Understanding the orgin of QPOs and constraining the neutron star parameters from the QPO triplets observed in 4U 1728-34

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Abstract

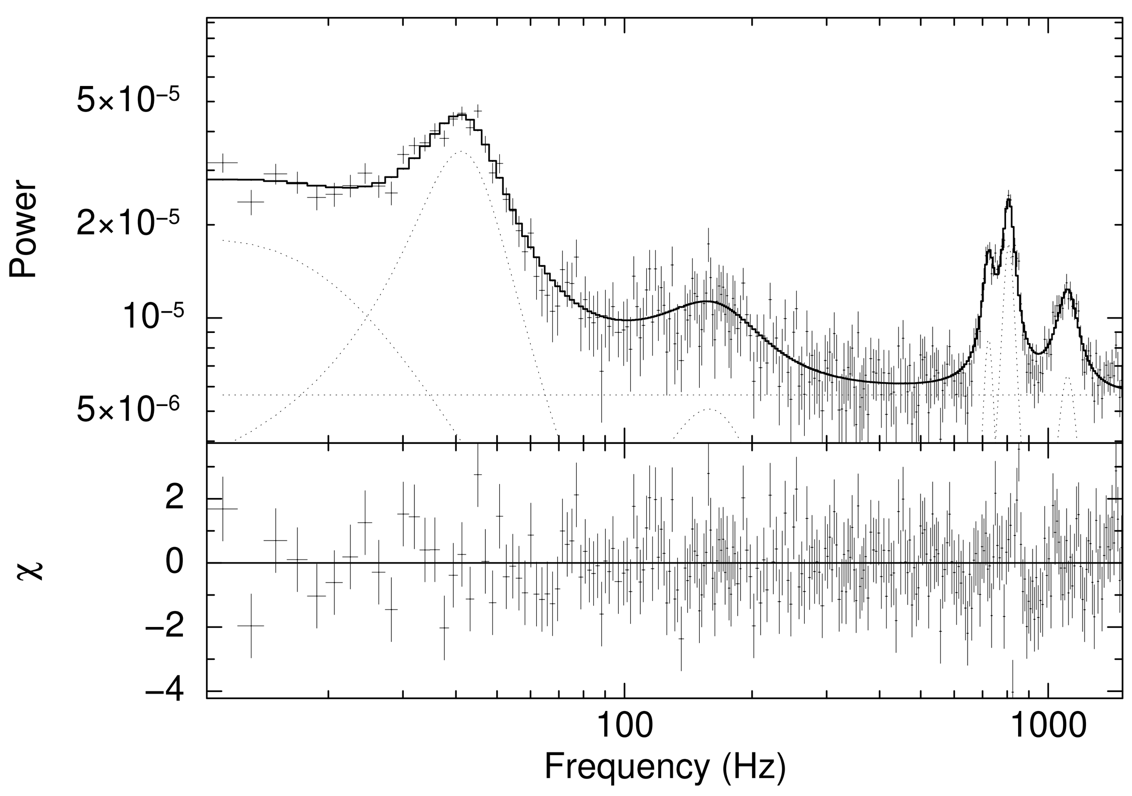
We report simultaneous detection of twin kHz and ~ 40 Hz quasi-periodic oscillations (QPOs) in the time-resolved analysis of the AstroSat/LAXPC observation of the neutron star low mass X-ray binary, 4U 1728-34. The frequencies of the multiple sets of triplets are correlated with each other and are consistent with their identification as the orbital, periastron and twice the nodal precessions frequencies. **The observed relations, along with the known spin of the neutron star, put constraints on the mass and the ratio of moment of inertia to the mass of the neutron star to be $M^*_\odot = 1.92 \pm 0.01$ and $I_{45}/M^*_\odot = 1.07 \pm 0.01$ under the simplistic assumption that the metric is a Kerr one**. We crudely estimate that the mass and moment of inertia values obtained may differ by about 1% and 5%, respectively, if a self-consistent metric is invoked. Using the TOV equations for computing the moment of inertia of a neutron star in slow rotation approximation, having different equations of state, we find that the predicted values of neutron star parameters favor stiffer equations of state. We expect more stringent constraints would be obtained using a more detailed treatment, where the EOS-dependent metric is used to compute the expected frequencies rather than the Kerr metric used here. The results provide insight into both the nature of these QPOs and the neutron star interior.

