Observation of LMXBs to Constrain EoS of Neutron Stars

Arunava Mukherjee
Inter University Center of Astronomy and Astrophysics

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Motivation

Properties of ultra-dense degenerate matter

- Based on the assumed *microscopic properties* of the core matter, many equation of state (EoS) models have been proposed in the literature.
- These models connect the *macroscopic properties*: pressure (p) with the mass-energy density (ϵ) in a degenerate condition.

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NS EoS: TOV equation

Tolman-Oppenheimer-Volkoff (TOV) equation

$$\frac{\mathrm{d}p(r)}{\mathrm{d}r} = -\frac{G}{c^2}\frac{[p(r)+\epsilon(r)][m(r)+4\pi r^3 p(r)/c^2]}{r(r-2Gm(r)/c^2)}, \tag{1}$$

where, $m(r) = 4\pi \int_0^r \mathrm{d}r' \, r'^2 \epsilon(r')$ is the gravitational mass (hereafter, mass) inside a sphere of radius r.

For a non-spinning neutron star and for a given EoS model

stellar structure can be calculated by solving the Tolman-Oppenheimer-Volkoff (TOV) equation.

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Observational ways to constrain the EoSs

We need measure at least three independent observable astrophysical parameters

such as **mass (M), radius (R) and spin (S)** of the same neutron star in order to constrain the EoS models, and hence to understand the supra-nuclear core matter.

Motivation

Predicted M-R diagram for several NS EoS

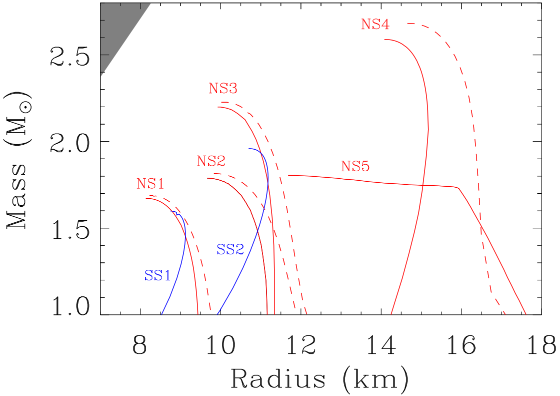


Figure : This figure shows the mass-radius ($M - R$) space of neutron stars (and strange stars) and the curves corresponding to a few representative EoS models. The solid curves are for non-spinning stars, while the dashed curves (corresponding to some of the solid curves) are for a stellar spin frequency of 600 Hz. (Ref: Bhattacharyya, S. 2010)

NS mass measurement

precise mass measurement for double NS binaries

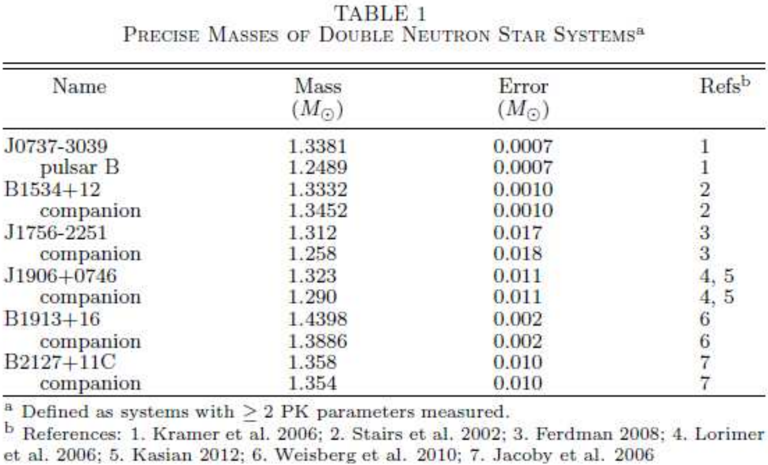


TABLE 1

PRECISE MASSES OF DOUBLE NEUTRON STAR SYSTEMS[a]

Name	Mass ($M_\odot$)	Error ($M_\odot$)	Refs[b]
J0737-3039	1.3381	0.0007	1
pulsar B	1.2489	0.0007	1
B1534+12	1.3332	0.0010	2
companion	1.3452	0.0010	2
J1756-2251	1.312	0.017	3
companion	1.258	0.018	3
J1906+0746	1.323	0.011	4, 5
companion	1.290	0.011	4, 5
B1913+16	1.4398	0.002	6
companion	1.3886	0.002	6
B2127+11C	1.358	0.010	7
companion	1.354	0.010	7

[a] Defined as systems with ≥ 2 PK parameters measured.

