Importance of stellar oblateness and relativistic effects on accretion disks around compact stars.

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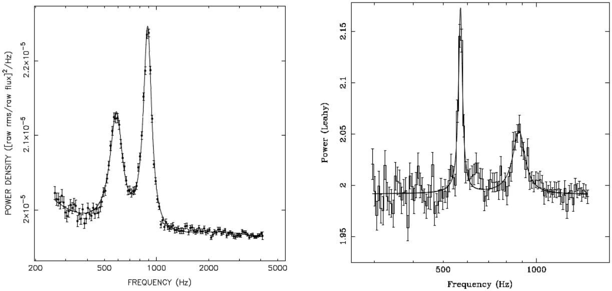
High Frequency Quasi-periodic Oscillations

The kHz Quasi-periodic oscillations (**kHz QPOs**) are among the most important scientific result of Rossi X-ray Timing Explorer (RXTE)

http://heasarc.gsfc.nasa.gov/docs/xte/GreatestHits/khz.qpo.html

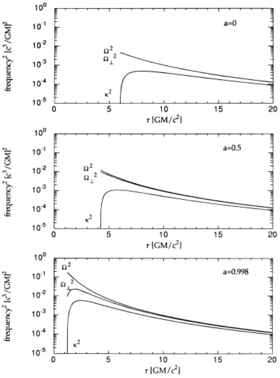


Twin kHz peaks in Sco X-1 (left; van der Klis et al. 1997) and 4U 1608-52 (right; Mendez et al. 1998)

To date kHz QPOs have been discovered in $\sim$ 26 neutron star LMXBs (Wang et al. 2014) - mostly showing double peaks (ν_1,ν_2): 0.1-1.33 kHz (van der Klis 2000)

Models of HF QPOs

Many different models try to explain the **origin of kHz QPOs**. Most of them involve orbital Ω_{orb} and epicyclic ($\Omega_{\rm r}$, $\Omega_{\rm vert}$) frequencies. **Examples:** Stella et al. 1999 ($\Omega_{\rm orb}$, $\Omega_{\rm orb}$ - $\Omega_{\rm r}$), Abramowicz and Kluźniak, 2003 ($\Omega_{\rm vert}$, $\Omega_{\rm r}$)



Perez et al. 1997

The effect of spin on the epicyclic frequencies around black hole:

- Newtonian 1/r gravity: $\Omega_{\rm orb} = \Omega_{\rm r} = \Omega_{\rm vert}$.
- GR, Schwarzschild: $\Omega_{\rm r} < \Omega_{\rm orb}$
- GR, Kerr: $\Omega_{\rm vert} < \Omega_{\rm orb}$ (prograde)

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Neutron Star and Strange Quark Star model

MIT bag model

- quark matter is composed of massless u, d quarks, massive s quarks and electrons.
- three physical quantites describing the model: the mass of strange quark, m_s, the bag constant B, and the strength of QCD coupling constant, α.

The equation of state is given by simple formula:

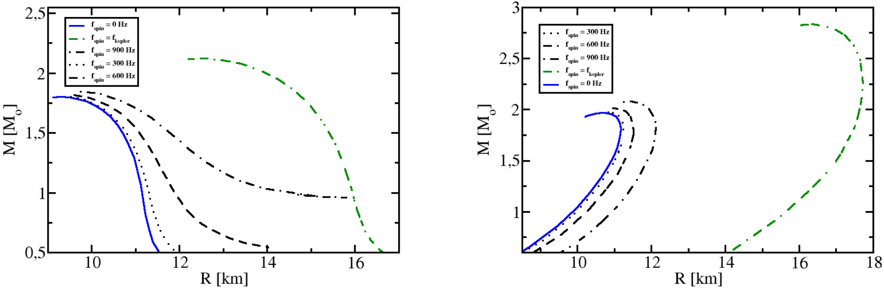
$$P = a(\rho - \rho_0)c^2$$

where P is the pressure, ρ the mass-energy density, and c is a speed of light.

