Discovery of a Second Transient Low-mass X-ray Binary in the Globular Cluster Ngc 6440

Citation

Permanent link

Terms of Use

Share Your Story

DISCOVERY OF A SECOND TRANSIENT LOW-MASS X-RAY BINARY IN THE GLOBULAR CLUSTER NGC 6440

C. O. Heinke[1], D. Altamirano[2], H. N. Cohn[3], P. M. Lugger[3], S. A. Budac[1], M. Servillat[4], M. Linares[2,5],
T. E. Strohmayer[6], C. B. Markwardt[6], R. Wijnands[2], J. H. Swank[6], C. Knigge[7], C. Bailyn[8], AND J. E. Grindlay[4]

[1] Department of Physics, University of Alberta, Room 238 CEB, Edmonton, AB T6G 2G7, Canada; heinke@ualberta.ca
[2] Astronomical Institute "Anton Pannekoek," University of Amsterdam, Science Park 904, 1098 XH, Amsterdam, The Netherlands
[3] Department of Astronomy, Indiana University, 727 East Third St., Bloomington, IN 47405, USA
[4] Harvard College Observatory, 60 Garden Street, Cambridge, MA 02138, USA
[5] MIT Kavli Institute for Astrophysics & Space Research, 70 Vassar St., Cambridge, MA 02139, USA
[6] Astrophysics Science Division, NASA/GSFC, Greenbelt, MD 20771, USA
[7] School of Physics and Astronomy, University of Southampton, Hampshire SO17 1BJ, UK
[8] Department of Astronomy, Yale University, P.O. Box 208101, New Haven, CT 06520, USA
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 $L_X \sim 1.5 \times 10^{36}$ erg s^{-1} and lasted for <4 days above $L_X = 10^{35}$ 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 $J \gtrsim 18.5$ and $K \gtrsim 17$ during the July outburst from CTIO 4 m ISPI imaging. Archival *Chandra* X-ray images of the core do not detect the quiescent counterpart ($L_X < (1–2) \times 10^{31}$ erg s^{-1}) and place a bolometric luminosity limit of $L_{NS} < 6 \times 10^{31}$ 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 $L_X \sim 6 \times 10^{31}$ erg s^{-1}. NGC 6440 X-2 currently shows the shortest recurrence time ($\sim$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 ($L_X > 10^{35}$ 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; Di 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 luminous transient 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 $N_H = 5.9 \times 10^{21}$ 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 positionally identified 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
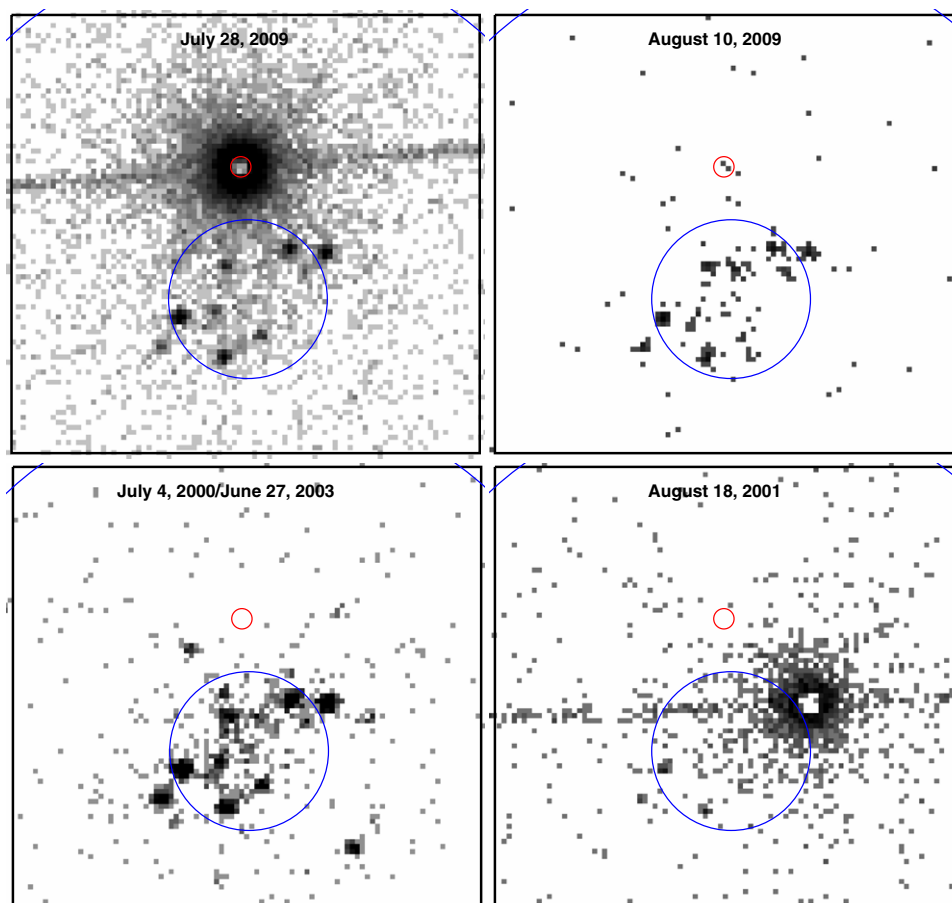
Figure 1. *Chandra*/ACIS-S images of NGC 6440 during the 2009 July outburst of NGC 6440 X-2 (upper left, 0.5–2.5 keV) and 13 days later (upper right, 0.3–7 keV). Below, we show a merged image from quiescent epochs in 2000 and 2003 (lower left, 0.3–7 keV) and an image from the 2001 outburst (lower right, 0.3–7 keV). The positions of NGC 6440 X-2 (red circle, 1″) and the cluster core (0″.13) and half-mass (0″.58) radii (large circles) are indicated. North is up, east to the left.
(A color version of this figure is available in the online journal.)

