3:2 ?

Gabriel Török

Institute of Physics, Faculty of Philosophy and Science, Silesian University in Opava, Bezručovo nám. 13,CZ-74601 Opava, Czech Republic

Abstract. Quasiperiodic oscillations (QPOs) are observed in various neutron star (NS) and black hole (BH) X-ray binaries. Special kind of QPOs corresponds to kilohertz frequency range. These kHz QPOs attract a large part of astrophysical community due to a possible link to an orbital motion in a strong gravity close to the binary central compact object. In BH case frequencies of observed kHz QPO modulation remains usually constant for a given source. When more distinct kHz frequencies are measured within a given BH source, they appear in ratios of small natural numbers, typically in a 3:2 ratio. On the other hand, frequencies of NS kHz QPOs varies in individual sources even on scales of hundreds Hertz. *It has been discussed in a serie of papers whether the 3:2 (and other) ratios pop up also in these variable frequencies of NS systems or not. Here we present a brief overview of the "3:2 subject" and summarize several recent findings of different autors which partially resolve this question. Finally, we specify some consequences for orbital QPO models.*

Keywords: X-rays:binaries – stars:neutron – accretion – observation – theory
PACS: 95.30.Sf; 97.10.Gz; 97.10.Ld; 97.80.Jp

BLACK HOLE VS. NEUTRON STAR KHZ QPOS

A number of black hole (BH) and neutron star (NS) sources in low mass X-ray binaries (LMXBs) display narrow features (peaks) in the Fourier power density spectra (PDS) of their observed X-ray fluxes. The term *quasi-periodic oscillations* (QPOs) has been established for this aperiodic variability.

Frequencies of QPOs range from $\sim 10^{-2}$ Hz to $\sim 10^{3}$ Hz. Three main groups are usually distinguished. While the so-called *low-frequency QPOs* represent a complex of several features with variable frequencies up to 100 Hz, the *hectohertz QPOs* arising between 100 and 200 Hz show a moreless constant frequency characteristic for a given system. We focus on so-called *high-frequency (or kHz) QPOs* displayed in the range 200 – 1300 Hz [see 1 for a review].

In the BH systems kHz QPO peaks are typically detected at constant frequencies characteristic for a given source. When more kHz QPO frequencies are detected, they usually appear in ratios of small natural numbers, typically in a 3 : 2 ratio [see 2–4].

On the other hand, in NS kHz QPOs there arise two distinct modes having the frequencies changing over time. The two modes follow their own correlations between a frequency and properties of the peak which have been largely investigated during past few years [see 5–7]. There is always the same inequality of frequencies when both modes are observed simultaneously. Because of that, the modes are called *lower and upper QPO* and their frequencies often denoted as $\nu_L < \nu_U$.

Simultaneous occurences of $\nu_L,\ \nu_U$ are known as *twin kHz QPOs*. The twin kHz QPOs in individual NS span a large frequency range following a nearly linear ν_U–ν_L relation specific for a given source [8–10].

Figure 1(left) illustrates some kHz twin peak QPO frequency measurements. In next we briefly review a question of possible link between the observed BH 3:2 ratio and NS variable frequencies.

CLUSTERING

Abramowicz et al. [11] examined twin kHz QPOs in the Z-source Sco X-1 and in several other NS sources. In the sample of data accumulated from published works they found that *the ratios of the lower and upper QPO frequencies (in next ratios) cluster most often close to the value* $\nu_U/\nu_L = 3/2$; see the insert in the left panel of Figure 1. In Sco X-1 they find also evidence for a possible clustering close to $\nu_U/\nu_L = 5/4$ in addition to the value 3/2. They suggested that these findings point to a common QPO mechanism in both BH and NS sources, in particular to a resonant mechanism.

A preference of the frequencies related to commensurable frequency ratios in various sources has been later systematically explored by a group of Belloni and his collaborators who have re-examined the ratio distribution in Sco X-1 and later also in a larger sample comprising four atoll sources including 4U 1636-53 and 4U 1820-30 [see 9].

Although the results of both groups have been frequently quoted, several specific points have not been discussed for longer time in detail.

Preferred ratios and frequencies

In the context of the above QPO data clustering there are few related questions which can be asked for individual sources as well as for their groups:

- i *Is there a preferred frequency ratio in the observed distribution ?*
- i* Is there a preferred frequency ratio in the distribution produced by source(s)?
- ii *Is there preferred (lower or/and upper) frequency in the observed distribution ?*
- ii* Is there preferred (lower or/and upper) frequency in the distribution produced by source(s)?

* By “distribution produced” we mean those which would be measured in vicinity of the system with an “ideal” detector. It should be also related to a concrete physical mechanism (QPO model).

