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

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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.

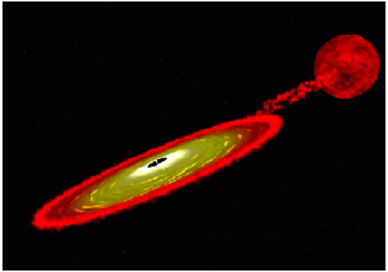

Figure: Accretion in an X-ray binary.[a]

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

For $R \gg R_*$, we obtain

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

where T_* is given by:

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

[a]Image Source: School of Physics and Astronomy, University of Birmingham.

Introduction to XRBs

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

LMXB

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

HMXB

- Mass of companion star $> 10M_\odot$.
- Accretion: Through stellar wind mechanism.
- Magnetic field $\sim 10^{9-12}$ 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).

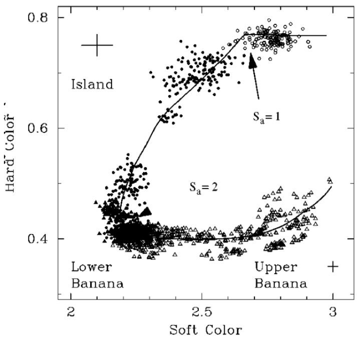

Figure: CCD of the atoll source 4U 1608-52 (Mendez et al. 1999).

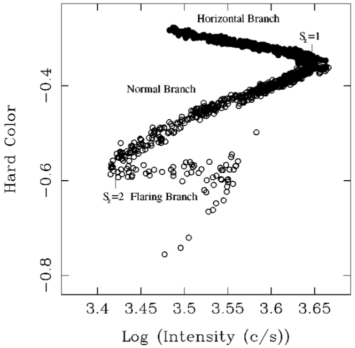

Figure: CCD of the Z-type source GX 340+0 (Jonker et al. 2000).

Introduction: AstroSat/LAXPC

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

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

Introduction

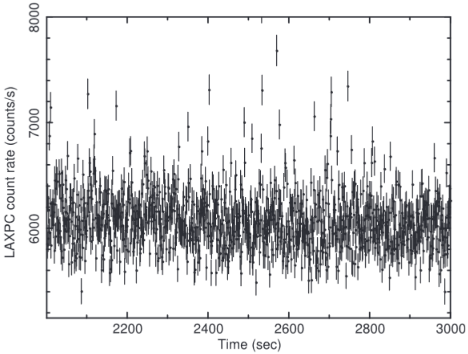

Figure: 3-80 keV light curve of GRS 1915+105 as obsrved from LAXPC for the orbit number 2363. Ref: Yadav et. al. (2016)

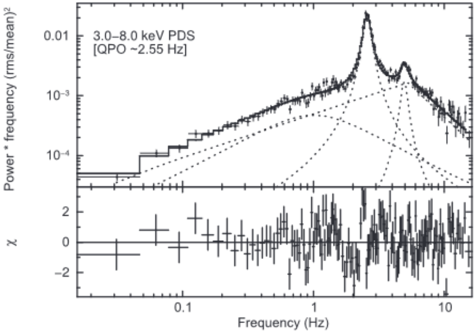

Figure: PDS of light curve shown on the left panel. It shows QPO and its harmonic at $\sim 2.5\ Hz$ and $\sim 5\ Hz$ respectively

Outline

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

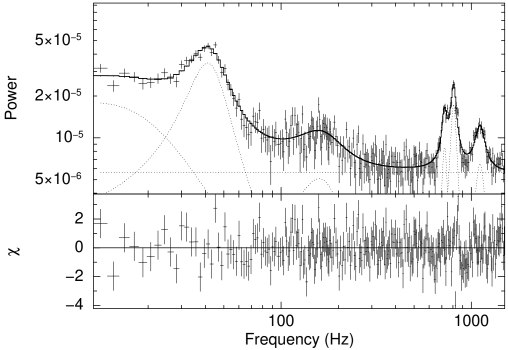

Figure: 3-30 keV PDS of persistent emission. It shows LF QPO at $\sim$ 40 Hz (Q $\sim$ 1.96), lower kHz QPO $\sim$ 800 Hz (Q $\sim$ 14) and upper kHz QPO $\sim$ 1100 Hz (Q $\sim$ 7). The reduced chi-squared is 1.22 for 244 DOF.