Introduction

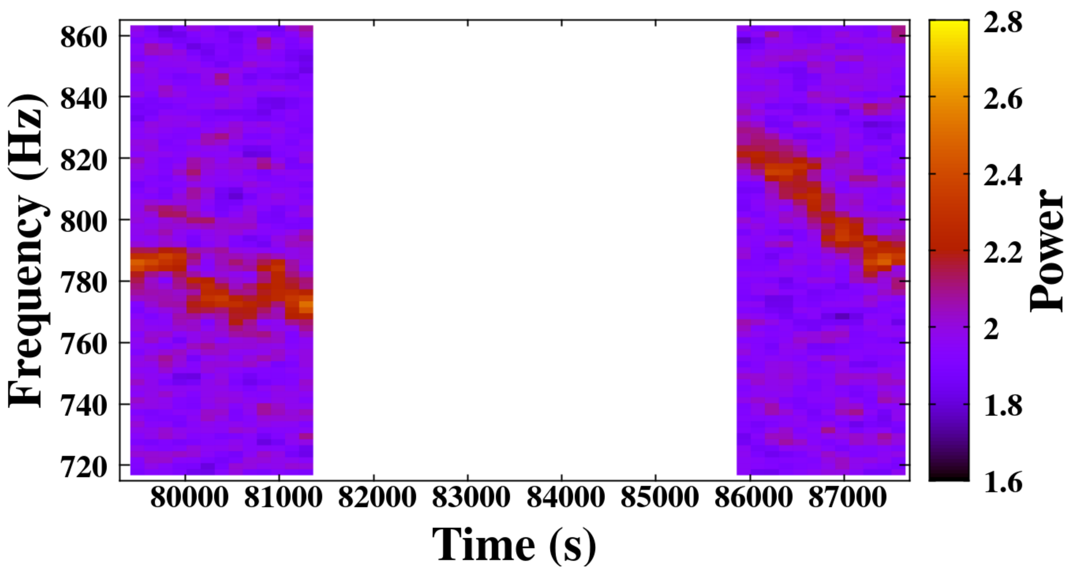
- 4U 1728-34 is an atoll source discovered by SAS-3 satellite which was launched by NASA on 7 May 1975.
- The distance of 4U 1728-34 from the earth is roughly 5.2 kpc and N_H has been approximated to be 2.6×10^{22} cm^{-2}.
- The various observational studies from RXTE have reported the presence of kHz QPOs and burst oscillation (~ 363 Hz) in this source.
- The very first kHz QPO features at ~ 800 Hz and ~ 1100 Hz were discovered in a Z source SCO-X1 from the observation made by RXTE in 1996.
- Among the atoll sources, 4U 1728-34 was the first to exhibit kHz QPOs.

Observation

- To carry out the analysis of persistent emission, we removed thermonuclear bursts from the data and divided it into 16 segments.



- For one of the segments, lower kHz QPO frequency varies from ~ 770 Hz to ~ 830 Hz.



The RPM

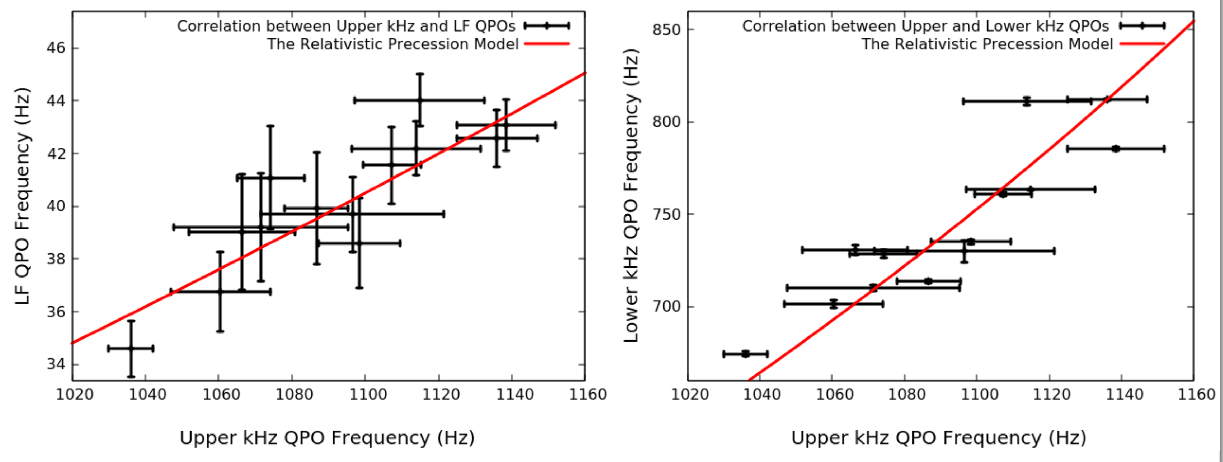
$$\nu_\phi = \pm M^{1/2} r^{-3/2} \left[2\pi (1 \pm \tilde{a} M^{1/2} r^{-3/2}) \right]^{-1}. \quad (1)$$