[b] References: 1. Kramer et al. 2006; 2. Stairs et al. 2002; 3. Ferdman 2008; 4. Lorimer et al. 2006; 5. Kasian 2012; 6. Weisberg et al. 2010; 7. Jacoby et al. 2006

NS mass measurement

mass measurement for WD-NS binaries

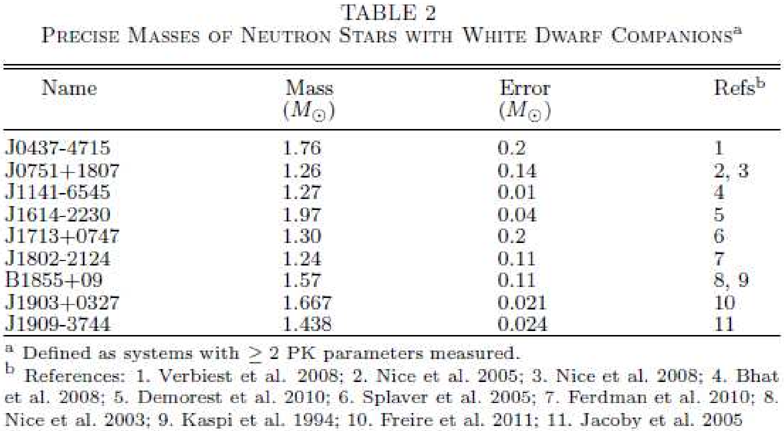


TABLE 2

PRECISE MASSES OF NEUTRON STARS WITH WHITE DWARF COMPANIONS[a]

Name	Mass ($M_\odot$)	Error ($M_\odot$)	Refs[b]
J0437-4715	1.76	0.2	1
J0751+1807	1.26	0.14	2, 3
J1141-6545	1.27	0.01	4
J1614-2230	1.97	0.04	5
J1713+0747	1.30	0.2	6
J1802-2124	1.24	0.11	7
B1855+09	1.57	0.11	8, 9
J1903+0327	1.667	0.021	10
J1909-3744	1.438	0.024	11

[a] Defined as systems with ≥ 2 PK parameters measured.

[b] References: 1. Verbiest et al. 2008; 2. Nice et al. 2005; 3. Nice et al. 2008; 4. Bhat et al. 2008; 5. Demorest et al. 2010; 6. Splaver et al. 2005; 7. Ferdman et al. 2010; 8. Nice et al. 2003; 9. Kaspi et al. 1994; 10. Freire et al. 2011; 11. Jacoby et al. 2005

NS mass measurement

mass measurement for eclipsing X-ray pulsars

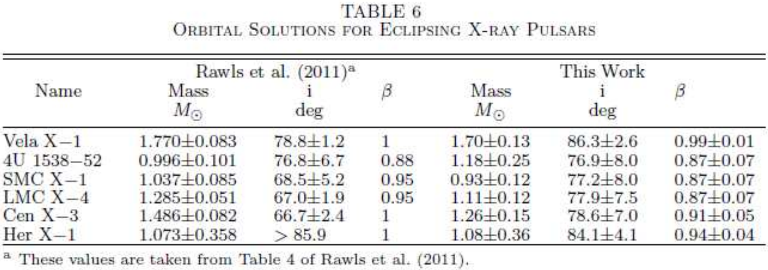
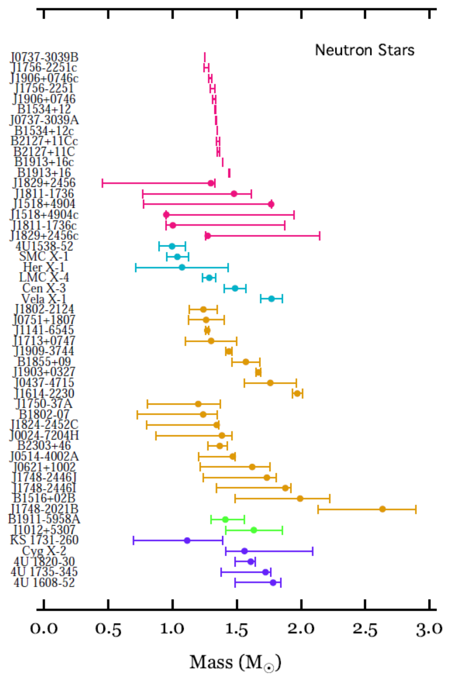


TABLE 6
ORBITAL SOLUTIONS FOR ECLIPSING X-RAY PULSARS

	Rawls et al. (2011)[a]			This Work		
Name	Mass $M_\odot$	i deg	β	Mass $M_\odot$	i deg	β
Vela X−1	1.770±0.083	78.8±1.2	1	1.70±0.13	86.3±2.6	0.99±0.01
4U 1538−52	0.996±0.101	76.8±6.7	0.88	1.18±0.25	76.9±8.0	0.87±0.07
SMC X−1	1.037±0.085	68.5±5.2	0.95	0.93±0.12	77.2±8.0	0.87±0.07
LMC X−4	1.285±0.051	67.0±1.9	0.95	1.11±0.12	77.9±7.5	0.87±0.07
Cen X−3	1.486±0.082	66.7±2.4	1	1.26±0.15	78.6±7.0	0.91±0.05
Her X−1	1.073±0.358	> 85.9	1	1.08±0.36	84.1±4.1	0.94±0.04

