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| As Published | http://dx.doi.org/10.1088/0004-637x/714/1/894 |
| Publisher | Institute of Physics/American Astronomical Society |
| Version | Final published version |
| Accessed | Thu Feb 14 10:16:12 EST 2019 |
| Citable Link | http://hdl.handle.net/1721.1/95972 |
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Detailed Terms
DISCOVERY OF A SECOND TRANSIENT LOW-MASS X-RAY BINARY IN THE GLOBULAR CLUSTER NGC 6440


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Received 2009 October 27; accepted 2010 March 17; published 2010 April 15

ABSTRACT

We have discovered a new transient low-mass X-ray binary, NGC 6440 X-2, with Chandra/ACIS, RXTE/PCA, and Swift/XRT observations of the globular cluster NGC 6440. The discovery outburst (2009 July 28–31) peaked at \( L_X \sim 1.5 \times 10^{36} \text{ erg s}^{-1} \) and lasted for <4 days above \( L_X = 10^{35} \text{ erg s}^{-1} \). Four other outbursts (2009 May 29–June 4, August 29–September 1, October 1–3, and October 28–31) have been observed with RXTE/PCA (identifying millisecond pulsations) and Swift/XRT (confirming a positional association with NGC 6440 X-2), with similar peak luminosities and decay times. Optical and infrared imaging did not detect a clear counterpart, with best limits of \( V > 21, B > 22 \) in quiescence from archival Hubble Space Telescope imaging, \( g' > 22 \) during the August outburst from Gemini-South GMOS imaging, and \( J \geq 18.5 \) and \( K \geq 17 \) during the July outburst from CTIO 4 m ISPI imaging. Archival Chandra X-ray images of the core do not detect the quiescent counterpart (\( L_X < (1–2) \times 10^{31} \text{ erg s}^{-1} \)) and place a bolometric luminosity limit of \( L_{\text{bol}} < 6 \times 10^{31} \text{ erg s}^{-1} \) (one of the lowest measured) for a hydrogen atmosphere neutron star. A short Chandra observation 10 days into quiescence found two photons at NGC 6440 X-2’s position, suggesting enhanced quiescent emission at \( L_X \sim 6 \times 10^{31} \text{ erg s}^{-1} \). NGC 6440 X-2 currently shows the shortest recurrence time (<31 days) of any known X-ray transient, although regular outbursts were not visible in the bulge scans before early 2009. Fast, low-luminosity transients like NGC 6440 X-2 may be easily missed by current X-ray monitoring.

