

## KHZ QUASI-PERIODIC OSCILLATIONS IN THE LOW-MASS X-RAY BINARY 4U 0614+09

Boutelier, M.<sup>1</sup>, Barret D.<sup>1</sup> and Miller, M.C.<sup>2</sup>

**Abstract.** We report on a comprehensive analysis of the kilohertz ( $\geq 400$  Hz) quasi-periodic oscillations (kHz QPOs) detected from the neutron star low-mass X-ray binary 4U 0614+09 with the Rossi X-ray Timing Explorer (RXTE). With a much larger data set than previously analyzed (all archival data from February 1996 up to October 2007), we first investigate the reality of the 1330 Hz QPO reported by van Straaten et al. (2000). This QPO is of particular interest since it has the highest frequency reported so far. A thorough analysis of the same observation fails to confirm the detection. On the other hand, over our extended data set, the highest QPO frequency we measure for the upper kHz QPO is at  $\sim 1224$  Hz; a value which is fully consistent with the maximum values observed in similar systems. Second, we demonstrate that the frequency dependence of the quality factor ( $Q = \nu/\Delta\nu$ ) and amplitude of the lower and upper kHz QPOs follow the systematic trends seen in similar systems. In particular, 4U 0614+09 shows a drop of the quality factor of the lower kHz QPO above  $\sim 760$  Hz. If this is due to an approach to the innermost stable circular orbit, it implies a neutron star mass of  $\sim 1.9 M_{\odot}$ .

### 1 Introduction

Kilohertz quasi-periodic brightness oscillations (kHz QPOs) have been reported from 4U 0614+09 by Ford et al. (1997), van Straaten et al. (2000, 2002), Barret et al. (2006), and Mendez (2006). The peculiar properties of its kHz QPOs motivate the present work for two main reasons. First, among kHz QPO sources, 4U 0614+09 holds the record for the highest claimed QPO frequency, 1330 Hz (van Straaten et al. 2000), whereas in most sources the maximum frequency for the upper kHz QPO lies around 1200 Hz. This is of particular importance because it sets the most stringent constraints on the mass and radius of the NS, under the assumption that 1330 Hz is an orbital frequency (e.g., Miller et al. 1998). Unfortunately 4U 0614+09 tends to have a low count rate and broad QPOs compared to similar sources, hence its QPOs are challenging to characterize.

Second Barret et al. (2006) have performed a systematic study of the quality factor of the lower and upper kHz QPOs in six systems: 4U 1636-536, 4U 1608-522, 4U 1735-44, 4U 1728-34, 4U 1820-303 and 4U 0614+09. Using data available in the RXTE archive at the end of 2004, they found that all the sources except 4U 0614+09 showed evidence of a reproducible drop in the quality factor of their lower kHz QPOs at high frequency. This result is consistent with what is expected if the drop is produced by the approach of an active oscillating region to the innermost stable circular orbit (ISCO), a key feature of strong-gravity general relativity. For 4U 0614+09 only the rising part of the quality factor versus frequency curve was reported. The availability of more data in the RXTE archive, together with the developments of procedures adapted for broad and weak QPOs, led us to re-analyze all the archival data to search for the same effects seen in other sources.

### 2 Observations and data analysis

For the purpose of this paper, we have retrieved from the HEASARC archive science event mode data recorded by the RXTE Proportional Counter Array (PCA). The data set spans over eleven years from February 26th, 1996 to October 17th, 2007. We consider segments of continuous observation (ObsIDs): 763 ObsIDs were