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 4.1[9] 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.[10] 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.

---

[9] http://cxc.harvard.edu/ciao
[10] See the *Chandra* Proposer's Observatory Guide, chapter 6.

Table 1
Spectral Fits to NGC 6440 X-2

Start Time (2009)	Instrument	Exposure (ks)	N_H ($\times 10^{21}$ cm^{-2})	Γ	χ^2_ν/dof	L_X, 0.5–10 keV (erg s^{-1})	ObsID
Jun 4, 01:04	*Swift*/XRT	1.1	0.59[a]	2.4 ± 0.5	49[b]	$3.3 \pm 0.8 \times 10^{34}$	00031421001
Jun 11, 17:32	*Swift*/XRT	1.9	0.59[a]	$4.2^{+1.2}_{-1.1}$	59[b]	$1.0^{+1.0}_{-0.5} \times 10^{34}$	00031421002
Jul 28, 20:17	*Chandra*/ACIS-S	49.1	0.69 ± 0.06	1.79 ± 0.10	0.98/59	$1.55 \pm 0.06 \times 10^{36}$	10060
Jul 30, 18:47	*RXTE*/PCA	1.9	0.59[a]	$2.1^{+0.8}_{-0.7}$	0.57/27	$9.5^{+13}_{-4.5} \times 10^{34}$	94044-04-01-00
Jul 31, 04:55	*Swift*/XRT	1.8	0.59[a]	2.3 ± 0.4	92[b]	$3.1 \pm 0.6 \times 10^{34}$	00031421003
Aug 4, 16:26	*Swift*/XRT	1.0	0.59[a]	$2.9^{+1.2}_{-1.1}$	37[b]	$7^{+8}_{-3} \times 10^{33}$	00031421004
Aug 6, 01:50	*Swift*/XRT	1.9	0.59[a]	$3.4^{+1.2}_{-1.0}$	99[b]	$1.1^{+0.9}_{-0.5} \times 10^{34}$	00031421005
Aug 10, 13:28	*Swift*/XRT	0.5	0.59[a]	c	. . .	$7^{+8}_{-5} \times 10^{33}$	00031421007
Aug 10, 08:10	*Chandra*/ACIS-S	4.9	0.59[a]	c	. . .	$6^{+9}_{-5} \times 10^{31}$	11802
Aug 30, 1:31[d]	*RXTE*/PCA	3.2	0.59[a]	1.79 ± 0.02	0.84/54	$2.55 \pm 0.05 \times 10^{36}$	94044-04-02-00
Sep 1, 3:43[d]	*RXTE*/PCA	14.1	0.59[a]	$1.5^{+0.8}_{-0.8}$	0.8/33	$< 4 \times 10^{34}$	94044-04-02-01
Sep 1, 4:33	*Swift*/XRT	1.0	0.59[a]	$3.8^{+0.7}_{-0.6}$	90[b]	$6 \pm 2 \times 10^{34}$	00031421009
Sep 2, 13:01	*Swift*/XRT	0.4	0.59[a]	c	. . .	$1.2^{+1.1}_{-6} \times 10^{34}$	00031421010
Sep 4, 06:49	*Swift*/XRT	0.4	0.59[a]	c	. . .	$1.5^{+1.3}_{-0.7} \times 10^{34}$	00031421012
Oct 1, 08:47	*Swift*/XRT	0.7	0.59[a]	1.79 ± 0.19	1.0/16	$5.9 \pm 0.6 \times 10^{35}$	00031421014
Oct 1, 21:58	*RXTE*/PCA	1.5	0.59[a]	$1.8^{+0.1}_{-0.2}$	0.49/29	$4.5^{+0.4}_{-0.4} \times 10^{35}$	94044-04-03-00
Oct 2, 20:24	*Swift*/XRT	1.0	0.59[a]	1.9 ± 0.3	0.35/6	$1.0^{+0.2}_{-0.1} \times 10^{35}$	00031421015
Oct 3, 08:12	*RXTE*/PCA	3.2	0.59[a]	. . .	1.1/28	$< 3 \times 10^{34}$	94044-04-04-00
Oct 4, 10:46	*Swift*/XRT	0.6	0.59[a]	c	. . .	$6^{+6}_{-4} \times 10^{33}$	00031421017
Oct 5, 18:59	*Swift*/XRT	0.6	0.59[a]	c	. . .	$7^{+7}_{-4} \times 10^{33}$	00031421016
Oct 28, 22:29	*RXTE*/PCA	0.9	0.59[a]	$1.8^{+0.1}_{-0.1}$	0.34/39	$8.6^{+0.9}_{-0.8} \times 10^{35}$	94315-01-04-01
Oct 29, 00:19	*Swift*/XRT	1.2	0.59[a]	$1.7^{+0.1}_{-0.1}$	1.03/40	$5.5^{+0.3}_{-0.3} \times 10^{35}$	00031421018
Oct 29, 20:25	*RXTE*/PCA	0.9	0.59[a]	$2.2^{+0.6}_{-0.5}$	0.58/27	$2.1^{+2.2}_{-0.8} \times 10^{35}$	94315-01-04-02
Oct 30, 13:28	*Swift*/XRT	0.9	0.59[a]	$2.3^{+0.3}_{-0.4}$	1.15/8	$8.6^{+1.4}_{-1.4} \times 10^{34}$	00031421019
Oct 30, 19:58	*RXTE*/PCA	0.8	0.59[a]	$3.0^{+4.4}_{-2.3}$	0.52/15	$5 \pm 4 \times 10^{34}$	94315-01-03-01
Oct 31, 13:33	*Swift*/XRT	0.9	. . .	c	. . .	$1.2^{+0.6}_{-0.4} \times 10^{34}$	00031421020
Oct 31, 17:48	*RXTE*/PCA	1.1	0.59[a]	(2)	0.58/23	$< 3.1 \times 10^{34}$	94315-01-03-02
Nov 1, 13:39	*Swift*/XRT	0.9	. . .	c	. . .	$6^{+4}_{-3} \times 10^{33}$	00031421021
Nov 2, 13:45	*Swift*/XRT	0.9	. . .	c	. . .	$4^{+4}_{-2} \times 10^{33}$	00031421022

