DISCOVERY OF A NEW BLACK HOLE TRANSIENT WITHIN 100” (400 PC) of M31*

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ABSTRACT
We identified a new X-ray transient CXOM31 004252.457+411631.17 (T13) in M31 during a 2013 June Chandra observation. This system is particularly exciting because it is located within 100” of M31; it is thought that this region of the bulge is sufficiently dense to form X-ray binaries dynamically, but only systems with black hole accretors and/or short periods are expected to survive. A follow-up XMM-Newton observation yielded a soft spectrum, well described by a 0.39 ± 0.02 keV disk blackbody; applying this model to the Chandra observation yielded an observed 0.3–10 keV luminosity peak of 6.2 ± 0.6×1037 erg s⁻¹ (4.7±1036 erg s⁻¹ in the 2.0–10 keV band). Observing with Hubble Space Telescope/Advanced Camera for Surveys did not reveal an optical counterpart, but allowed us to place an upper limit of B > 26.9, corresponding to an absolute V band magnitude > 2.0. From the 2–10 keV luminosity and absolute V magnitude, we estimate an orbital period < 5 h from an empirical relation. Fitting a disk blackbody + blackbody model allows us to reject a neutron star accretor at a 14σ level.

Key words: stars: black holes – X-rays: binaries – X-rays: general

Online-only material: color figures

1. INTRODUCTION
We have been monitoring the central region of M31 for the last ~13 years with Chandra, averaging ~1 observation per month, in order to discover X-ray transients. Promising examples are followed up with two Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS) observations, the first is taken a few weeks after outburst, and the second observation is taken ~6 months later; this allows us to identify the counterpart via difference imaging (see, e.g., Barnard et al. 2012, and references within). We summarized the results of the first 12 transients (labeled T1–T12) found via this effort in Barnard et al. (2012). In this work, we study CXOM31 004252.457+411631.17, referred to hereafter as T13.

We discovered T13 in the 2013 June, 5 ks Chandra ACIS observation of the M31 center, ~95” from the M31 nucleus (M31∗) (Barnard et al. 2013a). We obtained 92 net source photons, insufficient for spectral modeling; however, the transient was likely to be in one of two spectral states, and we estimated the luminosity for both states. Assuming a 1 keV disk blackbody model with line-of-sight absorption equivalent to 7×10¹⁹ H atom cm⁻² yielded a 0.3–10 keV luminosity of 6.1 ± 0.6×10⁳⁷ erg s⁻¹ (Barnard et al. 2013a); this corresponds to a black hole binary in a thermally dominated state (Remillard & McClintock 2006). A power law emission model with spectral index 1.7 yielded a 0.3–10 keV luminosity of 8.9 ± 0.9×10³⁷ erg s⁻¹ (Barnard et al. 2013a); this corresponded to a black hole binary in its low state (Remillard & McClintock 2006). Hence, the two possible spectral states for T13 yielded rather similar 0.3–10 keV luminosities. We found that the locale of T13 was serendipitously observed in one of our earlier HST observations, meaning that we only required one new HST observation.

X-ray transients within the central region of M31 are most likely to contain a low mass secondary, as the majority of stars there are old. Low mass X-ray binaries may be transient X-ray sources due to instabilities in their accretion disks; the disk has two stable phases (hot and cold), and an unstable intermediate phase—matter accumulates in the disk in the cold phase, and is rapidly dumped onto the compact object in the hot phase (see, e.g., Lasota 2001). However, the X-rays produced by accretion from the hot disk prevent the disk from cooling; the X-ray luminosity decays exponentially if the whole disk is ionized, and linearly if only part of the disk is ionized (King & Ritter 1998).

