

# Discovery of the upper kilohertz quasi-periodic oscillation from the X-ray transient Aql X-1

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## ABSTRACT

We report on a comprehensive analysis of the kilohertz ( $\geq 600$  Hz) quasi-periodic oscillations (kHz QPOs) detected from the neutron star X-ray transient Aquila X-1 (Aql X-1) with the Rossi X-ray Timing Explorer, between 1997 and 2007. Among kHz QPO sources, Aql X-1 is peculiar because so far only 1-kHz QPO has been reported, whereas in most sources, 2-kHz QPOs are usually detected (a lower and an upper kHz QPO). The identification of the QPOs reported so far has therefore been ambiguous, although it has been proposed that they were likely to be the lower QPO. Following up on previous work, we confirm the identification of the QPOs previously reported as lower QPOs, because of their high-quality factors and the quality factor versus frequency dependency, which are similar to those observed in other sources. Combining all segments of data containing a lower QPO, we detect for the first time an upper kHz QPO. As in other sources for which the neutron star spin frequency is larger than 400 Hz (550.25 Hz in Aql X-1), the frequency difference between the 2-kHz QPOs is close to half the spin frequency. Based on this result, we re-examine the link between the neutron star spin and the frequency of the kHz QPOs to show that a model in which the separation of the lower and the upper QPOs relates to the neutron star spin frequency is still as good as any comparably simple model.

**Key words:** accretion, accretion discs – stars: neutron – X-rays – stars.

## 1 INTRODUCTION

Since its launch in 1995, the Rossi X-ray Timing Explorer (Bradt, Rothschild & Swank 1993) has detected kilohertz quasi-periodic oscillations (kHz QPOs) in more than 25 accreting systems containing a weakly magnetized neutron star (see van der Klis 2006 for a review). In most sources, 2-kHz QPOs are usually detected, the lower of the two is seen as a relatively narrow peak in the Fourier power density spectrum (PDS) with a quality factor ( $Q = \nu/\Delta\nu$ ) exceeding 200 (e.g. Barret et al. 2005a), whereas the upper QPO is typically much broader ( $Q \sim 5\text{--}20$ ). This makes the lower QPO easier to detect, especially on short time-scales. Both the lower and the upper QPOs vary in frequency with time, but the frequency difference remains always close to the spin frequency of the neutron star (or half its value). Removing the contribution of the frequency drift to the measured QPO width, Barret, Olive & Miller (2005b) have demonstrated that the lower and the upper QPOs follow a, they found that the quality factor of the lower kHz QPOs different path in a quality factor versus frequency diagram. In particular increases smoothly with frequency, saturates at a maximum value, beyond

which a sharp drop is observed (Barret et al. 2005b). The same behaviour has been observed in several different systems (Barret et al. 2006), suggesting that the drop is related to a special location in space–time, e.g. the innermost stable circular orbit (ISCO) (Barret, Olive & Miller 2006, 2007).

Previous investigations of the kHz QPOs detected from the recurrent X-ray transient Aql X-1 (Cui et al. 1998; Zhang et al. 1998; Reig et al. 2000; Méndez, van der Klis & Ford 2001; Reig, van Straaten & van der Klis 2004) have reported only a single QPO, making its identification difficult. By comparison with the properties of lower QPOs seen in twin QPO sources (correlation of the frequency and spectral colours, QPO width, rms-frequency dependency, energy spectrum of the QPOs), it was, however, proposed that the QPOs detected were likely to be lower QPOs (Méndez et al. 2001).

Aql X-1 contains a rapidly rotating neutron star, spinning at 550.25 Hz, as inferred from the discovery of an episode of coherent pulsation in its persistent emission (Casella et al. 2007). This frequency is close to the previously detected frequency of X-ray burst oscillations (Zhang et al. 1998). By analogy with other sources spinning at a frequency above 400 Hz, one would therefore expect an upper QPO to be detected with a frequency separation close to 275 Hz (see van der Klis 2006 for a review). Despite extensive searches, no such QPO has yet been reported.

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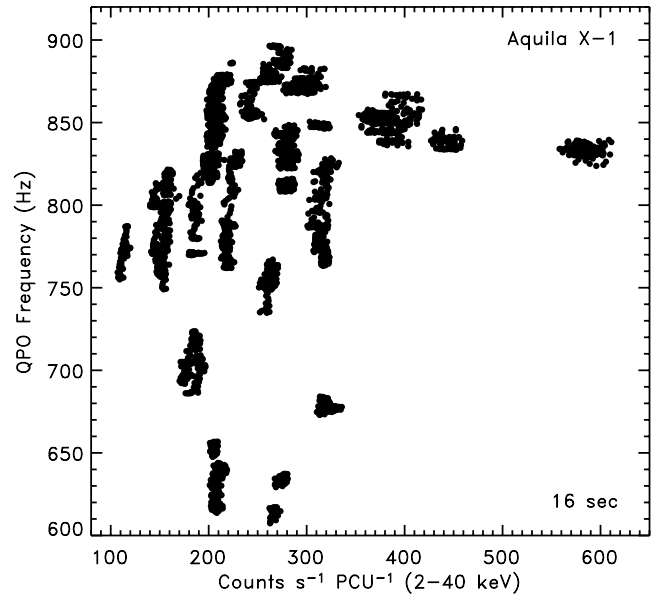
In this paper, we analyse in a homogenous way all archival *RXTE* data on Aql X-1, with the goal of studying the quality factor of the QPOs and searching for an upper QPO. The data used here have been presented in Zhang et al. (1998), Cui et al. (1998), Reig et al. (2000), Méndez et al. (2001) and Reig et al. (2004). In the next section, we present our analysis scheme, which builds upon previously described procedures in Barret et al. (2005b, 2006, 2007). We then present our results, which reveal for the first time (i) that the quality factor of the lower QPOs follows the same pattern seen in other sources (e.g. 4U 1608–522 and 4U 1636–536, Barret et al. 2006) and (ii) Aql X-1 displays an upper QPO, that is, detected close to half the spin frequency of the neutron star (275 Hz), when combining all the data available. Starting with this result, we then discuss on the link between kHz QPOs and neutron star spin.

