

Constraining the neutron star mass and moment of inertia from QPO triplets observed in 4U 1728-34

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Joint NICER/IXPE Workshop 2024

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31 July 2024



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- 2 Quasi-periodic Oscillations (QPOs)
- 3 Origin of QPO: Precessions in General Relativity
- 4 Constraining Neutron Star Parameters
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Introduction

- X-ray Binaries (XRBs) comprise of a Neutron Star (NS) or Black Hole (BH) as a primary star and a gaseous star as a secondary.
- Due to the strong gravity primary star accretes the matter from its stellar companion.

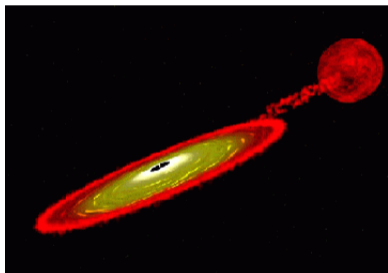


Figure: Accretion in an X-ray binary.^a

^aImage Source: School of Physics and Astronomy, University of Birmingham.

$$T^4(R) = \frac{3GM\dot{M}}{8\pi R^3\sigma} \left[1 - \left(\frac{R_*}{R} \right)^{1/2} \right]$$

For $R \gg R_*$, we obtain

$$T(R) = T_* \left(\frac{R_*}{R} \right)^{3/4}$$

where T_* is given by:

$$T_* = \left(\frac{3GM\dot{M}}{8\pi R_*^3\sigma} \right)^{1/4}$$

Introduction to XRBs

- Based on the mass of secondary star, XRBs have been classified in two categories: LMXB ($< 2 M_{\odot}$) and HMXB ($> 10 M_{\odot}$).

LMXB

- Mass of companion star $< 2 M_{\odot}$.
- Accretion: Through Roche lobe overflow.
- Magnetic field $10^6 - 10^8 G$.
- e.g. Sco X-1, 4U 1728-34, GRS 1915+105, GX339-4 etc.

HMXB

- Mass of companion star $> 10 M_{\odot}$.
- Accretion: Through stellar wind mechanism.
- Magnetic field $10^9 - 10^{12} G$.
- e.g. Cygnus X-1, 4U 1538-522, Cygnus X-3 etc.

Introduction to XRBs

- NS-LMXBs are further classified as Z-type and Atoll-type sources.
- HR2 (9.7-17.0 keV/6.4-9.7 keV) and HR1 (3.5-6.4 keV/2.0-3.5 keV).

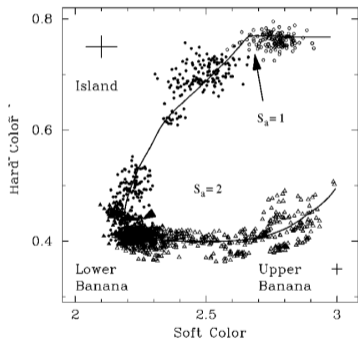


Figure: CCD of the atoll source 4U 1608-52 (Mendez et al. 1999).

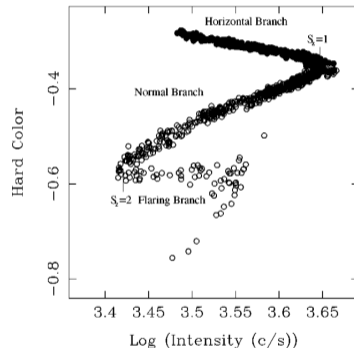


Figure: CCD of the Z-type source GX 340+0 (Jonker et al. 2000).

Introduction: AstroSat/LAXPC

- LAXPC works in 3-80 keV with a time resolution of $10\mu s$ and an effective area 6000 cm^2 .
- For data analysis, we used LAXPCsoftware & HeaSoft version 6.29.



Figure: Image Source: Department of Astronomy & Astrophysics, TIFR.

