DRAFT VERSION MAY 20, 2018
Preprint typeset using LaTeX style emulateapj v. 01/23/15

A DEEP PULSE SEARCH IN ELEVEN LOW MASS X-RAY BINARIES

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Draft version May 20, 2018

ABSTRACT

We present a systematic coherent X-ray pulsation search in eleven low mass X-ray binaries (LMXBs). We select a relatively broad variety of LMXBs, including persistent and transient sources and spanning orbital periods between 0.3 and 17 hours. We use about 3.6 Ms of data collected by the *Rossi X-Ray Timing Explorer* (*RXTE*) and *XMM-Newton* and apply a semi-coherent search strategy to look for weak and persistent pulses in a wide spin frequency range. We find no evidence for X-ray pulsations in these systems and consequently set upper limits on the pulsed sinusoidal semi-amplitude between 0.14% and 0.78% for ten outbursting/persistent LMXBs and 2.9% for a quiescent system. These results suggest that weak pulsations might not form in (most) non-pulsating LMXBs.

Keywords: binaries: general — stars: neutron — stars: rotation — X-rays: binaries — X-rays: stars

1. INTRODUCTION

An important question in the study of neutron star low mass X-ray binaries (LMXBs) is why most of them do not show accretion powered pulsations. Only a small fraction of them has measurable pulsations, with typical pulsed amplitudes of the order of 1-10%, that reveal the spin frequency of the neutron star. The spin is a key quantity to measure because it is related to a number of important fundamental physics and stellar astrophysics problems, like the equation of state of ultradense matter (Lattimer & Prakash 2007), the evolution of the neutron star magnetic field (Bhattacharya & van den Heuvel 1991) and allows tests of general relativity in strong gravity via pulse profile modelling (Morsink & Leahy 2011). Those systems that show pulsations with spin periods in the millisecond range are classified in two broad categories:

- accreting millisecond X-ray pulsars (AMXPs), with accretion powered pulsations (19 systems known to date, see Patruno & Watts 2012; Strohmayer & Keek 2017);
- nuclear powered X-ray pulsars (NXPs), with burst oscillations seen during thermonuclear bursts (10 systems known to date, beside a few AMXPs which are also NXPs; Galloway et al. 2008; Watts 2012).

The reason why some bursting LMXBs show burst oscillations is not completely understood and it is currently believed that this might be related to the physical conditions at the ignition point on the neutron star surface (see e.g., Galloway et al. 2017). If a neutron star LMXB has a magnetic field of the order of 10^8 G or more, it should display X-ray pulsations since the field is sufficiently strong to channel the gas towards the magnetic poles. The fact that most neutron star LMXBs are not AMXPs is therefore not understood. There are several models that attempt to explain the lack of pulsations, but they all come with weaknesses that seem incompatible with the growing body of observational results collected so far (see Patruno & Watts 2012 for a detailed discussion).

An important aspect of this conundrum is that the current non-detection of pulsations might be simply ascribed to the presence of very weak pulses which are below the sensitivity of current instrumentation and/or current search techniques. All AMXPs have indeed been discovered so far by simply looking at the power spectra and by identifying the spin frequency by eye inspection (see for example Wijnands & van der Klis 1998; Markwardt et al. 2003; Altamirano et al. 2010, 2011). The fractional amplitude of their pulsations reaches values of 20–30% (Patruno et al. 2010a; Altamirano et al. 2011), whereas the smallest pulsed fractions observed so far are around $\sim 1\%$ (Galloway et al. 2007; Patruno et al. 2009b).

A complication in this scenario is the existence of three so-called intermittent AMXPs (Galloway et al. 2007; Gavriil et al. 2007; Casella et al. 2008; Altamirano et al. 2008) which show pulsations only sporadically during their outbursts. The mechanism behind their intermittent behavior is still not known. Furthermore, more sophisticated attempts to detect weak pulses in the neutron star LMXB 4U 1820–371 (Dib et al. 2004) and Aql X-1 (Messenger & Patruno 2015) have led to negative results, with upper limits on the pulsed fraction of less than ≈ 0.3–0.5%.

Apart from these rare exceptions, upper limits smaller than $\approx 1\%$ on the pulsed fraction are not available beside a few of the brightest LMXBs (the so-called Z sources, see Vaughan et al. 1994). Therefore it is important to push the current upper limits to smaller values, since there is no a-priori reason to believe that LMXBs should not be able to form pulsations with fractional amplitudes smaller than 1%. In this work we thus investigate this problem more systematically than done in the past.