Key words: dense matter – pulsars: general – stars: neutron – X-rays: binaries

Online-only material: color figures

1. INTRODUCTION

The dense cores of globular clusters are known to be efficient factories for dynamically producing tight binaries containing heavy stars and thus X-ray binaries (Clark 1975; Hut et al. 1991; Pooley et al. 2003). Thirteen luminous (\( L_X > 10^{35} \text{ erg s}^{-1} \)) low-mass X-ray binaries (LMXBs) have previously been identified in Galactic globular clusters (see Verbunt & Lewin 2006), concentrated in the densest and most massive clusters (Verbunt & Hut 1987; Verbunt 2003). Luminous LMXBs in globular clusters of other galaxies are clearly concentrated in the most massive, most metal-rich, and densest globular clusters (Kundu et al. 2002; Sarazin et al. 2003; Jordán et al. 2004). A critical question for studies of globular cluster LMXBs is whether X-ray emission from a globular cluster is due to one LMXB or multiple LMXBs. This affects the inferred nature of sources (Dotani et al. 1990; D’Stefano et al. 2002; Maccarone et al. 2007) and luminosity functions (Sivakoff et al. 2007). For example, an apparent contradiction in the qualities of the LMXB in M15 was resolved by the identification of two persistent X-ray sources in the cluster (White & Angelini 2001). Identification with Chandra of multiple quiescent LMXBs in several globular clusters (Grindlay et al. 2001; Pooley et al. 2002; Heinke et al. 2003) has suggested that transient LMXB outbursts from a cluster might arise from different sources, although some LMXBs possess distinctive characteristics (e.g., the Rapid Burster; Homer et al. 2001). Here, we report the discovery and outburst monitoring of the 14th luminous LMXB in a Galactic globular cluster, NGC 6440, the first cluster to show two transient luminous LMXBs (both of which show millisecond pulsations). In a companion paper, Altamirano et al. (2010a) identify this LMXB as a new ultracompact accreting millisecond X-ray pulsar (AMXP), after discovering coherent 206 Hz pulsations (Altamirano et al. 2009) and fitting the frequency drift to a 57.3-minute orbital period. NGC 6440 is a globular cluster near the Galactic center, at a distance of 8.5 kpc (Ortolani et al. 1994), with \( N_H = 5.9 \times 10^{21} \text{ cm}^{-2} \) (Harris 1996). A luminous X-ray source (MX 1746–20) was identified in this cluster in 1971 (Markert et al. 1975), and the cluster was detected at a much lower flux level in 1980 (Hertz & Grindlay 1983), identified with quiescent emission from the luminous X-ray source. An X-ray source in the cluster (SAX J1748.9–2021) was observed in outburst again in 1998 (in’t Zand et al. 1999), 2001 (in’t Zand et al. 2001), and 2005 (Markwardt & Swank 2005). Pooley et al. (2002) observed the cluster with Chandra in 2000, identifying 24 sources within two core radii of the cluster. One (CX1) was positioned with a blue variable optical counterpart during the 1998 outburst (Verbunt et al. 2000) and with the outbursting LMXB in 2001 (in’t Zand et al. 2001). Altamirano et al. (2008) identified intermittent 442 Hz pulsations in both the 2001 and 2005 outbursts (the latter also identified by Gavriil
et al. 2007). Thus, CX1 can be confidently held responsible for the 1998, 2001, and 2005 outbursts. We here identify a second transient luminous LMXB in NGC 6440 and confidently identify five outbursts from this transient during 2009 using its source position. Preliminary results were presented in Heinke & Budac (2009) and Heinke et al. (2009a, 2009c); these results supersede those.

2. X-RAY ANALYSIS

2.1. Chandra in Outburst

NGC 6440 was observed with the Chandra ACIS-S detector for 49.1 ks, from 2009 July 28, 15:16 (TT) to 2009 July 29, 05:15, using a 1/2 subarray. We searched for periods of elevated background, but found none. We used the level-2 event files provided by the CXC and CIAO 4.19 for our analysis. Images were produced in the 0.3–7 keV and 0.5–2.5 keV bands, both of which are dominated by the scattered halo (a combination of dust grain scattering and the intrinsic point-spread function of the Chandra mirrors) and readout streak from a bright transient LMXB, heavily affected by pileup.\(^9\) Several faint point sources are clearly visible, which can be confidently identified with the cluster X-ray sources identified by Pooley et al. (2002). In Figure 1, we show Chandra images of NGC 6440 during the 2009 outburst, shortly after the 2009 outburst, during quiescent observations in 2000–2003 (Pooley et al. 2002; Cackett et al. 2005) and during the 2001 outburst (in’t Zand et al. 2001). Clearly this is a new transient.

The CIAO detection algorithm wavdetect was run on a 0.3–7 keV image of the cluster core to identify the positions of known cluster sources, which we shift (ΔR.A. = +0.008s, Δdecl. = +0′.31) to align with the (ICRS) astrometry of Pooley et al. (2002). We estimated (by eye) the center of the symmetric “hole” in the counts by matching circles to the doughnut-shaped locus of maximum count rate in the LMXB halo, in both wavebands. Our result is (J2000) R.A. = 17:48:52.76(2), decl. = −20:21:24.0(1) (1σ values, after our astrometric correction), giving it the IAU name CXOGlb J174852.7−202124 and (for shorthand) NGC 6440 X-2. Detailed analysis of the remaining cluster sources will be presented elsewhere.

To measure the spectrum and luminosity of the transient, we extracted a spectrum from the readout streak, excluding a 20″ radius circle around the piled-up transient. We extracted background from rectangular regions above and below the readout streak, computed response functions for the position of the transient, and corrected the exposure time of the spectrum. We binned the spectrum to 60 counts per bin to improve its statistics, and excluded data over 8 keV and below 0.5 keV. An absorbed power law fits the data (Table 1, Figure 2), with photon index 1.7 ± 0.1. We found no evidence for a 6.4 or 6.7 keV iron line, with a 90% upper limit of 0.4 keV on its equivalent width.