## 2 OBSERVATIONS AND RESULTS

For the purposes of this paper, we have retrieved all science event files for Aql X-1 from the *RXTE* High Energy Astrophysics Science Archive Research Center (HEASARC) archives. Data up to the July 2007 are used. The files are identified with their observation identifier (ObsID) following the *RXTE* convention. An ObsID identifies a temporally contiguous collection of data from a single pointing. Type I X-ray bursts and data gaps are removed from the files.

For each file identified with its ObsID, we have computed Leahy normalized Fourier PDS between 1 and 2048 Hz over 16 s intervals (with 1 Hz resolution), using events with energy between 2 and 40 keV.  $N$  16-s PDS are thus computed.  $N$  is typically around 150–200 in most files, whose duration  $\sim 3000$  s is consistent with the orbital period of the *RXTE* spacecraft. A PDS averaging the  $N$  PDS is first computed. This averaged PDS is then searched for a high-frequency QPO between 500 and 1500 Hz, using a scanning technique which looks for peak excesses above the Poisson counting noise level (Boirin et al. 2000). The strongest excess is then fitted within a 400 Hz window (200 Hz on each side of the peak) with a Lorentzian of three parameters (frequency, full width at half-maximum and its integral) to which a constant is added to account for the counting noise level (close to 2.0 in a Leahy normalized PDS). If the significance of the fitted excess is less than  $3\sigma$ , the ObsID is not considered for further processing. A QPO (with  $Q > 10$ ) is detected in 47 ObsIDs.

We wish to estimate the quality factor of the QPO, after removing as much as possible the contribution from the frequency drift to the measured width (Barret et al. 2005b, 2006). For this, we must first reconstruct the time evolution of the QPO frequency, within each ObsID of interest. Because the frequency may change significantly (up to tens of Hz in 1000 s), we must consider the shortest time-scales to track those frequency changes. Given the strength of the QPOs of Aql X-1, we have found that 256 s was an appropriate time-scale, which allows a homogeneous study of all its QPOs. Using a sliding time window of 256 s with a time-step of  $256/4 = 64$  s, we have averaged 16 16-s PDS. This PDS is then searched for an excess around the mean QPO frequency, and the strongest excess is again fitted with a Lorentzian within a 400 Hz frequency window. Between two consecutive QPO detections (above a given significance threshold), a linear interpolation enables us to estimate the instantaneous QPO frequency in the 16-s PDS. In addition, the QPO may not be detected all the time (due for instance to statistical fluctuations or a rapid frequency jump), so gaps of duration shorter than 256 s are filled with a linear interpolation. Those PDS for which no estimate of the QPO frequency has been obtained are



**Figure 1.** QPO frequency versus 2–40 keV count rate. There are 4364 individual measurements representing the count rate integrated over 16 s.

removed from the subsequent analysis. Taking  $3\sigma$  for the significance threshold, we were able to reconstruct the time evolution of the QPO frequency in 39 out of the 47 ObsIDs in which a QPO was detected. Fig. 1 shows the instantaneous QPO frequency against the 2–40 keV count rate per PCA unit. As can be seen, those QPOs are detected between 600 and 900 Hz. The source displays the so-called parallel tracks on the left-hand side of the figure, but the tracks seem to have collapsed at higher count rates. It is interesting to note that the high-count rate high frequency part of the diagram has not been sampled yet (unlike other sources, e.g. 4U 1636–536, Barret et al. 2005b).

Having reconstructed the time history of the QPO frequency, in each ObsID, we can now shift-and-add the PDS associated with a frequency to a reference frequency and fit the resulting QPO. In Table 1, we list the measured parameters of the QPOs, in particular, its mean quality factor. The minimum  $Q$  value is 60 with a maximum around 200. As shown in Fig. 2, there is a trend for the quality factor to increase with frequency. Both the high  $Q$  value and its dependency suggest that these QPOs are lower QPOs.

In order to get a better description of the quality factor of the QPOs, we have grouped all the instantaneous frequencies with a bin of 50 Hz. All 16-s PDS falling into the same bin are then shifted to the mean frequency and added. The mean quality factor of the QPOs so recovered is shown in Fig. 3. Although the sample of QPOs is relatively limited (tens of ObsID containing a QPO, as opposed to more than 200 in the case of 4U1636–536, Barret et al. 2005b), our data are consistent with a saturation of the quality factor, and even suggestive of a decrease at high frequencies. This behaviour is clearly reminiscent of the lower kHz QPO, as the upper QPO is generally characterized in this frequency range by a much lower  $Q$  (up to 20 at most), rising steadily with frequency. Therefore, our results support previous claims that the strong QPOs detected so far from Aql X-1 are lower QPOs (Méndez et al. 2001).

