Probing neutron star core matter using EM observations

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Measurement of neutron star parameters

Neutron Star: Surface and Interior

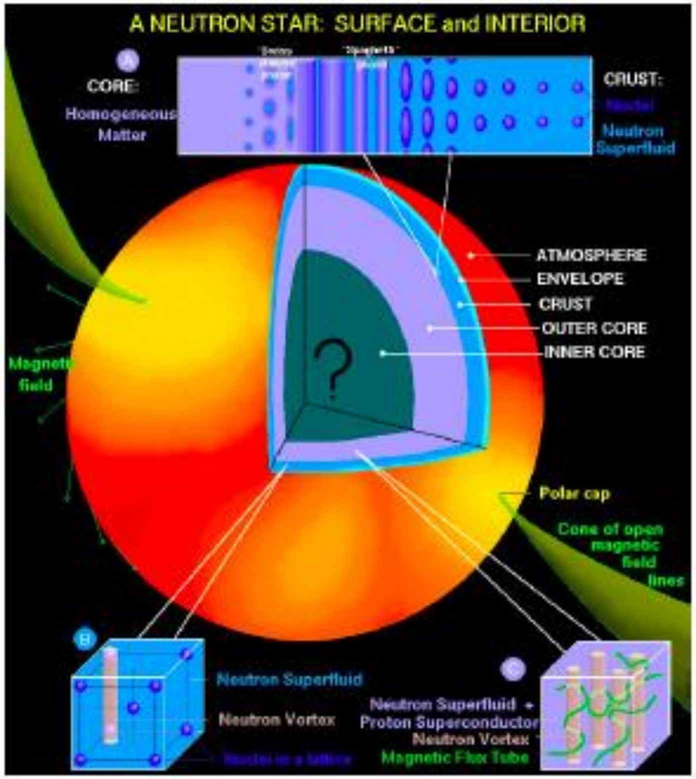
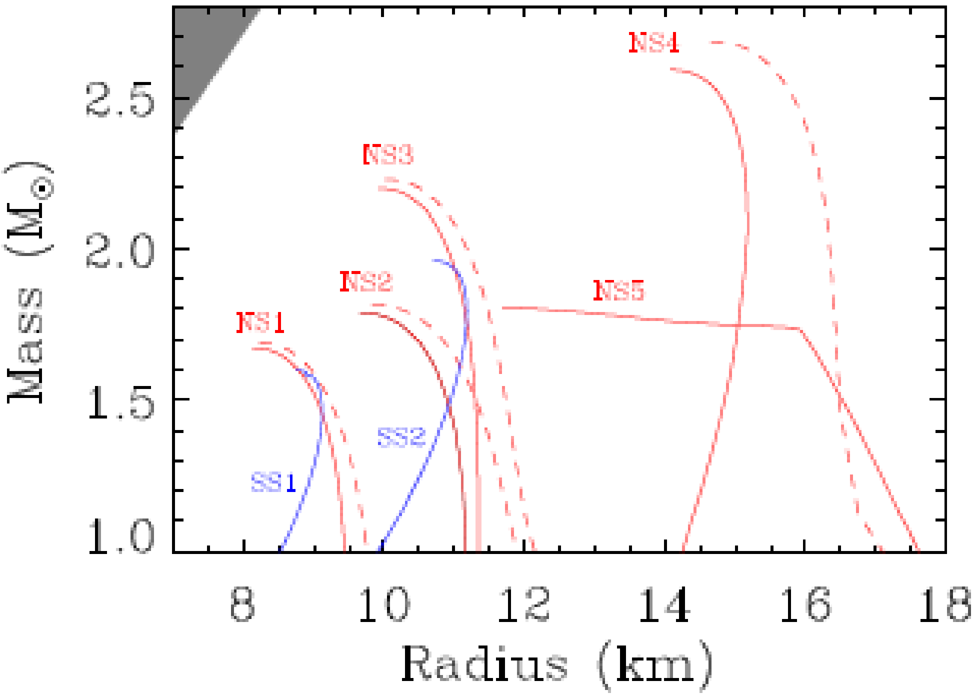


Figure courtesy: D. Page

How to constrain EoS models?