Notes. Absorbed power-law spectral fits, using distance of 8.5 kpc. Errors are 90% confidence for a single parameter. *Swift* results apply to flux from entire cluster (see the text for details), while *RXTE* results subtract the quiescent *RXTE*/PCA fitted spectrum (inferred $L_X = 4 \times 10^{35}$ ergs s^{-1}) produced by the Galactic Ridge. After an *RXTE*/PCA observation finds only an upper limit during the decline of an outbursts, we omit the later *RXTE*/PCA observations from this table (omitted ObsIDs are 94044-04-02-13, 94044-04-02-02, 94044-04-02-03, 94044-05-01-00, 94315-01-03-03, 94315-01-03-04, 94315-01-03-09, 94315-01-03-05, 94315-01-03-06, 94315-01-03-00, and 94315-01-03-07).
[a] N_H is held fixed at cluster value.
[b] Statistics low, *C*-statistic used and goodness reported.
[c] Too few counts (< 10) detected for any spectral fitting; see the text.
[d] Including an Fe line at 6.6 keV, assumed width 0.1 keV; see the text for details.

The light curve from the readout streak events shows a clear decline during the *Chandra* observation by a factor of ∼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.[11] 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 $L_X \sim 10^{38}$ ergs s^{-1} from NGC 6440, suggesting X-ray bursts, their 6σ 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 5σ detection on 2009 July 28, near the beginning

---

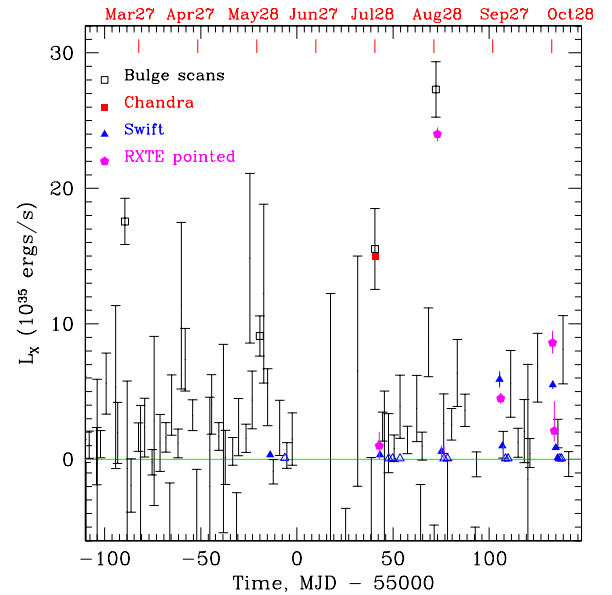[11] http://lheawww.gsfc.nasa.gov/users/craigm/galscan/main.html
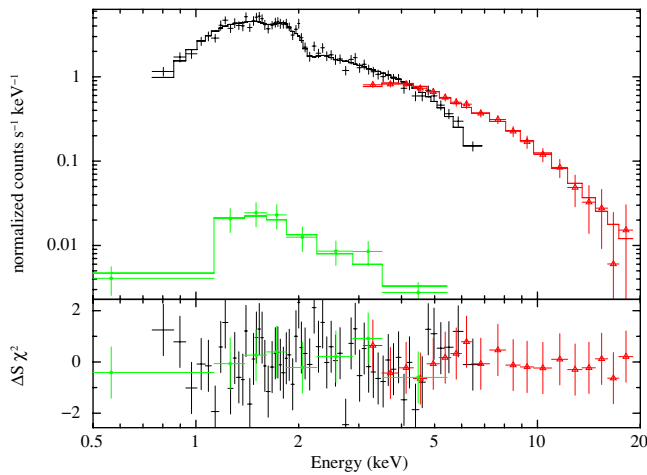
Figure 2. Spectra of NGC 6440 X-2 during the July/August outburst as observed by *Chandra*/ACIS-S (black online), *RXTE*/PCA (triangles; red online), and *Swift*/XRT (filled circles; green online). Top: data and absorbed power-law models. Bottom: residuals to fits. See Table 1 for details of spectral fits.

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

Figure 3. X-ray light curve of NGC 6440 over six months, with linear vertical scale. *RXTE*/PCA bulge scans are in black, with a box if they are $>4\sigma$ above zero. *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.)

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 ($\sim$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 timing analysis is described in Altamirano et al. (2010a).

