Mass and radius of neutron star in 4U1608-52

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Introduction

We focus on Quasi Periodic Oscillations observed in X-rays of the 4U 1608-52 and on the possibility to use this source to constrain mass and radius of the neutron star. The results are combined with the constraints coming from X-ray bursts reported by Poutanen et al 2014.

Quasi Periodic Oscillations (QPOs)

Two peaks observed in power density spectra of several low mass X-ray binaries (LMXBs)

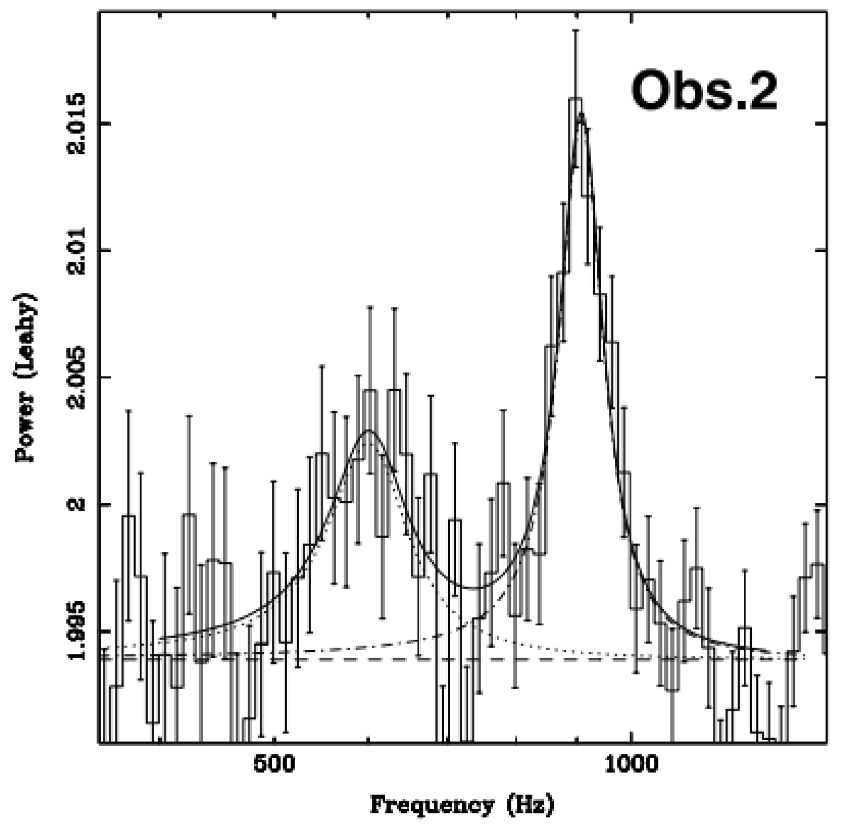

Fig. 1: QPOs in 4U1635. Taken from Figure 2 of Sanna et al, *Broad iron emission line and kilohertz quasi-periodic oscillations in the neutron star system 4U 1636-53*, MNRAS, 2014, Volume 440, Issue 4, p.3275-3284

Key properties of QPOs:

- Frequencies are not necessarily observed in pairs (see e.g. Sanna et al, MNRAS 2014, vol 440, 4, p. 3275-3284
- No common consensus on how the QPOs are generated, where are the frequencies coming from etc.
- Generally, it is believed that they are related to accretion on the neutron star
- Several models are identifying detected frequencies with frequencies of orbital motion or with oscillation frequencies of the accretion disks around neutron star

4U 1608-52

- Rotational frequency is identified with X-ray burst frequency (620Hz)
- Constraints on mass and radius come also from X-ray bursts
- We combine QPO constraints with X-ray burst constraints following Poutanen et al 2014