In addition to the observations listed in Table 1, there are eight ObsIDs in which the QPO frequency could not be tracked with the above method (shorter observations or weaker signal). For those observations (eight in total), only the mean QPO parameters over

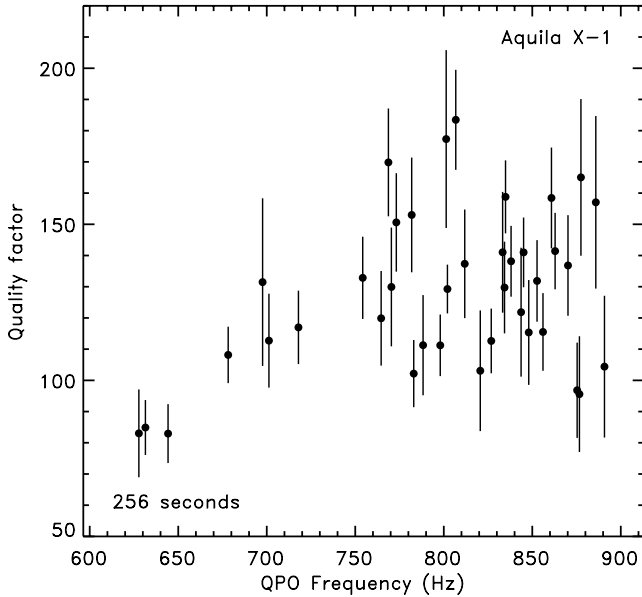
**Table 1.** QPOs from Aql X-1. The observations are ObsID sorted. The name of the ObsID, the starting date of the observation, the cumulative integration time of all the 16 PDS shifted ( $T_{\text{obs}}$ , the fraction of PDS per ObsID, for which an instantaneous frequency could be estimated varies from about 40 per cent up to 100 per cent), the total source count rate (counts  $\text{s}^{-1}$ ), the QPO frequency ( $\bar{\nu}$ ) to which all the PDS were shifted, the range of variation of the QPO frequency within the ObsID ( $\nu_{\text{min}} - \nu_{\text{max}}$ ), the mean quality ( $\bar{Q}$ ) and mean amplitude (rms) are listed. All errors are computed such that  $\Delta\chi^2 = 1$ . The rms is computed as  $\sqrt{I_{\text{lor}}/S}$ , where  $I_{\text{lor}}$  is the fitted Lorentzian integral and  $S$  is the source count rate. Because the error on the source count rate is negligible, the error on rms is computed as  $1/2 \times \text{rms} \times \Delta I_{\text{lor}}/I_{\text{lor}}$ , where  $\Delta I_{\text{lor}}$  is the error on  $I_{\text{lor}}$ , computed with  $\Delta\chi^2 = 1$ . The significance of the QPO which is  $I_{\text{lor}}/\Delta I_{\text{lor}}$  can thus be retrieved from the error quoted on the rms: it exceeds typically  $\sim 7\sigma$  and goes up to  $\sim 20\sigma$ . The high-quality factor recovered suggests that the QPOs detected are all lower kHz QPOs. Previous analysis of these data has been presented in Zhang et al. (1998), Cui et al. (1998), Reig et al. (2000), Méndez et al. (2001) and Reig et al. (2004).