We extracted spectra from the PCA (Jahoda et al. 2006) detectors (PCU2 was consistently on, sometimes joined by other PCUs), excluding times when elevation angle ELV $< 10°$, source offset $>0°.02$, or the time since the last South Atlantic Anomaly passage was <30 minutes. The background was modeled using the latest faint background model pca_bkgd_cmfaintl7_eMv20051128.mdl and the recorded times of South Atlantic Anomaly passage.[12] Response files were created with the PCARMF (v. 11.1) tool. For spectral fitting, we exclude data below 3 keV and above where the source can no longer be detected above our modeled background; this cut ranged between 10 and 30 keV, depending on the observation. HEXTE (cluster B, sensitive to the 20–200 keV energy range) did not detect the source even in the brightest (August 30) pointed *RXTE* observation. N_H was fixed to the cluster value due to *RXTE*'s relative insensitivity to N_H. All our reported L_X values are for 0.5–10 keV (for consistency with other instruments; this extrapolation may incur additional systematic errors) assuming a distance of 8.5 kpc.

The July 30 pointed observation could be fit with an absorbed power law with photon index 2.2 ± 0.1 and a luminosity of $(5 \pm 1) \times 10^{35}$ erg s^{-1}, 3.5 times lower than the July 28 *Chandra* observation (Table 1; but 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 6×10^{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 $L_X = (1 \pm 1) \times 10^{35}$ 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 $6.6^{+0.6}_{-0.4}$ 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., SAX J1808.4$-$3658, Cackett et al. 2009; Papitto et al. 2009; HETE J1900.1$-$2455, Cackett et al. 2010; Swift J1756.9$-$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

---

[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 $\Gamma = 1.78 \pm 0.15$, $L_X(0.5–10) = 8.4^{+0.8}_{-0.5} \times 10^{35}$ 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 $L_X(0.5–10\,\mathrm{keV}) = 8.6^{+0.9}_{-0.8} \times 10^{35}$ ergs 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 4σ 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 (± 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 ± 10 days around this date). The bulge scan point in March is off the prediction by 7 ± 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 detections and upper limits from *Swift* and *Chandra*) in Figure 3; see also Altamirano et al. (2010a). We use an absorbed power law of photon index 2 to convert *RXTE*/PCA bulge scan fluxes to 0.5–10 keV unabsorbed fluxes with PIMMS[13] and assume a distance of 8.5 kpc to estimate luminosities.

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 downloaded the response matrix swxpc0to12_20010101v009.rmf from the *Swift* Web site[14] and created effective area files using the XRTMKARF tool. Spectra with more than 50 counts were binned with 15 counts/bin for χ^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

FTOOL 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 $4.2^{+1.2}_{-1.1}$ and $L_X = 1.0^{+1.0}_{-0.5} \times 10^{34}$ 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 of index 2.2, $L_X(0.5–10\,\mathrm{keV}) < 7.4 \times 10^{30}$ erg s^{-1}, while for a hydrogen-atmosphere neutron star model (Heinke et al. 2006), $L_X(0.5–10\,\mathrm{keV}) < 1.6 \times 10^{31}$ erg s^{-1} and $L_{NS}(0.01–10\,\mathrm{keV}) < 6.0 \times 10^{31}$ 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 $L_X(0.5–10\,\mathrm{keV}) \sim 5 \times 10^{32}$ erg s^{-1}, similarly to SAX J1808.4−3658 at the end of its 2008 outburst

---
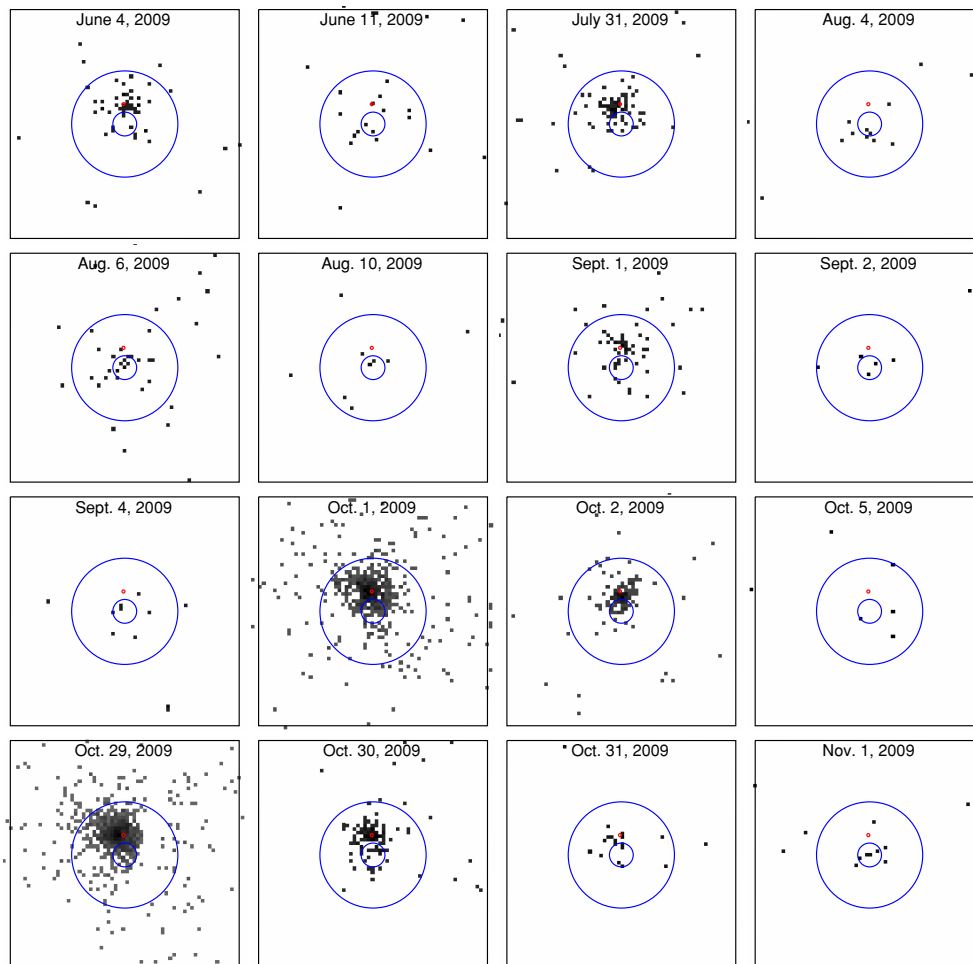
Figure 4. X-ray images (0.7–7 keV) of NGC 6440 during and after the five observed outbursts from the *Swift* XRT, each $2.'5$ by $2.'5$. The position of NGC 6440 X-2 is indicated (small red circle), as are the core and half-mass radii of NGC 6440 (blue circles), as in Figure 1. Exposure times vary (see 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).

