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DISCOVERY OF A 205.89 Hz ACCRETING–MILLISECOND X-RAY PULSAR IN THE GLOBULAR CLUSTER NGC 6440

D. ALTAMIRANO¹, A. PATRUNO¹, C. O. HEINKE², C. MARKWARDT^{3,4}, T. E. STROHMEYER³,
M. LINARES¹, R. WIJNANDS¹, M. VAN DER KLIS¹, J. H. SWANK³*Draft version March 25, 2010*

ABSTRACT

We report the discovery of the second accreting millisecond X-ray pulsar (AMXP) in the globular cluster NGC 6440. Pulsations with a frequency of 205.89 Hz were detected with the Rossi X-Ray Timing Explorer on August 30th, October 1st and October 28th, 2009, during the decays of $\lesssim 4$ day outbursts of a newly X-ray transient source in NGC 6440. By studying the Doppler shift of the pulsation frequency, we find that the system is an ultra-compact binary with an orbital period of 57.3 minutes and a projected semi-major axis of 6.22 light-milliseconds. Based on the mass function, we estimate a lower limit to the mass of the companion to be $0.0067 M_{\odot}$ (assuming a $1.4 M_{\odot}$ neutron star). This new pulsar shows the shortest outburst recurrence time among AMXPs (~ 1 month). If this behavior does not cease, this AMXP has the potential to be one of the best sources in which to study how the binary system and the neutron star spin evolve. Furthermore, the characteristics of this new source indicate that there might exist a population of AMXPs undergoing weak outbursts which are undetected by current all-sky X-ray monitors. NGC 6440 is the only globular cluster to host two known AMXPs, while no AMXPs have been detected in any other globular cluster.

Subject headings:

1. INTRODUCTION

Accreting millisecond X-ray pulsars (AMXPs) are rapidly spinning neutron stars accreting matter from a low-mass stellar companion. These systems are thought to be the progenitors of the millisecond radio pulsars (Alpar et al. 1982; Backer et al. 1982). Therefore, their study allows us to better understand how neutron stars in low-mass X-ray binaries (LMXB) evolve into radio millisecond pulsars. Furthermore, AMXPs are perfect laboratories to study the interaction between the neutron star magnetosphere and the accretion disk (see, e.g., Poutanen 2006, and references therein).

A total of ten AMXPs among the ~ 100 neutron star LMXBs were known by August 2009. Seven of these AMXPs showed outbursts lasting a few days to months, and recurrence times of at least 2 years. In all seven cases, the pulsations were detected persistently during the whole outburst. The remaining three AMXPs showed pulsations only intermittently (Galloway et al. 2007; Gavriil et al. 2007; Casella et al. 2008; Altamirano et al. 2008; Patruno et al. 2009), bridging the gap between the small number of AMXPs and the large group of non-pulsating LMXBs (Altamirano et al. 2008). The reason why only a small amount of neutron star LMXBs show pulsations is still under debate. One of the proposed scenarios for the non-pulsating systems is that the neutron-star magnetic field could be temporarily buried by the accreted matter

(Cumming et al. 2001). If the time-averaged mass accretion rate of the accretors is relatively high, the accreted matter can bury the field throughout the life of the X-ray binary so the neutron star does not pulsate. However, if the average accretion rate is low enough that the magnetic field can diffuse through the accreted matter faster than it is buried, then these systems will probably exhibit pulsations. Another of the proposed scenarios that explains why the majority of neutron stars in LMXBs do not pulsate is that of Lamb et al. (2009); if neutron stars undergo long periods of accretion (at high rates), then their magnetic poles are naturally forced to align to their spin axes as they spin up. When the accretion rate decreases, the magnetic poles can move away from the rotation axis (due to magnetic dipole and other braking torques which cause neutron stars to spin down) and oscillations powered by accretion should become visible. Both Cumming et al. (2001) and Lamb et al. (2009) present clear predictions: we should find pulsations in many (if not all) of the systems which show low time-averaged mass accretion rates.