van Paradijs & McClintock (1994) found an empirical relation between the ratio of X-ray and optical luminosities of Galactic X-ray binaries and their orbital periods, suggestive that the optical emission is dominated by reprocessed X-rays in the disk; this relation holds over a 10 mag range in optical luminosity, and appears to be insensitive to inclination. Their chosen X-ray band was 2–10 keV. For an irradiated accretion disk with radius a, X-ray luminosity LX, optical luminosity LOpt, and temperature T, Tᵣ ≈ LX/a²; while the surface brightness of the disk, S, ∝ T² for typical X-ray binaries (van Paradijs & McClintock 1994). Since LOpt ∝ S a², LX ∝ LOrb, a ∝ P⁻²/₃, where POrb is the orbital period.

van Paradijs & McClintock (1994) defined Σ = (LX/LEDD)¹/₂ (Porb/1 hr)²/₃, choosing LEDD = 2.5×10³⁸ erg s⁻¹ as a normalizing constant, and found

\[ M_V = 1.57(±0.24) - 2.27(±0.32) log Σ. \] (1)

However, van Paradijs & McClintock (1994) sampled a mixture of neutron star and black hole binaries, in various spectral states. A cleaner sample was obtained by A. Moss et al. (2013, in preparation), who used only black hole transients at the peaks of their outburst, and found

\[ M_V = 0.84(±0.30) - 2.36(±0.30) log Σ. \] (2)

We note that these two relations only differ significantly in normalization, caused by black hole X-ray binaries having larger disks than neutron star binaries with the same period. We have period estimates for 12 M31 transients (T1–T12) observed by Chandra and HST (Barnard et al. 2012).

T13 is particularly interesting because of its close proximity to M31∗. Voss & Gilfanov (2007) found an excess of XBs within
We have observed T13 twice with Chandra, and once more with HST. Furthermore, we were granted an ∼8 ks XMM-Newton observation as part of the target of opportunity (TOO) program. In this paper we present our analysis of the Chandra, HST, and XMM-Newton data.

2. OBSERVATIONS AND DATA REDUCTION

2.1. X-Ray Analysis

We extracted spectra from our X-ray observations of T13 using the appropriate mission-specific software suites: CIAO v.4.4 for C1–C2, and XMM-Newton SAS v.13.0.0 for X1. We used the CALDB version distributed with CIAO. Spectral analysis was performed with XSPEC v12.8.0.

2.1.1. Chandra Analysis

For each of our Chandra ACIS observations, we extracted source and background 0.3–7.0 keV spectra from circular regions with 2′′5 radii. We then created the appropriate response files (response matrix and ancillary response file). The source spectra were grouped to give a minimum of 20 counts per bin.

2.1.2. XMM-Newton Analysis

XMM-Newton observations often experience intervals of greatly increased background levels. We searched for such flaring intervals by creating a lightcurve using the expression “(PATTERN==0)&(PI in [10000:12000])&(&FLAG==0)” and 100 s bins; this observation was flare-free. We extracted a 0.3–10 keV source spectrum from a circular region with 240 pixel radius, to avoid contamination from a nearby source. A circular background region was chosen to be near the source, on the same chip, and at a similar off-axis angle; its radius was 550 pixels. These spectra were filtered by the expression “(PATTERN<==4)&(&FLAG==0).” We also obtained a corresponding response files. The source spectrum was grouped to a minimum of 20 counts per bin.

2.2. Locating the X-Ray Source

We used 27 X-ray bright globular clusters (GCs) to register a combined ∼300 ks ACIS image (supplied by Z. Li) to the B band Field 5 image of M31 provided by the Local Galaxy group Survey (LGS; Massey et al. 2006). We used pc-iraf v2.14.1 to perform the registration, following the same procedure as described in Barnard et al. (2012). This yielded 1σ position uncertainties of 0′′.11 in R.A., and 0′′.09 in decl. (Barnard et al. 2012). We reprojected the H2 DRZ image into the coordinates of the H1 DRZ image, to produce an accurate difference image; see Barnard et al. (2013b) for further details. To do this, we first registered the H1 and H2 images to the LGS Field 5 image, using unsaturated stars that were close to the target; the uncertainties were negligible. Then, we reoriented the H2 image to match the H1 image. The difference image was produced by subtracting H1 from H2.

