Very low-frequency oscillations from the 11 Hz pulsar in Terzan 5: frame-dragging back on the table.

L. du Buisson1⋆, S. Motta1 and R. Fender1,2

1Department of Physics, University of Oxford, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK.
2Department of Astronomy, University of Cape Town, R. W. James Building, Rondebosch, Cape Town, 7700, South Africa.

Accepted XXX. Received XXX; in original form XXX

ABSTRACT

We present a re-analysis of 47 Rossi X-ray Timing Explorer observations of the 11 Hz accreting pulsar IGR J17480–2446 in Terzan 5 during its 2010 outburst. We studied the fast-time variability properties of the source and searched for quasi-periodic oscillations (QPOs) in a large frequency range. General Relativity predicts that frame-dragging occurs in the vicinity of a spinning compact object and induces the precession of matter orbiting said object. The relativistic precession model predicts that this frame-dragging can be observed as QPOs with a characteristic frequency in the light curves of accreting compact objects. Such QPOs have historically been classified as horizontal branch oscillations in neutron star systems, and for a neutron star spinning at 11 Hz these oscillations are expected at frequencies below 1 Hz. However, previous studies of IGR J17480–2446 have classified QPOs at 35–50 Hz as horizontal branch oscillations, thus casting doubts on the frame-dragging nature of such QPOs. Here we report the detection of seven very low-frequency QPOs, previously undetected, with centroid frequencies below 0.3 Hz, and which can be ascribed to frame-dragging. We also discuss the possible nature of the QPOs detected at 35–50 Hz in this alternative scenario.

Key words: binaries: close - X-rays: stars - stars: individual: GR J17480 – 2446

1 INTRODUCTION

Low-mass X-ray binaries (LMXBs) are systems containing either a neutron star (NS) or a black hole (BH) that accretes mass from a companion star. Accretion happens via an accretion disc, which produces radiation with a characteristic spectrum peaking in the X-rays (Shakura & Sunyaev 1973). NS LMXBs have historically been classified as either Atolls or Z-sources, based on the patterns they trace in their Colour-Colour diagrams or Hardness-Intensity diagrams (CCDs and HIDs, Hasinger & van der Klis 1989), and later connected with the average accretion rates typically observed in either class: very high (often super-Eddington) for Z-sources, and relatively low (below 50% Eddington) for Atolls (Homan et al. 2007). Mu˜noz-Darias et al. (2014) showed that the same state/transition scheme typically used for BH systems (via the HID, Homan et al. 2001, and the rms-intensity diagrams, RIDs, Muñoz-Darias et al. 2011) is evident in NS systems as well, which show hard, intermediate and soft states very similar to those in BH systems.

The X-ray power density spectra (PDS) of both Atolls and Z-sources evolve along the HID track showing different types of narrow features superposed, usually, on broad-band noise, called quasi-periodic oscillations (QPOs). NS LMXB QPOs have been divided into high- and low-frequency QPOs. Low-frequency QPOs (LF QPOs) have centroid frequencies ranging between ~ 0.1 Hz and ~ 60 Hz. For Z-sources, LF QPOs have been historically divided into normal-branch oscillations (NBOs, Middleditch & Fridrikhs 1986), horizontal-branch oscillations (HBOs, van der Klis et al. 1985), and flaring-branch oscillations (FBOs, van der Klis 1989) based on where they are detected along the CCD. Similar QPOs have been found in Atoll sources (see e.g. Di Salvo et al. 2003), which were divided into HBO-like and FBO-like QPOs (Motta et al. 2017) in analogy with the oscillations typical of Z-sources (note that there are no NBO-like QPOs in Atoll sources).

High-frequency QPOs (HF QPOs, Strohmayer 2001; Belloni et al. 2012) are called kHz QPOs in NS systems. These often appear in pairs, and thus are divided into upper and lower kHz QPOs, both with centroid frequencies spanning the range between a few hundred hertz and over a thousand hertz (van der Klis et al. 1996).

X-ray QPOs originate in the innermost regions of the accretion flow, and are believed to be related to the geometry and dynamics of the accretion flow (van der Klis 2006). However, despite being known for decades now (Patterson et al. 1977; Ingram & Motta 2020), QPOs remain poorly understood, and their physical origin is still largely debated. There are different groups of suggested QPO mechanisms in the literature, all somewhat involving either the characteristic motion of matter in a strong field regime, or the oscillation of different parts of the accretion flow (see Ingram & Motta 2020 for a recent review). The relativistic precession model

⋆ E-mail: lise.dubuisson@chch.ox.ac.uk

© 2018 The Authors
(RPM), originally proposed by Stella & Vietri (1998), considers the motion of matter with elliptical orbits slightly tilted with respect to the spin of a compact object, and associates such motions to specific types of QPOs visible in the PDS. In particular, the nodal precession ascribed to the motion of matter related to the frame-dragging occurring around spinning compact objects - known as the Lense-Thirring (LT) effect (Bardeen & Petterson 1975) - has been associated to the HBO and HBO-like QPOs observed in NS LMXBs. The precession of the elliptical orbit’s semi-major axis - the periastron precession - and the orbital frequency are instead associated to the lower and upper kHz QPOs, respectively.