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

(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) $L_X = 6^{+9}_{-4} \times 10^{31}$ 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
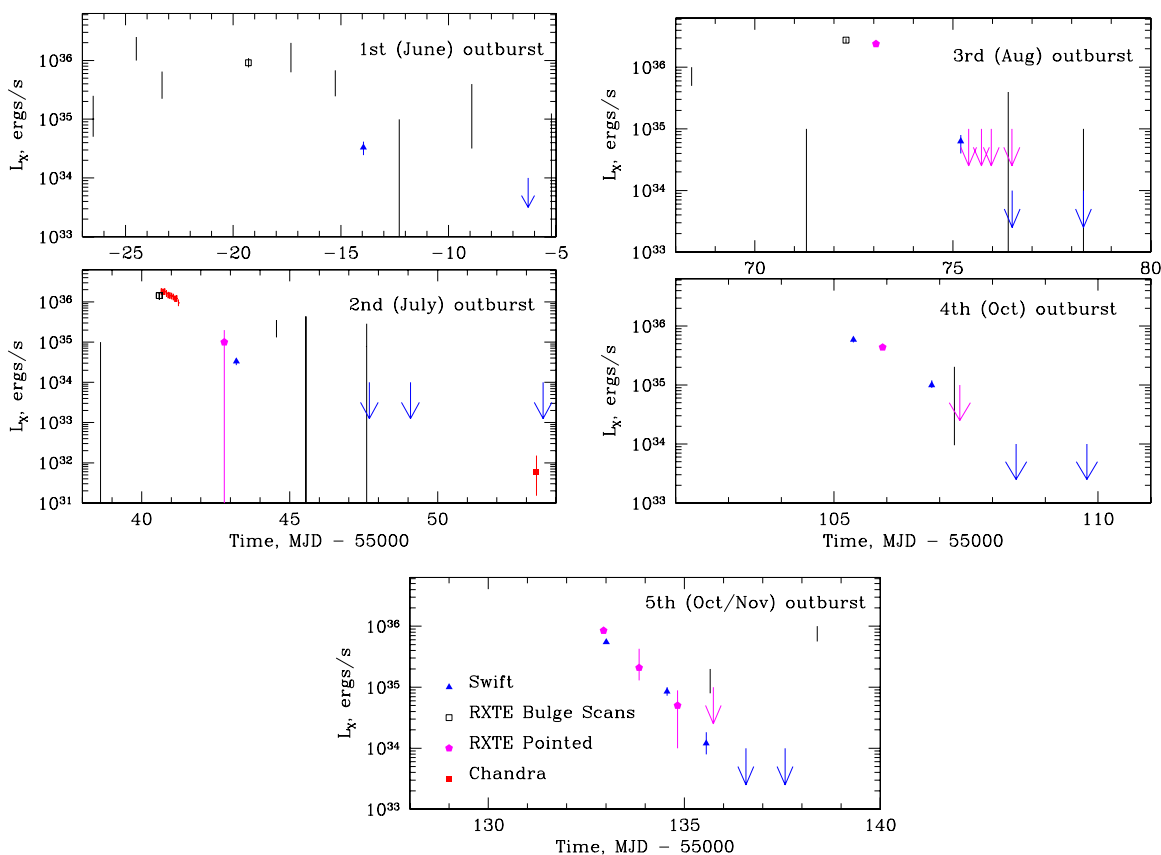
Figure 5. X-ray light curve measurements of NGC 6440 X-2 over its five known outbursts, with a logarithmic vertical scale. *RXTE*/PCA bulge scans are black error bars, with a box point if they are >4σ above zero (some points appear more significant than they are due to the log scale). *RXTE*/PCA-pointed 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).