We select eleven accreting neutron stars in LMXBs with different orbital parameters spanning a relatively large range, in order to avoid the selection of a specific sub-type of LMXBs or a specific evolutionary stage of the binary. We then apply a semi-coherent search strategy, first developed by Messenger (2011) and then applied to the source Aql X-1 by Messenger & Patruno (2015). To do so we use archival *Rossi X-ray Timing Explorer* (*RXTE*) data collected over the lifetime of the instrument, as well as *XMM-Newton* data. We present the selection of LMXBs in Section 2, the data reduction in Section 3, the details of the semi-coherent search strategy in Section 4 and the results of the search in Section 6. We discuss the physical implications of our results in Section 7

2. SELECTION OF LMXBS

When searching for pulsations with a semi-coherent search code, it is highly desirable that the following two criteria are met, in order to allow a deep pulse search when operating with limited computational resources. First, the neutron star should have relatively precise constraints on at least one of its orbital/spin parameters, in order to reduce the volume of parameter space that must be searched. Second, the data need to be relatively closely spaced in time. The computational cost of a semi-coherent search scales rapidly with the total *timespan* of the data, whereas the search sensitivity scales much more slowly with the total *amount* of data contained within the timespan. Closely-spaced data will therefore maximize the search sensitivity given a fixed computational budget; for further discussion see Messenger (2011) and Messenger & Patruno (2015).

In order to meet the aforementioned criteria we have looked for LMXBs with either a robust detection of the orbital period (usually from optical observations) or sources with a relatively well known spin frequency (thanks to burst oscillations). Indeed the purpose of this work is not only to find the spin frequency of new sources, but also to verify whether weak and persistent pulsations exist. Therefore sources like 4U 1608–52 and 4U 1636–53, both with a known spin frequency and with a relatively well constrained orbit, are optimal candidates for our search. We have also included the source XTE J1739–2859 despite the lack of any constraint on the orbital parameters, to verify whether we can find the candidate spin frequency of 1122 Hz reported by Kaaret et al. (2007).

To avoid selecting a biased sample of LMXBs with a specific evolutionary and/or accretion state we have used a mixture of sources, both persistent and transient, at high and low inclinations and with different orbital periods corresponding to ultra-compacts (orbital period $P \approx 0.3$ hr) up to relatively wide binaries ($P \approx 17$ hr). To be conservative in our search, we have also used a broader parameter space than the formal uncertainties provided in the literature on the spin/orbit of each source. The selection of the parameter space to explore is based on a number of factors, like the available computational resources and the robustness of the orbital parameters measured in previous works. The semi-major axis is calculated assuming the most extreme combination of donor and neutron star masses ($M_{\rm NS} = 1.2$–$2.3 M_{\odot}$). We assume that all binaries have zero eccentricity and that, aside from one source, the orbital phase is unknown. A summary of the parameter space explored is given in Table 1 and a more detailed description of each source selected is provided in the following subsections.

2.1. *4U 1323–619*

This is a dipping LMXB with a very well determined orbital period from X-ray observations (Parmar et al. 1989; Levine et al. 2011) and it shows very regular bursts. For this source we used a 2σ interval around the best determined orbital period of Levine et al. (2011) but also a much wider parameter space from Parmar et al. (1989).

2.2. *4U 1456–32 (Cen X-4)*

4U 1456–32, also known as Cen X-4, is a relatively wide binary with a period of 15.1 hr. It is the only quiescent LMXB in our sample and we used 80 ks of *XMM-Newton* data collected during March 1, 2003. This is the same dataset used in D'Angelo et al. (2015) and we refer to that paper for details. In this work we have pushed the search to a deeper sensitivity than was done in D'Angelo et al. (2015), who found a 6.4% upper limit on the pulsed fraction.

2.3. *4U 1543–624*

The persistent LMXB 4U 1543–624 is an ultra-compact binary with an orbital period of 18.20 ± 0.09 minutes (Wang et al. 2015). We used an uncertainty on the orbital period about 7 times larger than the nominal one.

2.4. *4U 1608–52*

4U 1608–52 is a transient LMXB showing burst oscillations at 619 Hz (Hartman et al. 2003) and it is the fastest known spinning accreting neutron star. The binary orbit is approximately 12.89 hours and it has been determined from optical variability (Wachter et al. 2002). However, some ambiguities still exist on the possibility that the observed variability is due to a super-hump. There is a very large amount of data recorded by *RXTE* on this source, so we selected only two outbursts.

2.5. *4U 1636–53*

This is a persistent LMXB with thermonuclear bursts showing burst oscillations at a frequency of about 581 Hz. Optical data provide a relatively well constrained orbital period of about 3.8 hours (Pedersen et al. 1981) which has been refined by VLT observations taken in 2003 (Casares et al. 2006).

2.6. *XTE J1710–28*

The eclipsing LMXB XTE J1710–28 has a very well constrained orbital period of about 3.3 hours (Jain & Paul 2011) with a nominal error of about 30 μs. However, "glitches" in the mid-eclipse time were detected at the level of a few milliseconds. We thus used a range about 10 times larger than the glitch size.

2.7. *4U 1735–44*

This is a persistent LMXB and a burster (but no burst oscillations have been seen), with an orbital period of about 4.6 hours determined from optical observations of the irradiated donor star and an inclination of 36–60 deg. (Casares et al. 2006). The ephemeris are determined with great precision, with a 1σ statistical error on the orbital period of only 0.3 seconds. We chose a wider range of about 3 seconds for our search.