The RPM has been used to interpret QPOs in both NS (Stella & Vietri 1999a; Ingram & Done 2010; du Buisson et al. 2019) and BH systems (Motta et al. 2014a,b). A remarkable exception is however represented by a NS LMXB located in the globular cluster Terzan 5, the 11 Hz accreting pulsar IGR J17480-2446, which seems to show QPOs that cannot be explained in terms of LT precession (Altamirano et al. 2012, ALT2012 from here onwards). ALT2012 analysed the fast-time variability of the source using data from the Rossi X-ray Timing Explorer (RXTE)\(^1\), and found LF QPOs in the range \(\sim 35 - 50 \text{ Hz} \) in 6 observations, and kHz QPOs in the range \(\sim 800 - 920 \text{ Hz} \), which in some cases appeared simultaneously with the LF QPOs. These authors classified the LF QPOs as HBOs, and showed that given the slow spin rate of the NS in the system, they could not be interpreted as the effect of LT precession, which should instead result in QPOs at frequencies strictly below \(0.5 \text{ Hz} \), which were however not detected. These findings thus cast doubt on the LT interpretation of HBOs in NS LMXBs.

In this paper we present the results of a new analysis of the RXTE observations of IGR J17480-2446 during its 2010 outburst, consisting of 47 observations. All observations had source count rates above 10 cts/s/PCU\(^2\), ensuring adequately high signal-to-noise ratios (S/N) for the subsequent analysis.

For each observation we considered Binned, Event, Single Bit and Good Xenon PCA data modes (Jahoda et al. 1996; Bradt et al. 1993) and calculated the PDS using a custom software under IDL\(^3\). We used a maximum time resolution of 1/8192 s (\(\sim 122 \mu\text{s}\)), and divided each observation into segments of both 16 and 512 seconds, respectively, for average PDS production (see Case 1 and Case 2 below). We excluded from the analyses in Case 1 and Case 2 short observations which contained fewer than five segments, and averaged the Leahy-normalised PDS created from each segment to produce one averaged PDS per observation with a Nyquist frequency of 4096 Hz, or two or more average PDS in the case of observations longer than 12000s. We did not subtract the contribution of the Poisson noise \(a_{priori}\), but fitted it when modelling the source PDS. We note that observation 95437-01-01-00 contains a lunar eclipse which was cut from the observation before any further analysis (Motta et al. 2011, Riggio et al. 2012). In cases of sudden drops in an observation’s count rate (usually towards the beginning or end of an observation) that can be ascribed to the re-pointing of the satellite, the beginning/end of an observation is clipped away to prevent the inclusion of low-quality data. It should be noted that all data gaps are removed prior to any FFT being carried out. Our method of PDS production differed depending on the type of QPO we were attempting to detect, as described in Case 1 and Case 2 below.

We also computed the HID for the 47 observations of IGR J17480-2446 we consider here (see Figure 3). The count rates necessary for the computation of the HID were obtained using energy spectra extracted from Standard 2 data, and only using PCU unit 2. For each observation, the source intensity was measured in the 2 – 16 keV energy band, while the hardness was calculated as the ratio of counts in two energy bands as \(H_{\text{HID}} = A/B\), where \(A\) stretches between 6 – 10 keV and \(B\) stretches between 4 – 6 keV (Standard 2 channels 6-9 and 11-19, respectively).

---

1. RXTE: https://heasarc.gsfc.nasa.gov/docs/rxte/

2. PCU: Proportional Counter Unit

3. GHATS: http://www.brera.inaf.it/utenti/belloni/GHATS_Package/Home.html

---

3 OBSERVATIONS AND DATA ANALYSIS

We analysed all publicly available archival RXTE observations of the 11 Hz accreting pulsar IGR J17480-2446 during its 2010 outburst, consisting of 47 observations. All observations had source count rates above 10 cts/s/PCU\(^2\), ensuring adequately high signal-to-noise ratios (S/N) for the subsequent analysis.