Very recently, a Chandra X-ray observation serendipitously discovered a new X-ray transient in the globular cluster NGC 6440 (Heinke et al. 2009c; Heine & Budac 2009; Heine et al. 2009b, identified as NGC 6440 X-2). RXTE and Swift follow-up observations not only showed that this source has a very low time-average accretion rate ($\lesssim 2 \cdot 10^{-12} M_{\odot} \text{ year}^{-1}$, see Heine et al. 2009a) but, as predicted by the models discussed above, also millisecond X-ray pulsations (Altamirano et al. 2009). One of the most interesting properties of this new AMXP is its very short recurrence time (~ 1 month, see also Heine et al. 2009a). If its outbursts continue, it will be possible to study the evolution of spin and orbital parameters on timescales never before probed.

In this Letter we report the discovery of X-ray pulsations in NGC 6440 X-2. In a companion work

¹ Email: d.altamirano@uva.nl ; Astronomical Institute, “Anton Pannekoek”, University of Amsterdam, Science Park 904, 1098XH, Amsterdam, The Netherlands.

² University of Alberta, Department of Physics, Room 238 CEB, 11322-89 Avenue, Edmonton, AB T6G 2G7, Canada.

³ Laboratory for High-Energy Astrophysics, NASA Goddard Space Flight Center, Greenbelt, MD 20771, U.S.A.

⁴ Department of Astronomy, University of Maryland, College Park, MD 20742., U.S.A.

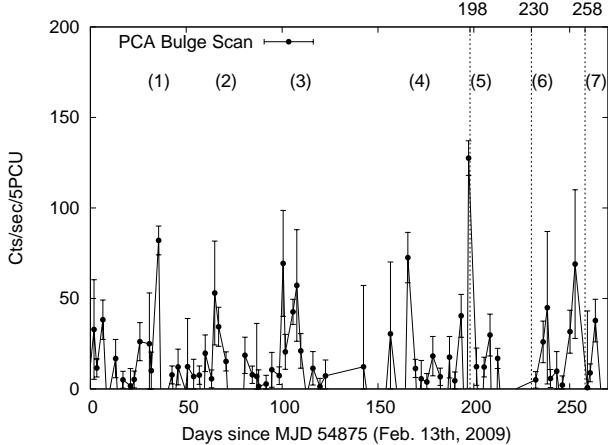


FIG. 1.— Intensity (2.0–10.0 keV cts/sec/5PCU) vs. time as measured by the PCA Bulge Scan monitoring (Swank & Markwardt 2001). The dashed lines mark the times when we detected X-ray pulsations (August 30th, October 1st and October 28th, 2009); note that the bulge scans did not sample the October 1st outburst. See Heinke et al. (2009a) for more details.

(Heinke et al. 2009a), we report on a detailed description of the evolution of the source's outbursts based on our multiwavelength campaign on this source. Our results demonstrate that there may exist a population of AMXPs undergoing low-luminosity outbursts which are undetected by current all-sky X-ray monitors.

2. LMXBS IN THE GLOBULAR CLUSTER NGC 6440

NGC 6440 is a globular cluster at 8.5 ± 0.4 kpc (Ortolani et al. 1994). Using Chandra images, Pooley et al. (2002) studied the population of the low-luminosity X-ray sources in NGC 6440. These authors found 24 X-ray sources above a limiting luminosity of $\sim 2 \cdot 10^{31}$ ergs s $^{-1}$ (0.5–2.5 keV) inside the half-mass radius of the cluster (all of which lie within ~ 2 core radii of the cluster center); there is strong evidence that 8 of these systems are LMXBs in quiescence (Heinke et al. 2003). Pooley et al. (2002) also found excess emission in and around the core of NGC 6440, suggesting unresolved point sources.

Bright X-ray outbursts from a LMXB were observed in 1971, 1998, 2001 and 2005 (Markert et al. 1975; in't Zand et al. 1999; Verbunt et al. 2000; in't Zand et al. 2001; Markwardt & Swank 2005). From X-ray and optical observations, in't Zand et al. (2001) concluded that the 1998 and 2001 outbursts were from the same object, which they designated SAX J1748.9–2021. Altamirano et al. (2008) detected intermittent X-ray pulsations at ~ 442 Hz in the 2001 and 2005 outbursts (see also Gavril et al. 2007). Whether the 1971 outburst was from SAX J1748.9–2021 is uncertain.

Between MJD 54875 and 55075 at least 5 short-duration (\sim days) outbursts have been detected in NGC 6440. As discussed in Heinke et al. (2009a), Chandra, RXTE and Swift data indicates that all outbursts were from the same source, denoted NGC 6440 X-2.