ObsID	Date	$T_{\text{obs}}$	counts $\text{s}^{-1}$	$\bar{\nu}$	$\nu_{\text{min}} - \nu_{\text{max}}$	$\bar{Q}$	rms (per cent)
20092-01-01-02	1997/08/13-11:09:35	656.0	1380.2	833.7	829.0 – 837.6	129.7 ± 14.7	7.2 ± 0.3
20092-01-02-01	1997/08/15-19:03:17	1232.0	1520.1	875.2	869.5 – 883.0	96.8 ± 15.3	5.6 ± 0.3
20092-01-02-03	1997/08/17-06:06:08	592.0	1571.9	848.3	846.3 – 850.6	115.3 ± 16.8	6.6 ± 0.4
20092-01-05-01	1997/09/06-12:50:24	1360.0	1313.1	877.8	874.3 – 885.5	165.0 ± 25.1	5.6 ± 0.3
20092-01-05-01	1997/09/06-14:14:55	1504.0	1380.3	886.2	883.1 – 892.2	157.0 ± 27.6	5.2 ± 0.3
20092-01-05-01	1997/09/06-15:52:47	864.0	1360.4	890.9	885.5 – 896.6	104.4 ± 22.7	5.5 ± 0.4
20098-03-07-00	1997/02/27-05:54:24	1040.0	1098.4	773.4	761.9 – 787.5	150.6 ± 15.8	7.8 ± 0.3
20098-03-07-00	1997/02/27-06:54:23	3152.0	1111.8	801.9	766.7 – 832.6	129.3 ± 7.8	8.1 ± 0.2
20098-03-08-00	1997/03/01-21:34:47	2192.0	778.4	783.0	749.0 – 802.1	102.2 ± 10.8	8.9 ± 0.4
20098-03-08-00	1997/03/01-22:56:32	3088.0	765.0	797.9	769.5 – 821.5	111.2 ± 9.9	9.3 ± 0.3
30072-01-01-01	1998/03/03-14:01:46	1104.0	1603.2	678.2	673.0 – 684.1	108.1 ± 9.0	7.0 ± 0.2
30072-01-01-02	1998/03/04-14:00:40	1232.0	1994.6	856.3	849.1 – 867.5	115.5 ± 12.4	5.8 ± 0.2
30072-01-01-03	1998/03/05-12:24:38	1104.0	2212.4	838.3	833.6 – 846.1	138.2 ± 11.4	5.9 ± 0.2
40047-02-05-00	1999/05/31-15:30:26	2640.0	1112.4	852.7	843.9 – 857.8	131.9 ± 13.1	6.2 ± 0.2
40047-03-02-00	1999/06/03-15:33:09	2640.0	975.0	861.1	852.0 – 874.7	158.4 ± 16.2	6.8 ± 0.2
40047-03-03-00	1999/06/04-13:48:20	3152.0	1035.7	845.2	834.9 – 859.9	141.0 ± 11.2	7.4 ± 0.2
40047-03-03-00	1999/06/04-15:23:28	3024.0	1032.2	862.8	851.6 – 873.6	141.4 ± 12.2	7.3 ± 0.2
50049-02-13-00	2000/11/07-07:01:35	1952.0	1750.6	833.3	823.8 – 839.5	141.0 ± 19.3	4.4 ± 0.2
50049-02-15-03	2000/11/13-20:57:38	2064.0	1164.4	870.3	867.3 – 874.9	136.8 ± 16.1	6.2 ± 0.3
50049-02-15-03	2000/11/13-22:14:40	3024.0	1121.6	834.9	822.1 – 848.5	158.8 ± 11.7	7.1 ± 0.2
50049-02-15-04	2000/11/14-01:42:39	1744.0	836.5	811.7	808.3 – 815.9	137.3 ± 17.4	7.3 ± 0.3
50049-02-15-04	2000/11/14-03:02:23	2704.0	785.3	754.3	734.8 – 767.1	132.8 ± 13.2	7.4 ± 0.3
50049-02-15-05	2000/11/15-04:30:45	3152.0	841.3	631.3	613.7 – 642.9	84.9 ± 8.8	7.6 ± 0.3
50049-02-15-05	2000/11/15-06:06:40	2784.0	825.6	643.8	627.7 – 656.8	82.9 ± 9.4	7.4 ± 0.3
50049-02-15-06	2000/11/16-04:47:43	1808.0	745.0	717.6	712.0 – 723.6	117.0 ± 11.8	8.7 ± 0.3
50049-02-15-07	2000/11/16-06:33:43	1104.0	564.7	698.6	686.0 – 709.1	131.5 ± 26.9	8.1 ± 0.6
60054-02-03-03	2001/07/10-18:59:27	1552.0	452.2	770.4	755.0 – 787.2	129.9 ± 19.0	11.4 ± 0.6
60054-02-03-05	2001/07/12-17:15:12	1232.0	579.7	801.9	798.8 – 813.3	177.3 ± 28.5	8.9 ± 0.5
60429-01-05-00	2002/02/18-22:14:08	1824.0	558.0	787.9	769.7 – 819.6	111.3 ± 16.1	9.4 ± 0.5
60429-01-09-00	2002/02/27-21:42:07	1472.0	775.3	843.1	835.6 – 850.2	121.8 ± 20.7	6.9 ± 0.4
70069-03-01-01	2002/03/07-10:26:39	2192.0	945.8	807.0	786.1 – 828.4	183.5 ± 16.0	7.1 ± 0.2
70069-03-01-02	2002/03/07-15:17:35	1296.0	941.0	781.8	771.6 – 797.2	153.0 ± 18.4	7.2 ± 0.3
70069-03-02-00	2002/03/11-22:17:20	1648.0	815.4	627.7	607.4 – 637.3	83.0 ± 14.1	7.1 ± 0.4
70069-03-02-01	2002/03/10-00:54:39	656.0	1593.4	768.5	763.4 – 775.9	169.8 ± 17.3	7.3 ± 0.3
70069-03-03-03	2002/03/17-20:48:59	1120.0	859.5	876.6	870.2 – 886.3	95.6 ± 18.5	7.2 ± 0.5
70069-03-03-06	2002/03/18-12:45:43	656.0	819.6	821.1	813.4 – 832.4	103.1 ± 19.3	8.3 ± 0.6
70069-03-03-07	2002/03/18-20:34:39	2336.0	797.1	827.0	816.6 – 844.3	112.6 ± 10.4	8.5 ± 0.3
70069-03-03-09	2002/03/19-14:07:43	976.0	882.4	700.9	692.0 – 711.7	112.7 ± 15.0	8.8 ± 0.4
70069-03-03-14	2002/03/21-20:03:39	1952.0	600.5	764.7	756.6 – 771.8	119.9 ± 15.2	9.4 ± 0.4