For each observation we considered Binned, Event, Single Bit and Good Xenon PCA data modes (Jahoda et al. 1996; Bradt et al. 1993) and calculated the PDS using a custom software under IDL\(^3\). We used a maximum time resolution of 1/8192 s (\(\sim 122 \mu\text{s}\)), and divided each observation into segments of both 16 and 512 seconds, respectively, for average PDS production (see Case 1 and Case 2 below). We excluded from the analyses in Case 1 and Case 2 short observations which contained fewer than five segments, and averaged the Leahy-normalised PDS created from each segment to produce one averaged PDS per observation with a Nyquist frequency of 4096 Hz, or two or more average PDS in the case of observations longer than 12000s. We did not subtract the contribution of the Poisson noise \(a_{priori}\), but fitted it when modeling the source PDS. We note that observation 95437-01-01-00 contains a lunar eclipse which was cut from the observation before any further analysis (Motta et al. 2011, Riggio et al. 2012). In cases of sudden drops in an observation’s count rate (usually towards the beginning or end of an observation) that can be ascribed to the re-pointing of the satellite, the beginning/end of an observation is clipped away to prevent the inclusion of low-quality data. It should be noted that all data gaps are removed prior to any FFT being carried out. Our method of PDS production differed depending on the type of QPO we were attempting to detect, as described in Case 1 and Case 2 below.

We also computed the HID for the 47 observations of IGR J17480-2446 we consider here (see Figure 3). The count rates necessary for the computation of the HID were obtained using energy spectra extracted from Standard 2 data, and only using PCU unit 2. For each observation, the source intensity was measured in the 2 – 16 keV energy band, while the hardness was calculated as the ratio of counts in two energy bands as \(H_{\text{HID}} = A/B\), where \(A\) stretches between 6 – 10 keV and \(B\) stretches between 4 – 6 keV (Standard 2 channels 6-9 and 11-19, respectively).
3.1 Case 1: searching for very low frequency QPOs

Following the prescriptions of the RPM, ALT2012 calculated that the HBO QPO of IGR J17480-2446 should fall strictly below 0.82 Hz. In order to detect such very low frequency (VLF) QPOs, it is necessary to calculate PDS with a frequency resolution of 0.08 Hz or better. We therefore divided our observations into segments of 512 seconds, from which we calculated PDS with a frequency resolution of 1/512 Hz ~ 0.002 Hz, sufficient for the task at hand.

The observations of IGR J17480-2446 contain, however, a large number of Type-I X-ray bursts (see Motta et al. 2011). These bursts have a soft, thermal spectrum, but their short recurrence times (down to about 200s) introduces quasi-periodic variability in the light curve that can take the form of a QPO in the PDS (in this case generated from the NS surface) that is not easily distinguishable from other (accretion-driven) types of QPOs, thereby obstructing the process of finding VLF QPOs. The short Type-I X-ray burst recurrence time implies that - in most cases - cutting the bursts out of our observations leaves too little data for proper analysis. In other words, apart from for a few cases, it was impossible to recover data stretches long enough to reach the frequency resolution needed for our analysis.

We therefore instead performed an energy selection on our data, considering only photons in higher energy bands. In order to select bands that sufficiently removed Type-I X-ray bursts, we applied the following cuts to the entire dataset and inspected the resulting light curves:

- 0 – 120 keV (absolute PCA channels 0 – 249)
- 8 – 120 keV (absolute PCA channels 20 – 249)
- 10 – 120 keV (absolute PCA channels 25 – 249)
- 12 – 120 keV (absolute PCA channels 30 – 249)
- 15 – 120 keV (absolute PCA channels 35 – 249)
- 17 – 120 keV (absolute PCA channels 40 – 249).

An example of the effect of these cuts on an observation’s light curve can be seen in Appendix A. From this assessment, it was found that cuts associated to the 15 – 120 keV and 17 – 120 keV bands adequately removed the Type-I X-ray bursts. We finally decided to use the ~15 – 120 keV band (absolute PCA channels 35 to 249) to derive our PDS, as this still allowed for a high enough S/N in the PDS for the subsequent analysis. We also note that the accretion-driven aperiodic and quasi-periodic variability trend to have a hard spectrum (e.g., Sobolewska & Życki 2006), meaning our strategy effectively reduces the number of soft, non-variable photons, thus emphasising the remaining variability. Following the described strategy, we effectively minimise the contribution of Type-I X-ray bursts in our PDS while retaining possible HBO QPOs.

The recurrence time of the Type-I X-ray bursts in our observations vary between 200s to over 500s, depending on the observation. Their presence could therefore generate peaks in PDS at frequencies smaller than 0.005 Hz. We thus conservatively exclude all significant QPO-like features falling below 0.000 Hz from our analysis (which could still be due to residual X-ray burst contributions) in order to avoid any possible contamination of our results.

3.2 Case 2: searching for low frequency QPOs and kHz QPOs

ALT2012 found LF QPOs in the ~35 – 50 Hz range, and kHz QPOs between ~800 Hz and 920 Hz. In order to find these features in the observations considered here, we divided each of our observations into intervals of 16 seconds for the calculation of PDS, resulting in a frequency resolution of 0.0625 Hz. This is preferable to the 512s intervals used for Case 1, as the large number of PDS produced in this way is averaged, significantly increasing the S/N. However, it can happen that the averaged PDS from long observations contain broadened features due to the movement of QPOs in frequency as time progresses. For the cases where an observation was longer than 12000s, we split the observation into shorter segments of approximately 3500s in length, and calculated an averaged PDS for each of them, which we fitted individually.

