AN X-RAY TRANSIENT AND OPTICAL COUNTERPART IN THE M31 BULGE

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Received 2005 January 17; accepted 2005 April 8

ABSTRACT

We have obtained snapshot images of a transient X-ray source in M31 from Chandra ACIS-I and the Hubble Space Telescope (HST) Advanced Camera for Surveys (ACS). The Chandra position of the X-ray nova was R.A. = 00°42′56″038 ± 0°08, decl. = +41°12′18″50 ± 0°07. The transient was active for at least 6 months. Previous observations set an upper limit before the X-ray outburst, demonstrating variability by a factor of >100 and confirming the transient nature of the source. For the first 6 months after the initial detection, the X-ray luminosity was ~6 × 10^{37} \text{ ergs s}^{-1}; it then decayed to <5 × 10^{36} \text{ ergs s}^{-1} over the following 2 months. An HST observation 29 days after the initial X-ray detection revealed a source at R.A. = 00°42′56″042, decl. = +41°12′18″45 that was B = 24.52 ± 0.07. This optical source faded to B = 24.95 ± 0.08 in 9 months. The HST identification of an optical source at the same position as the X-ray source, fading in concert with the X-ray source, indicates that this optical source is the counterpart of the X-ray transient. The lack of high-mass stars in the region suggests that this source is a low-mass X-ray binary, and the X-ray and optical luminosities provide a rough orbital period estimate of 8^{+12}_{-5} days for the system.

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

1. INTRODUCTION

Most Galactic soft X-ray transient (SXT) sources in low-mass X-ray binaries show compelling dynamical evidence that they contain a stellar-mass black hole (McClintock & Remillard 2005). The variability on millisecond timescales and short-term X-ray luminosities reaching >10^{39} \text{ ergs s}^{-1} provide further support that these are some of the most likely black hole candidates known (Charles 1998). Such objects are therefore of intense interest as sites for more detailed studies of general relativity. Finding such sources in the Galaxy requires all-sky monitoring and difficult distance estimates. Searches for bright transient X-ray sources in nearby galaxies, such as M31, therefore provide a very efficient method for expanding the known sample of these fascinating sources.

Since the M31 bulge is at a known distance, has low extinction, and can be surveyed in a single Chandra observation, it presents an excellent laboratory for searching for transient X-ray sources. Such transient sources appear about once each month in the M31 bulge alone (Williams et al. 2004), and M31 surveys have already discovered nearly 50 transient X-ray sources (Trudolyubov et al. 2001; Kong et al. 2002; Di Stefano et al. 2004; Williams et al. 2004, 2005).

Furthermore, the exquisite angular resolution of the Hubble Space Telescope (HST) allows the individual stars in the M31 bulge to be resolved. Combining this resolution with the positional accuracy of Chandra allows one to search for optical counterparts for transient X-ray sources in the M31 bulge. Currently, optical counterpart candidates have been identified from HST for three transient X-ray sources in M31 (Williams et al. 2004, 2005). Here we report the discovery of a new transient X-ray source in the M31 bulge found by our Chandra/HST monitoring campaign. Exceptional positional accuracy and image alignments for the nearly contemporaneous Chandra and HST data sets provide a reliable identification of the optical counterpart.

We obtained Chandra Advanced CCD Imaging Spectrometer (ACIS-I) images of the M31 bulge on 2003 November 26, 2003 December 27, 2004 January 31, 2004 May 23, and 2004 July 17. The observations were performed in “alternating exposure read-out,” so that every sixth frame had 0.6 s of exposure instead of the canonical 3.2 s. This mode lowers the effective exposure time by ~20%, but it provides a second low-exposure image in which bright sources are not piled up. The details of these observations, including target coordinates, roll angle of the telescope, and exposure time, are provided in Table 1.

These X-ray observations were all reduced in an identical manner using the X-ray data analysis package CIAO version 3.1. We created exposure maps for the images using the CIAO script merge_all,2 and we found and measured positions, position errors, and 0.3–10 keV fluxes for the sources in the image using the CIAO task wavdetect.3 The positions and errors from the first two detections of the new X-ray transient found in the 2003 November 26 ACIS-I (ObsID 4679) observation are given in Table 1. Each data set detected sources down to (0.3–10 keV) fluxes of ~8 × 10^{-6} photons cm^{-2} s^{-1}.

We cross-correlated the X-ray source positions of all three observations against all previously published X-ray catalogs and the SIMBAD4 database to look for any new, bright X-ray source likely to be an X-ray nova (XRN). We found several new X-ray sources in the data. Here we focus on one bright new source in particular at R.A. = 00°42′56″038, decl. = +41°12′18″50, which we name CXO M31 J004256.0+421218, following the naming convention described in Kong et al. (2002). We also give the source a short name, r2-70, which is derived from the position using the description given in Table 2 of Williams et al. (2004). The source is 2.1 east and 3.8 south of the nucleus.