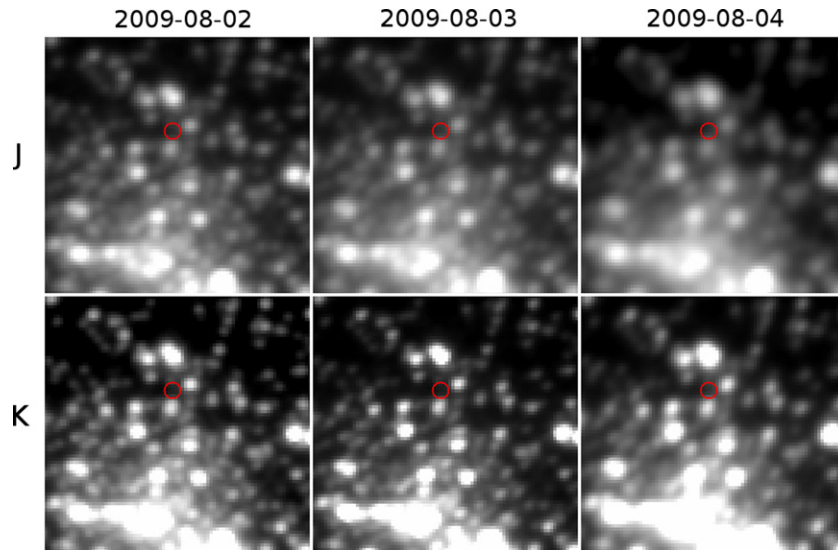(A color version of this figure is available in the online journal.)
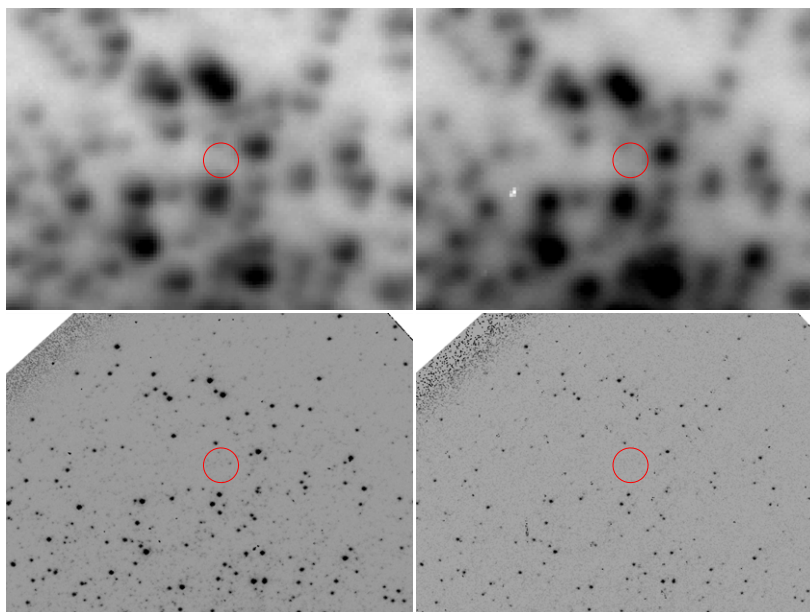
Figure 6. Optical images of NGC 6440, plotting an 0″.8 (4σ) error circle for NGC 6440 X-2. Upper left: archival NTT *R* frame; upper right: new Gemini *g′* frame; lower left: *HST* WFPC2 *V* frame; lower right: *HST* WFPC2 *B* frame. All 19″ × 14″, with N at top.

(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)

Figure 7. Infrared ISPI images (each $25'' \times 25''$, N at top) with the CTIO 4 m on the dates specified. Top: images in J; bottom: images in K. Circles ($0\rlap{.}''8$ in radius) indicate the positions of NGC 6440 X-2.

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

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 $0\rlap{.}''8$ (4σ) 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 6×10^{34} erg s^{-1}.

4. DISCUSSION

The discovery of millisecond pulsations (Altamirano et al. 2010a) clearly identifies NGC 6440 X-2 as a neutron star LMXB system and provides the orbital period of 57.3 minutes. The ultracompact nature of NGC 6440 X-2 confirms the trend (Deutsch et al. 2000) for globular clusters to have a higher fraction of ultracompact LMXBs than field systems, indicating a different formation mechanism (Ivanova et al. 2005). However, it goes against the apparent trend (Zurek et al. 2009) for ultracompacts in globular clusters to have shorter periods than ultracompacts in the field. The lack of optical detections is not surprising, when the ultracompact orbit is considered. Using the relation between absolute magnitude, orbital period, and X-ray luminosity derived by van Paradijs & McClintock (1994), we predict $M_V = 3.8$ and thus $V = 21.8$ at peak. The scatter in this relation is about 1.5 magnitudes and our optical observations all occurred during the outburst decays, so our limits on NGC 6440 X-2 are consistent with this relation.

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, 2.8×10^{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 detailed modeling of outbursts of hydrogen-poor accretion disks with extreme mass ratios (and thus likely superhumps, Whitehurst 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
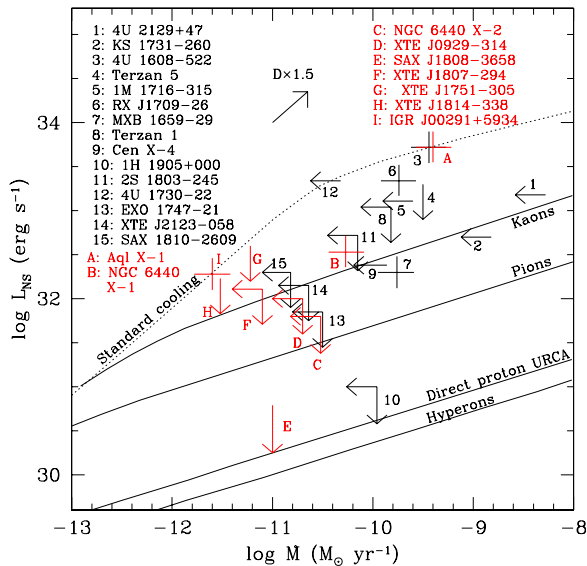
Figure 8. Measurements of, or limits on, the quiescent thermal luminosity of various NS transients, compared to estimates of, or upper limits on, their time-averaged mass accretion rates. Data from compilations of Heinke et al. (2007, 2009b), with NGC 6440 X-2 added. Predictions of standard cooling and several enhanced cooling mechanisms are plotted, following Yakovlev & Pethick (2004). Accreting millisecond pulsars are indicated separately (in 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 companion star. Such activity has also been suggested to explain SAX J1808.4−3658's large current rate of orbital period increase (Hartman et al. 2008) and decades-long variations in mass transfer rates in LMXBs (Durant et al. 2010). If such a mechanism is active here, it requires a partly nondegenerate, convective companion. Alternatively, the increased activity could indicate a change in the orbital parameters, induced by a distant companion (making this a triple system; testable with monitoring of future outbursts by *RXTE*) or a recent close interaction with another star (its position outside the core suggests that this is less likely).