FPS equation of state

- tabulated equation of state of Neutron Star
- developed by Friedman, Pandharipande and Skyrme (Pandharipande and Ravenhall 1989).

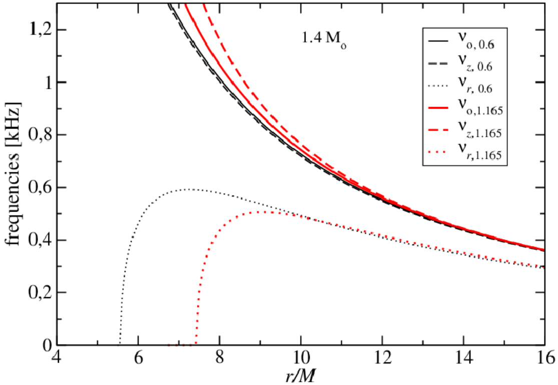
Mass-Radius relation for NS and SQS



Gravitational mass (in the units of the mass of Sun) versus **equatorial radius** in kilometers for neutron stars described by the FPS equation of state (left panel) and strange quark stars described by the MIT bag model (right panel). The **blue solid line** corresponds to **static case**, the **green line** corresponds to **keplerian limit**, the **black dotted line** correspond to configurations with spin frequency **300 Hz**, the **black dashed line** corresponds to configurations with spin frequency **600 Hz** and the **black dotted-dashed line** corresponds to configurations with spin frequency **900 Hz**.

- We have calculated axisymmetric models of strange quark stars and neutron stars and their exterior metrics using a highly accurate relativistic code, **RNS** (Stergioulas and Friedman 1995, see Stergioulas 1998 for a description)
- the equilibrium models are obtained following KEH method (Komatsu et al. 1989), in which the field equations are converted to integral equations using appropriate Green's functions.
- We have computed the metric outside uniformly rotating neutron stars and strange quark stars of masses and rotation rates typical for LMXBs.

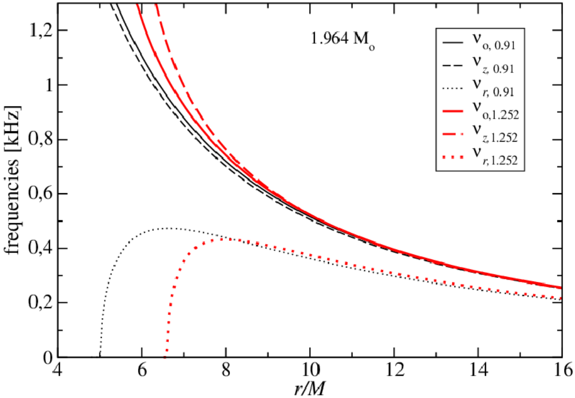
1.4 $M_\odot$ Strange Quark Star



Orbital and epicyclic frequencies versus radius (scaled with gravitational stellar mass M) for numerical models of an $\mathbf{M = 1.4M_\odot}$ uniformly rotating **strange quark star** rotating at a fixed frequency, **600 Hz** (thin black lines) and **1165 Hz** (thick red lines).

Gondek-Rosińska, Kluźniak, Stergioulas, Wiśniewicz, 2014

1.964 $M_\odot$ Strange Quark Star



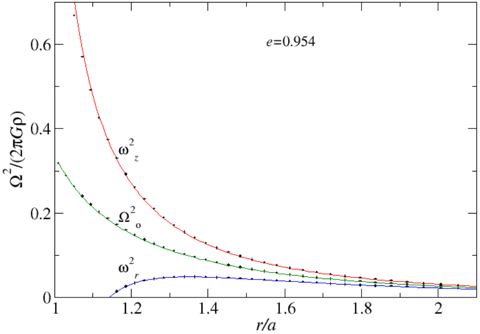
Orbital and epicyclic frequencies versus radius (scaled with gravitational stellar mass M) for numerical models of an $\mathbf{M = 1.964M_\odot}$ uniformly rotating **strange quark star** rotating at a fixed frequency, **910 Hz** (thin black lines) and **1252 Hz** (thick red lines).