We stress that (because of measurement thresholds, etc.) the questions denoted by asterisk can be answered only when making strong assumptions on weak (or missing) features in PDS and on a QPO mechanism itself. We also stress that (i) and (ii) do not merge. There is no guarantee that lower QPO is always accompanied by the upper QPO and vice versa. In addition, a transformation between correlated fequencies and the frequency ratio is nonlinear. Thus,a finite distribution of QPO pairs uniform in frequency can imply a clear maximum in ratio distribution.

The above specific questions should be clearly distinguished in the discussion on QPO clustering. When attempting to identify a QPO mechanism any answer to any of questions (i) and (ii) may represent a strong hint.

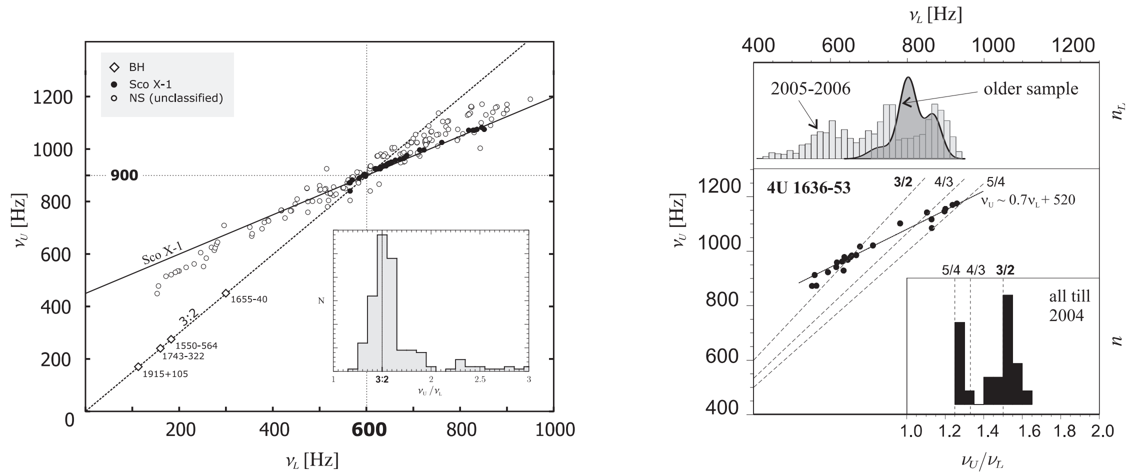

FIGURE 1. Left: After M. Bursa. NS QPO measurements used in [11] and the data of four Galactic microquasar BH sources. Linear correlation approximating data of Sco X-1 is denoted. Insert displays NS ratio distribution. Right: Frequency–frequency plot which depicts joint distribution of lower and upper kHz QPOs in 4U 1636-53. Insert in bottom shows relevant ratio distribution (using all RXTE data available till 2004 - see [12] for details). Top panel, after Belloni et al. (2007), compares the distribution of lower QPO frequency between two large samples of data from different epochs (see the study [13] for details).

4U 1636-53

The results of Abramowicz et al. [11] answered the question (i) for Sco X-1 and a group of few other sources indicating the existence of a preffered ratio. The later study of Belloni et al. [9] focused primarily on (ii) and pointed to a need of its further investigation.

Recently, Belloni et al. [13] studied systematically a long term evolution of QPO frequencies in 4U 1636-53. They compared the distributions of lower QPO frequencies from two different observational epochs. The two distributions differ, being similar to products of random walks. The result indicate that *there is most likely no preffered lower QPO frequency in the distribution of 4U 1636-53* (see Fig. 1, right).

Török et al. [12] have examined occurrences of the twin QPOs in 4U 1636-53. They found that *the ratio distribution clearly peaks near 3:2 and 5:4* (Figure 1, right). Interestingly this is very similar to case of Sco X-1. In addition, they also found that the detections of single (i.e. that with missing or insignificant counterpart) lower/upper QPOs occurs most often for frequencies higher/lower than those corresponding to 3:2 ratio (Figure 2, left).

Links between the clustering and QPO properties

With present X-ray detectors, the strength of observed QPOs is often around the measurement sensitivity threshold. Because of that a (previously) visible QPO may certainly disappear from detections, e.g., only when its amplitude decrease of factor of two [see, e.g., 1, for details].