Oscillating Cusp Torus (OCT) as a Model for QPO

We adopt QPO model from Török et al, MNRAS, 2016, Volume 457, Issue 1, p. L19-23

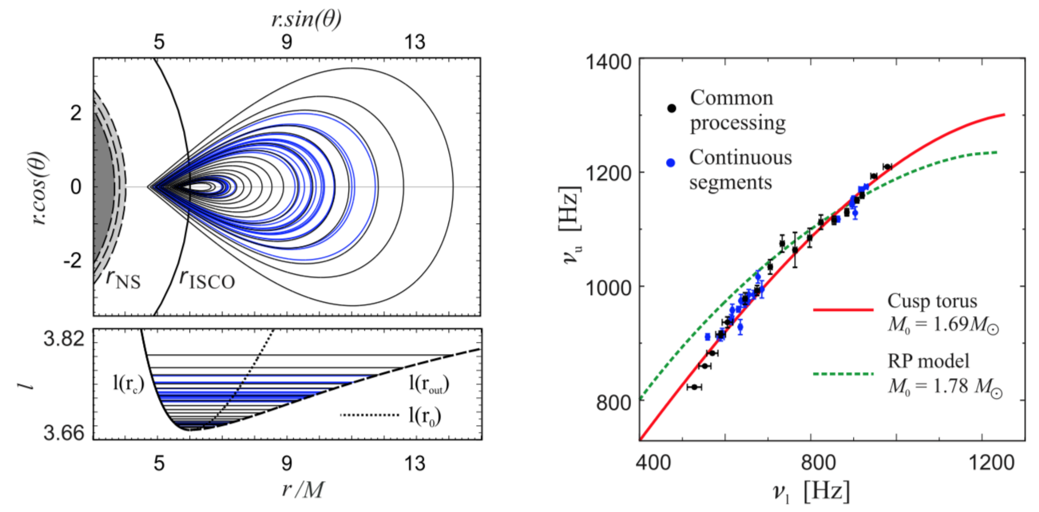

Fig. 2: Oscillating cusp torus model for QPOs in 4U1635. Taken from Figure 1 of Török et al, *Twin peak quasi-periodic oscillations as signature of oscillating cusp torus 4U 1636-53*, MNRAS, **2016**, Volume 457, Issue 1, p. L19-23

Main features of the OCT model

- Each frequency pair is corresponding to the torus of maximal size (with cusp) possible on given radial coordinate
- Frequencies are corresponding to the frequencies of the fluid oscillations

Hartle- Thorne Space-time

- We adopt a metric that is more suitable for rotating neutron stars (Hartle & Thorne, ApJ, 1968, Volume 153, p. 807)

- We use universal relations to calculate metric parameters (M, j, q) for star of given M, R, f=620Hz (Yagi & Yunes, Physics Reports 2017, Vol 681, p. 1-72; Urbanec, Miller, Stuchlík, MNRAS 2013, Vol 433, p1903)
- We also calculate equatorial radius R_{eq}
- sdf

Parameter space tested

- Mass: $1.0 < M/M_{\odot} < 3.0$
- Radius: 8km < R < 25km
- Radial coordinate of the disc's center $r_{min} \leq r \leq 4xr_{min}$
- r_{min} is either the star's equatorial radius or the radius of marginally stable circular orbit, depending on which one of them is bigger

Likelihood

- We use Lorentzian for each observed pair of frequencies

$$\mathcal{L}_i \sim \frac{\Delta_{u(i)}\Delta_{l(i)}}{\pi^2}\frac{1}{(\nu_U(i)-f_u(i))^2+\Delta^2_{u(i)}}\frac{1}{(\nu_L(i)-f_l(i))^2+\Delta^2_{l(i)}},$$

Observed QPO frequencies used

- From the paper of van Doesburg and van der Klis, MNRAS, 2017
- With reported full-width-at-half maxima

Results

We bin the parameter space in M,R, r in 300x300x30000 bins.

For each set of parameters we calculate the likelihood and we the marginalize over the radial coordinate of the disc's center to obtain posterior on mass and radius.