$$\nu_r^2 = \nu_\phi^2 \left(1 - 6Mr^{-1} \pm 8\tilde{a} M^{1/2} r^{-3/2} - 3\tilde{a}^2 r^{-2} \right), \quad (2)$$

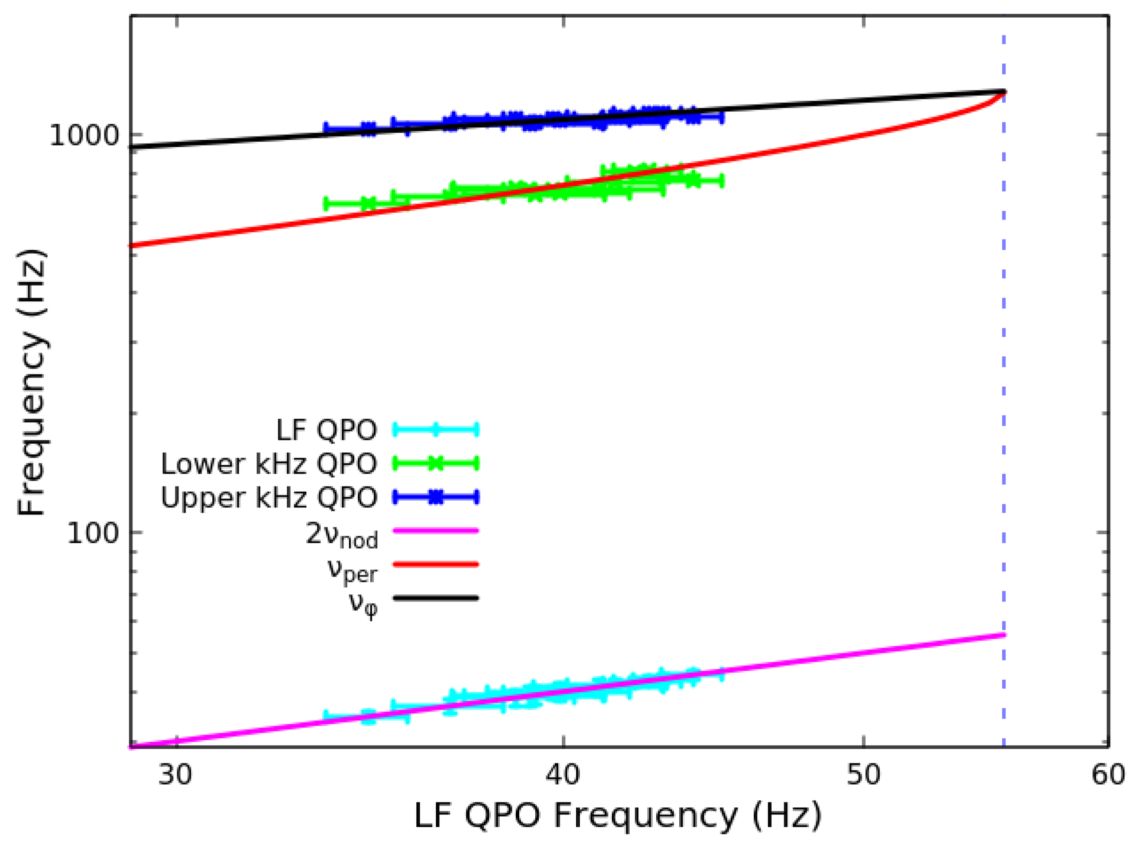
$$\nu_\theta^2 = \nu_\phi^2 \left(1 \mp 4\tilde{a} M^{1/2} r^{-3/2} + 3\tilde{a}^2 r^{-2} \right). \quad (3)$$