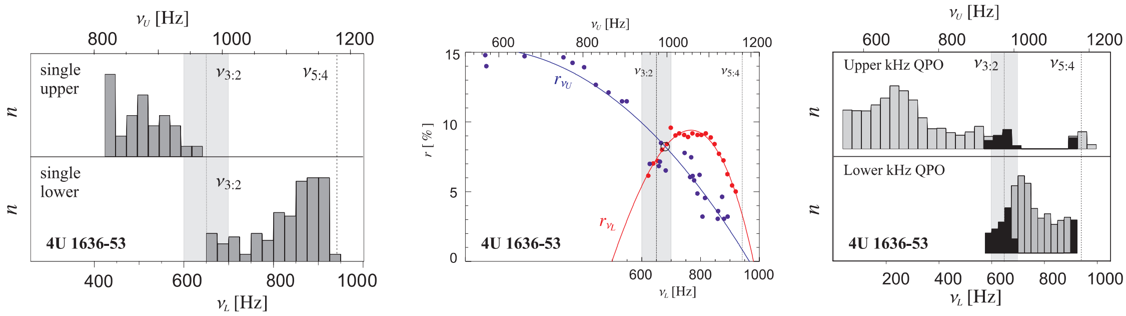

FIGURE 2. Left: Distribution of QPOs having insignificant or missing counterpart. Frequency axes are aligned according to the linear approximation of the frequency correlation (Figure 1, right). The shadow denotes a 50 Hz scatter about the lower QPO frequency related to a 3:2 ratio. Middle: Behaviour of QPO amplitudes r in 4U 1636-53. Similar but not so clear equality appears also in the behaviour of quality factors Q. See [5, 14] for details. Right: Simulated observational QPO distributions based on r and Q behaviour. Dark bars correspond to twins, light to "single" detections. A simple random walk model with no preffered frequency in the source distribution was considered. See [14] for details.

In 4U 1636-53 amplitudes of both the QPOs nearly equal where the twin QPO detections cluster (Figure 2, middle). Török et al. [14] discussed a connection of the clustering with the varying properties (amplitude r and quality factor Q) of QPOs. Assuming approximative relations for the observed correlations of the QPO properties, they attempt to reproduce the frequency and ratio distributions using a simple model of a random-walk evolution along the observed frequency correlation. The simulation assuming *no preferred QPO frequency in the source distribution* quantitatively well resemble the observation (Figure 2, right).

Even if the source frequency distributions were simultaneous and uniform, there would be a non-trivial profile of the observed distributions and the twin peak detection clustering due to behaviour of r and Q determined by the QPO mechanism.[1]

4U 1820-30

Barret & Boutelier [15] examined the distributions of QPO detections in 4U 1820-30. The study indicates a clear clustering of detections close to 4/3 frequency ratio as well as clustering of both QPO frequencies. Similarly to case of 1636-53 r and Q nearly equal where the distribution clusters. The same equality appears also again close to 3/2 ratio. Contrary to 1636 there is a lack of detections of this ratio. The simulation based on QPO properties however predicts such detections.

Thus, there is most likely preferred narrow interval in the distribution produced by 1820 (assuming that detected and possible undetected oscillations are distributed in the same way). Comparing important findings of [15] to case of 1636 shows that our understanding to QPO clustering is still poor ...

[1] A possible interpretation of the simulation suggests that the ratio clustering may origin in the exchange of dominance between the two modes when one mode fades in and the other one fades out.

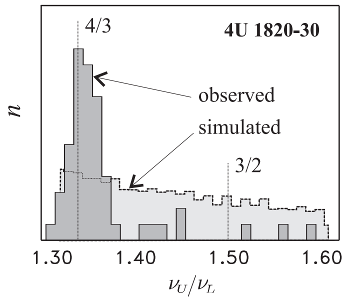

FIGURE 3. Recent result of Barret & Boutelier (2008): observed ratio distribution in 4U 1820-30 is more peaked than those predicted from Q and r behaviour [see 15 for details and several related findings].

SUMMARY AND DISCUSSION

Several neutrons star sources displaying clustering of kHz twin peak QPO detections close to 3/2 or to other rational ratios are well documented in the literature. *The very recent detailed studies of the two atoll sources 4U 1636-53 and 4U 1820-30 bring large amount of information.* Namely,

- I *There are preferred frequency ratios in the observed distributions (but different in the two sources). In 1636 these are* $\sim 3/2$ *and* $5/4$ *while in 1820 it is* $\sim 4/3$.
- I* Contrary to 1636 there is most likely preferred ($\sim 4/3$) frequency ratio in the distribution produced by 1820.
- II *Contrary to 1636, in 1820 there is preferred (lower and upper) frequency in the observed distribution.*
- II* Contrary to 1636, there is is most likely preferred (lower and upper) frequency in the distribution produced by 1820.
- III In both sources the QPO properties are comparable when the correlation pass ratio $\sim 3/2$. There is similar equality for ratio $\sim 5/4$ in 1636 and for $\sim 4/3$ in 1820.

The above facts suggest the existence of a deeper link between QPO properties (especially amplitudes) and the clustering. Nature of the link remains however unclear. Comparing 1636 and 1820, one can speculate that the clustering can have *something* to do with an exchange of the dominance between the QPO modes but a further observational and theoretical development of this idea is obviously needed. A complex study of several sources can help to our understanding of this phenomena.