3. OBSERVATIONS, DATA ANALYSIS AND RESULTS

We used data from the RXTE Proportional Counter Array (PCA, for instrument information see Jahoda et al. 2006). Between August 1998 and November 4th, 2009, there were 49 pointed observations

TABLE 1
TIMING PARAMETERS FOR NGC 6440

| Parameter | Value |
|---|---------------|
| Orbital period, P_{orb} (seconds) | 3438(33) |
| Projected semi major axis, $a_x \sin i$ (lt-ms) | 6.22(7) |
| Time of ascending node, T_{asc} (MJD/TDB) | 55073.0344(6) |
| Eccentricity, e (95% c.l.) | < 0.07 |
| Spin frequency ν_0 (Hz) | 205.89215(2) |
| Pulsar mass function, $f_x \times 10^{-7} M_\odot$ | 1.6(1) |
| Minimum companion mass ¹ , $M_c (M_\odot)$ | 0.0067 |

All errors are at $\Delta\chi^2 = 1$.

¹: The minimum companion mass is estimated assuming a neutron star mass of $1.4 M_\odot$.

of the globular cluster NGC 6440 each covering 1 to 5 consecutive 90-min satellite orbits. Usually, an orbit contains between 1 and 5 ksec of useful data separated by 1–4 ksec data gaps due to Earth occultations and South Atlantic Anomaly passages. The first 27 observations sample 3 outbursts of the Intermittent AMXP SAX J1748.9–2021 (Altamirano et al. 2008). The remaining 22 were triggered based on results of the PCA Bulge Scan program or ToO Swift observations, and sample the 5 outbursts of NGC 6440 X-2 (see also Heinke et al. 2009a).

We performed a timing analysis using the high-time resolution data collected in the Event (E_125us_64M_0_1s), Good Xenon and Single-Bit modes. Fourier power spectra were constructed for each observation, using data segments of 128, 256 and 512 seconds and with a Nyquist frequency of 4096 Hz. No background or dead-time corrections were made prior to the calculation of the power spectra, but all reported rms amplitudes are background corrected; deadtime corrections are negligible.

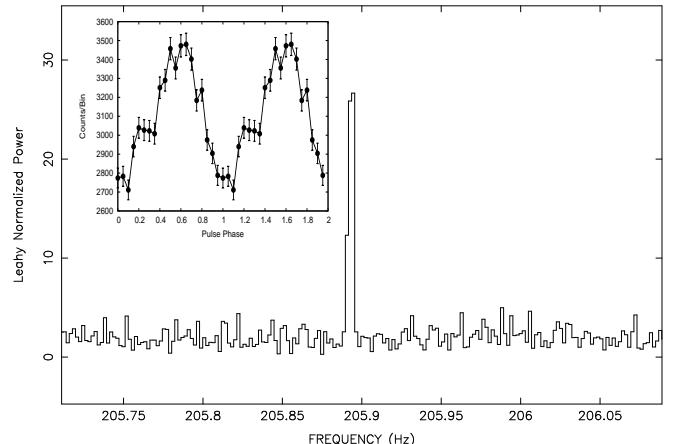


FIG. 2.— Leahy normalized (Leahy et al. 1983) power spectrum of August 30th observation (~ 3 ksec of data). The signal is distributed on at least three independent frequency bins of size 1/512 Hz. Inset: Pulse profile in the 2–14.8 keV range (two cycles are plotted for clarity). The fractional rms amplitudes of the fundamental and first overtone are $7.5 \pm 0.6\%$ and $2.3 \pm 0.6\%$ rms, respectively. Count rates (in counts/bin) are corrected for background.

3.1. Light curves and power spectra

In Figure 1 we plot the intensity (2.0–10.0 keV cts/sec/PCA) of the globular cluster NGC 6440 as measured with PCA Bulge Scans (Swank & Markwardt 2001). The data suggest that between MJD 54875 and

55075 the globular cluster has brightened for short periods (\sim days) on ~ 5 occasions (see also Heinke et al. 2009a). However, we note that some of these points might be spurious given that the intensity measured is systematically uncertain due to the contributions from diffuse galactic emission and other nearby sources in the PCA field of view. In none of the pointed nor the Bulge Scan observations did we detect thermonuclear X-ray bursts.