Introduction

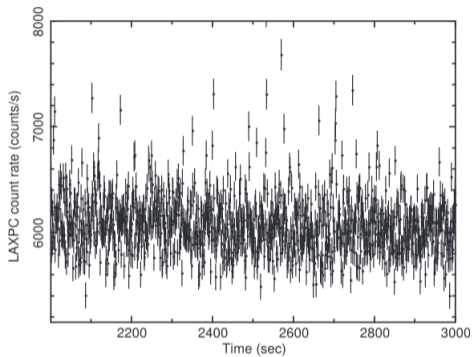


Figure: 3-80 keV light curve of GRS 1915+105 as observed from LAXPC for the orbit number 2363. Ref: Yadav et. al. (2016)

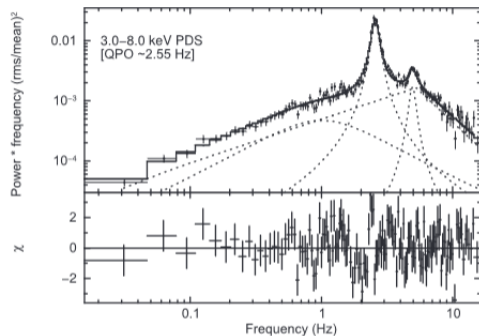


Figure: PDS of light curve shown on the left panel. It shows QPO and its harmonic at 2.5 Hz and 5 Hz respectively

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- AstroSat observed 4U 1728-34 during 7-8 March 2016.

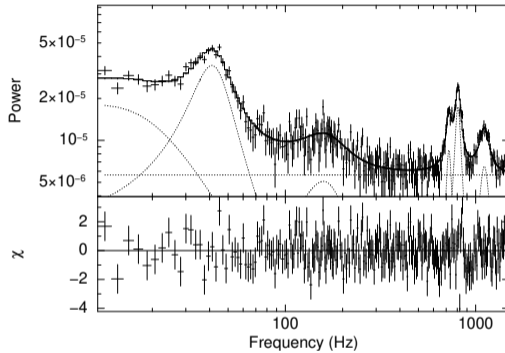


Figure: 3-30 keV PDS of persistent emission. It shows LF QPO at 40 Hz ($Q = 1.96$), lower kHz QPO 800 Hz ($Q = 14$) and upper kHz QPO 1100 Hz ($Q = 7$). The reduced chi-squared is 1.22 for 244 DOF.

Quasi-Periodic Oscillations (QPOs)

- To see the time evolution of QPO frequencies, we divided the entire data set into sixteen segments.

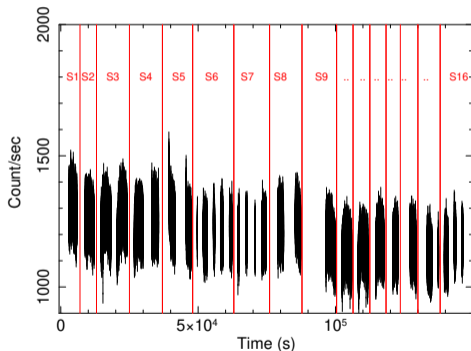


Figure: 3-80 keV background-subtracted light curve of persistent emission after removing

Quasi-Periodic Oscillations (QPOs)

- 3-30 keV PDS extraction was done for each segment.

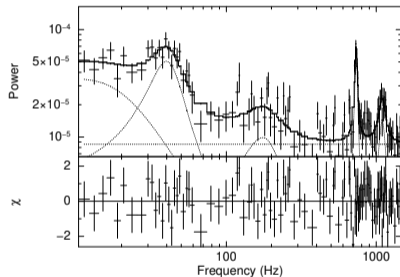


Figure: 3-30 keV PDS for segment 6. QPOs are at 38 Hz, 734 Hz and 1098 Hz with χ_{red}^2 of 1.25 for 102 DOF.