Consequences for orbital QPO models

Several (not all) orbital QPO models relate given twin peak kHz QPO to a particular radius inside of an accretions disk. As discussed many times in past years the observed clustering can be related to a preference of certain orbits close to inner edge of the disk. This issue has been examined in details for 4U 1636 and RP model by [16]. In Figure 4 we illustrate the relation between QPO modes as would appear in 1636 for RP model of Stella and Vietri [17].

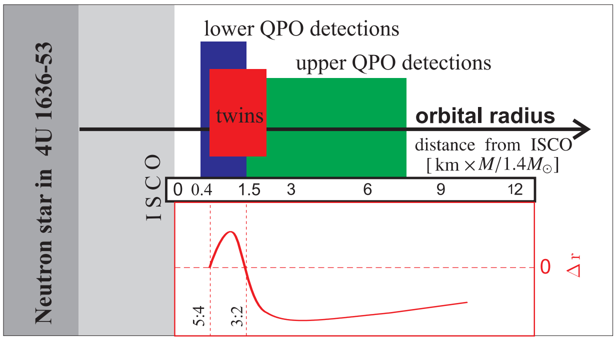

FIGURE 4. Schematic figure indicating orbital regions responsible for QPO detections in individual observations of 4U 1636-53. RP model with the Schwarzschild metric is assumed. From the individual observations both modes can be sometimes detected on the whole covered scale $\nu_U/\nu_L \sim 1.2-3$, but outside of denoted color region rarely, dependently on a method and tresholds (connected to the sensitivity of present instruments). Red curve shows difference between lower and upper QPO amplitude as interpolated from a large amount of measurements [see 18]. Radial scale (0.4 – 10km) based on [16] is calculated from the Innermost Stable Circular Orbit and for a distant observer. Dashed vertical lines denote radius corresponding to a 3/2 and 5/4 ratio. Figure is valid also for a consideration of the $m=1$ radial and $m=2$ vertical disc oscillation modes and qualitatively valid for several other models.

ACKNOWLEDGMENTS

I thank all colleagues who contributed to the discussion from which this paper supported by the Czech grant MSM 4781305903 arises.

REFERENCES

1. M. van der Klis, in *Compact Stellar X-Ray Sources*, ed. W. H. G. Lewin & M. van der Klis, Cambridge, 39–112 (2006)
2. M.A. Abramowicz, W. Kluźniak, *A&A* **374L**, 19A, astro-ph/0105077 (2001)
3. T. Belloni, Proc. SPIE Conference Fluctuations and Noise, e-print arXiv:0802.0376 (2008)
4. J. E. McClintock, R. A. Remillard, R. A., astro-ph/0306213 (2003)
5. D. Barret, J. F. Olive, M. C. Miller, *Monthly Notices Roy. Astronom. Soc.* **361**, 855 (2005)
6. D. Barret, J. F. Olive, M. C. Miller, *Astronomical Notes* **326**, 9, 808 (2005)
7. M. Méndez, *Monthly Notices Roy. Astronom. Soc.* **371**, 1925 (2006)
8. M. A. Abramowicz, D. Barret, M. Bursa, J. Horák, W. Kluźniak, P. Rebusco, *AN* **326**, 864 (2005)
9. T. Belloni, M. Méndez, J. Homan, *Astronomy and Astrophysics* **437**, 209 (2005)
10. C. M. Zhang, H. X. Yin, Y. H. Zhao, F. Zhang, L. M. Song, *MNRAS* **366**, 1373 (2006)
11. M.A. Abramowicz, T. Bulik, M. Bursa, W. Kluźniak, *A& A* **404**, L21 (2003)
12. G. Török, M. A. Abramowicz, P. Bakala, M. Bursa, J. Horák, W. Kluźniak, P. Rebusco, Z. Stuchlík, *Acta Astronomica* **58/1**, pp. 15–21 (2008)
13. T. Belloni, M. Méndez, J. Homan, *MNRAS* **379**, 1, 247, e-print arXiv:0705.0793 (2007)
14. G. Török, M. A. Abramowicz, P. Bakala, M. Bursa, J. Horák, P. Rebusco, Z. Stuchlík, *Acta Astronomica*, accepted, to appear in 58/2, 2008, arXiv:0802.4026 (2008)
15. Barret, D., Boutelier, M., *New Astronomy Reviews* **Volume 51**, Issue 10-12, p. 835-840 (2008)
16. G. Török, P. Bakala, Z. Stuchlík, P. Čech, *Acta Astronomica* **58/1**, pp. 1–14 (2008)
17. Stella, L. & Vietri, M., *Phys. Rev. Lett.* **82**, 17 (1999)
18. G. Török, *A&A*, 2008, submitted