Analysis & Results

- Using the RPM, we obtain $M^*_\odot = 2.12 \pm 0.01$ and $I_{45}/M^*_\odot = 2.21 \pm 0.02$ with known $\nu_s = 363$ Hz.



- We also considered the situation where the LF QPO frequency is twice the nodal precession frequency, which resulted in $M^*_\odot = 1.92 \pm 0.01$ and $I_{45}/M^*_\odot = 1.07 \pm 0.01$ (equivalently $a = 0.145 \pm 0.001$).



- We have assumed that the metric to be a Kerr one, while the actual metric around a spinning NS will be different and will depend on its EOS. Since such a metric has to be generally obtained numerically.

Summary

- The time-averaged PDS clearly shows LF QPO at ~ 41 Hz and twin kHz QPOs at ~ 800 Hz and ~ 1100 Hz, along with a broad feature at ~ 158 Hz.
- In the RPM, we assumed LF QPO frequency to be twice the nodal precession frequency to estimate the mass and moment of inertia of NS by using BO frequency as spin frequency. This leads to the best-fit estimates $M^*_\odot = 1.92 \pm 0.01$ and $I_{45}/M^*_\odot = 1.07 \pm 0.01$.
- We estimated the moment of inertia of a NS for ten different EOSs using the TOV equations and found that our results favor relatively stiff EOS (WFF2, SLY, AP4, and ALF2) and are consistent with constraints obtained from the Gravitational-wave event GW170817.