Table 1
Spin–Orbit Parameter Space

Source	Spin Frequency ν (Hz)	Orbital Period P (s)	Projected Semi-major Axis a (lt-s)	Time of Ascension t_{asc}
4U 1323–619 (wide)	50–1500	10590–10592	0.1745–1.1689	assumed unknown
4U 1323–619 (narrow)	50–1500	10590–10591	0.545–0.633	assumed unknown
4U 1456–32 (Cen X-4)	50–1500	54000–54720	0.04–1.9	assumed unknown
4U 1543–624	50–1500	1073–1111	0.00143–0.0599	assumed unknown
4U 1608–52	615–625	44064–47521	0.3–4	assumed unknown
4U 1636–53	580–583	13655–13656	0.35–1.2	MJD 50869.00225–50869.02625
XTE J1710–28	50–1500	11811–11812	0.136–0.9	assumed unknown
4U 1735–44	50–1500	16746–16748	0.05–2.3	assumed unknown
XTE J1739–2859	1120–1124	3600–43200	0.01–2	assumed unknown
4U 1746–37	50–1500	18586–18590	0.2–1.5	assumed unknown
XTE J2123–058	50–1500	21384–21492	0.1–2.45	assumed unknown
4U 2129+12 (AC 211)	50–1500	61603–61608	0.39–1.69	assumed unknown

2.8. *XTE J1739–2859*

This is a transient source with unknown orbital parameters. The reason why we include it in our search is because Kaaret et al. (2007) reported the detection of burst oscillations at a frequency of 1122 Hz. This detection has remained, so far, unconfirmed. However, we are not aware of sophisticated attempts to search for accretion powered pulsations from this source. Since our limited computational resources require that the parameter space to search is not too large, we restricted the candidate orbital periods to values between 1 and 12 hours.

2.9. *4U 1746–37*

The persistent source 4U 1746–37 is located in the globular cluster NGC 6441. It shows bursts (but no burst oscillations) and dips that give an accurate orbital period of 5.16 hr (Bałucińska-Church et al. 2004; Levine et al. 2011).

2.10. *XTE J2123–058*

This is a transient and a bursting pulsar with no known burst oscillations but a well determined orbital period of about 5.9 hours from optical spectroscopic data collected with the Very Large Telescope (Casares et al. 2002). The nominal 1σ error reported was about 0.2 s and it was obtained by combining the results with the photometric studies of Zurita et al. (2000). To avoid any possible uncertainty due to systematics we used a much broader range of about ± 50 s around the best determined orbital period.

2.11. *4U 2129+12 (AC 211)*

4U 2129+12, also known as AC 211, is located in the globular cluster M15 and its orbital period of approximately 17 hours, very well determined from X-ray observations of eclipses (Wen et al. 2006; Ioannou et al. 2002). The 17 hours orbit implies that the donor cannot be a main sequence star (that would underfill its Roche lobe) since the turn off mass of M15 is about $0.8 M_{\odot}$. Furthermore the system is a peculiar one since it is an accretion disk corona (ADC) source, i.e., the central source should be permanently obscured by a cloud of material. However, we included the source in our sample because there is a known ADC source with a slow accreting pulsar with pulsed fractions of about 1-2% (Jonker & van der Klis 2001).

3. X-RAY OBSERVATIONS

We used pointed observations collected with the Proportional Counter Array (PCA) aboard *RXTE* of ten of the eleven LMXBs; for the remaining source Cen X-4 we used *XMM-Newton* data (see Section 2.2). Since the volume of data recorded is sometimes very large and since we are using limited computational resources, we selected (for certain sources) only a subset of the total data available. A total of $\approx$3.6 Ms of data have been used in this work.

The data were recorded either as Event (2^{-13} s sampling time) or GoodXenon (2^{-20} s). The GoodXenon data were rebinned by a factor 8192 so to match the Event time resolution. This speeds up the calculations while still retaining the necessary narrow pulse sensitivity. We then retained only photons falling within the absolute channel range 5–37 ($\sim$ 2–16 keV), which, at least in known AMXPs, usually maximizes the signal-to-noise ratio of the pulsations. To avoid that this specific selection of the energy band might bias our search, we selected a broader energy band, corresponding to absolute channels 5–67 ($\sim$ 2–30 keV), for three (arbitrarily chosen) sources.

We then removed all thermonuclear bursts, by defining a burst start and end as the points in the lightcurves where the X-ray flux becomes twice the pre-burst level. The data are then barycentered according to the best available ephemeris (J2000) found in the literature, by using the DE405 JPL Solar System ephemeris. The source list along with all the program IDs used, the total duration of the observations, total number of photons collected, absolute channels and the right ascensions and declinations used are reported in Table 2.

4. SEMI-COHERENT SEARCH

A detailed description of the semi-coherent search strategy used in this work can be found in Messenger (2011) with an application to the LMXB Aql X-1 in Messenger & Patruno (2015). Here we briefly summarize the most relevant aspects of the semi-coherent search useful to understand our results.