Quasi-Periodic Oscillations (QPOs)

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

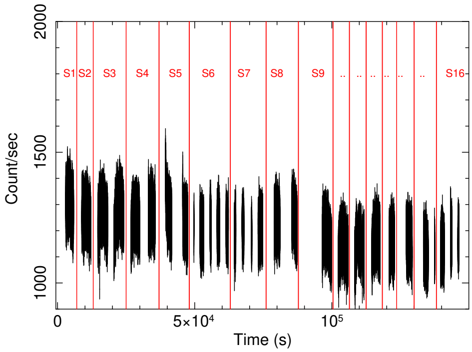

Figure: 3-80 keV background-subtracted light curve of persistent emission after removing

Quasi-Periodic Oscillations (QPOs)

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

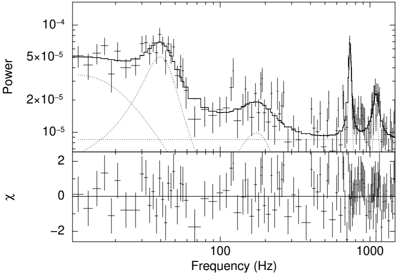

Figure: 3-30 keV PDS for segment 6. QPOs are at $\sim$ 38 Hz, $\sim$ 734 Hz and $\sim$ 1098 Hz with χ^2_{red} of 1.25 for 102 DOF.

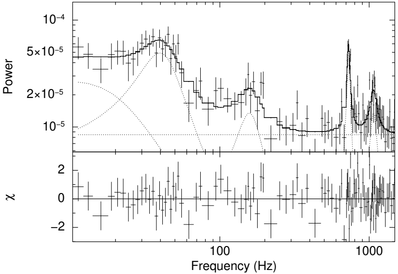

Figure: 3-30 keV PDS for segment 7. QPOs are at $\sim$ 41 Hz, $\sim$ 728 Hz and $\sim$ 1074 Hz with χ^2_{red} of 1.26 for 87 DOF.

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.

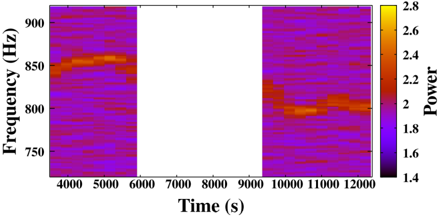

Figure: 3-30 keV dynamic PDS for segment 1.

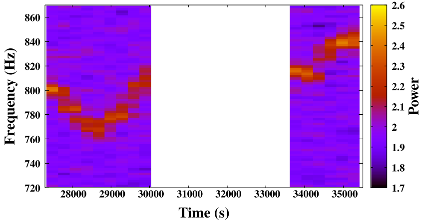

Figure: 3-30 keV PDS dynamic PDS for segment 3.

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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]

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

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

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

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

Origin of QPO: Precessions in General Relativity

$\nu_{per} = \nu_{\phi} - \nu_{r}$ $\nu_{nod} = \nu_{\phi} - \nu_{\theta}$

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

Orbital motion → Upper kHz QPO

Periastron precession → Lower kHz QPO

Nodal precession → LF QPO

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Constraining Neutron Star Parameters