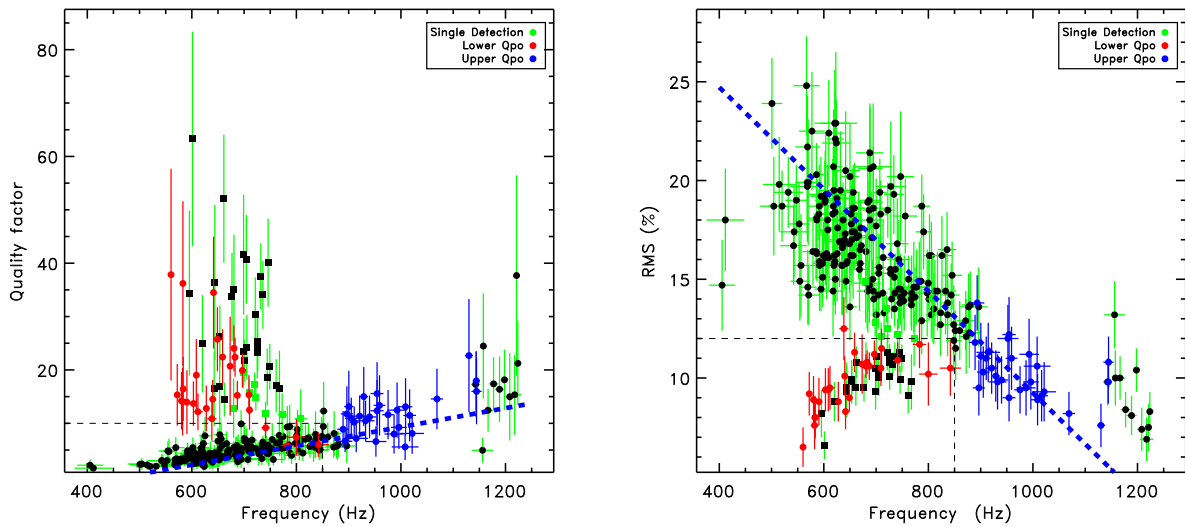
---

<sup>1</sup> Centre d'Etude Spatial des Rayonnements, CNRS/UPS, 9 avenue du Colonel Roche, 31028 Toulouse Cedex 04, France

<sup>2</sup> University of Maryland Department of Astronomy and Maryland Astronomy Center for Theory and Computation, College Park, MD 20742-2421, USA

analyzed with a typical duration of 3000 seconds. For each ObsID, we have computed an average Power Density Spectrum (PDS) with a 1 Hz resolution, using events recorded between 2 and 40 keV. The PDS are normalized according to Leahy et al. (1983), so that the Poisson noise level is constant around 2. The PDS is then blindly searched for excesses between 300 Hz and 1400 Hz using a scanning technique, as presented in Boirin et al. (2000). Each excess (at most the 2 strongest) is then fitted with a Lorentzian with three free parameters; frequency, full width at half maximum and amplitude (the Poisson noise level is fitted separately above 1500 Hz: a frequency domain free of QPOs). The amplitude of the Lorentzian is then converted into a root mean square (RMS), expressed in fraction of the total source count rate.

As a result of this systematic analysis, in 235 ObsIDs we detected a single QPO above a  $3\sigma$  threshold (single trial), and in 27 ObsIDs we found two simultaneous QPOs (in one ObsID, two QPOs were detected but not simultaneously). The remaining ObsIDs, which contained no QPOs, were removed from the subsequent analysis. The quality factor and RMS amplitude versus frequency of all detected QPOs are shown in Fig 1. The patterns identified in other similar systems by Barret et al. (2006) are also seen for 4U 0614+09. In particular, in the quality factor versus frequency plot, lower and upper QPOs occupy two distinct regions: the quality factor of lower QPOs is larger than the quality factor of upper QPOs and the quality factor of the upper QPOs rises steadily with frequency (note that the scatter in the quality factor of the lower QPOs is in part because it is not corrected for the frequency drift within the ObsID). Similarly, there is a clear trend for the RMS amplitude of the upper QPOs to decrease with increasing frequency, whereas the RMS amplitude of the lower QPOs increases first before reaching a plateau (but see below).



**Fig. 1.** Quality factor (left) and RMS amplitude (right) versus frequency of all detected QPOs. Each point represents the average over one ObsID. Red and blue filled circles are respectively for lower and upper twin QPOs. Black filled squares with green error bars are for single detected QPO identified as lower QPO. Black filled circles with green error bars are for single detected QPO identified as upper QPO.