4.1. *Method*

The semi-coherent search method comprises two stages. First, in the coherent stage, the data are partitioned into M short segments of duration T; in this work T ranges from 20 to 3600 seconds. The signal phase[1]

$$\phi(t) = 2\pi\nu\left[t - t_0 - a\sin\left(\Omega(t-t_0)+\gamma\right)\right] \quad (1)$$

[1] Note that Eq. (1) fixes two sign errors with respect to Eq. (13) in Messenger & Patruno (2015)

Table 2
Summary of X-Ray Observations

Source	Abs. Channels	Right Ascension	Declination	Program IDs	Duration (ks)
4U 1323–619	5–37	13:26:36.31	-62:08:9.9	20066, 40040, 70050, 90062, 95442, 96405	339.5
4U 1456–32 (Cen X-4)	0.3-10 keV	14:58:21.92	-31:40:07.4	0144900101 (XMM)	68.5
4U 1543–624	5–37	15:47:54.29	-62:34:11.2	20064, 20071	39.5
4U 1608–52	5–37	16:12:43.0	-52:25:23	70058, 70059, 70069 91405	442.0
4U 1636–53	5–37	16:40:55.57	-53:45:05.2	30053	49.9
XTE J1710–28	5–37	17:10:12.3	-28:07:54	40135,40407,60049, 80045 91018, 91045, 93052, 94314 96329	598.3
4U 1735–44	5–67	17:38:58.3	-44:27:00.0	10068, 10072, 20084, 30056, 40030,40031,40033, 50025, 50026, 50029, 60042, 70036, 91025, 91152, 93200, 93406, 96325, 96331 96325, 96331	1177.9
XTE J1739–2859	5–37	17:39:53.95	-28:29:46.8	91015	106.9
4U 1746–37	5–67	17:50:12.7	-37:03:8.0	10112, 30701, 60044-02-*, 70050, 90044, 91037	441.9
XTE J2123–058	5–67	21:23:14.54	-5:47:53.2	30511	66.5
4U 2129+12 (AC 211)	5–37	21:29:58.3124	+12:10:02.670	10077, 20076, 40041, 92440, 95443, 96408, 96428	374.6

in the mth segment is approximated by a Taylor expansion:

$$\phi(t) \approx 2\pi \sum_{s=0}^{s^*} \frac{\nu_s^{(m)}}{s!}(t-t_0)^s \,, \tag{2}$$

where $\nu_s^{(m)} \equiv d(\phi(t)/2\pi)/dt|_{t=t_0}$, and t_0 is a reference time. The search parameters ν, a, $\Omega \equiv 2\pi/P$ and $\gamma \equiv \Omega(t_0 - t_{\rm asc})$ identify the spin frequency, projected neutron star semi-major axis, orbital frequency and orbital phase, where $t_{\rm asc}$ is the time of ascension. Matched filtering of the data against the model of Eq. (2) is performed over a search grid in $(\nu_0^{(m)}, \nu_1^{(m)}, \ldots, \nu_{s^*}^{(m)})$. The highest derivative order s^* ranges from 2 to 4, depending on the value of ΩT; larger ΩT require higher-order expansions.

Second, in the incoherent stage, we combine the results of the coherent searches from each segment. For each orbital template (ν, a, Ω, γ), the derivatives $(\nu_0^{(m)}, \nu_1^{(m)}, \ldots, \nu_{s^*}^{(m)})$ are computed for $m = 1$ to M, and the M matched filters corresponding to those derivatives in the M segments are selected. Finally the powers in the M matched filters are summed to give our detection statistic. The number of orbital templates used in the search scales as

$$n = \log\left(\frac{1}{1-\eta}\right) \frac{\pi^4 T^4 \tau_s}{25920 m^2} \left(\nu_{\rm max}^4 - \nu_{\rm min}^4\right) \times \left(a_{\rm max}^3 - a_{\rm min}^3\right) \left(\Omega_{\rm max}^4 - \Omega_{\rm min}^4\right) \left(\gamma_{\rm max} - \gamma_{\rm min}\right) \,, \tag{3}$$

where τ_s is the total timespan of the observation, μ is the maximal mismatch, i.e. the maximal fractional loss in squared signal-to-noise ratio, and η is the covering probability, i.e. the probability of any particular point in the space having a mismatch $< \mu$. The subscripts "max" and "min" identify the maximum and minimum values of the parameter ranges; see Table 1. The nominal sensitivity of our search to pulsations with a fractional amplitude A scales as

$$A = 2 M^{-1/4} \rho_\Sigma^{1/2} \langle \mathcal{N} \rangle^{-1/2} \,, \tag{4}$$

where ρ_Σ is the effective signal-to-noise ratio and $\langle \mathcal{N} \rangle$ is the average number of photons in each segment.