We determined the position of r2-70, discovered in the data set from 2003 November 27 (ObsID 4679), by aligning the

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2 See http://cxc.harvard.edu/ciao3.1/threads/merge_all.

3 See http://cxc.harvard.edu/ciao3.0/download/doc/detect_html_manual/Manual.html.

4 See http://simbad.u-strasbg.fr/.
observation with the coordinate system of the Local Group Survey (LGS; Massey et al. 2001). The LGS images have an assigned J2000 (FK5) world coordinate system accurate to $\sim 0\farcs25$, and they provided the standard coordinate system to which we aligned all of our data for this project. We aligned the positions of six X-ray sources with known globular cluster counterparts to the positions of the centers of their host globular clusters in the images of the LGS, using the IRAF\textsuperscript{5} tasks imcentroid and ccmap.

We repeated this alignment process for the second detection of the source on 2003 December 27 (ObsID 4680; see Fig. 1) and for the third detection of the source on 2004 January 31 (ObsID 4681). Using the independent position measurements for these detections, which were the three detections with the highest number of counts, allowed checks for consistency as well as the ability to reduce the final errors in the position of the X-ray source. The alignment errors between \textit{Chandra} and the LGS are shown for each observation in column $\sigma_{\text{AL}}$ in Table 2; random position errors for the source, as measured by \texttt{wavdetect}, are given in column $\sigma_{\text{POS}}$. Alignments allowed for adjustments in pixel scale as well as rotation and shifts in $X$ and $Y$.

We extracted the X-ray spectrum of r2-70 from all four detections using the CIAO task \texttt{psextract}.\textsuperscript{6} We then fit these spectra independently, binning so that each energy bin contained

\begin{table}
\centering
\caption{\textit{Chandra} ACIS-I Observations}
\begin{tabular}{lcccc}
\hline
ObsID & Date & R.A. (J2000) & Decl. (J2000) & Roll (deg) & Exposure (ks) \\
\hline
4678 & 2003 Nov 9 & 00 42 44.4 & 41 16 08.3 & 239.53 & 3.9 \\
4679 & 2003 Nov 26 & 00 42 44.4 & 41 16 08.3 & 261.38 & 3.8 \\
4680 & 2003 Dec 27 & 00 42 44.4 & 41 16 08.3 & 285.12 & 4.2 \\
4681 & 2004 Jan 31 & 00 42 44.4 & 41 16 08.3 & 305.55 & 4.1 \\
4682 & 2004 May 23 & 00 42 44.4 & 41 16 08.3 & 79.99 & 3.9 \\
4719 & 2004 Jul 17 & 00 42 44.3 & 41 16 08.4 & 116.83 & 4.1 \\
\hline
\end{tabular}
\end{table}

\begin{figure}
\centering
\includegraphics[width=\textwidth]{fig1}
\caption{Top left: The combined 2 $\sigma$ ($\pm 0\farcs16$ in R.A., and $\pm 0\farcs14$ in decl.) X-ray position errors for r2-70 are shown by a black ellipse on the \textit{HST} image from 2003 December 25. The optical counterpart candidate is the northeast portion of the bright blend in the south part of the error ellipse. Top right: The same error ellipse is shown on the \textit{HST} image from 2004 October 2. The blend is now well resolved, and the northeast component has faded. Bottom left: The ACIS-I image of r2-70 from 2003 December 27. The white ellipse marks the best position for the X-ray source in this detection. Bottom right: The same error ellipse is shown on the ACIS-I image from 2004 July 17. Source r2-70 is not detected.}
\end{figure}

\textsuperscript{5} IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

\textsuperscript{6} See http://cxc.harvard.edu/ciao/ahelp/psextract.html.
in Figure 1. The images reveal a fading optical source at the same position as the transient X-ray source, indicating that we detected the optical counterpart of the X-ray event. However, the counterpart has a bright neighbor, which is apparent in the second HST image. This neighbor led to some complications in measuring the photometry of the counterpart.