As can be seen in Figure 1, on August 30th, 2009 (MJD 55072) the PCA bulge scan detected the highest intensity in the direction of NGC 6440 over a period of more than 250 days. A ToO RXTE observation (ObsID: 94044-04-02-01) found NGC 6440 at a luminosity of $L_{2-10\text{keV}} \sim 1.7 \cdot 10^{36}$ ergs s $^{-1}$ (using a distance of 8.5 kpc, see Ortolani et al. 1994). The energy spectrum is well fitted with an absorbed power law with index of 1.83 ± 0.3 ($\chi^2/\text{dof} = 0.84$ for 47 degrees of freedom; the interstellar absorption N_h was fixed to a value of $5.9 \cdot 10^{21}$ cm $^{-2}$, consistent with the cluster value and the absorption measured by Chandra, see Heinke et al. 2009a). The power spectrum of this observation shows two features with characteristic frequencies (Belloni et al. 2002) of 7.4 ± 0.8 and 1.13 ± 0.06 Hz, quality factor Q of 1.3 ± 0.6 and 0.71 ± 0.07 , and rms amplitudes of $28 \pm 3\%$ and $42 \pm 2\%$, respectively. We searched for kHz QPOs, but found none. The average (background-subtracted) count rate during this observation was ~ 22 cts/sec and only one proportional counter unit (PCU) was active (2–60 keV). Additional RXTE observations were performed on the 1st and 2nd of September; fluxes were consistent with background emission. These measurements are consistent with the fluxes measured by Swift between the 1st and the 4th of September (Heinke et al. 2009a). If we take into account that a PCA bulge scan observation did not detect significant flux in the direction of NGC 6440 on August 28th, we can estimate an outburst duration of no more than ~ 3 days (above $\sim 10^{35}$ erg s $^{-1}$).

On July 30th, October 1st and October 28th, 2009, RXTE sampled three other outbursts of NGC 6440 (Heinke et al. 2009a) for $\sim 1.5 - 2.5$ ksec. We did not find any significant QPOs nor broad band noise in their power spectra, probably due to poor statistics (note that the total count rates measured are dominated by background counts). These observations ranged from $L_{2-10\text{keV}} = 1 \times 10^{35}$ to 5.2×10^{35} ergs s $^{-1}$, thus providing poorer statistics than on August 30th. We found no evidence for dips or eclipses in any of the RXTE pointed observations of NGC 6440 X-2.

3.2. Pulsations

Adopting a source position $\alpha = 17^h 48^m 52^s.75$, $\delta = -20^\circ 21' 24''.0$ (from Chandra images, see Heinke et al. 2009a), we converted the photon arrival times to the Solar System barycenter with the FTOOL faxbary, which uses the JPL DE-405 ephemeris along with the space-craft ephemeris and fine clock corrections to provide an absolute timing accuracy of $3.4 \mu\text{s}$ (Jahoda et al. 2006).

We found a strong signal at a frequency of ~ 205.89 Hz in the August 30th RXTE observation. In Figure 2 we show the Leahy normalized power spectrum. We calculated a dynamical power spectrum with a 512 sec sliding window and found that the pulse frequency is modulated in a way that is typical from Doppler shifts due to the

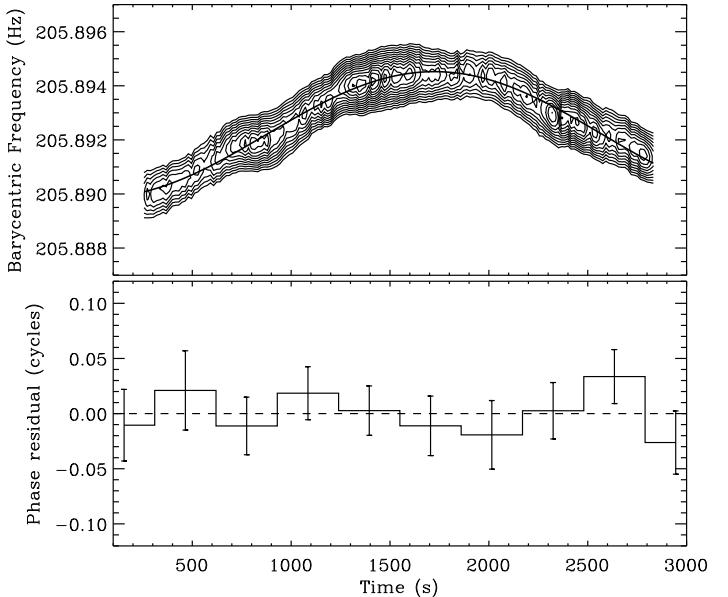


FIG. 3.— *Upper panel:* Dynamical power spectrum of August 30th observation with a 512 sec sliding window. The frequency is modulated as expected from the Doppler shifts due to the orbital motion of a pulsar in a binary system. The data sample a little less than a full orbital cycle. The filled line represents our best orbital solution. *Lower panel:* Phase residuals as estimated from 300 sec data segments. All errors are at $\Delta\chi^2 = 1$.