For this work, the implementation of the above method used in Messenger & Patruno (2015) underwent some optimisations. Instead of evaluating the derivatives $\nu_s^{(m)}$ for every search frequency ν, they are evaluated for a range of ν values, i.e. $\nu_s^{(m)}(\nu) \approx \nu_s^{(m)}(\nu_0)$ where $\nu \in [\nu_0 - \Delta\nu, \nu_0 + \Delta\nu]$. This reduces the number of computationally-expensive sine and cosine evaluations in Eq. (2). The range $\Delta\nu$ is chosen such that the difference $|\nu_0^{(m)}(\nu) - \nu_0^{(m)}(\nu)|$ never exceeds half a grid spacing in $\nu_0^{(m)}$. The summation of power over segments was also vectorised using single instruction, multiple data (SIMD) operations. A factor of ~ 7 speed-up was gained by these optimisations.

4.2. *Search and Follow-Up Pipeline*

For each LMXB, the setup of the search, defined by their variables (M, T, μ) given above, is optimized so as to maximize the sensitivity of the search at fixed computational cost, following the methodology of Prix & Shaltev (2012). The sensitivity of the search is estimated using a variant of the analytic method derived in Wette (2012); throughout this paper we assume 1% false alarm and 10% false dismissal probabilities. The value of η was set to 90%. We chose to spend, per source, 24000 core-hours of the Atlas computer cluster of the Max Planck Institute for Gravitational Physics, which at the time comprised chiefly of Intel Xeon[2] cores.

The top 10 candidates from each search are then subjected to a follow-up search. The parameter space for each follow-up search are centered on each candidate; the range in ν was reduced to 1 Hz, and the ranges in a, Ω, and γ are reduced to 10% of their initial values. The setups of each follow-up search are optimised as per the initial search, with the requirement that the minimum value of T for each follow-up search must be twice that of the initial search. The results of each follow-up search were then examined manually; any search where noticeable peaks were seen in each parameter were

[2] E3-1220, 3.10GHz

subject to additional follow-up searches following the above procedure. If the signal is real, then this procedure should increase the signal-to-nose of the candidate and highlight the presence of true pulsations.

5. VALIDATION

Prior to analyzing the data of the eleven LMXBs, we performed several tests to validate our data preparation, search pipeline, and sensitivity estimates. These expand upon similar tests of the search pipeline in Messenger & Patruno (2015).

To check the ability of our search pipeline to recover signals of varying strength, we prepared simulated datasets spanning ~ 134 ks, with ~ 25.7 ks of on-source time. These datasets contained a randomly-generated background of $\sim 2.18\times10^6$ photons and a simulated signal, following Eq. (1), with fractional amplitudes of 10%, 3.3%, 1.1%, and 0.37%. The datasets were searched using a search with an estimated sensitivity of 1%; relative to this sensitivity the four injections correspond to strong, moderate, borderline, and subthreshold strengths respectively. Table 3 compares the parameters of the loudest candidate recovered from each search against the actual parameters of the injected signal. We see that, aside from the subthreshold case, our recovered parameters are mostly in good agreement with their actual values. The difference between recovered and actual fractional amplitudes A are within a few factors of the expected error given by the standard deviation of the detection statistic (Messenger & Patruno 2015, Eqs. 10). The differences between recovered and actual parameters ν, a, Ω, and γ are, with a few expections, within a few factors of the expected error given by the Cramér–Rao lower bound.

To further test our data preparation and search pipeline, we performed the following blind injection challenge. One author prepared a simulated outburst with the same length and number of photons as found in 4U 1323–619, and injected a fake signal in the simulated data. The data was then blindly searched by another author who was unaware of the true parameters of the fake signal. The search covered a wide parameter space of $\nu \in$ 100–1000 Hz, $a \in$ 0.810–0.817 lt-s, $\Omega \in (2.4896\text{–}2.4957)\times10^{-4}$ rad/s, and $\gamma \in 0\text{–}2\pi$, and had a sensitivity of 0.74%. As seen in Table 3, the signal was recovered at a fractional amplitude and parameters broadly consistent with the expected errors.

To confirm that our search pipeline is able to find pulsations from real pulsars, we then searched data from the known AMXPs SAX J1808.4–3658 (using the 1998 outburst) and IGR J00291+5934 (the 2008 outburst), using data recorded by *RXTE* and prepared using the same processing described in Section 3. Data from IGR J00291+5934 was split into 3 sections within which pulsations are recorded at fractional amplitudes of 10%, 6%, and 1%[3] respectively. For strong pulsations (SAX J1808.4–3658 and IGR J00291+5934, section 1) our recovered fractional amplitudes are slightly less than expected; for SAX J1808.4–3658 A = 7.3% recovered against 7.8% expected, and for IGR J00291+5934, section 1, A = 8% recovered against 10% expected. Nevertheless we clearly recover the known pulsar signal, and at the correct parameters. The same statement is true of the weaker 6% pulsations in IGR J00291+5934, section 2; for IGR J00291+5934, section 3, the 1% pulsations are below the 1.5% sensitivity of the search, and therefore we do not expect a detection.