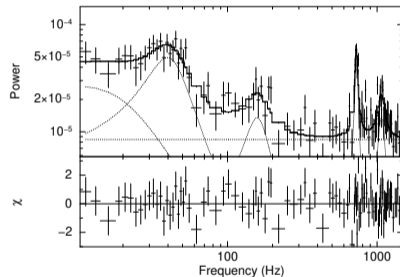


Figure: 3-30 keV PDS for segment 7. QPOs are at 41 Hz, 728 Hz and 1074 Hz with χ_{red}^2 of 1.26 for 87 DOF.

Quasi-Periodic Oscillations (QPOs)

- We also plotted dynamic PDS for individual segments. The frequency bin is 2 Hz and the time bin is 300 s.

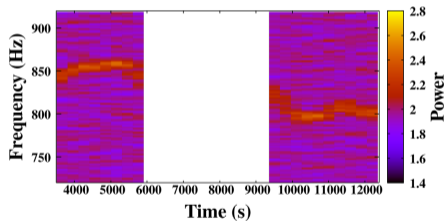


Figure: 3-30 keV dynamic PDS for segment 1.

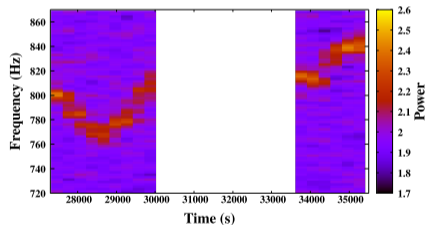


Figure: 3-30 keV PDS dynamic PDS for segment 3.

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Origin of QPO: Precessions in General Relativity

The orbital frequency (ν_ϕ) of a particle moving around a KBH can be written as [SVM99]

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

Now, if the particle is perturbed by an external agent giving it the slight momenta along θ and r . [OKF87, Kat90]

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

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

Origin of QPO: Precessions in General Relativity

$$\nu_{per} = \nu_{\phi} - \nu_r \quad \nu_{nod} = \nu_{\phi} - \nu_{\theta}$$

The RPM (Ref: Stella et al. (1999))



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Constraining Neutron Star Parameters

- 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.

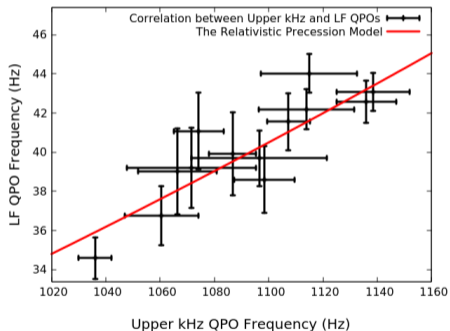


Figure: Correlation between LF QPO and kHz QPO fitted with the RPM

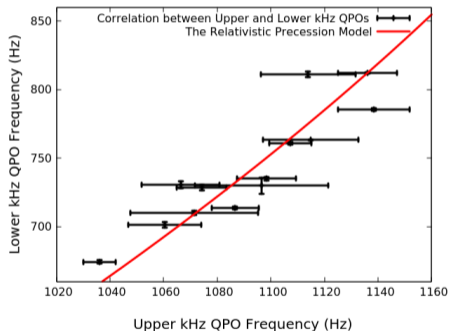


Figure: Correlation between lower and upper kHz QPOs.

Constraining Neutron Star Parameters

- The value of I_{45}/M_{\odot}^* obtained is significantly larger than expected theoretical values.
- The orientation of accretion disk might produce stronger signal at second harmonic of ν_{nod} .
- Considering this situation, we get $M_{\odot}^* = 1.92 \pm 0.01$ and $I_{45}/M_{\odot}^* = 1.07 \pm 0.01$.
- Metric around a spinning NS star deviates from that of the Kerr metric.
- Can we use the RPM to determine mass and spin of NS?