Gondek-Rosińska, Kluźniak, Stergioulas, Wiśniewicz, 2014

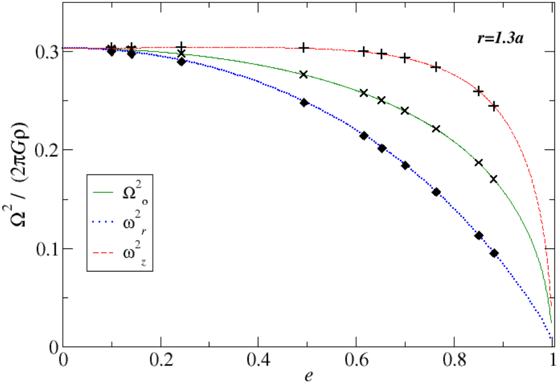
Orbital and epicyclic frequencies in Newtonian gravity (Maclaurin spheroids)

ISCO exists in the Newtonian Theory for $\mathbf{e} > \mathbf{e}_{\mathrm{crit}} = \mathbf{0.83458}$ - Amsterdamski, Bulik, Gondek-Rosińska, Kluźniak, 2002 (analytic formulae), Zdunik & Gourgoulhon, 2001

Ω_{vert} **always higher** than Ω_{orb}, and $\Omega^2_{\mathrm{vert}} + \Omega^2_r = 2\Omega^2_{\mathrm{orb}}$ (Kluźniak & Rosińska, 2013)



Orbital and epicyclic frequencies in Newtonian gravity



symbols - numerical results of RNS **relativistic code** for **M = 0.001 $M_\odot$ strange quark stars**

Gondek-Rosińska, Kluźniak, Stergioulas, Wiśniewicz, 2014

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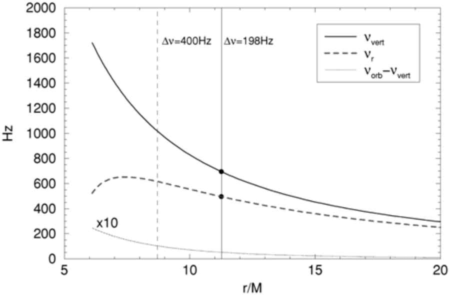
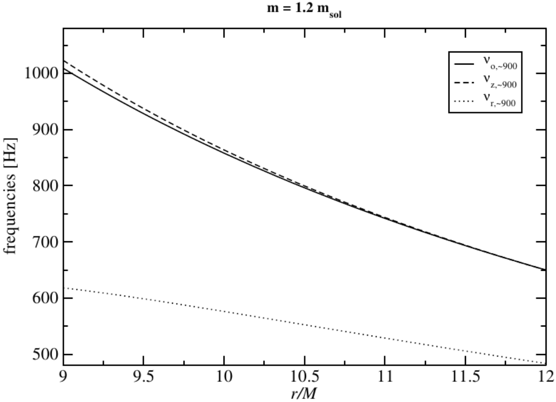
Previous studies - Epicyclic frequencies around $1.22 M_\odot$ neutron star (Kluźniak et al. 2004



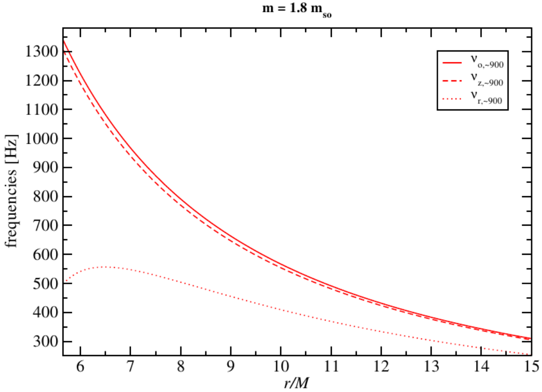
The effect of rotation on the epicyclic frequencies in numerical solutions for a **1.22 $M_\odot$ neutron star** (FPS) rotataing at **400 Hz** has been clearly seen in the unusually small difference $\Omega_{orb} - \Omega_{vert} \simeq 0$ between the orbital frequency and the vertical epicyclic one (Kluźniak et al. 2004)