We then investigated three different methods of PDS production to determine which one resulted in the optimal detection of LF QPOs and kHz QPOs. First, we simply derived the PDS using the energy band ~2 – 120 keV (absolute PCA channels 0 to 249). Next we used the same energy band, but also cut the Type-I X-ray bursts out of observations. The short time intervals used to calculate PDS allowed us to generate a good S/N for the average PDS using the time intervals between consecutive Type-I X-ray bursts. Finally, we produced PDS in the energy band ~15 – 120 keV (absolute PCA channels 35 to 249) without any burst cuts. The first method presented us with the largest number of significant QPOs in our data, and it was therefore employed to search for LF QPOs and kHz QPOs.

3.3 Power spectral fitting

To find the QPOs present in our dataset, we preselected the PDS of observations that visually contained these features for each of the cases above. The features of each power spectrum were fit with a combination of Lorentzians and a power-law component (to account for the Poisson noise) by means of the XSPEC package (Arnaud 1996) by using a one-to-one energy-frequency conversion for our PDS and a unity response matrix. We excluded all non-significant features from the analysis: for very low frequencies (where flat-top noise or red noise were present), this meant excluding features below a significance\(^4\) of 2\(\sigma\) (in order to account for the lower relative frequency resolution); at all other frequencies features had to be significant at or above 3\(\sigma\). QPOs were identified by requiring that a given feature is detected at a significance of 3\(\sigma\) or above, and has a quality factor \(Q \geq 2\) (taking uncertainties into account). Here \(Q = v_c/\Delta v\), where \(v_c\) is the centre frequency and \(\Delta v\) the FWHM\(^5\) of the Lorentzian.

Due to the X-ray pulsar nature of the NS in IGR J17480-2446, a very narrow peak corresponding to the 11 Hz pulsation is visible in our PDS. We do not cut this peak from the PDS - instead, we fit it along with the rest of the features.

4 RESULTS

We report in Table 1 the VLF QPOs found by carrying out the analysis described in Case 1 and fitting the resulting PDS (top section), as well as the LF and kHz QPOs found through the analysis described in Case 2 (bottom two sections). For more information on the fitting of the PDS of the observations containing VLF QPOs, see Appendix B. We found 7 VLF QPOs having centre frequencies

\(^4\) Significance is calculated as the integral of the power of the Lorentzian used for the fitting of the feature divided by the negative 1\(\sigma\) error on this integral.

\(^5\) FWHM: full width at half maximum
late to a peak (if any) in the PDS at were removed by our energy cuts) were found, the recurrence times for Type-I X-ray bursts (before they further note that for the observations in which VLF QPOs were detections correspond exactly to those reported in ALT2012. We not given. It is therefore not trivial to determine if and when our exclusion of all significant QPO-like features falling below 0 kHz QPOs in the range ∼ kHz QPOs were found through our LF and kHz QPOs fall within those reported by ALT2012. We note, however, that the analysis performed by these authors differed our LF and kHz QPOs were found through Case 2 analysis (see Section 3.2). In the cases where observations were cut into two or more independent segments, an extra digit attached at the end of their observation IDs indicate which segment was used. See the text for more details. All errors reported in this table are 1 σ errors.

| Obs ID          | Frequency (Hz) | Q factor | Significance |
|-----------------|----------------|----------|--------------|
| **VLF QPOs**    |                |          |              |
| 95437-01-02-01  | 0.0101±0.0011  | 1.9±0.7  | 4.3σ         |
| 95437-01-10-05  | 0.010±0.0002   | 1.6±0.3  | 6.2σ         |
| 95437-01-11-03  | 0.016±0.002    | 2±1      | 3.2σ         |
| 95437-01-11-06* | 0.020±0.001    | 4±1      | 3.9σ         |
| 95437-01-12-04* | 0.0175±0.0006  | 5±2      | 4.2σ         |
| 95437-01-13-04  | 0.029±0.002    | 3±1      | 3.8σ         |
| 95437-01-14-00  | 0.014±0.002    | 2±1      | 3.2σ         |
| **LF QPOs**     |                |          |              |
| 95437-01-07-00  | 47.5±0.5       | 3.2±0.4  | 11.9σ        |
| 95437-01-08-00-1| 49.2±0.8       | 5±2      | 4.8σ         |
| 95437-01-09-00  | 44.7±0.6       | 5±1      | 6.9σ         |
| **kHz QPOs**    |                |          |              |
| 95437-01-07-00  | 840±7         | 12±5     | 3.3σ         |
| 95437-01-09-00  | 854±4         | 22±8     | 4.9σ         |
| 95437-01-10-01  | 870±6         | 21±10    | 3.7σ         |