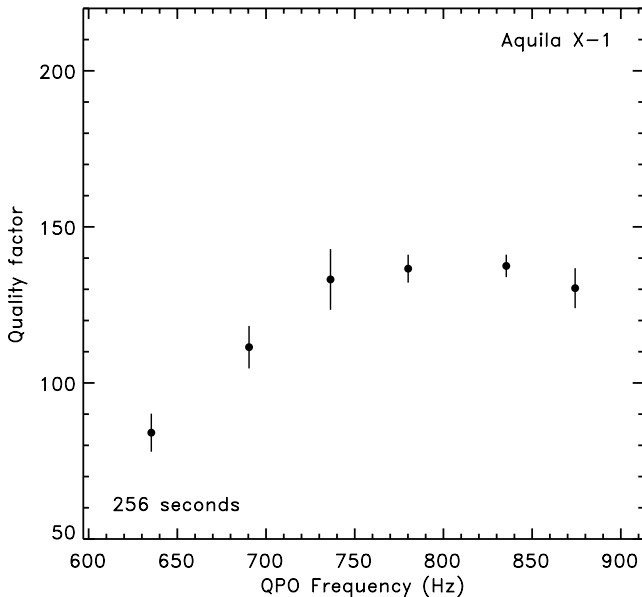
the ObsID have been measured. In Table 2, we list the parameters of the additional QPOs detected. Their significance is typically around  $4\sigma$ . Their  $Q$  values, although not corrected for the drift, are rather high ( $\geq 50$ , in all but one case) suggesting that they may also be lower QPOs. The highest frequency measured is about 900 Hz. It is unfortunate that we have not been able to measure the quality factor at this frequency. If the drop seen in other sources is also present in Aql X-1, one would expect the quality factor to be less than the one where it saturates.

Assuming that the QPOs detected are indeed lower kHz QPOs, one can shift-and-add all of them to a reference frequency. By doing that for all the observations listed in Table 1, the second strongest (and the only one) excess of the resulting PDS, is found above

the main peak at a frequency separation which is consistent with half the spin frequency of the neutron star (275 Hz). Combining the observations of Table 1 and those of Table 2, increases the significance of the detection above  $3\sigma$ . The results of the fitted QPOs in both cases are listed in Table 3. This, together with the fact that the frequency separation is exactly in the expected range, gives us strong confidence that our QPO detection is real. The two QPOs detected by combining the segments of Tables 1 and 2 are shown in Fig. 4. We have searched for an upper QPO 250–300 Hz above the lower QPO within individual ObsIDs and found no significant (above  $3\sigma$ ) QPOs (upper limit ranging from  $\sim 6$  to 10 per cent rms, depending on the source count rate for a QPO width of 100 Hz). Clearly, our detection has been made possible through the



**Figure 2.** Quality factor versus frequency dependency of the strong QPO detected for Aql X-1, as recovered within 39 ObsIDs, after correction for the frequency drift. There is a trend for  $Q$  to increase with frequency. Albeit with large scatter, a saturation in  $Q$  is also suggested. This behaviour is typical of a lower QPO.



**Figure 3.** Mean quality factor versus frequency dependency for Aql X-1. The data shown in Fig. 2 have been grouped over a 50-Hz bin (the same scales as Fig. 2 are used on each axis). The rise and the saturation (possibly a drop) of the quality factor is a behaviour similar to that of other known lower kHz QPOs (see Barret et al. 2006).

use of the shift-and-add technique and the combination of more than  $\sim 70$  ks of data.

### 3 DISCUSSION

We have studied the properties of the lower kHz QPOs from Aql X-1. We have fewer details than for other sources, but the behaviour of the lower QPOs is similar to that seen previously. More

observations of this source are needed to fully sample the quality factor versus frequency diagram, in particular, the high-frequency part, where the drop of coherence may be detected (around 900 Hz). The main result of this paper is the detection for the first time of an upper kHz QPO in this source, with an average frequency separation that is consistent with half the spin frequency of the neutron star.

This result affords us a fresh opportunity to evaluate the relation between the spin frequency and the QPO separation frequency in neutron star low mass X-ray binaries (LMXBs). It has long been known that the separation frequency is not constant in a given source, and indeed can change in rather complicated ways (e.g. see the data for 4U 1608–52 in fig. 3 of Méndez et al. 1998). As a result, no simple model can reproduce exactly the observed behaviour. However, although the absolute goodness of fit of simple models is therefore poor, it is possible, in the same spirit as Zhang et al. (2006), to do a statistical comparison between candidate models (e.g. through a  $\Delta\chi^2$  test), to determine which is closest to current data and perhaps to provide guidance about the underlying physics.

To do this we compare six models. ‘Spin’ is the most commonly discussed model, in which the separation is equal to the spin frequency if  $\nu_{\text{spin}} < 400$  Hz, but equal to half the spin frequency otherwise (Miller, Lamb & Psaltis 1998; Lamb & Miller 2003). ‘Const’ assumes a constant frequency separation for all sources, as in fig. 3 of Méndez & Belloni (2007). ‘Linear’ applies the formula  $\Delta\nu = 390 \text{ Hz} - 0.2\nu_{\text{spin}}$  from Yin et al. (2007). ‘Epicycle’ is the proposal (Stella & Vietri 1998) that the upper peak frequency is the orbital frequency at some radius and the lower peak is the radial precession frequency at that same radius, meaning that the difference frequency is expected to change and to be equal to the radial epicyclic frequency at the given radius (this therefore requires an assumed mass for each source). ‘Power law’ is inspired by Psaltis, Belloni & van der Klis 1999:  $\nu_{\text{upper}} = (\nu_{\text{lower}}/\nu_0)^p$ , where  $\nu_0$  and  $p$  are the same for all sources. Finally, ‘Ratio’ is a model following Abramowicz et al. (2003), in which the ratio between the upper and the lower kHz QPO is fixed at the same value for all sources.