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\(^9\) http://cxc.harvard.edu/ciao

\(^{10}\) See the Chandra Proposal’s Observatory Guide, chapter 6.
The light curve from the readout streak events shows a clear decline during the *Chandra* observation by a factor of \sim 40%. Power spectra from the readout streak events show a clear periodicity at 1000.0 s and its harmonics, identical to one of the spacecraft dither frequencies and thus a likely artifact (it is not seen in *Rossi X-ray Timing Explorer (RXTE)* data). No other periodicities (such as the 57-minute orbital period, Altamirano et al. 2010a) were identified, suggesting that the transient is not seen at high inclination.

### 2.2. RXTE

The *RXTE* has conducted regular scans of the Galactic bulge region since 2000 (generally covering NGC 6440 twice/week), in part to search for faint transient sources below the sensitivity of *RXTE*'s all-sky monitor (Swank & Markwardt 2001), with results promptly made available. The PCA scans are significantly more sensitive in the Galactic bulge than the *RXTE* all-sky monitor data. (Although dwell-by-dwell all-sky monitor data suggest a few points at \( L_X \sim 10^{38}\) erg s\(^{-1}\) from NGC 6440, suggesting X-ray bursts, their 6\(\sigma\) maximum significance is matched by similar points from black hole candidates in the Galactic center. Thus, we cannot be assured of their reality.) Scans in late 2009 May showed evidence for an increased count rate from NGC 6440 (see the third red line in Figure 3). An outburst was confirmed by *Swift* observations in early June (see below). No further activity was observed until a scan showed a 5\(\sigma\) detection on 2009 July 28, near the beginning...
of the Chandra observation. A pointed RXTE observation on July 30 showed a significant decline from the Chandra and bulge scan fluxes (details below). Later bulge scans (on August 1 and 2) were consistent with a decay below the PCA’s (background-limited, due to its non-imaging nature) sensitivity (Figure 3).

A third bulge scan peak on 2009 August 29 triggered a pointed observation on August 30, which discovered millisecond pulsations from NGC 6440 X-2 with a frequency of 205 Hz (Altamirano et al. 2010a). Further RXTE observations starting on September 1 found fluxes returning to quiescence. Upon identifying a fourth outburst with Swift/XRT on 2009 October 1, a pointed RXTE observation on October 2 detected NGC 6440 X-2 near the detection limit (∼1.5 mCrab). Altamirano et al. (2010a) report the detection of pulsations at a 3.4σ level, further confirming the identification of this transient with NGC 6440 X-2. RXTE observations on October 3 found it below the PCA’s sensitivity limit. A fifth outburst was caught by RXTE/PCA on October 28, returning to quiescence by November 1. Below, we describe spectral analysis of these data; all RXTE/PCA pointed observations are magenta pentagons. Swift observations are blue triangles (open if upper limits). The outburst Chandra observation is a red filled box. Red marks and dates at the top indicate the suggested 30.7-day recurrence epochs, which coincide with five clear episodes of X-ray activity. (A color version of this figure is available in the online journal.)

The July 30 pointed observation could be fit with an absorbed power law with photon index 2.2 ± 0.1 and a luminosity of \( (5 ± 1) \times 10^{35} \) erg s\(^{-1}\), 3.5 times lower than the July 28 Chandra observation (Table 1; see below). The August 30 observation showed a photon index of 1.84 ± 0.02 and \( L_X = 2.9 \times 10^{36} \) erg s\(^{-1}\). The series of observations on September 1 and 2 showed much lower fluxes, averaging \( L_X = 4 \times 10^{35} \) erg s\(^{-1}\); the longest one also shows clear evidence of an iron line at 6.7 ± 0.2 keV. However, simultaneous Swift observations (see below) find much lower fluxes from the cluster of \( 6 \times 10^{34} \) erg s\(^{-1}\), consistent with the quiescent cluster emission and inconsistent with the transient position. Therefore, we attribute the RXTE/PCA flux observed on September 1 to the Galactic Ridge emission at this location. Subtracting this flux from the July 30 RXTE/PCA measurement gives \( L_X = (1 ± 1) \times 10^{35} \) erg s\(^{-1}\), a very marginal detection, and makes its spectral parameters unreliable.