orbital motion of a pulsar in a binary system (see Figure 3); the data sample a little less than a full orbital cycle.

To improve the signal to noise of the pulsations, we first modeled the pulse drifts with a sinusoid (assuming zero eccentricity). We found that the frequency drift is consistent with a system with an orbital period of 57 minutes and a projected semi-major axis of 6.2 lt-ms. With this provisional solution, we folded the 3 ks of lightcurve into 10 pulse profiles of ~ 300 s each and fitted them with a constant plus two sinusoids representing the pulse frequency and its first overtone. We then phase-connected the pulse phases by fitting a constant pulse frequency plus a circular Keplerian orbital model. The procedure is described in detail in Patruno et al. (2009). In Table 1 we report the best fit. In the inner panel of Figure 2 we show the folded pulse profile in the 2–14.8 keV range (i.e. channels 0–35) after correcting for the effects of the orbital modulation. The fractional rms amplitudes of the fundamental and first overtone are 7.5 ± 0.6 and $2.3 \pm 0.6\%$, respectively (2.0–14.8 keV).

We applied the above technique to three energy bands: 2–5.7 keV, 6.1–14.8 keV and 15.2–60 keV. (We note that we could only choose these bands, as the data were split in two Single-bit modes – SB_125us_0_13_1s & SB_125us_14_35_1s – and one Event mode – E_62us_32M_36_1s.) The pulsed fractional rms amplitudes of the fundamental were $(7.5 \pm 1.0)\%$ and $(8.2 \pm 1.0)\%$ in the 2–5.7 keV and 6.1–14.8 energy band. The first overtone was significantly detected in the latter band, with an amplitude of $3.3 \pm 0.8\%$ rms. Due to the low quality of the data at high energies, only upper limits of 21% rms (at 95% confidence level) can be put on the fundamental in the 15.2–60 keV band. (NGC 6440 X-2 was more than 100 times brighter than the other 24 X-ray sources in NGC 6440 (Pooley et al. 2002), so their

contributions can be ignored. However, Galactic Ridge emission does provide additional background at this location, not included in standard RXTE background estimates, and therefore the rms amplitudes we quote above might be slight underestimates).

We also searched for pulsations in the observations on July 30th, October 1st and October 28th, 2009, by correcting for the orbital motion of the system and folding the data around the best spin period determination. No pulsations were found on July 30th, with 95% c.l. upper limits of 8% rms on the pulse fractional amplitude. On October 1st and 28th we found 3.4σ and 8.9σ detections, respectively, of pulsations with characteristics consistent with those we found on August 30th.

RXTE observed NGC 6440 during the three outbursts of the AMXP SAX J1748.9–2021 (see, e.g., Altamirano et al. 2008; Patruno et al. 2009). Although improbable, it is possible that NGC 6440 X-2 was also active during these periods. To further investigate this, we searched all previous RXTE observations of NGC 6440 for the presence of pulsations at $\sim 205 - 206$ Hz. We barycentered all data in the same manner as above and divided the data in 3 groups, corresponding to the 1998, 2001 and 2005 outbursts. For each group we performed Fourier transforms of all the data and calculated a single averaged power spectra. We found no significant pulsations in the $\sim 205 - 206$ Hz range. We also searched for evidence of intermittent pulsations such as those found in other AMXPs (Galloway et al. 2007; Gavriil et al. 2007; Altamirano et al. 2008; Casella et al. 2008), but found none. In the above searches, we did not correct for the orbital motion of the binary; although these corrections would improve our sensitivity, such analysis is beyond the scope of this Letter.

Finally, we note that it was not possible to search for pulsations in the Swift observations. These data-sets were obtained in photon-counting mode with a time resolution of 2.5 seconds.