It is difficult to estimate NGC 6440 X-2's mass transfer rate due to its extreme faintness and the limitations of existing surveys. We identify two limiting cases: one based on its recent outburst history and the other using the full bulge scan light curve. For the first case, we estimate the outbursts as lasting 3 days at an average $L_X \sim 1.5 \times 10^{36}$ erg s^{-1}, and occurring every 31 days. For canonical neutron star mass and radius estimates, this gives a time-averaged mass accretion rate of 3×10^{-11} $M_\odot$ yr^{-1}. Although this represents the mass transfer rate over the past few months, it is clear that NGC 6440 X-2 has not shown such outbursts regularly over the entire bulge scan epoch, where only five outbursts have been identified. Assuming (generously) that two-thirds of all outbursts have been missed (the October and November outbursts were missed by bulge scans, and it seems likely that outbursts in June/July and April/May were missed; Figure 3), and that the average outburst is like those seen so far, we estimate NGC 6440 X-2's mass transfer rate over the entire bulge scan epoch (ten years) as 1.3×10^{-12} $M_\odot$ yr^{-1}. This latter rate is consistent with an ultracompact binary with an orbital period of 57 minutes experiencing conservative mass transfer driven by general relativistic angular momentum loss (Deloye & Bildsten 2003), though a higher rate is not inconsistent with a relatively high-entropy (partly nondegenerate) donor.

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.

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

Altamirano, D., Casella, P., Patruno, A., Wijnands, R., & van der Klis, M. 2008, ApJ, 674, L45
Altamirano, D., Patruno, A., Heinke, C., Linares, M., Markwardt, C., & Strohmayer, T. 2010b, ATel, 2500
Altamirano, D., et al. 2009, ATel, 2182
Altamirano, D., et al. 2010a, ApJ, 712, L58
Arzoumanian, Z., Fruchter, A. S., & Taylor, J. H. 1994, ApJ, 426, L85
Bertin, E. 2006, in ASP Conf. Ser. 351, Astronomical Data Analysis Software and Systems XV, ed. C. Gabriel et al. (San Francisco, CA: ASP), 112
Borges, B. W., Baptista, R., Papadimitriou, C., & Giannakis, O. 2008, A&A, 480, 481
Cackett, E. M., et al. 2005, ApJ, 620, 922
Cackett, E. M., et al. 2009, ApJ, 694, L21
Cackett, E. M., et al. 2010, ApJ, submitted (arXiv:0908.1098)
Campana, S., Stella, L., & Kennea, J. A. 2008, ApJ, 684, L99
Clark, G. W. 1975, ApJ, 199, L143
D'Avanzo, P., Campana, S., Casares, J., Covino, S., Israel, G. L., & Stella, L. 2009, A&A, 508, 297
Deloye, C. J., & Bildsten, L. 2003, ApJ, 598, 1217

Deutsch, E. W., Margon, B., & Anderson, S. F. 2000, ApJ, 530, L21
Di Stefano, R., Kong, A. K. H., Garcia, M. R., Barmby, P., Greiner, J., Murray, S. S., & Primini, F. A. 2002, ApJ, 570, 618
Dotani, T., Inoue, H., Murakami, T., Nagase, F., & Tanaka, Y. 1990, Nature, 347, 534
Durant, M., Cornelisse, R., Remillard, R., & Levine, A. 2010, MNRAS, 401, 355
Gavriil, F. P., Strohmayer, T. E., Swank, J. H., & Markwardt, C. B. 2007, ApJ, 669, L29
Gehrels, N. 1986, ApJ, 303, 336
Grindlay, J. E., Heinke, C., Edmonds, P. D., & Murray, S. S. 2001, Science, 292, 2290
Harris, W. E. 1996, AJ, 112, 1487
Hartman, J. M., et al. 2008, ApJ, 675, 1468
Heinke, C. O., Altamirano, D., & Markwardt, C. 2009a, ATel, 2180
Heinke, C. O., & Budac, S. A. 2009, ATel, 2139
Heinke, C. O., Grindlay, J. E., Lugger, P. M., Cohn, H. N., Edmonds, P. D., Lloyd, D. A., & Cool, A. M. 2003, ApJ, 598, 501
Heinke, C. O., Jonker, P. G., Wijnands, R., Deloye, C. J., & Taam, R. E. 2009b, ApJ, 691, 1035
Heinke, C. O., Jonker, P. G., Wijnands, R., & Taam, R. E. 2007, ApJ, 660, 1424
Heinke, C. O., Rybicki, G. B., Narayan, R., & Grindlay, J. E. 2006, ApJ, 644, 1090
Heinke, C. O., et al. 2009c, ATel, 2143
Hertz, P., & Grindlay, J. E. 1983, ApJ, 275, 105
Homer, L., Deutsch, E. W., Anderson, S. F., & Margon, B. 2001, AJ, 122, 2627
Hut, P., Murphy, B. W., & Verbunt, F. 1991, A&A, 241, 137
in 't Zand, J. J. M., van Kerkwijk, M. H., Pooley, D., Verbunt, F., Wijnands, R., & Lewin, W. H. G. 2001, ApJ, 563, L41
in 't Zand, J. J. M., et al. 1999, A&A, 345, 100
in 't Zand, J., et al. 2004, Nucl. Phys. B, 132, 486
Ivanova, N., Rasio, F. A., Lombardi, J. C., Jr., Dooley, K. L., & Proulx, Z. F. 2005, ApJ, 621, L109
Jahoda, K., et al. 2006, ApJS, 163, 401
Jonker, P. G., Steeghs, D., Chakrabarty, D., & Juett, A. M. 2007, ApJ, 665, L147
Jordán, A., et al. 2004, ApJ, 613, 279
Kundu, A., Maccarone, T. J., & Zepf, S. E. 2002, ApJ, 574, L5
Lasota, J. P. 2001, New Astron. Rev., 45, 449
Lewin, W. H. G. 1993, Space Sci. Rev., 62, 223
Li, W., Chornock, R., & Filippenko, A. V. 2009, ATel, 2144
Linares, M., Wijnands, R., & van der Klis, M. 2007, ATel, 1055
Maccarone, T. J., Kundu, A., Zepf, S. E., & Rhode, K. L. 2007, Nature, 445, 183
Markert, T. H., Backman, D. E., Canizares, C. R., Clark, G. W., & Levine, A. M. 1975, Nature, 257, 32