We refine our spectral fitting of the August 30 observation by extracting spectra from only the top layer of PCU2 and modeling the inferred Galactic Ridge emission using our fits to the August 1 data. Fitting with an absorbed power law gives a good reduced chi-squared, but a residual near 6.5 keV suggests the addition of an iron line (this is in addition to the Galactic Ridge iron line seen in the September data). Freezing \( N_H \) to the cluster value, we obtain \( \Gamma = 1.78 \pm 0.03 \), \( L_X(0.5–10 \text{ keV}) = (2.4 \pm 0.1) \times 10^{36} \) erg s\(^{-1}\), with an iron line at 6.6+0.4 keV, of equivalent width 54 ± 39 eV (90% confidence). An F-test suggests that this is reasonable, providing 3.6% probability of such a \( \Delta \chi^2 \) by chance. Other AMXPs have displayed evidence of Fe K lines (e.g., SAXJ1808.4−3658, Cackett et al. 2009; Papitto et al. 2009; HETE J1900.1−2455, Cackett et al. 2010; Swift J1756.9−2508, Patruno et al. 2010a), often showing relativistic broadening which our observations are unable to resolve.

Two RXTE/PCA observations were obtained during the early October outburst, both during the source’s decline. We identified

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12 http://heasarc.gsfc.nasa.gov/docs/xte/pca_news.html
pulsations in the first (October 1) observation, confirming that pulsations are common from this object (Altamirano et al. 2010a). The second (October 3) occurred after NGC 6440 X-2 had dipped below the PCA’s sensitivity limit. We model the Galactic Ridge contribution to the October 1 observation, using the October 3 observation, finding $\Gamma = 1.78 \pm 0.15$, $L_X(0.5–10) = 8.4^{+0.5}_{-0.3} \times 10^{35}$ erg s$^{-1}$ (see Table 1).

Three RXTE/PCA observations were able to detect the October/November outburst. The first (on October 28) identified pulsations again (Altamirano et al. 2010a), at $L_X(0.5–10 \text{ keV}) = 8.6^{+0.9}_{-1} \times 10^{35}$ erg s$^{-1}$ (see Table 1), after subtraction of Galactic Ridge emission. RXTE/PCA observations detected emission over background on October 29 and (marginally) October 30, and observations on October 31 and after were consistent with Galactic Ridge emission.

The full RXTE/PCA Galactic bulge scan data reveals seven times from 2000 to 2009 when NGC 6440’s count rates are 4$\sigma$ above zero. The two brightest outbursts ($L_X > 10^{37}$ erg s$^{-1}$) have been identified with the other transient in NGC 6440, SAX J1748.9–2021 = CX1 (Altamirano et al. 2008; in’t Zand et al. 2001). The other five potential outbursts are much fainter and briefer (only a single bulge scan point each, so lasting less than a week), of which three were discussed above. The other two are 2007 April 15 and 2009 March 20. A period of 30.7 days ($\pm 0.3$ days, from the uncertainties in the peak of the late October outburst), with reference date MJD 55040.5, reasonably predicts the peaks of the four well-studied outbursts. The model predicts missed outbursts on April 27 (weak activity is suggested by bulge scans on April 18–20), May 28 (a bulge scan detection occurred on May 25, followed by a faint Swift detection on June 4), and June 27 (no bulge scans conducted $\pm 10$ days around this date). The bulge scan point in March is off the prediction by 7 $\pm 1$ days, indicating either that the outburst period has slightly decreased over time (as the April and May evidence also suggest) or that the March point is not a real outburst. Sensitive monitoring since November 2 (up to 2010 February 11) has not been possible due to solar constraints and an outburst of SAX J1748.9–2021 (Suzuki et al. 2010; Patruno et al. 2010b).

We show the bulge scan data in the relevant date range (and to 0.5–10 keV unabsorbed fluxes with PIMMS 13 and assume a RXTE law of photon index 2 to convert $L_X$ to $L_X(0.5–10 \text{ keV})$)

Three $L_X(0.5–10 \text{ keV})$ are shown in Figure 4.