2.3. Optical Analysis

All optical analysis was performed with pc-iraf Revision 2.14.1, except where noted. Each HST observation included four flat-fielded (FLT) images, and one drizzled (DRZ) image. We used the DRZ images from H1 and H2 to create a difference image; however, we used the H2 FLT images for our aperture photometry because the software used (daophot) prefers images in that format.

2.3.1. Measuring the Optical Counterpart

For H2 we used the daophot package released with iraf to obtain the net source counts in the FLT images, for a total of C_{tot} counts over T seconds. We converted this to Vega B magnitude via

\[ B \simeq -2.5 \log (C_{\text{tot}}/T) + 25.77, \]

following Barnard et al. (2013b). We can convert from B magnitude to M_V via

\[ M_V = B + 0.09 - N_H \times (1 + 1/3)/1.8 \times 10^{21} - 24.47, \]

where N_H is the line of sight absorption; (see Barnard et al. 2012 and references within).

3. RESULTS

3.1. Searching for an Optical Counterpart

The X-ray position of T13 included final 1σ uncertainties of 0′′.19 in R.A. and 0′′.14 in decl. Figure 1 shows a detail of the difference image overlaid with an ellipse that represents the 3σ uncertainties in the X-ray position for T13; white objects are brighter during H2 (during outburst) than in H1 (when T13 was in quiescence). We found no evidence for an optical counterpart.

Instead, we calculated the 4σ upper limit to the B magnitude of the counterpart by summing the total counts within a circle with 3 pixel radius for each FLT image, and dividing by the total exposure time; this radius corresponds to ∼3 times the FWHM
for the ACS. We obtained \( \sim 180,000 \) photons over \( \sim 4.8 \) ks. The 4\( \sigma \) upper limit was estimated to be \( 4C^{0.5}_\sigma T / T \), and Equation (3) yielded \( B > 26.9 \) at the 4\( \sigma \) level.

3.2. The XMM-Newton Spectrum

We obtained 1455 net source counts from the pn spectrum in X1. This spectrum was thermally dominated, and well described by a 0.39 ± 0.02 keV disk blackbody, with line-of-sight absorption equivalent to \( 7.2 \pm 1.5 \times 10^{20} \) H atom cm\(^{-2}\), and \( \chi^2 / \text{dof} = 60 / 65 \). There was very little power above \( \sim 5 \) keV; the \( \sim 0.3–5 \) keV spectrum is shown in Figure 2.

We also applied a double thermal emission model (disk blackbody + blackbody), for comparison with the soft states observed in neutron star binaries studied by Lin et al. (2007, 2009, 2012). The best fit yielded a 0.29 ± 0.05 keV disk blackbody plus a 0.57\(^{+0.22}_{-0.11}\) keV blackbody, absorbed by 1.1 ± 0.3 \( \times 10^{21} \) H atom cm\(^{-2}\); this fit is show in Figure 3. We have used the disk blackbody component in this double thermal model to identify 35 black hole candidates (BHCs) in M31; neutron star XBs exhibit soft spectra at luminosities \( \gtrsim 3 \times 10^{37} \) erg s\(^{-1}\), with disk blackbody temperatures \( > 1 \) keV in all cases, while all 35 BHCs inhabited a separate parameter space (Barnard et al. 2013c). We note that our measured disk blackbody temperature for T13 is 14\( \sigma \) below the limit for luminous neutron star XBs, and reject a neutron star accretor.

The \( 0.3–10 \) keV unabsorbed luminosity for T13 was \( 4.0 \pm 0.3 \times 10^{37} \) erg s\(^{-1}\) in X1. Therefore the X-ray to optical flux ratio was \( > 1250 \), ruling out a foreground star. We conclude that T13 contains a black hole.

