ABSTRACT

We study three transient X-ray sources, that were bright in the central region of M31 galaxy in the year 2000. Observations with Chandra and XMM-Newton allowed us for the first time in the history of X-ray astronomy, to build light curves of transient sources in M31 suitable for studying their variability on a time scale of months and, in some periods, weeks. The three sources demonstrate distinctly different types of X-ray variability and spectral evolution. XMMU J004234.1+411808 is most likely a black hole candidate based on the similarity of its X-ray light curve and spectra to typical transient low-mass X-ray binaries observed in our Galaxy. The outburst of CXO J004242.0+411608 lasted longer than a year, which makes the source an unusual X-ray transient. The supersoft transient XMMU J004319.4+411759 is probably a classical nova-like system containing a magnetized, rapidly-spinning white dwarf. We estimate a total rate of X-ray transient outbursts in the central bulge of M31 to be of the order $\sim 10$ per year. The rate of the hard X-ray transients ($\sim 5$ year$^{-1}$) in the central part of the Andromeda Galaxy appears to be comparable to that of the central part of our own Galaxy.

1. INTRODUCTION

There are about 200 known X-ray binaries in our Galaxy. These contain either a neutron star or a black hole (van Paradijs 1995). About one third of them are classified as transients (see Tanaka & Shibazaki 1996 for a review). Some of the X-ray transients, most notably Be-binary pulsars, erupt on regular intervals, while others erupt dramatically, but irregularly, with peak luminosities above $10^{37}$ erg/s and typical decay times orders a month. This last group represent the majority of known Galactic black hole candidates, and provides the best opportunity to study the processes near black hole in relative proximity to the Earth. Galactic transients have been therefore a focus of substantial observational and theoretical effort by X-ray astronomers. Much less, however, is known about X-ray transients in other galaxies. Previous observations with Einstein and ROSAT, and hundreds of X-ray sources were detected (Trinchieri & Fabbianio 1991; Primini et al. 1993; Supper et al. 1997; Supper et al. 2001). This Letter discusses transients discovered in the M31 core in recent sensitive observations by Chandra and XMM-Newton.

2. OBSERVATIONS AND DATA ANALYSIS

We analyzed a series of Chandra data consisting of seven observations with Advanced CCD Imaging Spectrometer (ACIS) and seven High Resolution Camera (HRC) observations. We used all publicly available observations of M31 central region covering the period from Oct 1999 to July 2000 (Table [1]). A more detailed description of the observations can be found in Garcia et al. 2000 (hereafter G00) and DiStefano et al. 2001. The data were processed using the CIAO (M31), the closest spiral galaxy to our own (we assume $\sim 760$ kpc distance throughout this Letter - van der Bergh 2000), are of special interest, because M31 is in many respects similar to the Milky Way. M31 was observed previously with Einstein and ROSAT, and hundreds of X-ray sources were detected (Trinchieri & Fabbianio 1991; Primini et al. 1993; Supper et al. 1997; Supper et al. 2001). This Letter discusses transients discovered in the M31 core in recent sensitive observations by Chandra and XMM-Newton.
We used data from two European Photon Imaging Camera (EPIC) instruments: the MOS1 and MOS2 detectors (Turner et al. 2001). In all observations the EPIC instruments operated in full window mode (30' FOV) with a medium optical blocking filter.

We reduced EPIC data with the XMM-Newton Science Analysis System (SAS v5.01)\(^3\). To obtain the spectra of individual point sources, we used a source circle of \(\sim 20 - 30''\) and took backgrounds from adjacent source-free regions. We used data in the 0.3 – 7 keV energy range, for consistency with Chandra data and because of uncertainties in the calibration of the EPIC instruments. This is the default energy band for all fluxes and luminosities presented below.

The energy spectra of the two hard sources (XMMU J004234.1+411808 and CXO J004242.0+41608) were fitted to an absorbed power law, and an absorbed black body radiation model was applied to fit the spectrum of the supersoft transient XMMU J004319.4+411759 (Table 2). Since the flux from the latter was negligible above 1.5 keV, we considered only its 0.3–1.5 keV spectrum. EPIC-MOS1 and MOS2 data were fit simultaneously, but with independent normalizations.

3. RESULTS AND DISCUSSION

3.1. Hard X-ray Nova XMMU J004234.1+411808

A new bright source, XMMU J004234.1+411808, was discovered on June 25, 2000 during the first XMM-Newton observation of M31 (S01, O01, T01). Our analysis of the archival Chandra data revealed the presence of a bright X-ray source at the position consistent with XMMU J004234.1+411808 as early as June 21, 2000, and again on July 2 and July 29 (Table 2). Based on the Chandra aspect solution, which is currently limited by systematics to \(\sim 0.6''\) accuracy, we measure the position of XMMU J004234.1+411808 to be \(\alpha = 00^h42^m34.44^s, \delta = 41^\circ18'09.7''\) (2000 equinox).