1.2 $M_\odot$ Neutron Star



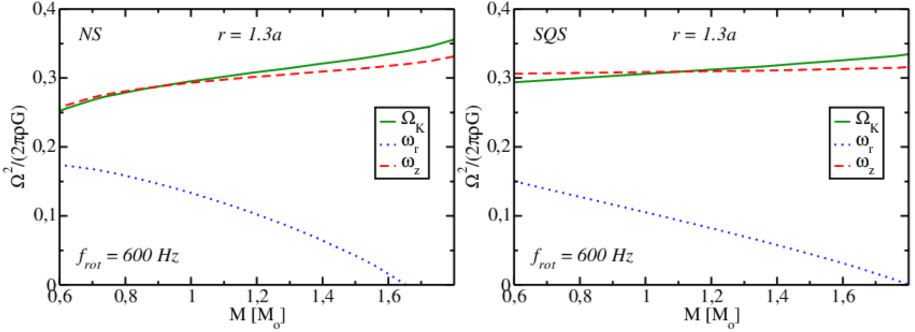
Orbital and epicyclic frequencies versus radius for numerical models of an **M = 1.2 M**$_\odot$ neutron star uniformly rotating at $\sim$ **900 Hz**.

1.8 $M_\odot$ Neutron Star



Orbital and epicyclic frequencies versus radius (scaled with gravitational stellar mass M) for numerical models of an **M = 1.8 M**$_\odot$ uniformly rotating **neutron star** rotating at a fixed frequency, $\sim$ **900 Hz**.

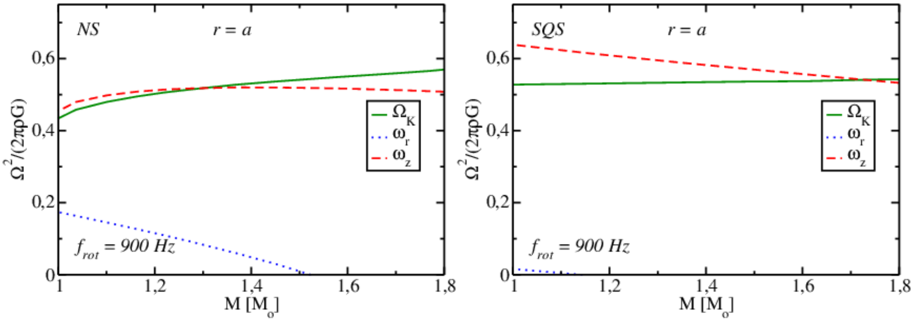
Epicyclic frequencies for Neutron Stars and Quark Stars



Frequencies (squared) at **r = 1.3a** versus gravitational mass for **neutron stars** (left panel), and **quark stars** (right panel), rotating at **600 Hz**.
The solid green line: orbital frequency.
The dashed red line: vertical epicyclic frequency.

The dotted blue line: radial epicyclic frequency.

Epicyclic frequencies for Neutron Stars and Quark Stars



Frequencies (squared) at **r = a** versus gravitational mass for **neutron stars** (left panel), and **quark stars** (right panel), rotating at **900 Hz**.
The solid green line: orbital frequency.
The dashed red line: vertical epicyclic frequency.

The dotted blue line: radial epicyclic frequency.

Summary

- Stellar spin has two opposing effects on epicyclic frequencies: **frame dragging** vs. **stellar oblateness**
- Frame dragging decreases the vertical epicyclic frequency and increases the radial epicyclic frequency of prograde orbits
- Stellar oblateness increases the vertical frequency and decreases the radial epicyclic frequency
- In rapidly rotating strange quark stars and **neutron stars** the effects of oblateness dominate the behavior of the vertical epicyclic frequency near the star. The effect is also visible in rapidly rotating neutron stars.

THANK YOU FOR YOUR ATTENTION!