected in five XMM-Newton observations of the central part of M31 (Osborne et al. 2001; Trudolyubov et al. 2001; Pietsch et al. 2005; this work). More than a half of these sources (60%) can be classified as black hole candidates. The remaining sources include two supersoft transients with probable white dwarf primaries (20%) and two systems that could contain either black holes or neutron stars.

Given a number of the detected sources, and the coverage factor of the XMM-Newton observations, one can estimate the expected total rate of X-ray transient outbursts in the bulge and inner disk of M31. Assuming the average duration of a bright...
phase of a typical transient of $\sim 1$–2 months gives a total rate of $\sim 6$–12 outbursts per year,\footnote{Note the large uncertainty of this estimate, due to the limited statistics and scatter in the observed outburst durations.} consistent with estimates based on earlier XMM-Newton and Chandra results (Trudolyubov et al. 2001; Kong et al. 2002; Williams et al. 2004).

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