in the range ∼ 0.01 – 0.03 Hz (for illustration, three of these are shown in Figure 1), 3 LF QPOs in the range ∼ 44 – 50 Hz and 3 kHz QPOs in the range ∼ 840 – 870 Hz. The frequency ranges of our LF and kHz QPOs fall within those reported by ALT2012. We note, however, that the analysis performed by these authors differed slightly from ours, and a list of their six observations considered is not given. It is therefore not trivial to determine if and when our detections correspond exactly to those reported in ALT2012. We further note that for the observations in which VLF QPOs were found, the recurrence times for Type-I X-ray bursts (before they were removed by our energy cuts) were > 670s - this would translate to a peak (if any) in the PDS at < 0.0015 Hz. Our conservative exclusion of all significant QPO-like features falling below 0.009 Hz from our analysis (see Section 3.1) is therefore justified.

In order to compare the quasi-periodic features we detected with the predictions of the RPM, we used the RPM equations given in Motta et al. 2014a (see also Section 2) to plot the theoretical estimates of $\nu_{\text{fad}}, \nu_{\text{jet}}$ and $\nu_{\text{g}}$ as a function of the emission radius $r$. We used the measured spin frequency $\nu = 11$ Hz of the source, and calculated the minimum and maximum dimensionless spins ($a_{\text{min}}$ and $a_{\text{max}}$) by assuming a minimum and maximum moment of inertia for the NS ($I_{\text{min}}$ and $I_{\text{max}}$), respectively. To do so, we followed Mukherjee et al. (2018), and in particular their Figure 4, which shows the moment of inertia as a function of different NS masses inferred for a number of realistic candidate NS equations of state. We found $I_{\text{min}} = 0.75 \times 10^{55}$ g cm$^2$ for a NS mass of $M_{\text{min}} = 1.0$ M$_\odot$ and $I_{\text{max}} = 5 \times 10^{55}$ g cm$^2$ for a mass of $M_{\text{max}} = 2.7$ M$_\odot$. We then calculated the minimum and maximum dimensionless spin parameters $a_{\text{min}}$ and $a_{\text{max}}$, to find $0.0054 \leq a \leq 0.0059$. Next, we used Equations 9, 6 and 1 in Ingram & Motta (2014) to determine the minimum and maximum theoretical estimates of $\nu_{\text{fad}}, \nu_{\text{jet}}$ and $\nu_{\text{g}}$ as a function of the emission radius $r$, assuming first $a_{\text{min}}$ and $M_{\text{min}}$, and then $a_{\text{max}}$ and

![Figure 1](image-url)
function of the radius by the same authors.

Table 1), with centroid frequencies consistent with those reported of the compact object, we hypothesised that given the very low BH systems, should show at least a mild dependence on the spin.

5 DISCUSSION

The HID for our data is shown in Figure 3, showing the source count rate and hardness of each observation in our analysis. Consecutive observations are connected via thin lines, with the earliest and latest observations circled and numbered. Red data points indicate observations containing VLF QPOs, light blue observations contain LF QPOs and black observations contain kHz QPOs (note that in two cases LF QPOs and kHz QPOs are detected simultaneously). VLF QPOs are detected both at the beginning and at the end of the outburst, in a hard state, while LF QPOs and kHz QPOs are found in a relatively soft state, close to the peak of the outburst which, according to Motta et al. (2011), reached and possibly exceeded the Eddington limit.

Figure 2. The minimum and maximum theoretical values of \( v_{\text{nod}}, v_{\text{per}} \) and \( \nu_{\text{ph}} \) as a function of the emission radius \( r \) for IGR J17480-2446, inferred using the RPM. Coloured lines indicate the maximum and minimum predicted values, respectively. Straight horizontal dashed lines mark the frequency ranges in which QPOs were found.

\( M_{\text{max}} \). Our result is displayed in Figure 2, where we also marked the frequency ranges where we detected QPOs in our data.

Concerning point (iii) we also tested for the non-simultaneity of the two QPOs in observations 95437-01-07-00 and 95437-01-09-00 by splitting each into several smaller segments, but both features seem to be present during a large fraction of these two observations. Assuming the correctness of the RPM, the simultaneity of the kHz QPOs and LF QPOs point to two main scenarios:

(i) The kHz QPOs that we detected are consistent with being either the upper or lower kHz QPOs, thus associated to the orbital or periastron precession frequency of matter at a radius lower than approximately \( 12\ R_g \) (\( \approx 25\ \text{km} \)) from the NS centre. The lack of a simultaneous detection of two kHz QPOs prevents any further classification.