We compare these models to the data available from the 10 sources listed by Méndez & Belloni (2007), as well as Aql X-1 and 4U 0614+091 (see footnote to Table 4 for the list of sources and primary references). There are a total of 57 independent measurements among these 12 sources, from which we compute total  $\chi^2$  values for the six models (note that the  $\chi^2$  statistic is applicable because each measurement of a QPO frequency has Gaussian statistical errors). We note that Méndez & Belloni (2007) suggest that the accretion-powered millisecond (ms) pulsars XTE J1807–294 and SAX J1808–3658 should be treated specially because some of their other frequency properties appear offset by a factor of roughly 1.5 from those of other sources. We thus compute total  $\chi^2$  values omitting these sources, and also including these sources but multiplying their frequency separations by a factor of 1.5, to evaluate the robustness of the model comparisons.

Table 4 shows the results. The Stella & Vietri (1998) ‘Epicycle’ model appears at first to be competitive when the ms pulsars are ignored or have their frequencies adjusted. This, however, is somewhat misleading: four sources (4U 1702–43, IGR J17191–2821, KS 1731–260 and SAX J1750.8–2900) have only one measurement each of a separation frequency, so it is possible to pick a neutron star mass that fits the single data point perfectly in those cases.

From these data, we can draw a few conclusions.

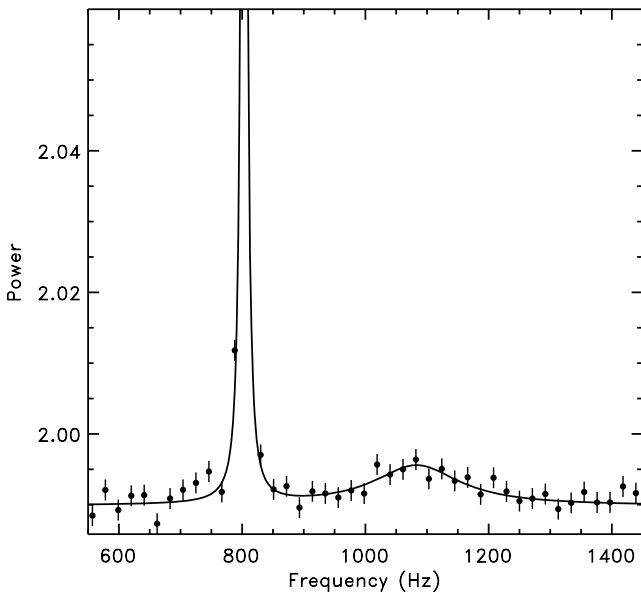
(i) All simple models fail badly in a statistical sense. There is clearly unmodelled complexity to these systems. For an example

**Table 2.** QPOs from Aql X-1 for which the correction for the frequency drift could not be applied, when estimating the quality factor. As expected, the QPOs have lower  $Q$  factors on average than the one listed in Table 1. The name of the ObsID, the starting date of the observation, the PDS integration time ( $T_{\text{obs}}$ ), the total source count rate, the mean QPO frequency ( $\bar{\nu}$ ), the mean quality factor ( $\bar{Q}$ ), the mean amplitude (rms), the significance of the detection ( $\sigma$ ) are listed. All errors are computed such that  $\Delta\chi^2 = 1$ . Although uncorrected for the frequency drift, the high-quality factor of those QPOs suggests that they are also lower QPOs. All significances listed in Tables 2 and 3 are single trial significance.

ObsID	Date	$T_{\text{obs}}$	counts $\text{s}^{-1}$	$\bar{\nu}$	$\bar{Q}$	rms (per cent)	$\sigma$
20092-01-01-01	1997/08/13-00:05:01	416.0	1419.6	$855.6 \pm 0.8$	$94.6 \pm 25.7$	$6.2 \pm 0.6$	5.3
20092-01-04-02	1997/09/03-01:38:02	1472.0	1541.0	$903.2 \pm 1.9$	$76.8 \pm 25.3$	$3.7 \pm 0.5$	3.8
30188-03-01-00	1998/03/06-08:07:12	1472.0	2442.1	$870.4 \pm 1.3$	$59.5 \pm 13.5$	$3.8 \pm 0.3$	5.8
40047-02-05-00	1999/05/31-18:48:32	2800.0	1521.3	$893.7 \pm 2.6$	$44.2 \pm 18.3$	$3.7 \pm 0.6$	3.4
40047-03-02-00	1999/06/03-17:02:23	3264.0	991.3	$892.0 \pm 1.3$	$61.0 \pm 11.0$	$5.5 \pm 0.4$	6.7
40047-03-02-00	1999/06/03-18:41:19	2896.0	1002.9	$896.7 \pm 1.6$	$62.9 \pm 22.5$	$4.5 \pm 0.6$	3.9
50049-02-15-03C	2000/11/13-20:36:31	1136.0	1189.4	$877.1 \pm 2.4$	$76.6 \pm 30.1$	$4.5 \pm 0.6$	3.5
50049-02-15-05	2000/11/15-07:43:28	3152.0	801.3	$600.9 \pm 4.4$	$13.0 \pm 4.2$	$7.6 \pm 1.0$	3.8