We processed the relevant sections of the final images with DAOPHOT II and ALLSTAR (Stetson et al. 1990) in order to find and measure the count rates of the optical counterpart. We converted the count rates measured on our images to Vega magnitudes using the conversion techniques provided in the ACS Data Handbook.9

4. RESULTS

4.1. X-Ray

The brightest flux at which the source was observed was $1.4 \times 10^{-4}$ photons cm$^{-2}$ s$^{-1}$. Since this source is in the region surveyed by Kong et al. (2002) to a detection limit of $\sim 8 \times 10^{-7}$ photons cm$^{-2}$ s$^{-1}$, the source demonstrates changes in flux of more than a factor of 100, indicating that the source was an X-ray nova.

| Date       | Counts | Flux  | Slope | $N_{H}$ | $\chi^{2}/$ | $Q$ | HR-1 | HR-2 | $L_{X}$ |
|------------|--------|-------|-------|---------|------------|-----|------|------|---------|
| 2003 Nov 26.. | 134    | 1.2 ± 0.1 | 1.7 ± 0.3 | 0.6 ± 0.9 | 7.08/10   | 0.72 | 0.38 ± 0.11 | 0.24 ± 0.12 | 29 ± 7 |
| 2003 Dec 27... | 145    | 1.3 ± 0.1 | 3.1 ± 0.5 | 2.6 ± 1.2 | 17.84/11  | 0.09 | 0.33 ± 0.09 | -0.19 ± 0.12 | 60 ± 22 |
| 2004 Jan 31..... | 161    | 1.4 ± 0.1 | 3.1 ± 0.3 | 2.1 ± 0.9 | 10.46/12  | 0.58 | 0.24 ± 0.08 | -0.47 ± 0.13 | 62 ± 16 |
| 2004 May 23.... | 109    | 1.0 ± 0.1 | 3.3 ± 0.6 | 2.6 ± 1.4 | 7.93/7   | 0.34 | 0.31 ± 0.11 | -0.42 ± 0.16 | 54 ± 23 |

9 See http://www.stsci.edu/hst/acs/documents/handbooks/DataHandbookv2/ACS_longdishcover.html.

The drizzled ACS images were aligned with the LGS coordinate system with ccmap, using stars common to both images. The alignment errors were $\sim 0.04$, indicating that the ACS images were accurately aligned to the LGS system. With the ACIS-I and ACS images aligned to the same coordinate system, we were able to compare the coordinates of the ACS and ACIS-I sources reliably. The X-ray position error ellipse for r2-70 is shown on the aligned HST images in Figure 1. The images reveal a fading optical source at the same position as the transient X-ray source, indicating that we detected the optical counterpart of the X-ray event.

PyRAF is a product of the Space Telescope Science Institute, which is operated by AURA for NASA. MultiDrizzle is a product of the Space Telescope Science Institute, which is operated by AURA for NASA. See http://stsdas.stsci.edu/pydrizzle/multidrizzle.
The results of the spectral fits to the four detections of r2-70 are given in Tables 3 and 4. All of these fits agree that r2-70 had a soft spectrum; however, the measured absorption is much higher for the power-law fits. In fact, the best fits using the disk blackbody model have no absorption, which is not possible considering the known Galactic foreground absorption toward M31 (∼6 × 10^{20} cm^{-2}). This result, along with the slightly lower quality of the disk blackbody fits, favors the power law as the correct spectral model, and an absorption-corrected X-ray luminosity of 10^{36} ergs s^{-1} (0.3–7 keV).

4.2. Optical

Inside the 2σ Chandra error ellipse on the first ACS image, DAOPHOT found three optical point sources. The brightest two of these are in the southern portion of the error ellipse. These sources are within 0.7′ of each other. The significant fading of the northeastern source between HST observations, as seen in Figure 1, distinguished it as an optical counterpart candidate for the transient X-ray event. Another source lies 0.7′′ to the north of the blended sources. It had magnitudes of B = 25.95 ± 0.09 and 25.97 ± 0.05 in the first and second ACS images, respectively. Since this source did not fade between observations, we did not consider it further as a counterpart candidate, leaving the northeastern member of the blended pair as our only counterpart candidate.

Distinguishing the photometry of the pair of bright optical sources, separated by only 0.0′′10, was difficult in the 2003 December 25 data set because the brighter northeastern source overpowered the fainter southwestern source. However, in the 2004 October 2 data set, the northeastern source had faded sufficiently that ALLSTAR was able to cleanly measure the photometry for both sources individually, finding the northeastern source to be B = 24.92 ± 0.06 and the southwestern source to be B = 24.90 ± 0.05. Therefore, assuming typical extinction to M31 (A_B = 0.4) and a distance modulus of 24.47 (Williams

| Date       | T_{in}^{a} | R_{in}^{b} | N_{H}^{c} | \chi^{2}/\nu | Q^{d} | L_{X}^{e} |
|------------|------------|------------|-----------|--------------|------|-----------|
| 2003 Nov 26 | 1.5 ± 0.2  | 5.0^{+3}_{-1} | ≤0.1      | 8.65/10      | 0.57 | 25 ± 13   |
| 2003 Dec 27 | 0.5 ± 0.1  | 3.0^{+2}_{-1} | 0.3 ± 0.1 | 23.26/11     | 0.02 | 20 ± 20   |
| 2004 Jan 31 | 0.58 ± 0.07 | 2.8^{+2}_{-2} | ≤0.1      | 12.82/12     | 0.38 | 20 ± 10   |
| 2004 May 23 | 0.50 ± 0.07 | 3.1^{+1}_{-2} | 0.25      | 10.30/8      | 0.24 | 14 ± 9    |