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2.3. Swift

Eighteen Swift/XRT observations were performed, tracking five outbursts from NGC 6440 X-2 (see Table 1). We extracted all Swift XRT spectra from 20 pixel radii (except for October 1 and 28, see below) and background from a surrounding annulus. We download the response matrix swxpc0to12_20010101v009.rmf from the Swift Web site 14 and created effective area files using the XRTPKARF tool. Spectra with more than 50 counts were binned with 15 counts/bin for $\chi^2$ statistics, those with fewer used C-statistics (either binned with 5 counts/bin or unbinned), while we produced only luminosity limits for less than 10 detected counts.

A Swift X-ray Telescope (XRT) observation on 2009 June 4 found enhanced X-ray emission from NGC 6440. Using the

FTOOLS XRTCENTROID on the June 4 XRT source, we identified a position of R.A. = 17:48:52.73, decl. = $−20:21:24.1$ with an error radius of 5′. This position is consistent with NGC 6440 X-2 (see Figures 1 and 4), but not with other known X-ray sources in NGC 6440, so we conclude it is the same source.

A second Swift observation on June 11 found much weaker emission, at position R.A. = 17:48:52.64, decl. = $−20:21:29.9$, with error radius 7.3′, consistent with either NGC 6440 X-2 or with the cluster center. Spectral fitting of the few detected photons with an absorbed power law derives a photon index of $4.2^{+1.3}_{−1.9}$ and $L_X = 1.0^{+1.6}_{−1.0} \times 10^{34}$ erg s$^{-1}$. This is consistent with emission from the rest of the cluster, containing a mixture of soft quiescent LMXBs and sources (likely cataclysmic variables) with harder spectra (Pooley et al. 2002; Heinke et al. 2003).

We obtained four Swift observations soon after the initial Chandra discovery (Table 1). On July 31, Swift/XRT found enhanced emission from NGC 6440 X-2’s position. Observations on August 4, 6, and 10 found fluxes and positions consistent with the cluster center, and soft spectra (Table 1, Figures 4 and 5). The centroid of the emission in the deepest of these observations (August 6, 1.9 ks) is R.A. = 17:48:52.9, decl. = $−20:21:35.1$, with an error radius of 6′1, which is consistent with the cluster center but not with NGC 6440 X-2.

After the August 29 bulge scan detection, Swift observed NGC 6440 on September 1, identifying emission from the location (R.A. = 17:48:52.6, decl. = $−20:21:24.9$, error radius 4′8) of NGC 6440 X-2 at $L_X = (6 \pm 2) \times 10^{34}$ erg s$^{-1}$ (Figures 4 and 5). Further Swift observations on September 2 and 4 found faint emission, consistent in position and flux with the cluster.

Swift monitoring on October 1 found NGC 6440 X-2 back in outburst. The count rate was high enough to produce pileup (in photon counting mode); we fit the radial profile with a King model and identified a 6′ core, so we extracted a spectrum from an annulus from 6′ to 45′ (20 pixels). On October 2, Swift identified a declining flux from NGC 6440 X-2, returning to quiescence by October 4 (Figures 4 and 5).

A Swift observation on October 29 confirmed that NGC 6440 X-2 was back in outburst, and relatively bright; we dealt with pileup as described above. Observations on October 30 and 31 observed X-2’s decay, which by November 1 was below Swift/ XRT’s detection limit (Figures 4 and 5).

2.4. Chandra in Quiescence

We combined two Chandra ACIS-S observations of NGC 6440 (total exposure 48 ks) when no transients were in outburst (ObsIDs 947 and 3799; Pooley et al. 2002; Cackett et al. 2005) to look for evidence of NGC 6440 X-2’s X-ray emission in quiescence. The observations were reprocessed and aligned, and filtered to produce a 0.3–7 keV band image (Figure 1). No photons lie within a 1″ circle around NGC 6440 X-2. Using 2.3 photons as our 90% confidence upper limit (Gehrels 1986), we compute limits on the unabsorbed quiescent luminosity. For a power law index of 2.2, $L_X(0.5–10 \text{ keV}) < 7.4 \times 10^{30}$ erg s$^{-1}$, while for a hydrogen-atmosphere neutron star model (Heinke et al. 2006), $L_X(0.5–10 \text{ keV}) < 1.6 \times 10^{32}$ erg s$^{-1}$ and $L_{NS}(0.01–10 \text{ keV}) < 6.0 \times 10^{31}$ erg s$^{-1}$ (we use $L_{NS}$ as the total emission from the NS surface).