3.3. The X-Ray Lightcurve of T13

If we assume the best fit disk blackbody model for X1, then observations C1 and C2 exhibited \( 0.3–10 \) keV luminosities of \( 6.2 \pm 0.6 \times 10^{37} \) and \( 1.30 \pm 0.16 \times 10^{37} \) erg s\(^{-1}\) respectively. We note that the luminosity for C1 is consistent with the luminosity that we previously obtained by assuming a 1 keV disk blackbody (Barnard et al. 2013a); hence the luminosity appears fairly insensitive to the disk blackbody temperature. Unfortunately, M31 was unobservable by Chandra in the \( \sim 3 \) months before C1, hence the start time of the outburst is uncertain; the peak is likely to have been unobserved.

Transient decays are expected to be exponential while the whole disk is illuminated, or linear when the disk is only partially illuminated (King & Ritter 1998). Shabazz et al. (1998) examined Galactic neutron star and black hole transients with known orbital periods and peak 0.4–10 keV fluxes and established that they followed this expectation. From Figure 1 of Shabazz et al. (1998), we only expect linear decay for systems with orbital periods \( \gtrsim 30 \) hr, assuming a 10 \( M_\odot \) primary, and a peak luminosity of \( \sim 6 \times 10^{37} \) erg s\(^{-1}\). We find a period \( < 5 \) hr for T13 (see next section); hence, we expect the decay to be exponential for a \( \sim 10 M_\odot \) BH.

We present the 0.3–10 keV unabsorbed luminosity lightcurve for T13 in Figure 4; the Chandra observations are represented by circles, while the XMM-Newton observation is represented...
by a diamond. A downward arrow indicates the time that H2 occurred. Time is quoted relative to C1. We present the best linear and exponential fits. Time is quoted relative to C1.

(A color version of this figure is available in the online journal.)

3.4. Estimating the Orbital Period

Since T13 appears to be a black hole transient in its high state, we estimated its orbital period using Equation (2); this relation requires the 2.0–10 keV luminosity. C1 was the closest observation to H2, with a separation of 15.4 days. Since the optical counterparts of X-ray transients tend to decay 2.2 times more slowly (Chen et al. 1997), we expect our measured $M_V$ to be 17% fainter than at the time of C1.

Assuming a 0.39 keV disk blackbody, and $N_\text{H} = 7.2 \times 10^{20}$ atom cm$^{-2}$, the 2.0–10 keV luminosity of T13 during C1 was $4.7 \times 10^{36}$ erg s$^{-1}$. We estimate an orbital period $<5$ hr for T13 from our 4σ upper limit to the B band luminosity, not including uncertainties in Equation (2); we used the 4σ limit to be consistent with the optical processing software. If we take the 3σ B band limit, $B > 27.2$, $M_V > 2.3$, and the orbital period is $<3$ hr, T13 appears to be the sort of system predicted by Voss & Gilfanov (2007).

4. DISCUSSION AND CONCLUSIONS

We have analyzed Chandra, HST, and XMM-Newton observations of a new X-ray transient (T13) that appeared within 100" of M31 in 2013 June. We obtained a 4σ upper limit to the $B$ band luminosity of $B > 26.9$; this translates to an absolute $V$ band magnitude $>2.0$.

The Chandra spectra did not yield sufficient counts for spectral fitting; however, the XMM-Newton pn spectrum yielded 1455 net source counts. The spectrum was well described by a $0.39 \pm 0.02$ keV disk blackbody. We also fitted a disk blackbody + blackbody model, for comparison with the complete range of soft neutron star/spectra observed by Lin et al. (2007, 2009, 2012); we rejected a neutron star accretor at a 14σ level.

We estimate an orbital period $<5$ hr, from an empirical relation that relates the X-ray to optical flux ratio and the orbital period. T13 appears to be just the type of system predicted by Voss & Gilfanov (2007), lending support to the theory that the bulge is sufficiently dense to form some X-ray binaries dynamically.

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Facilities: CXO (ACIS) HST (ACS) XMM (pn)

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