Finally, to double-check our sensitivity estimation and optimisation procedure, we reproduce the search for the 3rd outburst of Aql X-1 performed in Messenger & Patruno (2015). The search performed in this paper covered the same search parameter space as Messenger & Patruno (2015) using a setup with $M = 250$, $T = 275$ s, and $\mu = 0.0126$; for comparison Messenger & Patruno (2015) used $M = 258$, $T = 256$ s, and $\mu = 0.1$. The sensitivity of the search was estimated, using the procedure described in Section 4.1, to be 0.24%. This is consistent with the 0.26% estimated by Messenger & Patruno (2015) for the sensitivity of their analysis, and is expected given that the search setups are very similar (apart from the smaller μ used in this paper).

6. RESULTS

We find no new pulsations in the eleven LMXBs considered in this work. In Table 4 we report the 90% confidence level upper limits for the full parameter space explored ($A^{\mathrm{UL}90\%}$) along with the best upper limits from the follow-up search on candidates ($A^{\mathrm{UL}90\%}_{\mathrm{FU\ Best}}$). The best upper limits are of $\approx 0.2\%$ for the sources 4U 1608–52, 4U 1735–44, and 4U 1636–53. For 4U 1608–52 we find a maginally significant candidate during our full parameter space search, with a fractional amplitude of $A = 0.17\%$ and with parameters $\nu = 617.18$ Hz, $P = 45253$ s, $a = 0.72737$ lt-s and $\gamma = 0.92823$ rad. The candidate was not found, however, when folding the data coherently (using the code PRESTO; Ransom et al. 2002; Ransom 2011) and exploring a small parameter space around the best candidate. A search of a different *RXTE* dataset from 4U 1608–52 also revealed no pulsations at the same parameters.

The current upper limits are close to the best possible value that can be achieved with current datasets and computational resources. These results are similar in order of magnitude to what previously found in Aql X-1 (Messenger & Patruno 2015). Some upper limits represent an improvement of a factor of 10 with respect to previous upper limits either published in the literature or obtainable by simply looking at short-length[4] power spectra.

7. DISCUSSION

Together with other previous pulse searches in LMXBs (Vaughan et al. 1994; Dib et al. 2004; Messenger & Patruno 2015), the lack of weak pulsations in these eleven LMXBs implies that weak pulses are not present in most LMXBs. What was found in Aql X-1 (with upper limits of 0.27% on the pulsed fraction) therefore cannot be considered an anomalous behavior but rather the norm. The small values of the upper limits on the pulsed fractions imply that, if we are able to see the surface of the neutron stars, the emission pattern originating must be extraordinarily uniform with no obvious asymmetries.

The various mechanisms that might be responsible for this behaviour have been extensively discussed in the literature and we refer to Messenger & Patruno (2015) for details. Here we note that different pieces of evidence coming from a number of independent studies seem to be converging towards the lack of a magnetosphere around most accreting neutron

[3] In section 3, pulsations are observed at 2% in 3 out of 13 contiguous data stretches; no pulsations are observed in the remaining 10 stretches. The 3 stretches comprise $\sim 50\%$ of the photons accumulated during section 3, so we take the fractional amplitude over the entire section to be 1%.

[4] Assuming that a signal is present in a certain binary with a given orbit, the maximum time to keep all the power in one Fourier frequency bin when doing simple power spectra, without orbital corrections, is $2\pi a/P\nu$ (van der Klis 1988).