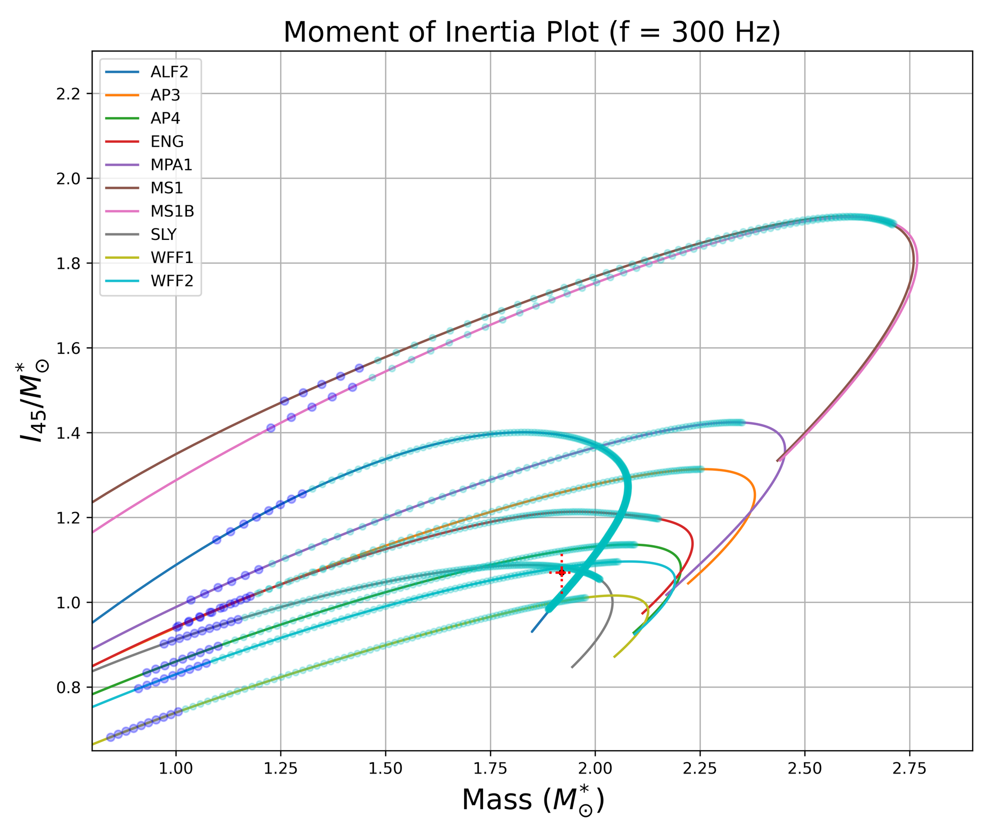
Constraining NS Parameters

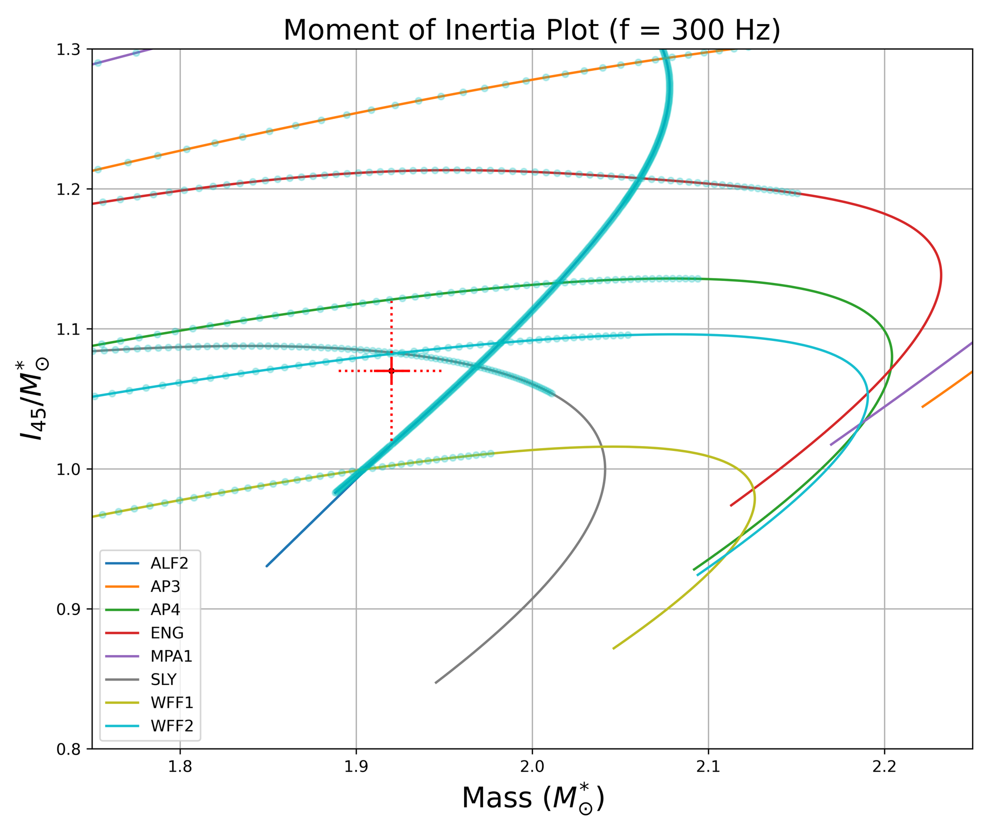
We make an approximate estimate of the moment of inertia of a NS, given an equation of state, i.e. pressure as a function of density $P(\rho)$. In particular, we numerically solve Tolman-Oppenheimer-Volkoff (TOV) equations for an EOS to obtain pressure as a function of radius $P(r)$. The moment of inertia is estimated numerically using the equation given below:

$$I = \frac{J}{1 + \frac{2GJ}{R^3 c^2}} \quad ; \quad J \equiv \frac{8}{3}\pi \int_0^R r^4 \left(\rho(r) + \frac{P(r)}{c^2} \right) \alpha(r) dr \quad (4)$$

where $\alpha(r) = \left(1 - \frac{2GM(r)}{Rc^2}\right)^{-1}$.

Here it is assumed that the neutron star is slowly rotating corresponding to a spin of ~ 300 Hz.





The Gravitational waveform for the event GW170817 leads to constraints on the dimensionless tidal deformability number, Λ. The cyan (blue) colored points in Figures represent the 50% (90%) confidence levels obtained from these Λ constraints, which we have obtained by solving the relevant equations.

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