(ii) The kHz QPOs that we detected are not consistent with the nodal precession frequency around a NS spinning at 11 Hz. They are, in principle, consistent with the periastron precession frequency of matter orbiting at a distance of \( 15 \sim 25\ R_g \) from the NS. However, we note that two of our LF QPOs are detected together with kHz QPOs at \( \sim 840\ \text{Hz} \) (see Table 1, observation 95437-01-07-00 and 95437-01-09-00). According to Figure 2, this would imply the simultaneous detection of QPOs at two very different radii, which would constitute a violation of one of the key assumptions of the RPM.

The first scenario pushes us toward the same conclusion drawn by ALT2012, i.e. that the RPM cannot explain the frequency properties of at least some of the QPOs, at least in its simplest form. The second scenario, instead, further stresses the question of the real nature of the LF QPOs observed between 35 and 50 Hz in IGR J17480-2446. ALT2012 classified the QPOs at 35 – 50 Hz based on their frequency (comparable with the values typically seen in other NS systems), and based on the position these features occupied in the so-called Wijnands – van der Klis correlation (Wijnands & van der Klis 1999), formed by the frequency of a broad PDS component (called \( L_5 \)) and the frequency of the HBO. The small number of QPOs detected by both ALT2012 and by ourselves does not really allow for the establishing of a correlation, and the fact that most of the components identifiable in a NS PDS correlate with one another (see Psaltis et al. 1999) suggests that ALT2012’s classification of the LF QPOs at 35 – 50 Hz might not be correct. Unfortunately, given the very low frequency of the VLF QPOs that we report in this work, it is not possible to determine whether these do fit into the Wijnands & van der Klis correlation (the \( L_5 \) component’s centroid frequency would be visible below 10 mHz, which is lower than our frequency resolution, assuming HBO frequencies between 1 and 2.7 \( M_\odot \), and adopting a dimensionless spin parameter \( 0.0054 \leq \alpha \leq 0.0059 \). By comparing our estimates with the QPOs we detected we observe the following:

(i) The VLF QPOs we detected are consistent with being HBOs - QPOs generated through LT precession of the accretion flow - at a radius larger than approximately 15 \( R_g \) (\( \approx 35\ \text{km} \)) from the NS centre. This is supported by the fact that these features all appear in a relatively hard state, as is clear from the HID, where the inner disc radius is believed to be truncated far from the NS surface (see e.g. Done et al. 2007).

(ii) The kHz QPOs that we detected are consistent with being either the upper or lower kHz QPOs, thus associated to the orbital or periastron precession frequency of matter at a radius lower than approximately 12 \( R_g \) (\( \approx 25\ \text{km} \)) from the NS centre. The lack of a simultaneous detection of two kHz QPOs prevents any further classification.

(iii) As already noted by ALT2012, the LF QPOs detected are not consistent with the nodal precession frequency around a NS spinning at 11 Hz. They are, in principle, consistent with the periastron precession frequency of matter orbiting at a distance of \( 15 \sim 25\ R_g \) from the NS. However, we note that two of our LF QPOs are detected together with kHz QPOs at \( \sim 840\ \text{Hz} \) (see Table 1, observation 95437-01-07-00 and 95437-01-09-00). According to Figure 2, this would imply the simultaneous detection of QPOs at two very different radii, which would constitute a violation of one of the key assumptions of the RPM.

We estimated the theoretical values of \( v_{\text{nod}}, v_{\text{per}} \) and \( \nu_{\text{ph}} \) as a function of the radius \( r \), obtained assuming a NS with mass \( M \) be-
be consistent with the periastron precession frequency of material orbiting at approximately 15 $R_g$ from the NS centre. The presence of kHz QPOs simultaneous to these LF QPOs, however, either disproves this hypothesis or invalidates one of the main assumptions of the RPM.

We have shown that VLQ QPOs at frequencies consistent with those expected for LF driven modulations are present in the data, even though more data are required to confirm the classification of such features. While not conclusive, our results cast (even more) doubt on the nature of the 35−50 Hz QPOs detected in IGR J17480−2446. These LF QPOs could either be associated with the periastron precession frequency (though in this case a key assumption of the RPM needs to be relaxed significantly), or with a type of QPO known as hectohertz QPOs, observed here at smaller frequencies possibly due to the low NS spin. It is also, of course, entirely possible that these LF QPOs are simply a new type of QPO, possibly peculiar to this unique system, or perhaps typical of slowly spinning accreting NS LMXBs, of which IGR J17480−2446 is currently the only example.

ACKNOWLEDGMENTS

LdB acknowledges support from the Rhodes Trust and Christ Church College. SEM acknowledges the Science and Technology Facilities Council (STFC) for financial support, and the Oxford Centre for Astrophysical Surveys, which is funded through generous support from the Hintze Family Charitable Foundation. The authors thank Diego Altamirano for valuable discussions.

DATA AVAILABILITY

The data underlying this article are publicly available from the RXTE Archive: https://heasarc.gsfc.nasa.gov/docs/xte/archive.html.