**Table 3.** Lower and upper kHz QPOs from Aql X-1. The left-hand column indicates the origin of the data averaged.  $T_{\text{obs}}$  is the cumulative integration time of all the PDS used to detect the upper QPO.  $\nu_{\text{lower}}$ ,  $\bar{Q}_{\text{lower}}$ ,  $\text{rms}_{\text{lower}}$  are, respectively, the frequency, quality factor and amplitude of the lower QPO.  $\nu_{\text{upper}}$ ,  $\bar{Q}_{\text{upper}}$ ,  $\text{rms}_{\text{upper}}$  are the same parameters for the upper QPO.  $\sigma_{\text{upper}}$  is the significance of the upper QPO (single trial).  $\Delta\nu$  is the frequency difference between the two QPOs. All errors are again computed such that  $\Delta\chi^2 = 1$ . The error on the centroid frequency is the statistical error on the aligned peak. Obviously, it does not reflect the distribution of the QPO frequencies entering in the shift-and-add procedure (the lower QPO frequency varies from about 600 Hz up to 900 Hz).

	$T_{\text{obs}}$	$\nu_{\text{lower}}$	$\bar{Q}_{\text{lower}}$	$\text{rms}_{\text{lower}}$	$\nu_{\text{upper}}$	$\bar{Q}_{\text{upper}}$	$\text{rms}_{\text{upper}}$	$\sigma_{\text{upper}}$	$\Delta\nu$
Table 1	69824	$795.45 \pm 0.04$	$129.32 \pm 2.25$	$7.26 \pm 0.05$	$1073.5 \pm 18.2$	$5.7 \pm 2.1$	$4.4 \pm 0.8$	2.6	$278.1 \pm 18.3$
Table 1 & 2	86432	$803.09 \pm 0.05$	$120.44 \pm 2.22$	$6.60 \pm 0.04$	$1083.2 \pm 13.3$	$6.3 \pm 2.0$	$4.3 \pm 0.7$	3.2	$280.1 \pm 13.4$



**Figure 4.** The lower and the upper kHz QPOs of Aql X-1, combining the data of Tables 1 and 2. The upper QPO is detected at  $3.2\sigma$  (the PDS has been linearly binned for illustrative purposes).

of how such complexity might affect the frequencies in the ‘Spin’ model, see Lamb & Miller (2001).

(ii) Of the models considered, the one assuming a constant ratio is overwhelmingly the worst, for any of our data sets. The next worst in all cases (but by a much smaller margin) is the one assuming a constant difference frequency for all systems. Other models are preferred by the data.

(iii) The treatment of data from the accretion-powered ms pulsars XTE J1807–294 and SAX J1808.4–3658 has a significant effect on the comparison between the remaining models. With the data as are, the standard ‘Spin’ model does best. If the frequency differences for just these sources are multiplied by a factor of 1.5, as advocated by Méndez & Belloni (2007), then the ‘Epicycle’ and ‘Power law’ models do best. It is not clear how significant this is; we note, for example, that for any particular model, if the two worst-fit sources are eliminated, the fit becomes much better in all cases.

We conclude that although the separation frequency is clearly a complex quantity, the standard model fits the data at least comparably well to similarly simple models, in addition to emerging from generally plausible input physics. It is therefore still a viable hypothesis that the spin frequency affects the kHz QPOs seen from neutron star low-mass X-ray binaries. On the other hand, the generally bad fits of all models and the possibly important role of individual sources both raise the unpalatable but real possibility that there are multiple mechanisms that can produce kHz QPOs in neutron-star LMXBs.

## 4 CONCLUSIONS

We have shown that the properties of the QPOs detected from Aql X-1 so far are consistent with those seen from similar systems, in particular, the quality factor of the lower QPOs and the frequency separation between the lower and the upper peaks, which we have measured for the first time to be close to half the spin frequency of the neutron star. It would be worth following up the lower QPOs closer to the saturation frequency (at 900 Hz), with adequate sensitivity to estimate the quality factor of the QPOs, and determine whether it drops as in other sources. This may become

**Table 4.**  $\chi^2$  values for models of QPO frequency separation and associated number of degrees of freedom.

Model <sup>a</sup>	$\chi^2$ – full data set <sup>b</sup>	$\chi^2$ – reduced data set <sup>c</sup>	$\chi^2$ – modified data set <sup>d</sup>
Spin	1628/56	1616/48	2200/56
Const	2994/56	2368/48	2391/56
Linear	2566/55	1666/47	1736/55
Epicyle	1742/45	1275/39	1305/45
Power law	1942/55	1194/47	1420/55
Ratio	17945/56	17623/48	19388/56