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

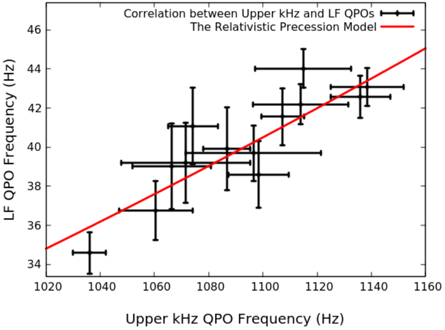

Figure: Correlation between LF QPO and kHz QPO fitted with the RPM

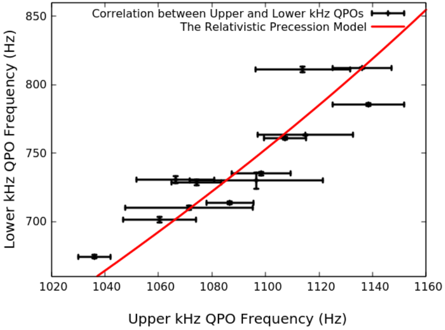

Figure: Correlation between lower and upper kHz QPOs.

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 $\boxed{\mathrm{M}^{*}_{\odot} = 1.92 \pm 0.01 \text{ and } I_{45}/M^{*}_{\odot} = 1.07 \pm 0.01.}$
- 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

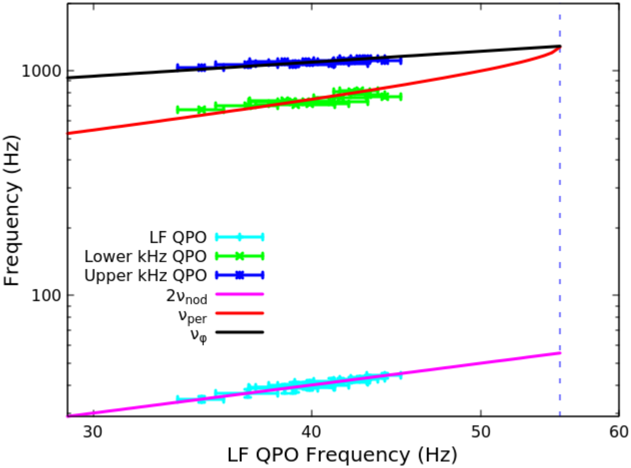

Figure: The RPM fitting to the QPO tiplets.

Constraining Neutron Star Parameters

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

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

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

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

- 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

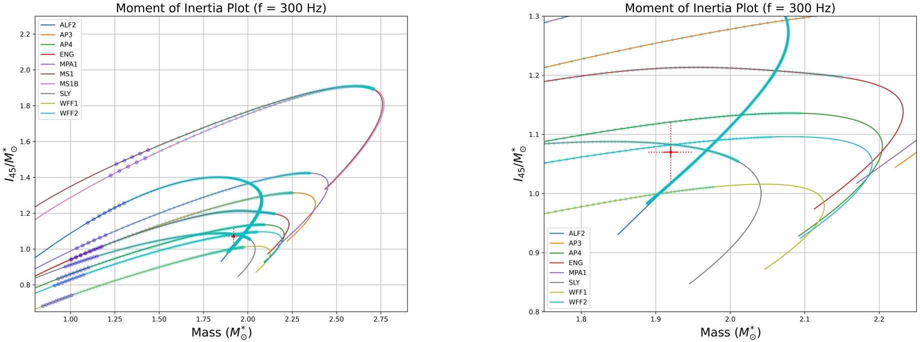

Figure: Variation of I with M of the NS for different equations of state (left). Zoomed-in version of the left side plot (right) in which the red cross indicates the location of the parameter space constrained by this work.[2]

[1] Credit: 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 frequnecy 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.

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References

- Shoji Kato, *Trapped one-armed corrugation waves and qpos*, Publications of the Astronomical Society of Japan **42** (1990), 99–113.
- Atsuo T Okazaki, Shoji Kato, and Jun Fukue, *Global trapped oscillations of relativistic accretion disks*, Publications of the Astronomical Society of Japan **39** (1987), 457–473.
- Luigi Stella, Mario Vietri, and Sharon M. Morsink, *Correlations in the quasi-periodic oscillation frequencies of low-mass x-ray binaries and the relativistic precession model*, The Astrophysical Journal **524** (1999), no. 1, L63.