REFERENCES

Altamirano D., van der Klis M., Méndez M., Jonker P. G., Klein-Wolt M., Lewin W. H. G., 2008, ApJ, 685, 436
Altamirano D., Ingram A., van der Klis M., Wijnands R., Linares M., Homan J., 2012, ApJL, 759, L20
Arnaud K. A., 1996, in G. H. Jacoby & J. Barnes ed., Astronomical Society of the Pacific Conference Series Vol. 101, Astronomical Data Analysis Software and Systems V, pp 17–+
Bardeen J. M., Petterson J. A., 1975, ApJ, 195, L65
Belloni T. M., Sanna A., Méndez M., 2012, MNRAS, 426, 1701
Bradt H. V., Rothschild R. E., Swank J. H., 1993, ApJ, 407, 535
Di Salvo T., Méndez M., van der Klis M., 2003, A&A, 406, 177
Done C., Gierlinski M., Kubota A., 2007, A&A, 464, 15
Branchini A., Motta S., Lodato G., 2017, MNRAS, 467, 145
Hasinger G., van der Klis M., 1989, A&A, 225, 79
Homan J., Wijnands R., van der Klis M., van Paradijs J., van der Klis M., 2007, ApJ, 656, 436
Ingram A., Done C., 2010, MNRAS, 405, 2447
Ingram A., Motta S., 2014, MNRAS, 444, 2065
Ingram A., Motta S., 2020, arXiv e-prints, p. arXiv:2001.08758
Ingram A., Done C., Fragile P. C., 2009, MNRAS, 397, L101
Jahoda K., Swank J. H., Giles A. B., Stark M. J., Strohmayer T., Zhang W., Morgan E. H., 1996, in Siegmund O. H., Gummin M. A., eds, Proc. SPIE Vol. 2808, EUV, X-Ray, and Gamma-Ray Instrumentation for Astronomy VII. pp 59–70, doi:10.1117/12.256034

Figure 3. The HID of IGR J17480-2446, where the source count rate is plotted against the spectral hardness. Each data point represents an observation, and consecutive observations are connected. The first and last observation considered are marked on the plot and denoted by ‘first’ and ‘last’, respectively. Small red dots are observations containing VLF QPOs, larger light blue dots are observations containing LF QPOs, and black crosses are observations containing kHz QPOs (see also Table 1). Light blue dots overlaid by black crosses contain both LF QPOs and kHz QPOs. A colour version of this figure is available online.

lower than 0.1 Hz). Only a new outburst form this source and new data will therefore allow us to reach more conclusive results.

Is there an alternative explanation for these LF QPOs? PDS from NS systems are notoriously more structured and feature-rich than those from BH systems. Among the still-largely unknown features typical of NS systems are hectohertz QPOs (see e.g. Altamirano et al. 2008). These QPOs have been detected in a number of Atoll sources - 4U0614+09, 4U1608-52, 4U1728-34 and 4U1636-53 - around ~100 Hz. Interestingly, all these sources contain NSs spinning at fairly high frequencies (415, 620, 363 and 581 Hz, respectively). While there is no known correlation between the NS spin and the frequency of hectohertz QPOs, it seems plausible that in a slowly spinning NS such as the one in IGR J17480-2446 hectohertz QPOs can appear at frequencies lower than ~100 Hz.

We therefore speculate that the LF QPOs detected in IGR J17480-2446 might be relatively low-frequency hectohertz QPOs.

6 SUMMARY AND CONCLUSIONS

We have examined all 47 RXTE PCA observations of the 11 Hz accreting pulsar IGR J17480-2446 located in the globular cluster Terzan 5 during its 2010 outburst. We searched for QPO features located between 0.01 Hz and ~4000 Hz.

We found 7 VLF QPOs with centre frequencies in the range ~0.01−0.03 Hz, 3 LF QPOs in the range ~44−50 Hz, and 3 kHz QPOs in the range ~840−870 Hz. We compared the theoretical values of the nodal frequency $\nu_{nod}$, periastron precession frequency $\nu_{pp}$ and orbital frequency $\nu_{o}$ as a function of the emission radius as predicted by the RPM to our findings. We find that the centroid frequencies of our detected VLF QPOs are consistent with the predicted nodal frequencies if generated at radii larger than 15 $R_g$. We also find that our LF QPOs detected at 40−50 Hz could be consistent with the periastron precession frequency of material
APPENDIX A: CASE 1 ENERGY BAND CUTS

In order to correctly select higher energy bands that would sufficiently remove Type-I X-ray bursts from observations in our Case 1 analysis, the following cuts were applied to the entire dataset:

- $0 - 120$ keV (absolute PCA channels 0 – 249)
- $8 - 120$ keV (absolute PCA channels 20 – 249)
- $10 - 120$ keV (absolute PCA channels 25 – 249)
- $12 - 120$ keV (absolute PCA channels 30 – 249)
- $15 - 120$ keV (absolute PCA channels 35 – 249)
- $17 - 120$ keV (absolute PCA channels 40 – 249).