The X-ray light curve of XMMU J004234.1+411808 shown in Fig. 2a. Combining the results of Chandra and XMM observations, we place an upper limit on the effective duration of the outburst of \(\lesssim 40\) days. We have no measurements of the outburst rise, but it was shorter than 20 days and followed by a slower decay. A fit to decaying part of the light curve with an exponential gives a characteristic e-folding time: \(\tau_{fold} = 17 \pm 2\) days. The source flux declined from \(\sim 3.3 \times 10^{-13}\) erg s\(^{-1}\) cm\(^{-2}\) on June 21 to \(\sim 3.4 \times 10^{-14}\) erg s\(^{-1}\) cm\(^{-2}\) on July 29, which corresponds to the luminosity drop from \(\sim 2.3 \times 10^{37}\) erg s\(^{-1}\) to \(\sim 2.3 \times 10^{36}\) erg s\(^{-1}\). From the ACIS observations prior to the outburst, and assuming the same spectrum as measured by XMM, we compute a 2\(\sigma\) upper limit to the quiescent luminosity of \(\sim 1.5 \times 10^{36}\) erg s\(^{-1}\), \(\sim 20\) times lower than maximum measured luminosity.

The energy spectrum of the source measured with ACIS-S on July 2 is similar to one detected with EPIC-MOS a week earlier (Fig. 2a) and both

\(^3\)http://asc.harvard.edu/ciao/

\(^4\)http://heasarc.gsfc.nasa.gov/docs/xanadu/xspec/index.html

\(^5\)http://heasarc.gsfc.nasa.gov/Tools/w3pimms.html

\(^6\)http://xmm.vilspa.esa.es/user/
The source was not detected with Chandra throughout whole Y2K (O01, T01). Chandra discovered on December 1999 during the first M31, and the first stellar mass black hole candidate in that XMMU J004234.1+411808 is an X-ray nova binary systems harbor black holes. We propose objects, radial velocity measurements proved that (Chen, Shrader, & Livio 1997). For many of these rise-exponential-decay (FRED-type) lightcurves candidates (Tanaka & Lewin 1995). Moreover, (see Table 2 for fit parameters).

The energy spectrum and X-ray luminosity of XMMU J004234.1+411808 correspond to the hard/low spectral state of Galactic black hole candidates ([Tanaka & Lewin 1993]). Moreover, the X-ray evolution of the source is typical for well established class of X-ray novae with fast-rise-exponential-decay (FRED-type) lightcurves (Chen, Shrader, & Livio 1997). For many of these objects, radial velocity measurements proved that binary systems harbor black holes. We propose that XMMU J004234.1+411808 is an X-ray nova and the first stellar mass black hole candidate in M31.

3.2. Transient source CXO J004242.0+411608

The X-ray source CXO J004242.0+411608 was discovered on December 1999 during the first Chandra observation of M31 (G00) and remained detectable throughout whole Y2K (O01, T01). The source was not detected with XMM on June 29, 2001 (Shirey 2001), which sets a lower limit of ~400 days to the outburst duration.

The source exhibited remarkable stability of the X-ray luminosity and spectral shape throughout the outburst (Fig. 2b, c and Table 2). The average energy spectrum may be approximated with an absorbed power law with $\alpha \sim 1.5 - 1.6$. We note that the ACIS spectra of the source tend to be generally flatter than EPIC-MOS spectra (Table 2). Best-fit values of the absorbing column are also systematically higher for the ACIS. Both discrepancies may be possibly attributed to the presence of a 10 – 15% pile-up in the ACIS spectra.

Long (>1 year) plateaus were detected in light curves of several black hole candidates, whereas shorter plateaus seem more typical for neutron star systems (Chen et al. 1997). The hard spectrum and long plateau make this outburst remarkably similar to the long-lasting hard transient GRS 1716-249 (Sunyaev et al. 1994; Revnivtsev et al. 1998).

3.3. Supersoft transient XMMU J004319.4+411759

The X-ray transient source XMMU J004319.4+411759 was discovered on June 25, 2000 by XMM (S01, O01). Our analysis of May 26 Chandra data revealed the presence of a bright Chandra data at the position $\alpha = 00^h 43^m 19.76^s, \delta = 41^\circ 17' 57.6''$ (2000 eq., error circle $\sim 0.6'$), consistent with previously reported XMM position (O01). The source remained active during the June 21 Chandra observation. An energy spectrum obtained with EPIC-MOS1 detector on June 25 is shown in Figure 3d. It may be satisfactorily fit to an absorbed black body radiation model with a characteristic temperature of $\sim 60$ eV and absorbing column of $\sim 1.4 \times 10^{21}$ cm$^{-2}$.