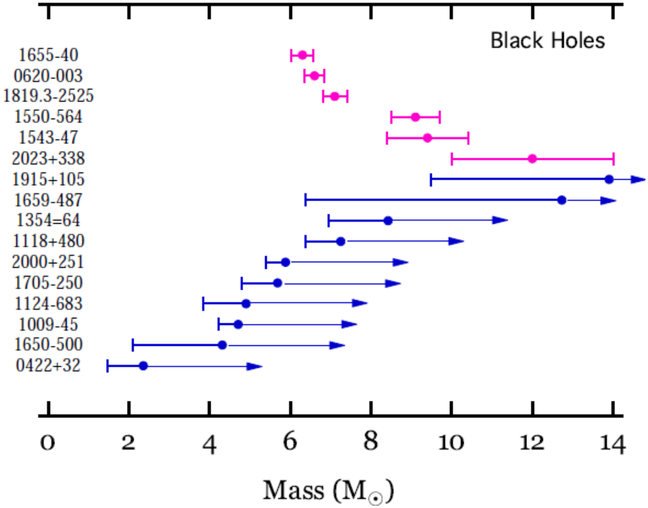
[a] These values are taken from Table 4 of Rawls et al. (2011).

ALL-NSs


Neutron Stars
J0737-3039B
J1756-2251c
J1906+0746c
J1756-2251
J1906+0746
B1534+12
J0737-3039A
B1534+12c
B2127+11Cc
B2127+11C
B1913+16c
B1913+16
J1829+2456
J1811-1736
J1518+4904
J1518+4904c
J1811-1736c
J1829+2456c
4U1538-52
SMC X-1
Her X-1
LMC X-4
Cen X-3
Vela X-1
J1802-2124
J0751+1807
J1141-6545
J1713+0747
J1909-3744
B1855+09
J1903+0327
J0437-4715
J1614-2230
J1750-37A
B1802-07
J1824-2452C
J0024-7204H
B2303+46
J0514-4002A
J0621+1002
J1748-2446J
J1748-2446I
B1516+02B
J1748-2021B
B1911-5958A
J1012+5307
KS 1731-260
Cyg X-2
4U 1820-30
4U 1735-345
4U 1608-52
0.0
0.5
1.0
1.5
2.0
2.5
3.0
Mass ($M_\odot$)

BH mass measurement

ALL-BHs



Kilo-hertz Quasi-periodic oscillations (kHz QPOs)

as a robust observational feature

Kilo-hertz quasi-periodic oscillation (kHz QPO) is one of the most promising tools to **probe strong gravitational effects (such as ISCO) as well as to constrain neutron star EoSs!**

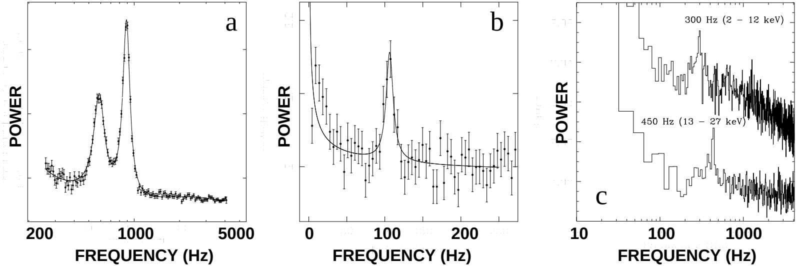


Figure : These are examples of lower and upper kHz QPOs along with the continuum PDSs we observed from several neutron star LMXBs with *RXTE* PCA. (Ref: van der Klis, M. 2006)

Physical origin?

upper and lower kilo-hertz Quasi-periodic oscillations (kHz QPOs)

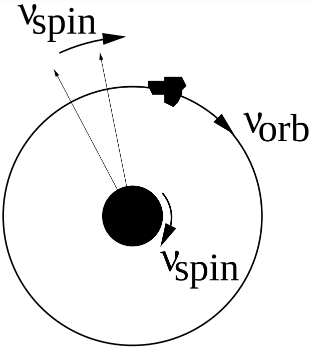


Figure : Frequencies of the upper kHz QPOs are associated with Keplerian Motion in the inner-most part of the accretion disk, while those of the lower kHz QPOs are thought to be the beats between the upper kHz QPO frequencies and magnetic field co-rotating with neutron star surfaces. (Ref: van der Klis, M. 2006)

Innermost Stable Circular Orbits (ISCO)

Observational evidences of ISCO?