4. DISCUSSION

We have discovered the second accreting millisecond X-ray pulsar in the globular cluster NGC 6440. Pulsations were detected in three RXTE pointed observations performed during the decay phase of three outbursts, each of which lasted less than ~ 3 days (Heinke et al. 2009a). The frequency drifts we observe are consistent with an orbital period of 57.3 minutes and a semi-major axis ($a_x \sin i$) of 6.22 light-msec, which shows that this new AMXP is in an ultra-compact binary system.

The characteristics of this new pulsar are similar to those of other AMXPs, particularly SWIFT J1756.9–2508 (Krimm et al. 2007; Patruno et al. 2010), which showed pulsations at a frequency of 182 Hz, an orbital period of 54.7 minutes, a projected semi-major axis of 5.94 lt-ms and a minimum companion mass of $0.0067 M_{\odot}$. As pointed out by Krimm et al. 2007, such a low mass for a companion in this type of system is probably inconsistent with brown dwarf models while white dwarf models suggest that the companion is probably a He-dominated donor.

The reason why only twelve⁵ NS LMXBs exhibit coherent pulsations out of about 100 systems is still unclear.

There is a strong tendency for the detected AMXPs to have rather low time-averaged accretion rates (over many outbursts, see, e.g., Chakrabarty 2005; Galloway 2006; Wijnands 2008). The time-averaged accretion rate of NGC 6440 X-2 is at most similar to that of the AMXP SAX J1808.4–3658, but could easily be much lower (see discussion by Heinke et al. 2009a). This is consistent with the general tendency and furthermore, with the theoretical predictions (Cumming et al. 2001; Lamb et al. 2009) that a significant fraction (if not all) of the NS LMXB systems with low time-averaged accretion rates harbor accreting millisecond X-ray pulsars (Wijnands 2008).

The outburst durations (~ 3 days) of the newly discovered AMXP are short compared with those of the other AMXPs, although not uniquely so. For example, short-duration outbursts of the AMXP XTE J1751–305 have been detected in 2005, 2007 and 2009 (Grebenev et al. 2005; Swank et al. 2005; Markwardt & Swank 2007; Markwardt et al. 2007; Linares et al. 2007; Markwardt et al. 2009b). Our discovery of NGC 6440 X-2 indicates that there might exist a population of AMXPs undergoing weak outbursts. Unfortunately, short low-luminosity outbursts cannot be detected with the current all-sky X-ray monitors (e.g., ASM aboard RXTE). More sensitive instruments like the “Monitor of All-sky X-ray Image” (MAXI, which should detect X-ray – 2–30 keV – sources of about 20 mCrab from 90 minutes observations, and sources of about 4.5 mCrab after a day observation, see Matsuoka et al. 2009) will probably allow us to discover many more potential low-luminosity AMXPs.

As discussed in Heinke et al. (2009a), NGC 6440 X-2 has been in outburst at least five times in the last 250 days. If true, this is the AMXP with the shortest recurrence time. If NGC 6440 X-2 continues undergoing this type of short outbursts and RXTE is able to observe them, then NGC 6440 X-2 has the potential to be the best millisecond X-ray pulsar in which to study the evolution of the binary as well as that of the neutron star spin (by means of coherent timing analysis).

The globular cluster NGC 6440 is known for having at least 24 faint X-ray sources to a limiting luminosity of $\sim 2 \cdot 10^{31}$ ergs s $^{-1}$ (0.5–2.5 keV, see Pooley et al. 2002). NGC 6440 is also known for hosting at least 6 millisecond radio pulsars, of which 3 are in binary systems (Freire et al. 2008). None of the known radio pulsars match the position (nor the characteristics) of NGC 6440 X-2. Although millisecond radio pulsars in binary systems have been found in other globular clusters (see, e.g., Ransom et al. 2005; Freire et al. 2008, and references therein), it is an intriguing question why NGC 6440 is the only globular cluster known today to host (two) AMXPs (SAX J1748.9–2021 – Gavriil et al. 2007 and Altamirano et al. 2008 – and NGC 6440 X-2 – this paper), while no AMXPs have been detected in any other globular cluster. This might be only a selection effect, as current all-sky monitors cannot detect short low-luminosity outbursts. Monitoring X-ray observations of different globular clusters would be needed to further investigate this.

⁵ See also the recent discovery of a 245 Hz AMXP by Markwardt et al. (2009a).

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