\(^{a}\) The temperature of the inner disk in keV.
\(^{b}\) The radius of the inner disk in km, assuming the distance to M31 is 780 kpc and the inclination (i) of the binary is 0°.
\(^{c}\) The absorption column in units of 10^{22} cm^{-2}.
\(^{d}\) The probability that this fit is representative of the true spectrum, determined from \chi^{2} per degree of freedom.
\(^{e}\) The absorption-corrected luminosity of the source in units of 10^{36} ergs s^{-1} (0.3–7 keV).
2003), the brightest stars consistent with the position of r2-70 have $M_B \sim 0$, fainter than the O and B stars found in high-mass X-ray binaries (HMXBs). Since most Galactic SXTs in low-mass X-ray binaries (LMXBs) contain black holes, the soft X-ray spectrum and lack of high-mass stars at the position of r2-70 suggest that it is a black hole binary.

We measured the total count rate of the blended sources in the first ACS image, using an aperture of radius 0.714 centered on the blend and subtracting the background level sampled in an annulus from 0.30 to 0.55. By subtracting the contribution of the light expected from the $B = 24.90$ southwestern neighbor, we obtained the count rate of the northeastern source alone. This technique yielded $B = 24.52 \pm 0.07$ for the northeastern source during the first HST observation. Assuming a distance modulus to M31 of 24.47 (Williams 2003) and extinction consistent with $N_H$, the absolute magnitude of the optical counterpart was $M_B = -1.3 \pm 0.5$.

For consistency, we applied the same aperture photometry technique to the second observation of the pair of optical sources. The technique yielded $B = 24.95 \pm 0.08$ for the northeastern source during the second HST observation. This measurement is equivalent at the 1 $\sigma$ level with the ALLSTAR measurement of the northeastern source in the second image, suggesting that this technique was successful at separating the photometry of the blended sources.

The aperture photometry reveals an optical source inside the X-ray position error ellipse that faded by 30% from the time the X-ray source was active to the time that the X-ray source was quiescent. This optical variability in concert with the X-ray source demonstrated by the brightest of the three optical sources detected in the error ellipse clearly indicates that this fading optical source was the counterpart to the transient X-ray event.

The bright optical luminosity ($B = 25$) apparent during X-ray quiescence may have several explanations. For example, r2-70 could be an intermediate-mass X-ray binary, similar to V4641 Sgr, whose binary companion is a late B or early A star (Chaty et al. 2003) and whose period is 2.8 days (Orosz et al. 2001). In this case, the optical light from the binary companion would contaminate the optical light from the accretion disk even during the X-ray outburst, and the optical brightening during outburst would be typically only 1–2 mag (see Orosz et al. 2001 and references therein). Another example of a black hole binary that is optically bright during quiescence is 4U 1543–47. While this source has peak X-ray luminosities of $>10^{39}$ ergs s$^{-1}$ during X-ray quiescence, the optical luminosity of the accretion disk during outburst would be typically only 1–2 mag (see Orosz et al. 2001 and references therein).

On the other hand, it is also possible that both of the $B = 25$ stars visible during X-ray quiescence are chance superpositions. In this case, the optical counterpart of the LMXB was only seen during the outburst but was not resolved because of its proximity to this pair of stars. Either of these possibilities would cause the optical luminosity of the accretion disk during outburst to be somewhat overestimated.

### 4.3. Orbital Period Prediction

We applied the relation of van Paradijs & McClintock (1994) in order to predict the orbital period of the LMXB that produced the X-ray transient we have named r2-70. This empirical relation seen in Galactic LMXBs shows that the X-ray/optical luminosity ratio of an LMXB is correlated with the orbital period of the system. The relation appears to hold even for more recently discovered systems (Williams et al. 2005).