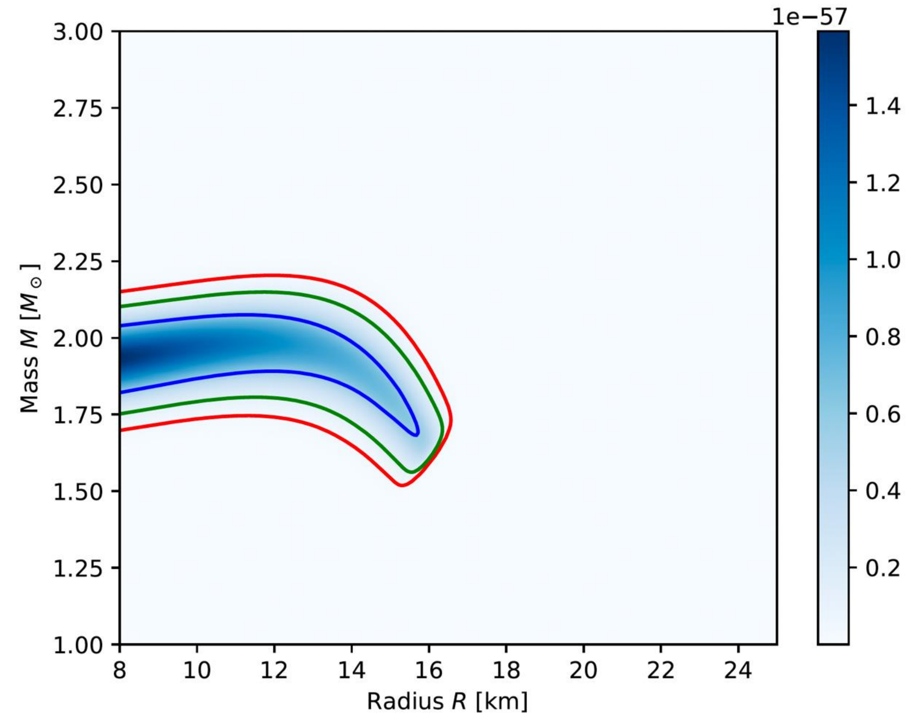

Fig. 3: Mass vs. radius of the neutron star in 4U 1608-52 based on **CT model**. The contours are corresponding to the 68 (blue), 90 (green) and 95 (red) credible area.

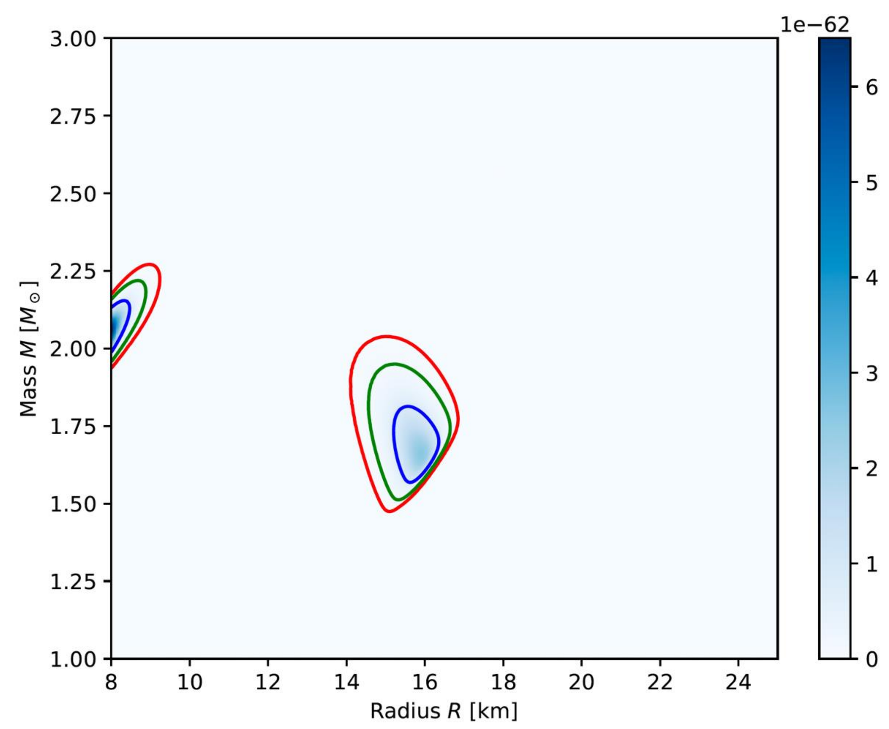

Fig. 4: Mass vs. radius of the neutron star in 4U 1608-52 from CT model kHz QPOs and XRBs. The contours are corresponding to the 68 (blue), 90 (green) and 95 (red) credible area.