We obtained a 5 ks ACIS-S follow-up Chandra Director’s Discretionary Time observation on 2009 August 10, to see if NGC 6440 X-2 had returned to full quiescence, or was continuing to accrete at $L_X(0.5–10 \text{ keV}) \sim 5 \times 10^{32}$ erg s$^{-1}$, similarly to SAX J1808.4–3658 at the end of its 2008 outburst.

13 http://asc.harvard.edu/toolkit/pimms.jsp
14 http://swift.gsfc.nasa.gov
Figure 4. X-ray images (0.7–7 keV) of NGC 6440 during and after the five observed outbursts from the Swift XRT, each 2.5 by 2.5. The position of NGC 6440 X-2 is indicated (small red circle), as are the core and half-mass radii of NGC 6440 (blue circles), as in Figure 1. Exposure times vary (see Table 1). Detections of NGC 6440 X-2 are seen on June 4, July 31, September 1, and October 1, 2, 29, 30, and 31; the remaining emission is attributable to the other cluster sources (see Figure 1).

(Campana et al. 2008). Two photons were detected at the position of NGC 6440 X-2 (see Figure 1). As the background is quite low (< 0.01 photons expected), both photons are probably from NGC 6440 X-2. We estimate (for an assumed spectrum similar to that in outburst) \( L_X = 6.3^{+4}_{-1} \times 10^{31} \text{ erg s}^{-1} \), with uncertainties from Gehrels (1986) at 90% confidence. This confirms that NGC 6440 X-2 returned to quiescence, although it appears brighter than the limits from the 2000 and 2003 quiescent observations (above).

3. OPTICAL/INFRARED OBSERVATIONS

3.1. Archival NTT and HST

The location of NGC 6440 X-2 has been previously observed by the European Southern Observatory’s New Technology Telescope (NTT) and by the Hubble Space Telescope (HST) (Piotto et al. 2002). The NTT imaging in R and B was described by Verbunt et al. (2000), and the HST imaging in V and B was described by Piotto et al. (2002). We identified UCAC2 standards to place the NTT R astrometric frame onto the ICRS frame, and then by identifying common stars in the WFPC2 and NTT frames, to place the HST astrometric frame onto the ICRS frame, with an uncertainty of 0.2″ (1σ). No star can be identified within 4σ of the transient position on the NTT and WFPC2 B frames, but one star in the WFPC2 V frame is located 0.4″ from the transient position (Figure 6). Calibrating our photometry with that in Piotto et al. (2002), we find a magnitude of \( V = 21.0 \pm 0.2 \) for this object. Based on objects in the HST image that are just barely detected in B, we estimate \( B > 22.0 \). These images were probably taken during quiescence, and NGC 6440 X-2’s 57 minute orbital period indicates that it will be very faint. As the ultracompact LMXB XTE J0929-314 in quiescence may have been detected with \( M_V = 13.2 \) (D’Avanzo et al. 2009), thus it would have \( V = 31 \) in NGC 6440, we think it unlikely that this star is the true counterpart.

3.2. Outburst and Decay

Li et al. (2009) reported that unfiltered images were taken of NGC 6440 on 2009 July 30 and 31 with the 0.76 m Katzman Automatic Imaging Telescope (KAIT). Their image subtraction against previous KAIT observations (2007, 2008) revealed no evidence of an optical transient, with limiting magnitudes of 19.5–20.0.