Table 3
Validation of Search Pipeline

Source	Search Sensitivity	Parameter	Recovered Value	Actual Value	Expected Error	|Recovered – Actual|/Error
Software injection (strong)	1%	A	9.8%	10%	0.066%	3.01
		ν / Hz	5.988999×10^{2}	5.989000×10^{2}	1.273335×10^{-5}	2.85
		a / lt-s	6.521037×10^{-2}	6.500000×10^{-2}	4.232632×10^{-5}	4.97
		Ω / rad/s	7.103837×10^{-4}	7.104380×10^{-4}	1.674751×10^{-8}	3.24
		γ / rad	2.797675	2.796213	0.000649	2.25
Software injection (moderate)	1%	A	3.2%	3.3%	0.069%	1.93
		ν / Hz	5.989001×10^{2}	5.989000×10^{2}	3.940856×10^{-5}	3.14
		a / lt-s	6.513522×10^{-2}	6.500000×10^{-2}	1.310070×10^{-4}	1.03
		Ω / rad/s	7.103238×10^{-4}	7.104380×10^{-4}	5.189617×10^{-8}	2.20
		γ / rad	2.792518	2.796213	0.002011	1.83
Software injection (borderline)	1%	A	1.1%	1.1%	0.089%	0.24
		ν / Hz	5.990859×10^{2}	5.989000×10^{2}	1.157234×10^{-4}	1600
		a / lt-s	5.647940×10^{-2}	6.500000×10^{-2}	3.774911×10^{-4}	22.5
		Ω / rad/s	7.236696×10^{-4}	7.104380×10^{-4}	1.724539×10^{-7}	76.7
		γ / rad	3.205199	2.796213	0.006683	61.1
Software injection (subthreshold)	1%	A	1%	0.37%	0.26%	2.48
		ν / Hz	6.033609×10^{2}	5.989000×10^{2}	1.205446×10^{-4}	37000
		a / lt-s	6.797894×10^{-2}	6.500000×10^{-2}	3.973361×10^{-4}	7.49
		Ω / rad/s	7.110951×10^{-4}	7.104380×10^{-4}	1.508134×10^{-7}	4.35
		γ / rad	5.850171	2.796213	0.005844	522
Blind injection challenge	0.74%	A	1.4%	1.2%	0.05%	3.03
		ν / Hz	2.873471×10^{2}	2.873470×10^{2}	4.785520×10^{-5}	2.71
		a / lt-s	8.113484×10^{-1}	8.110000×10^{-1}	9.445180×10^{-4}	0.36
		Ω / rad/s	2.493601×10^{-4}	2.493327×10^{-4}	6.910871×10^{-9}	3.96
		γ / rad	3.631982	3.676000	0.001164	37.8
SAX J1808.4–3658	0.53%	A	7.3%	7.8%	0.025%	20.3
		ν / Hz	4.009751×10^{2}	4.009752×10^{2}	7.716828×10^{-6}	5.41
		a / lt-s	6.296443×10^{-2}	6.280800×10^{-2}	3.139776×10^{-5}	4.98
		Ω / rad/s	8.668372×10^{-4}	8.667472×10^{-4}	6.426050×10^{-9}	14.0
		γ / rad	2.479961	2.539119	0.000498	118
IGR J00291+5934, section 1	0.99%	A	8%	10%	0.066%	30.7
		ν / Hz	5.988922×10^{2}	5.988921×10^{2}	1.565229×10^{-5}	8.38
		a / lt-s	6.358381×10^{-2}	6.498700×10^{-2}	5.199202×10^{-5}	26.9
		Ω / rad/s	7.108983×10^{-4}	7.104406×10^{-4}	2.109826×10^{-8}	21.6
		γ / rad	1.420043	1.477473	0.000817	70.2
IGR J00291+5934, section 2	1.3%	A	5.9%	6%	0.12%	1.17
		ν / Hz	5.988918×10^{2}	5.988921×10^{2}	4.185645×10^{-5}	5.72
		a / lt-s	6.393486×10^{-2}	6.498700×10^{-2}	1.391573×10^{-4}	7.56
		Ω / rad/s	7.102692×10^{-4}	7.104406×10^{-4}	8.578632×10^{-8}	1.99
		γ / rad	0.380340	0.423260	0.002176	19.7
IGR J00291+5934, section 3	1.5%	A	1.6%	1%	0.18%	3.31
		ν / Hz	5.988974×10^{2}	5.988921×10^{2}	1.088178×10^{-4}	49.3
		a / lt-s	7.467071×10^{-2}	6.498700×10^{-2}	3.669491×10^{-4}	26.3
		Ω / rad/s	7.002556×10^{-4}	7.104406×10^{-4}	4.621755×10^{-8}	220
		γ / rad	3.357818	5.418901	0.004914	419

stars in LMXBs. Beside the negative results of deep pulse searches (27 LMXBs with published results so far, including this work), the most important ones are:

- the aperiodic variability of AMXPs shows shifted correlations of power spectral components with respect to non-pulsating atoll sources (van Straaten et al. 2005);
- the quiescent LMXB Cen X-4 has shown no evidence for pulsations and modeling of its spectral behavior favour the presence of a radiatively inefficient accretion flow rather than a propeller (which would be expected if a magnetosphere were present; D'Angelo et al. 2015);
- the existence of two sub-populations in LMXBs (Patruno et al. 2017a), with the easiest possibility being that no magnetosphere is present in some LMXBs;
- very different behavior of burst oscillations in AMXPs & non-pulsating LMXBs, with the former showing pulse phase locking between accretion and nuclear powered pulsations (Watts et al. 2008; Cavecchi et al. 2011), burst oscillation frequency overshooting the spin frequency (Chakrabarty et al. 2003), burst oscillations present in all bursts (and only sometimes in non-pulsating LMXBs) and a strong harmonic content vs. little to no harmonic content in non-pulsating sources (Strohmayer et al. 2003; Watts et al. 2009);
- the lack of short intermittent pulse episodes in 40 LMXBs (Algera & Patruno in prep.);
- exponentially decreasing accretion torques in the intermittent AMXP HETE J1900.1–2455 compatible with a decreasing magnetosphere strength (Patruno 2012);