The spectrum of XMMU J004319.4+411759 is similar to the Galactic supersoft sources and may be interpreted as a result of thermonuclear burning of the accreted matter on the surface of the white dwarf (see Kahabka & van den Heuvel 1997 for a review). The source proved to be a pulsator with a $\sim 865$ s period (for more detailed discussion see O01). The transient behavior of the pulsator hints that it may be a classical Nova in the supersoft X-ray spectral phase, several tens of days after the peak of the outburst (Kahabka & van den Heuvel 1997, O01).

3.4. On the rate of transient outbursts

Given a number of transient sources detected with Chandra and XMM, one can estimate the total rate of transient outbursts in the central bulge of M31. Assuming a luminosity of $> 10^{37}$ erg s$^{-1}$ and an average source outburst duration to be more than a month, and taking into account the spacing of the Chandra and XMM observations, we estimate a rate of $\sim 10$ year$^{-1}$. We note a large uncertainty of this estimate, due to the limited statistics. About $\sim 50\%$ of a total amount of transients detected in M31 are hard X-ray sources corresponding to $\sim 5$ outbursts per year. It is interesting to compare their number with a number of X-ray transient detected in the corresponding region of the Galaxy. Based on regular monitoring of the Galactic Center with RXTE and BeppoSAX, the rate of hard transient outbursts in this region can be estimated as $\sim 4$ year$^{-1}$, which is comparable to our estimate for the central part of M31. This is further evidence for the similarity between the stellar populations of the Galaxy and M31.

Very high extinction of X-rays towards the center of our own Galaxy prevents effective detection of supersoft sources with current instrumentation.
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**Table 1**

_Chandra_ and _XMM-Newton_ observations of the central region of M31.

| Date (UT) | TJD<sup>a</sup> | Observatory | Obs ID | Instrument | Exposure<sup>b</sup> (ksec) |
|-----------|-----------------|-------------|--------|------------|---------------------------|
| 13/10/1999 | 464             | Chandra     | 303    | ACIS-I     | 9.0                       |
| 11/12/1999 | 523             | Chandra     | 305    | ACIS-I     | 4.1                       |
| 27/12/1999 | 539             | Chandra     | 306    | ACIS-I     | 4.1                       |
| 29/01/2000 | 572             | Chandra     | 307    | ACIS-I     | 4.1                       |
| 13/02/2000 | 587             | Chandra     | 270    | HRC-I      | 1.4                       |
| 16/02/2000 | 590             | Chandra     | 308    | ACIS-I     | 4.0                       |
| 08/03/2000 | 611             | Chandra     | 271    | HRC-I      | 2.4                       |
| 26/05/2000 | 690             | Chandra     | 272    | HRC-I      | 1.2                       |
| 01/06/2000 | 696             | Chandra     | 309    | ACIS-S     | 5.0                       |
| 21/06/2000 | 716             | Chandra     | 273    | HRC-I      | 1.2                       |
| 25/06/2000 | 720             | _XMM-Newton_ | 100 | EPIC      | 34.8                      |
| 02/07/2000 | 727             | Chandra     | 310    | ACIS-S     | 5.0                       |
| 29/07/2000 | 754             | Chandra     | 311    | ACIS-I     | 6.0                       |
| 28/12/2000 | 906             | _XMM-Newton_ | 193 | EPIC      | 12.4                      |

<sup>a</sup> – TJD - truncated Julian Date, TJD=JD-2451000

<sup>b</sup> – total exposure time

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**Fig. 1.**—The central region of M31 as it appears in a 1.2 ks _Chandra_ HRC-I observation (June 21, 2000). The transient sources are marked with arrows. The position of nuclear source is shown for comparison.
Table 2
Best-fit model parameters of the energy spectra of transient sources (Chandra-ACIS and XMM-Newton-MOS data). Parameter errors correspond to 1σ level.