With our optical and X-ray data of r2-70, we are able to measure the X-ray and optical luminosities. Assuming that r2-70 is an LMXB, as is suggested by its location in the M31 bulge, which contains very few, if any, young, high-mass stars (e.g., Stephens et al. 2003), and assuming that LMXBs in M31 follow the same relation between their photometric properties and their orbital periods as those in the Galaxy, our luminosity measurements for r2-70 put a constraint on the orbital period of the system.

To determine the V-band luminosity of r2-70 during the outburst, we first took our apparent $B$ magnitude of 24.52 ± 0.10 for r2-70 during the first ACS observation. We then determined the extinction toward r2-70 using the fits to the X-ray spectra. Taking the weighted mean of the four independent measurements of the column density given in Table 3, we obtained $N_H = (1.8 \pm 0.5) \times 10^{21}$ cm$^{-2}$. Using the relation of Predehl & Schmitt (1995) and the standard interstellar extinction law, this absorption translates to $A_B = 1.3 \pm 0.4$. Applying an intrinsic $B-V$ color of $-0.09 \pm 0.14$ determined from the Galactic LMXB catalog of Liu et al. (2001), and a distance of 780 kpc, our measurement of $M_V = -1.2 \pm 0.4$.

The X-ray luminosity was determined using the power-law spectral fits to the ACIS data (see Table 3). The absorption-corrected 0.3–7 keV X-ray luminosity of r2-70 on 2003 December 27, as measured from the Chandra data, was of $(6 \pm 2) \times 10^{37}$ ergs s$^{-1}$. Assuming this was the X-ray luminosity during the 2003 December 25 HST observation, this X-ray luminosity and the optical luminosity of $M_V = -1.2 \pm 0.4$, measured from the 2003 December 25 HST data, can be applied to the relation of van Paradijs & McClintock (1994). This calculation yields a predicted orbital period of $8 \pm 3$ days for this system.

We note that if the lower extinction ($2.5 \times 10^{20}$ cm$^{-2}$) and X-ray luminosity [(2.5 ± 1.3) $\times 10^{37}$ ergs s$^{-1}$] from the disk blackbody spectral fits are applied, $M_V = 0.0 \pm 0.2$ on 2003 December 25 and the orbital period prediction changes to $3 \pm 3$ days. We also note that if the optical luminosity of the accretion disk was actually lower than the measured value because the counterpart is an A star or because the counterpart was poorly resolved from its neighbors, the range of the predicted orbital period would decrease.

Comparisons with the other two optical detections of X-ray transients in M31 show that the properties of the optical counterpart for r2-70 were between those of the other transient counterparts. The counterpart for r2-70 was fainter than that seen for the X-ray transient r2-67 ($M_V = -2.4 \pm 0.8$; Williams et al. 2004) and brighter than that seen for the counterpart candidate for the X-ray transient s1-86 ($M_V = -0.25 \pm 0.27$; Williams et al. 2005). The predicted orbital period also falls between the values calculated for r2-67 (23 $\pm 16$ days; Williams et al. 2004) and s1-86 (1.0 $\pm 0.6$ days; Williams et al. 2005).

### 5. CONCLUSIONS

We have discovered a new transient X-ray source in the M31 bulge that appeared in 2003 November, which we have named r2-70. This source attained an X-ray flux more than a factor of 100 greater than the upper limits of previous surveys in which it did not appear. The transient event kept a high X-ray flux through the first half of 2004. When the source decayed, it did so with an e-folding decay time of $\leq 1$ month. The event had a
soft spectrum best fit by a power law with index $\sim 3$, and it had an absorption-corrected 0.3–7 keV luminosity $\sim 6 \times 10^{37}$ ergs s$^{-1}$.

Follow-up *HST* ACS F435W (B-band equivalent) imaging revealed a fading optical source within the tightly constrained error ellipse of the location of the transient X-ray event, showing that this optical source is the optical counterpart of the X-ray transient. The source decayed from $B = 24.52 \pm 0.07$ to $B = 24.95 \pm 0.08$ between epochs. Assuming that the transient event occurred in an LMXB, we can apply our X-ray and optical luminosity measurements to the empirical relation of van Paradijs & McClintock (1994) to predict that the system has an orbital period of $8^{+12}_{-5}$ days.

Finally, the lack of high-mass stars at the position of r2-70 suggests that it is an LMXB. Although the X-ray luminosity and spectrum do not exclude either an accreting neutron star or black hole, many Galactic LMXBs that exhibit such transient events and have such soft X-ray spectra contain stellar-mass black holes, making r2-70 a good black hole candidate in M31.

Support for this work was provided by NASA through grant GO-9087 from the Space Telescope Science Institute and through grant GO-3103X from the Chandra X-Ray Center. M. R. G. acknowledges support from NASA LTSA grant NAG5-10889.

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