<sup>a</sup>See the text for description of models. <sup>b</sup>All available published data, for XTE J1807–294 (Linares et al. 2005), SAX J1808.4–3658 (Wijnands et al. 2003), 4U 1608–52 (Méndez et al. 1998), 4U 1636–536 (Di Salvo, Méndez & van der Klis 2003), 4U 1702–43 (Strohmayer et al. 1998), 4U 1728–34 (Méndez & van der Klis 1999), 4U 1731–260 (Wijnands & van der Klis 1997), IGR J17191–2821 (Klein-Wolt et al. 2007), SAX J1750.8–2900 (Kaaret et al. 2002), 4U 1915–05 (Boirin et al. 2000), Aql X-1 (this work) and 4U 0614+091 [twin QPO frequencies taken from Barret et al. (2006) and spin frequency from Strohmayer, Markwardt & Kuulkers, 2008]. ‘Same as ‘Full data set’ except that we removed the data points due to the accretion-powered ms pulsars XTE J1807–294 and SAX J1808.4–3658. <sup>c</sup>Same as ‘Full data set’ except that the frequency separations for XTE J1807–294 and SAX J1808.4–3658 were multiplied by 1.5, following Méndez & Belloni (2007). There are 57 data points in the full and modified data sets, and 49 in the reduced data set. ‘Spin’, ‘Const’ and ‘Ratio’ have one parameter each, ‘Linear’ and ‘Power law’ have two each, and ‘Epicyle’ has 12 for the full and modified data sets and 10 for the reduced data set (which means the neutron star is left free for each source).

possible with *RXTE* during the next outburst of this very active transient.

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## REFERENCES

Abramowicz M., Bulik T., Bursa M., Kluźniak W., 2003, *A&A*, 404, L21  
 Barret D., Kluźniak W., Olive J. F., Paltani S., Skinner G. K., 2005a, *MNRAS*, 357, 1288  
 Barret D., Olive J.-F., Miller M. C., 2005b, *MNRAS*, 361, 855  
 Barret D., Olive J.-F., Miller M. C., 2006, *MNRAS*, 370, 1140  
 Barret D., Olive J.-F., Miller M. C., 2007, *MNRAS*, 376, 1139  
 Boirin L., Barret D., Olive J. F., Blosier P. F., Grindlay J. E., 2000, *A&A*, 361, 121  
 Bradt H. V., Rothschild R. E., Swank J. H., 1993, *A&AS*, 97, 355  
 Casella P., Altamirano D., Wijnands R., van der Klis M., 2007, 708, preprint (arXiv:0708.1110)  
 Cui W., Barret D., Zhang S. N., Chen W., Boirin L., Swank J., 1998, *ApJ*, 502, L49  
 Di Salvo T., Méndez M., van der Klis M., 2003, *A&A*, 406, 177  
 Kaaret P., Zand J. M. I., Heise J., Tomsick J. A., 2002, *ApJ*, 575, 1018

Klein-Wolt M., Wijnands R., Swank J. H., Markwardt C. B., 2007, *Astron. Telegram*, 1075, 1  
 Kluźniak W., Abramowicz M. A., 2005, *Ap&SS*, 300, 143  
 Lamb F. K., Miller M. C., 2001, *ApJ*, 554, 1210  
 Lamb F. K., Miller M. C., 2003, *ApJ*, submitted (astro-ph/0308179)  
 Linares M., van der Klis M., Altamirano D., Markwardt C. B., 2005, *ApJ*, 634, 1250  
 Méndez M. et al., 1998, *ApJ*, 494, L65  
 Méndez M., van der Klis M., 1999, *ApJ*, 517, L51  
 Méndez M., Belloni T., 2007, *MNRAS*, 381, 790  
 Méndez M., van der Klis M., Ford E. C., 2001, *ApJ*, 561, 1016  
 Méndez M., van der Klis M., Wijnands R., Ford E. C., van Paradijjs J., Vaughan B. A., 1998, *ApJ*, 505, L23  
 Miller M. C., Lamb F. K., Psaltis D., 1998, *ApJ*, 508, 791  
 Psaltis D., Belloni T., van der Klis M., 1999, *ApJ*, 520, 262  
 Reig P., Méndez M., van der Klis M., Ford E. C., 2000, *ApJ*, 530, 916  
 Reig P., van Straaten S., van der Klis M., 2004, *ApJ*, 602, 918  
 Stella L., Vietri M., 1998, *ApJ*, 492, L59  
 Strohmayer T. E., Zhang W., Swank J. H., Lapidus I., 1998, *ApJ*, 503, L147  
 van der Klis M., 2006, in Lewin W. H. G., van der Klis M., eds, *Compact Stellar X-ray Sources*. Cambridge Univ. Press, Cambridge, p. 39  
 Strohmayer T. E., Markwardt C. B., Kuulkers E., 2008, *ApJ*, 672, L37  
 Wijnands R. A. D., van der Klis M., 1997, *ApJ*, 482, L65  
 Wijnands R., van der Klis M., Homan J., Chakrabarty D., Markwardt C. B., Morgan E. H., 2003, *Nat*, 424, 44  
 Yin H. X., Zhang C. M., Zhao Y. H., Lei Y. J., Qu J. L., Song L. M., Zhang F., 2007, *A&A*, 471, 381  
 Zhang C. M., Yin H. X., Zhao Y. H., Zhang F., Song L. M., 2006, *MNRAS*, 366, 1373  
 Zhang W., Jahoda K., Kelley R. L., Strohmayer T. E., Swank J. H., Zhang S. N., 1998, *ApJ*, 495, L9

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