| Date (UT) | Photon Index | N_{\text{H}} \times 10^{22} \text{ cm}^{-2} | Flux^a | L_{\text{X}}^d (\times 10^{37} \text{ erg s}^{-1}) | \chi^2 | Instrument |
|-----------|--------------|---------------------------------------------|--------|-----------------------------------------------|-------|------------|
| CXO J004242.0+411608 | 13/10/1999 | 1.52 ± 0.10 | 0.25 ± 0.04 | 8.63 ± 0.27 | 7.76 ± 0.24 | 58.2(44) | ACIS-I |
| | 11/12/1999 | 1.35 ± 0.19 | 0.13 ± 0.07 | 8.12 ± 0.53 | 6.46 ± 0.42 | 34.9(42) | ACIS-I |
| | 27/12/1999 | 1.60 ± 0.21 | 0.17 ± 0.08 | 6.83 ± 0.43 | 6.00 ± 0.38 | 48.6(44) | ACIS-I |
| | 29/01/2000 | 1.84 ± 0.22 | 0.37^{+0.10}_{-0.18} | 6.38 ± 0.36 | 7.03 ± 0.40 | 42.8(53) | ACIS-I |
| | 16/02/2000 | 1.45 ± 0.17 | 0.20 ± 0.06 | 8.59 ± 0.44 | 7.33 ± 0.38 | 52.3(62) | ACIS-I |
| | 01/06/2000 | 1.25 ± 0.14 | 0.11 ± 0.03 | 8.40 ± 0.36 | 6.50 ± 0.28 | 45.6(46) | ACIS-I |
| | 25/06/2000 | 1.61 ± 0.05 | 0.10 ± 0.01 | 8.05 ± 0.16 | 6.59 ± 0.13 | 212.2(230) | EPIC-MOS |
| | 02/07/2000 | 1.30 ± 0.12 | 0.10 ± 0.03 | 8.08 ± 0.35 | 6.23 ± 0.27 | 38.8(23) | ACIS-S |
| | 28/12/2000 | 1.54 ± 0.11 | 0.06 ± 0.03 | 5.77 ± 0.25 | 4.39 ± 0.19 | 52.3(44) | EPIC-MOS |
| XMMU J004234.1+411808 | 25/06/2000 | 61 ± 2 | 0.14 ± 0.02 | 2.85 ± 0.07 | 1.29 ± 0.04 | 53.8(48) | EPIC-MOS |
| | 02/07/2000 | 1.96 ± 0.54 | 0.07 (fixed) | 1.44 ± 0.24 | 1.15 ± 0.19 | 4(5) | ACIS-S |

| Date (UT) | T_{bb} \text{ (eV)} | N_{\text{H}} \times 10^{22} \text{ cm}^{-2} | Flux^c | L_{\text{X}}^d (\times 10^{37} \text{ erg s}^{-1}) | \chi^2 | Instrument |
|-----------|------------------|---------------------------------------------|--------|-----------------------------------------------|-------|------------|
| XMMU J004234.1+411808 | 25/06/2000 | 61 ± 2 | 0.14 ± 0.02 | 2.85 ± 0.07 | 1.29 ± 0.04 | 53.8(48) | EPIC-MOS |

a – absorbed model flux in the 0.3 – 7.0 keV energy range in units of 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}

b – estimated unabsorbed X-ray luminosity in the 0.3 – 7.0 keV energy range in units of 10^{37} \text{ erg s}^{-1}

c – absorbed model flux in the 0.3 – 1.5 keV energy range in units of 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2}

d – estimated unabsorbed X-ray luminosity in the 0.3 – 1.5 keV energy range in units of 10^{38} \text{ erg s}^{-1}
Fig. 2.—X-ray flux histories of three transient sources in the 0.3–7.0 keV energy range. Upper panel: hard X-ray Nova XMMU J04234.1+411808. Middle panel: transient supersoft source XMMU J004319.4+411758. Lower panel: Chandra transient CXO J004242.0+411608. Filled circles, open circles and open squares denote ACIS, HRC-I and EPIC-MOS data respectively. The X-ray luminosities are in units of $\times 10^{37}$ erg s$^{-1}$. Upper limits correspond to a 2$\sigma$ level.
Fig. 3.— Representative count spectra of transient sources. EPIC-MOS1 data, 0.3 – 7 keV energy range. Spectral model fits are shown for comparison. Panel a: hard X-ray Nova XMMU J04234.1+411808, Jun. 25, 2000 observation, fit by absorbed power law model ($\alpha = 2.13$, $N_H = 7 \times 10^{20} \text{ cm}^{-2}$). Panel b: Chandra transient CXO J004242.0+411608, Jun. 25, 2000 observation, fit by absorbed power law model ($\alpha = 1.62$, $N_H = 1 \times 10^{21} \text{ cm}^{-2}$). Panel c: The same source, Dec. 28, 2000 observation, fit by absorbed power law model ($\alpha = 1.54$, $N_H = 6 \times 10^{20} \text{ cm}^{-2}$). Panel d: transient supersoft source XMMU J004319.4+411758, Jun. 25, 2000 observation, fit by absorbed black body radiation model ($T_{bb} = 61 \text{ eV}, N_H = 1.4 \times 10^{21} \text{ cm}^{-2}$).