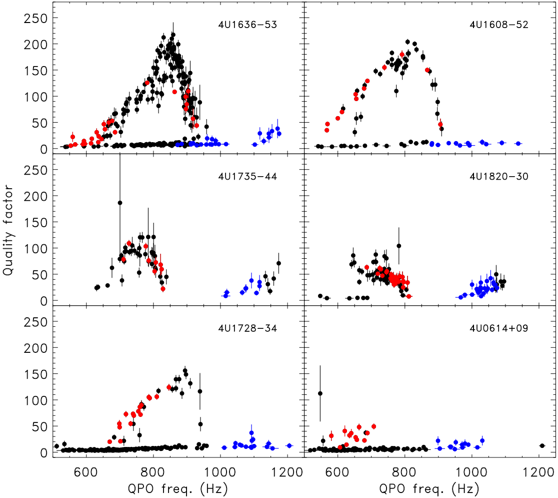


Figure : Frequency Versus Q-factor plots for six atoll sources.

Kilohertz Quasi-periodic Oscillations

constraining $M - R$ space

One can constrain the $M - R$ space:

mass dependent upper limit on R :

$R \leq r$

upper limit on M :

$r_{\mathrm{ISCO}} \leq r$

where, r_{ISCO} is the radius of the ISCO :

$$M < c^3/(2\pi 6^{3/2} G\nu_\phi|_r) \tag{2}$$

(for Schwarzschild spacetime); where, r is the radius of the orbit associated with ν_u or ν_l. These constraints on $M - R$ space are shown in next figures.

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Kilohertz Quasi-periodic Oscillations

How can it constrain EoSs?

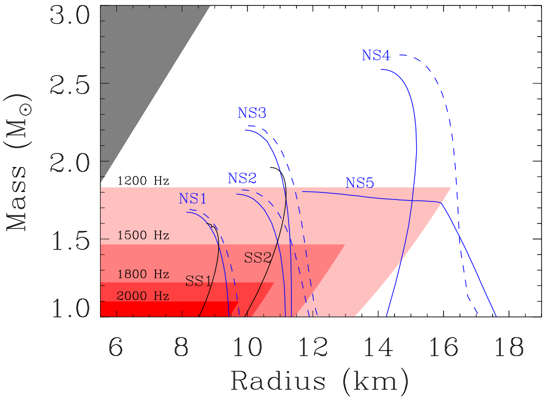
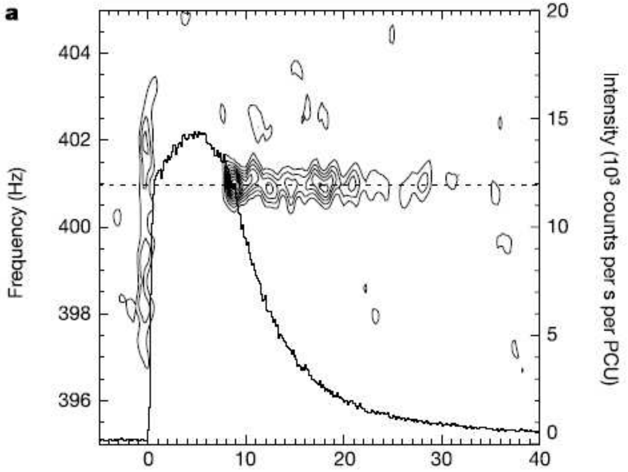


Figure : This figure shows the $M - R$ space of neutron stars with the curves corresponding to a few representative EoS models (same as Figure 1). The shaded regions show the allowed $M - R$ space using the ISCO model, corresponding to the upper kHz QPO frequencies as mentioned.

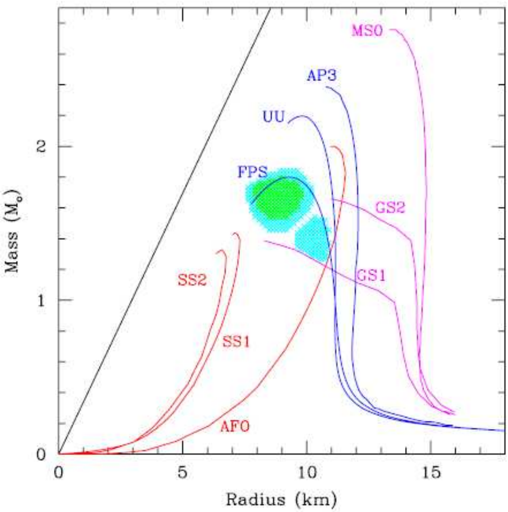
NS radius measurement

using thermonuclear X-ray bursts



NS radius measurement

EXO 1745-248



NS radius measurement

KS 1731-260