CAVEATS:

- In the Fig. 4 we haven't excluded the combinations of Mass and Radius that can be excluded by causality.
- We haven't combined the results from kHz QPOs with the results from low-frequency QPOs. This may help with further constraints.

Conclusion

The main *outcomes* of this work

- We developed a new way how to constrain properties of neutron star in 4U1608-52 using
  - the cusp torus of kHz QPO
  - universal relations among neutron star parameters
  - HT metric (including 2^{nd} order terms in star's frequency)
- The 2^{nd} order corrections contributions to frequencies of orbital motion **are crucial** for the constraints on mass and radius of neutron stars in LMXBs

The constraints on the radius from kHZ QPOs come as a cutoff at about 16km. This is caused by the highest observed QPO frequency that needs to come from above the star's surface.

It is evident that kHz QPOs strongly constrain the mass and further observations from other effect is needed to constrain the neutron star's equation of state.

Suplementary plots

Standard and most widely used model for kHz QPOs is relativistic precession (RP) model. On the following plot we show the constraints on mass and radius from RP model using the same method as described for CT model.

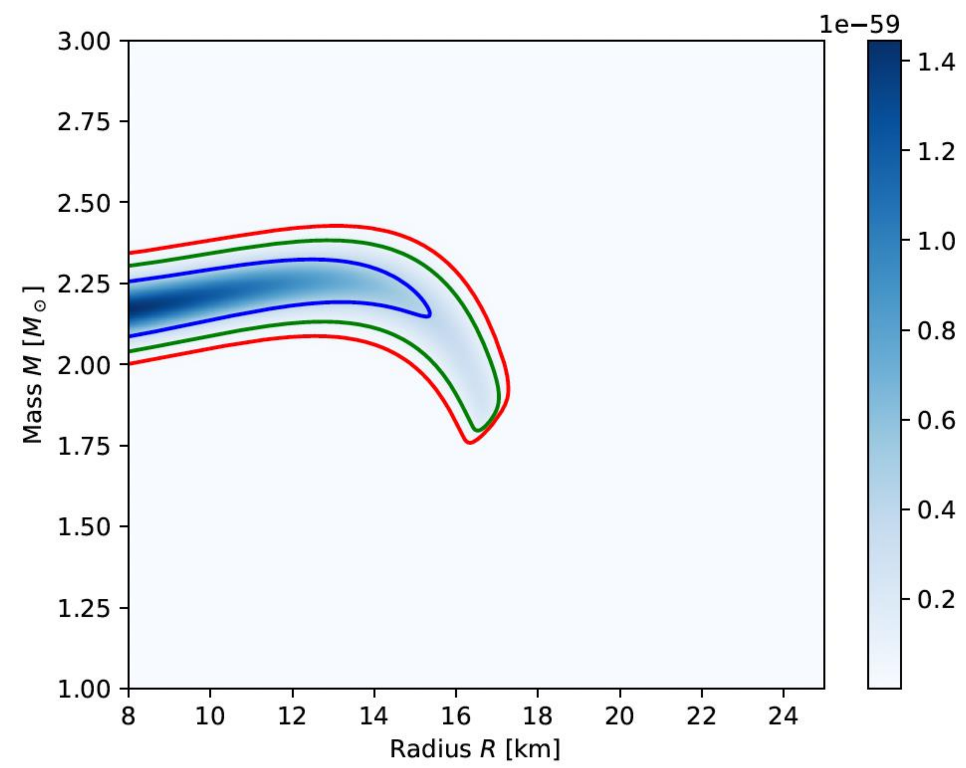

Fig. 5: Mass vs. radius of the neutron star in 4U 1608-52 based on **RP model**. The contours are corresponding to the 68 (blue), 90 (green) and 95 (red) credible area.

One can clearly see that the mass estimate from RP model is about 10% higher than for the CT model..

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