We obtained images with the CTIO 4-meter telescope using the ISPI infrared imager on 2009 August 2–4 in the J and K bands (Figure 7). The total exposure times were 12 and 8 minutes per night, giving theoretical magnitude limits of 19.5 and 18 in J and
Figure 5. X-ray light curve measurements of NGC 6440 X-2 over its five known outbursts, with a logarithmic vertical scale. RXTE/PCA bulge scans are black error bars, with a box point if they are >4σ above zero (some points appear more significant than they are due to the log scale). RXTE/PCA-pointed observation detections (background-subtracted, see the text) are magenta pentagons. Swift observations are blue triangles, or blue upper limits when they are not clear detections of NGC 6440 X-2. Chandra observations are the red-filled box and series of red crosses (showing the light curve from the June observation).

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

Figure 6. Optical images of NGC 6440, plotting an 0′′.8 (4σ) error circle for NGC 6440 X-2. Upper left: archival NTT R frame; upper right: new Gemini g′ frame; lower left: HST WFPC2 V frame; lower right: HST WFPC2 B frame. All 19′′ × 14′′, with N at top.

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

$K$, respectively (with a signal-to-noise ratio of 10). The airmass was around 1.1 and the seeing was 1″ the first night, increasing to 1″.5 the last night. The images have been taken using a dithered pattern and an offset blank field has been observed to estimate the sky contribution to the emission. We used IRAF common packages and the PANIC package (Martini et al. 2004)
to reduce the data and then SExtractor/Scamp (Bertin 2006) to
calibrate the astrometry and photometry of the image, using the
2MASS catalog as a reference (Skrutskie et al. 2006). Based
on the detection of sources around NGC 6440 X-2, a source of
magnitude $K = 17$ and $J = 18.5$ would have been detected.

We obtained three 500 s frames in each of $g'$ (note that the
g' bandpass is between $V$ and $B$) and $r'$ using Gemini-
South GMOS-S on 2009 September 1, during the outburst
decay (program GS-2009B-DD-2). Unfortunately the $r'$ frames
were saturated at the location of the transient, but the $g'$ frames
provided our best optical outburst limit (Figure 6). No star was
seen within 0.8 (4{$\sigma$}) of the transient position. An approximate
calibration of the $g'$ images was obtained using a star-by-star
comparison with the $B, V$ photometry of Martins et al. (1980).
We determined the detection limit for stars within an annulus
about the cluster center containing the location of the transient.
Based on the faintest 5% of the stars in the annulus, the estimated
detection limit is $g' \sim 22.0$. Thus, we adopt $g' > 22$ as an
approximate limit for NGC 6440 X-2, at a time when Swift
found its X-ray luminosity to be $6 \times 10^{34}$ erg s$^{-1}$.

NGC 6440 X-2’s outbursts differ from those of other globular
cluster LMXBs, both in the faintness of X-2’s outbursts (peak
0.5–10 keV, $L_X = 1.5 \times 10^{36}$ erg s$^{-1}$ for the July outburst,
$2.8 \times 10^{36}$ erg s$^{-1}$ for the August outburst), and in their brevity.
The July X-ray light curve indicates that the time spent above
$10^{35}$ erg s$^{-1}$ was no more than 4 days, and perhaps only 2.5 days
(Figure 5), one of the shortest transient LMXB outbursts so
far recorded (cf. Natalucci et al. 2000; in’t Zand et al. 2004;
Wijnands et al. 2009). The August outburst light curve indicates
< 3.5 days spent above $10^{35}$ erg s$^{-1}$, and the light curves from
the other outbursts, while less constraining, are consistent with
this timescale (Figure 5). We note that another ultracompact
AMXP, XTE J1751–305, has similarly shown short and faint
outbursts (Markwardt et al. 2007, 2009; Linares et al. 2007).

Why does NGC 6440 X-2 show such faint and brief outbursts?
The obvious drivers are accretion disk instabilities or magnetospheric
instabilities. However, magnetospheric instabilities occur
on much faster timescales (e.g., the Rapid Burster; Lewin
1993) and would require that the disk remains viscous (and thus
ionized) between outbursts, which seems unlikely. Standard accretion
disk instability models (e.g., Lasota 2001) predict quiescent
periods 10 times longer, and brighter and longer outbursts,
for systems with 57 minute orbital periods. Naively, we expect
longer intervals between outbursts for a 57 minute system than
for the other known ultracompact systems, if NGC 6440 X-2
is indeed an evolutionary descendant of systems like them, as
it will have a larger disk and lower mass transfer rate (e.g.,
Deloye & Bildsten 2003). However, we are not aware of de-
tailed modeling of outbursts of hydrogen-poor accretion disks
with extreme mass ratios (and thus likely superhumps, White-
hurst 1988), suggesting an avenue for further study.