Table 4
Search Parameters and Upper Limits on Pulsed Fraction

Source	Search					Follow-Up			
	T (s)	M	μ	n	$A^{\rm UL90\%}$	$T_{\rm FU}$	$\mu_{\rm FU}$	$n_{\rm FU}$	$A^{\rm UL90\%}_{\rm FU\ Best}$
4U 1323–619 (wide)	71	4600	0.724	1.1×10^{12}	1.6%	530	0.0768–0.498	4.2×10^{10}–1.3×10^{11}	0.65%
4U 1323–619 (narrow)	210	1552	0.716	2.6×10^{12}	1.0%	530	0.0123–0.123	7.6×10^{9}–1.4×10^{10}	0.64%
4U 1456–32 (Cen X-4)	183	315	0.0166	6.0×10^{12}	6.0%	1236–1522	0.0109–0.0224	1.4×10^{9}–7.2×10^{10}	2.9%
4U 1543–624	54	543	0.0928	8.7×10^{12}	0.84%	109	0.0675–0.0864	4.3×10^{8}–1.3×10^{9}	0.63%
4U 1608–52	256	152	0.126	1.0×10^{13}	0.18%	512	0.0118–0.0366	1.8×10^{11}–7.1×10^{11}	0.14%
4U 1636–53	347	142	0.0132	1.3×10^{9}	0.22%	695	0.0129–0.0186	5.5×10^{5}–1.3×10^{7}	0.17%
XTE J1710–28	120	4694	0.722	1.1×10^{12}	1.6%	590	0.0438–0.257	2.6×10^{10}–1.1×10^{11}	0.78%
4U 1735–44	331	193	0.68	8.1×10^{12}	0.21%	663	0.05–0.467	8.7×10^{8}–7.5×10^{9}	0.14%
XTE J1739–2859	20	4797	0.724	1.0×10^{12}	1.6%	40–556	0.0535–0.713	1.4×10^{11}–7.3×10^{11}	0.48%
4U 1746–37	119	3501	0.723	1.4×10^{12}	0.62%	238–796	0.0137–0.158	4.8×10^{10}–1.5×10^{11}	0.28%
XTE J2123–058	198	321	0.693	9.7×10^{12}	0.57%	396–594	0.0168–0.0274	2.3×10^{11}–4.5×10^{11}	0.34%
4U 2129+12 (AC 211)	570	578	0.703	6.0×10^{12}	0.58%	1800	0.0322–0.0639	2.4×10^{11}–3.0×10^{11}	0.35%

- the aperiodic variability of the intermittent source HETE J1900.1–2455 behaves as non-pulsating atoll sources rather than AMXPs (Patruno & Wijnands 2017).

It seems therefore plausible to suggest that the lack of pulsations in LMXBs can be ascribed to a weak/no magnetosphere. This scenario comes of course with shortcomings since a number of other observational results would still not be easily explained. For example, a weak magnetosphere would not justify why Aql X-1 has shown such short (≈ 150 s) but strong (≈ 6.5% pulsed fraction) pulse episode. It is also difficult to understand what causes the weakness of the magnetosphere. Initial suggestions (Bisnovatyi-Kogan & Komberg 1974; Cumming et al. 2001) focused on the mass accretion rate, which was proposed to be higher in non pulsating systems. However, the observational evidence now suggests that the mass accretion rate cannot be the only cause for the lack of pulsations since these are not seen also in some faint systems too (Patruno 2010). Furthermore, there is a strong tension between the lack of pulsations in Aql X-1 and the recent claim that a relatively strong magnetosphere is present around this system, with a disk truncated at a few tens of kilometer from the neutron star surface (Ludlam et al. 2017). Indeed any magnetosphere around this system requires a strong fine tuning of the parameters to explain the lack of pulses (see Messenger & Patruno 2015 for a discussion).

Another result whose explanation remains problematic is that the intermittent AMXP SAX J1748.9–2021 was observed first as a non-pulsating atoll source (in 1998), then it turned into an intermittent AMXP (in 2001, 2005 & 2009; Altamirano et al. 2008; Patruno et al. 2009a, 2010b) and then it became a persistent AMXP in 2015 (Sanna et al. 2016). In this case therefore the neutron star magnetosphere, if absent in 1998, must have re-emerged on a relatively short timescale for a reason not completely clear.

There is of course also the possibility that some of our underlying assumptions used in the pulse search were not correct. For example our upper limits are valid only if the weak pulsations are always present. If they are appearing intermittently then the upper limits we calculate might be off by a large amount (that depends on the fraction of time the pulsations are on). A second assumption is that the true orbital parameters really lie within the range explored in this search. In particular the orbital periods determined from optical observations are often affected by systematics and it might be possible that some unaccounted effects occur also in the determination of those here selected (see e.g., Patruno et al. 2017b for an overview of such effects). However, it is difficult to believe that none of the eleven (sometimes very conservative) ranges chosen contain at least one of the true orbital periods.

Finally, drifting pulse phases (often in response to X-ray flux variations) have been observed in basically all AMXPs (Hartman et al. 2008; Patruno et al. 2009c, 2012) and this effect has been interpreted as a moving hot spot on the neutron star surface. The drift occurs on timescales of hours/days but it can be as short as few minutes (Patruno 2012). However, if shorter and varying timescales are involved for the hot spot motion in most LMXBs (with the AMXPs being the sources where the motion is the slowest) it is possible to lose the coherence of the signal even if a relatively strong magnetosphere is present. This possibility remains speculative at the moment, but a better understanding of the physical mechanism inducing the hot spot motion might help to clarify the issue.

AP acknowledges support from a Netherlands Organization for Scientific Research (NWO) Vidi Fellowship. The pulse searches were performed on the Atlas computer cluster of the Max Planck Institute for Gravitational Physics.

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