An example of the effect of these cuts on an observation’s light curve (observation ID 95437-01-10-02) can be seen in Figure A1.
Figure A1. The effect of our energy cuts on the light curve of Obs ID 95437-01-10-02. From top to bottom, the cuts are as follows: 0 – 120 keV, 8 – 120 keV, 10 – 120 keV, 12 – 120 keV, 15 – 120 keV, and 17 – 120 keV. Absolute PCA channels used are indicated in the figure.
APPENDIX B: VLF QPO OBSERVATIONS

Table B1: Details of the fit parameters of the PDS containing VLF QPOs, found following the Case 1 analysis (see Section 3.1). Observation IDs are given in the first column, whereafter the next four columns report the center frequency, full width at half maxima (FWHM), integral power of the Lorentzian, and significance of the Lorentzians used for fitting VLF QPOs. Significance is calculated as the integral of the power of the Lorentzian divided by the negative 1σ error on this integral. All errors reported in this table are 1σ errors. The center frequency and FWHM of other Lorentzians used for fitting the remainder of the PDS are reported in the following two columns. In the case that more than one extra Lorentzian were required, the parameters are given on a new line. Obs ID 95437-01-11-06 and 95437-01-12-04 both contain QPOs separate from the VLF QPOs with significances of $4.7\sigma$ and $4.1\sigma$, respectively. These could be second harmonics of the VLF QPOs, and are given on the second line of each of these observations. Obs ID 95437-01-13-04 includes a peak with a significance of $4.8\sigma$ it a relevant residual at lower frequencies, but excluding it from being a QPO by our specification requirements (see Section 3.3). We note that this peak could possibly be the VLF QPO of this observation, but at this point its significance excludes it from being a contender. The fitting of each observation’s PDS further includes a power-law component to account for the Poisson noise, in the form $f(x) = Kx^{-\alpha}$; $\alpha$ is set to 0.0 for each observation, while $K$ is fit - the value of $K$ for each observation can be seen in the last column. Due to the X-ray pulsar nature of the NS in IGR J17480-2446, a very narrow peak corresponding to the 11 Hz pulsation is visible in some PDS. We fit this peak with a Lorentzian, whereafter we fix the parameters. Obs IDs of observation PDS including this peak is marked with a †. Any other parameters that were fixed during PDS fitting is marked with an asterisk.

| Obs ID     | Freq. (Hz) | FWHM (Hz) | Integral power | Sign. | Freq. (Hz) | FWHM (Hz) | Reduced $\chi^2$ | K          |
|------------|------------|-----------|----------------|-------|------------|-----------|------------------|------------|
| 95437-01-02-01† | $0.1010^{+0.0011}_{-0.0008}$ | $0.005 \pm 0.002$ | $7e-4 \pm 2e-4$ | $4.3\sigma$ | $0.003^*$ | $0.002^*$ | 1.1 | $0.036820 \pm 7e-6$ |
| 95437-01-10-05  | $0.016^{+0.002}_{-0.001}$ | $0.006 \pm 0.003$ | $4.0e-4 \pm 1.2e-4$ | $6.2\sigma$ | $0.0^*$ | $7e-8^*$ | 0.97 | $0.020404 \pm 5e-6$ |
| 95437-01-11-03  | $0.016 \pm 0.002$ | $0.006^{+0.003}_{-0.002}$ | $4e-4 \pm 1e-4$ | $3.2\sigma$ | $0.0^*$ | $5e-3^*$ | 1.0 | $0.020124 \pm 5e-6$ |
| 95437-01-11-06  | $0.020 \pm 0.001$ | $0.005 \pm 0.002$ | $9e-4 \pm 2e-4$ | $3.9\sigma$ | $0.002^*$ | $0.010^*$ | 1.0 | $0.018638 \pm 4e-6$ |
| 95437-01-12-04  | $0.0175 \pm 6e-4$ | $0.004^{+0.002}_{-0.001}$ | $1.6e-3 \pm 4e-4$ | $4.2\sigma$ | $0.0^*$ | $0.006^*$ | 0.94 | $0.022009 \pm 5e-6$ |
| 95437-01-13-04  | $0.029 \pm 0.002$ | $0.009^{+0.004}_{-0.003}$ | $1.2e-3 \pm 3e-4$ | $3.8\sigma$ | $2.4e-3 \pm 6e-4^*$ | $7.3e-3 \pm 8e-4^*$ | 0.91 | $0.038919 \pm 9e-6$ |
| 95437-01-14-00  | $0.014 \pm 0.002$ | $0.007 \pm 0.003$ | $2.2e-3 \pm 7e-4$ | $3.2\sigma$ | $0.0^*$ | $0.001^*$ | 0.97 | $0.13629 \pm 3e-5$ |