Constraining Neutron Star Parameters

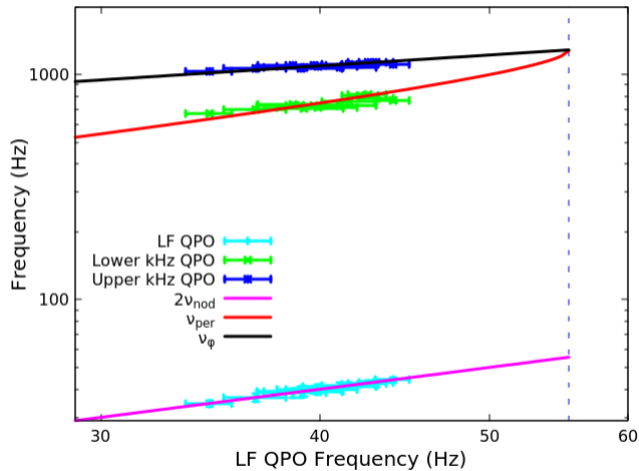


Figure: The RPM fitting to the QPO triplets.

Constraining Neutron Star Parameters

- We attempt to estimate the effect of the Kerr metric assumption that can be viewed as systematic errors.

$$\nu_\phi \quad \nu_k = \left(\frac{GM}{4\pi^2 r^3} \right)^{1/2}, \quad (3)$$

$$\nu_{per} = \nu_\phi \left[1 + \left\{ 1 + 6 \left(\frac{2\pi\nu_\phi GM}{c^3} \right)^{2/3} + \frac{32\pi^2\nu_s\nu_\phi}{c^2} \left(\frac{I}{M} \right) \right\}^{1/2} \right], \quad (4)$$

$$\nu_{nod} = \nu_\phi \left[1 + \left\{ 1 + \frac{16\pi^2\nu_s\nu_\phi}{c^2} \left(\frac{I}{M} \right) \right\}^{1/2} \right], \quad (5)$$

- Ignoring the higher order term, we obtain $M_\odot^* = 1.93 \pm 0.01$ & $I_{45}/M_\odot^* = 1.03 \pm 0.01$.

Constraining Neutron Star Parameters

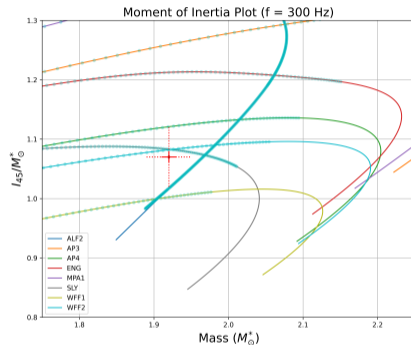
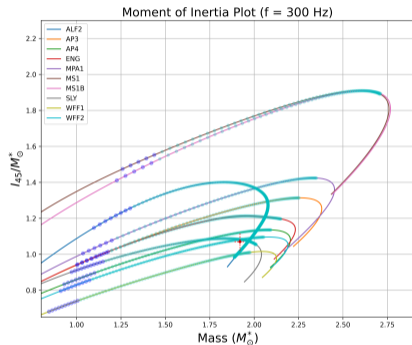


Figure: Variation of I with M of the NS for different equations of state (left). Zoomed-in version of the left side plot (right) in which the red cross indicates the location of the parameter space constrained by this work.²

¹Credit: Umang Kumar and Dipankar Bhattacharya

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Summary

- Multiple sets of rare QPO-triplet in 1728-34 from the AstroSat/LAXPC observation.
- These QPO triplets show remarkable correlation with each other.
- If LF QPO frequency is identified as $2\nu_{nod}$, we get well-constrained mass and moment of inertia $M = 1.92 \pm 0.01 M_{\odot}$ and $I_{45}/M_0 = 1.07 \pm 0.01$ respectively.
- The set of values of I and M obtained favors a few stiffer EOS.




Acknowledgments

We acknowledge Indian Space Science Data Centre (ISRO), LAXPC POC at TIFR, NASA's High Energy Astrophysics Science Archive Research Centre for HeaSoft, and Ashoka University HPC resources. I (K. Anand) express a sincere gratitude to IUCAA for local hospitality during the completion phase of this work.

Thank you for your kind attention!

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