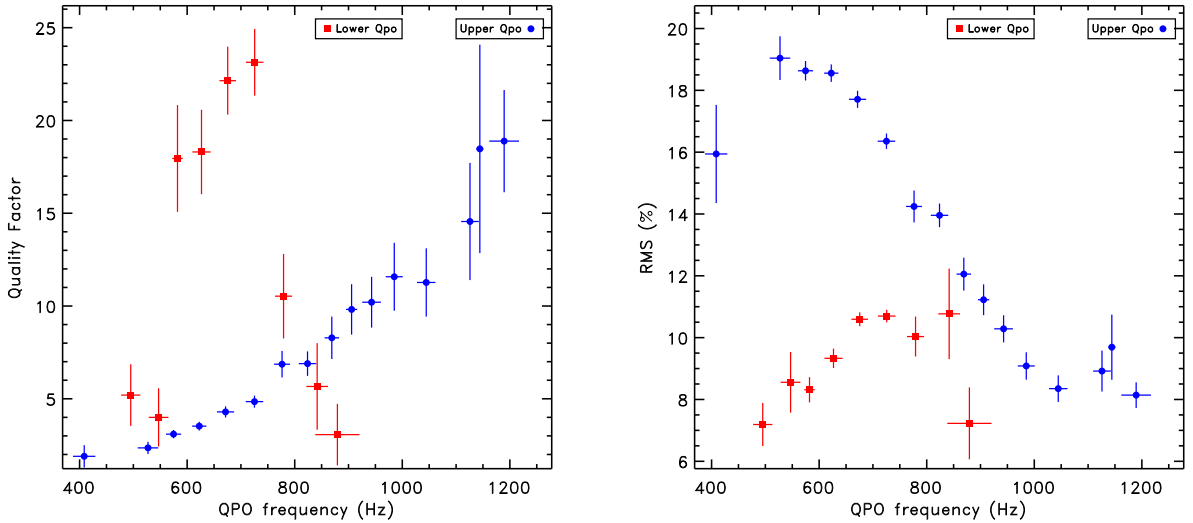
### 2.1 On the 1330 Hz QPO

As can be seen from Fig 1, the highest QPO frequency detected in our systematic analysis is at about 1220 Hz; hence we do not detect any QPOs at frequencies similar to the one reported at 1330 Hz by van Straaten et al. (2000). This could be because our significance threshold of  $3\sigma$  is close to the quoted single trial significance of the 1330 Hz QPO ( $3.5\sigma$ , van Straaten et al. 2000). We have repeated the analysis of van Straaten et al. (2000) for the ObsID 40030-01-04-00 in which the 1330 Hz QPO was reported (considering events from 5 keV to 97 keV). The strongest excess we could fit was at  $\nu = 1328.4 \pm 26.5$  Hz, FWHM =  $46.2 \pm 70.2$  Hz, RMS =  $4.6 \pm 1.7$  %, hence with a low significance of 1.3 (the errors are computed with  $\Delta\chi^2 = 1$ ). By looking at the count spectrum

of the source, it dominates over the background up to 20 keV. We have thus computed a PDS using only events from 2 to 20 keV. The strongest excess of the PDS is no longer around 1330 Hz (a  $\sim 1\sigma$  excess exists at 966 Hz). By initialising the parameters of the fit with the values of van Straaten et al. (2000), the Lorentzian parameters are badly constrained (as expected for a non significant excess) and discontinuity in the  $\chi^2$  curves prevents us from evaluating the errors. Restricting the energy range from 4 to 20 keV (to account for the fact that the RMS of the QPOs increases with energy) leads to a similar conclusion. From this, we conclude that the 1330 Hz QPO reported by van Straaten et al. (2000) was likely a statistical artifact.

## 2.2 Average properties of kHz QPOs

After having identified each QPO, either a lower QPO or an upper QPO, based on its position on Fig 1, one can align them using a shift-and-add technique (Mendez et al. 1998). This allows us to obtain a better description of their average properties; quality factor and RMS amplitudes. The results are presented in Fig. 2. This figure shows for the first time that the quality factor of the lower QPO starts by increasing with increasing frequency and then drops when it reaches a frequency around 700 Hz. Although this is not corrected for the frequency drift within each ObsID, it is worth mentioning that the maximum value of the quality factor of the lower QPO is only about 20, whereas in some other sources it goes up to 200 (see Barret et al. 2006 and Mendez 2006 for a discussion). At the same time, the quality factor of the upper QPOs increases steadily. The behaviour of the RMS amplitude of the lower QPO is consistent with other sources: it increases, saturates and then decreases with increasing frequency. On the other hand, for the upper QPO, there seems to be a discontinuity in the decrease of its amplitude around 1100 Hz. This effect, as well as the distribution of frequencies recovered from our analysis (revealing a possible gap around 1100 Hz) will be discussed in a forthcoming paper.