Markwardt, C. B., Altamirano, D., Strohmayer, T. E., & Swank, J. H. 2009, ATel, 2237
Markwardt, C. B., Pereira, D., & Swank, J. H. 2007, ATel, 1051
Markwardt, C. B., & Swank, J. H. 2005, ATel, 495
Martini, P., Persson, S. E., Murphy, D. C., Birk, C., Shectman, S. A., Gunnels, S. M., & Koch, E. 2004, Proc. SPIE, 5492, 1653
Martins, D. H., Harvel, C. A., & Miller, D. H. 1980, AJ, 85, 521
Muno, M. P., Pfahl, E., Baganoff, F. K., Brandt, W. N., Ghez, A., Lu, J., & Morris, M. R. 2005, ApJ, 622, L113
Natalucci, L., et al. 2000, ApJ, 536, 891
Ortolani, S., Barbuy, B., & Bica, E. 1994, A&AS, 108, 653
Papitto, A., di Salvo, T., Iaria, R., Burderi, L., Riggio, A., Menna, M. T., & Robba, N. R. 2009, A&A, 493, L39
Patruno, A., Altamirano, D., & Messenger, C. 2010a, MNRAS, 403, 1426
Patruno, A., et al. 2010b, ATel, 2407
Piotto, G., et al. 2002, A&A, 391, 945
Pooley, D., et al. 2002, ApJ, 573, 184
Pooley, D., et al. 2003, ApJ, 591, L131
Rutledge, R. E., Bildsten, L., Brown, E. F., Pavlov, G. G., & Zavlin, V. E. 2002, ApJ, 578, 405
Sarazin, C. L., Kundu, A., Irwin, J. A., Sivakoff, G. R., Blanton, E. L., & Randall, S. W. 2003, ApJ, 595, 743
Sivakoff, G. R., et al. 2007, ApJ, 660, 1246
Skrutskie, M. F., et al. 2006, AJ, 131, 1163
Suzuki, M., et al. 2010, ATel, 2360
Swank, J., & Markwardt, K. 2001, in ASP Conf. Ser. 251, New Century of X-ray Astronomy, ed. H. Inoue & H. Kunieda (San Francisco, CA: ASP), 94
van Paradijs, J., & McClintock, J. E. 1994, A&A, 290, 133
Verbunt, F. 2003, in ASP Conf. Ser. 296, New Horizons in Globular Cluster Astronomy, ed. G. Piotto et al. (San Francisco, CA: ASP), 245
Verbunt, F., & Hut, P. 1987, in IAU Symp. 125, The Origin and Evolution of Neutron Stars, ed. D. J. Helfand & J.-H. Huang (Dordrecht: Kluwer), 187
Verbunt, F., & Lewin, W. H. G. 2006, in Compact Stellar X-Ray Sources, ed. W. Lewin & M. van der Klis (Cambridge Astrophys. Ser. 39; Cambridge: Cambridge Univ. Press), 341
Verbunt, F., van Kerkwijk, M. H., in 't Zand, J. J. M., & Heise, J. 2000, A&A, 359, 960
White, N. E., & Angelini, L. 2001, ApJ, 561, L101
Whitehurst, R. 1988, MNRAS, 232, 35
Wijnands, R., Rol, E., Cackett, E. M., Starling, R. L. C., & Remillard, R. A. 2009, MNRAS, 393, 126
Wijnands, R., et al. 2006, A&A, 449, 1117
Wolff, M. T., Ray, P. S., Wood, K. S., & Hertz, P. L. 2009, ApJS, 183, 156
Yakovlev, D. G., & Pethick, C. J. 2004, ARA&A, 42, 169
Zurek, D. R., Knigge, C., Maccarone, T. J., Dieball, A., & Long, K. S. 2009, ApJ, 699, 1113