The X-ray record suggests that NGC 6440 X-2’s activity has
significantly increased in the past year. It would be difficult
to attribute this change to the disk (as it includes numerous
outburst cycles), and we suggest that it represents a signal of
mass transfer variations from the donor. Cyclical variations
in the orbital period are well established in longer-period cataclysmic
variables (Borges et al. 2008), LMXBs (Wolff et al. 2009),
and black widow pulsars (Arzoumanian et al. 1994) and seem likely to be due to magnetic activity in

![Figure 7](image-url) **Figure 7.** Infrared ISPI images (each 25″ × 25″, N at top) with the CTIO 4 m on the dates specified. Top: images in $J$; bottom: images in $K$. Circles (0.8″ in radius) indicate the positions of NGC 6440 X-2.

(A color version of this figure is available in the online journal.)
Figure 8. Measurements of, or limits on, the quiescent thermal luminosity of various NS transients, compared to estimates of, or upper limits on, their time-averaged mass accretion rates. Data from compilations of Heinke et al. (2007, 2009b), with NGC 6440 X-2 added. Predictions of standard cooling and several enhanced cooling mechanisms are plotted, following Yakovlev & Livini (2005). Accreting millisecond pulsars are indicated separately (red), while the effect of increasing the distance by a factor of 1.5 for any system is indicated with an arrow labeled “D×1.5.” (A color version of this figure is available in the online journal.)

The tight upper limit on NGC 6440 X-2’s quiescent emission is the third lowest for any neutron star LMXB, after the transients SAX J1808.4–3658 and 1H 1905+000 (Heinke et al. 2009b; Jonker et al. 2007, Figure 8). Deep Chandra observations might substantially improve these limits (e.g., 100 ks could reduce the quiescent flux limit by a factor of 3). Long-term study of outbursts from this system will allow a better measure of the average mass accretion rate. It will be of great interest to see if the outbursts continue to occur every ~31 days, turn off, or change their outburst frequency, as this system’s behavior is extremely unusual.

This is the first globular cluster to show two transiently outbursting X-ray sources. Many candidate quiescent LMXBs have been identified in globular clusters through their soft spectra, including eight in NGC 6440 (Grindlay et al. 2001; Rutledge et al. 2002; Pooley et al. 2002; Heinke et al. 2003), although few have been observed to undergo outbursts. Some of these quiescent LMXBs may be producing short, faint transient outbursts like NGC 6440 X-2’s, which are at or near the noise level for existing surveys such as the RXTE/PCA bulge scans and all-sky monitor. Even fainter X-ray transients have been studied in the Galactic center with dedicated observations (Muno et al. 2005; Wijnands et al. 2006). Swift could efficiently survey one or a few of the globular clusters richest in quiescent LMXBs for such small-scale outbursts.

We are grateful to N. Gehrels and the Swift team, H. Tananbaum and the Chandra team, M. Pretorius at ESO, M. Buxton at SMARTS, the RXTE team, N. Levenson, J. Radomski, R. Carrasco, and the Gemini-South science team, for rapidly scheduling observations of NGC 6440. We thank D. Pooley, S. Ransom, N. Degenaar, and A. Kong for discussions and the referee for a useful, clear, and rapid report. This research has made use of data obtained through the High Energy Astrophysics Science Archive Research Center (online service), provided by the NASA/Goddard Space Flight Center. We acknowledge the use of public data from the Swift, RXTE, Chandra, HST, and ESO data archives.

Facilities: RXTE (PCA), CXO (ACIS), Swift (XRT), Gemini:South (GMOS), HST (WFPC2), NTT, Blanco (ISPI IR Imager)

Note added in proof. As this paper went to press, NGC 6440 X-2 was detected again in outburst by Swift and RXTE, on 2010 March 19–21 (Altamirano et al. 2010b), confirming that its outbursts are continuing.

REFERENCES