**Fig. 2.** Quality factor (left) and RMS amplitude (right) versus frequency after grouping the ObsIDs with QPOs of similar type and frequency (within a 50 Hz interval). Red filled squares are for lower QPO. Blue filled circles are for upper QPO. An abrupt drop of coherence of the lower QPO around 750 Hz is now revealed.

## 3 Conclusions

Based on a systematic analysis of all archival RXTE data for 4U 0614+09, the main results presented in this paper can be summarised as follows:

- We do not confirm the previous claim of a QPO at 1330 Hz. This is based on a thorough reanalysis of the observation from which the QPO was reported, and the fact that in our analysis, the highest frequency

detected is at 1220 Hz; a value which is fully consistent with maximum frequencies observed in similar systems.

- We observe for the first time a drop of the quality factor of the lower QPO. Such a drop has been interpreted as being related to the oscillating region, crossing the innermost stable circular orbit, so our detection is consistent with that idea.
- The frequency difference is constant around 320 Hz, hence if the drop in quality factor for the lower kHz QPO is due to the ISCO, one can estimate the orbital frequency there. To do this we compute the maximum frequency of the lower QPO by extrapolating its quality factor to 0. This yields a limiting frequency of  $\sim 920 - 930$  Hz, corresponding to an orbital frequency of 1250 Hz at the innermost stable orbit ( $\nu_{ISCO}$ ). As a safety check, we note that the maximum QPO frequency detected for the upper QPO is indeed lower than  $\nu_{ISCO}$ . From this we can estimate the mass of the NS following the equation  $\frac{M}{M_{\odot}} \approx \frac{\nu_{ISCO}}{2200\text{Hz}} \times (1 + 0.75j)$  where  $j = \frac{cJ}{GM^2} \sim 0.1 - 0.2$  is the dimensionless angular momentum of the star. This leads to a gravitational mass for the neutron star of  $1.9 M_{\odot}$ , i.e. a relatively massive NS, but still consistent with realistic modern equations of state, which predict maximum masses for slowly rotating ( $j \ll 1$ ) stars of  $\sim 1.8 - 2.3 M_{\odot}$  (Akmal, Pandharipande & Ravenhall 1998; Lattimer & Prakash 2001; Klähn et al. 2006).

## References

- Akmal A., Pandharipande V. R., & Ravenhall D. G. 1998, PhRvC, 58, 1804
- Barret, D., Olive, J.-F., & Miller, M. C. 2006, MNRAS, 370, 1140
- Boirin, L., Barret, D., Olive, J. F., Bloser, P. F., & Grindlay, J. E. 2000, A&A, 361, 121
- Ford, E., Kaaret, P., Tavani, M., Barret, D., Bloser, P., Grindlay, J. E., Harmon, B. A., Paciesas, W. S., & Zhang, S. N. 1997, ApJL, 475, L123+
- Klähn T., Blaschke, D., Typel, S., van Dalen, E. N. E., Faessler, A., Fuchs, C., Gaitanos, T., Grigorian, H., Ho, A., Kolomeitsev, E. E., Miller, M. C., Röpke, G., Trümper, J., Voskresensky, D. N., Weber, F., & Wolter, H. H. 2006, Phys. Rev. C, 74, 035802
- van der Klis M. 2006, Advances in Space Research, 38, 2675
- Lattimer J. M., & Prakash M. 2001, ApJ, 550, 426
- Leahy, D. A., Darbro, W., Elsner, R. F., Weisskopf, M. C., Kahn, S., Sutherland, P. G., & Grindlay, J. E. 1983, ApJ, 266, 160
- Mendez, M. 2006, MNRAS, 371, 1925
- Mendez, M., van der Klis, M., van Paradijs, J., Lewin, W. H. G., Vaughan, B. A., Kuulkers, E., Zhang, W., Lamb, F. K., & Psaltis, D. 1998, ApJL, 494, L95
- Mendez, M., & Belloni, T. 2007, MNRAS, 381, 790
- Miller, M. C., Lamb, F. K., & Psaltis, D. 1998, ApJ, 508, 791
- Strohmayer, T. E., Markwardt, C. B., & Kuulkers, E. 2008, ApJL, 672, L37
- van Straaten, S., Ford, E. C., van der Klis, M., Mendez, M., & Kaaret, P. 2000, ApJ, 540, 1049
- van Straaten, S., van der Klis, M., di Salvo, T., & Belloni, T. 2002, ApJ, 568, 912