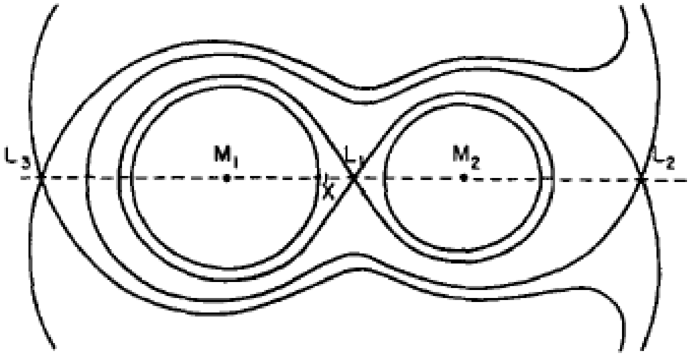


SB, AdSpR, 45, 949 (2010)

Mass, radius and spin frequency, or three independent structural parameters of the *same* neutron star are to be measured in order to constrain equation of state models.

Low-mass X-ray binary (LMXB)

Equipotential surfaces in a binary system

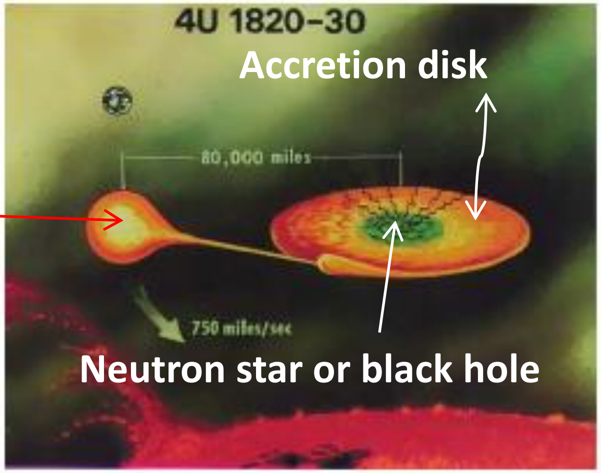


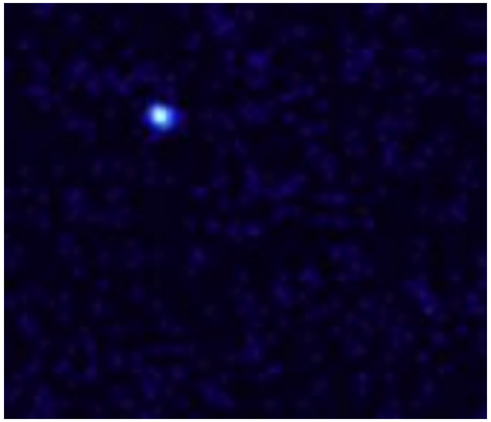
Courtesy: Bhattacharya & van den Heuvel (1991)

Low-mass X-ray binary (LMXB)

(Artist's impression; NASA website)

Low-mass (≤ 1 solar mass) companion star





Chandra image of KS 1731-260

Courtesy: NASA website

Angular size is so small that an LMXB cannot be spatially resolved.

Only spectral and timing methods are available to probe LMXBs.

(Exception: some jets).

Primarily emits X-rays. But also emits in other wavelengths.

A reasonably clean accretion process with disk extended close to the compact object →

Ideal to probe strong gravity and compact object properties.

List of complementary methods to measure parameters of neutron stars in low-mass X-ray binaries

1. Thermonuclear X-ray burst: Continuum spectrum method
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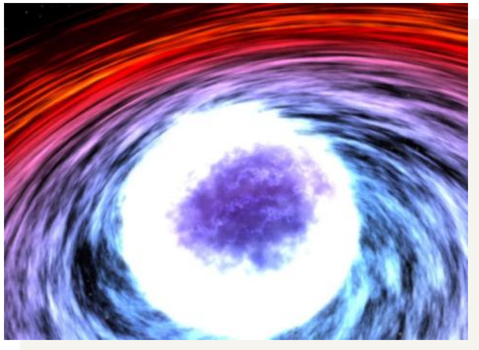
3. Thermonuclear X-ray burst: Milli-Hz QPO method
4. Thermonuclear X-ray burst: Burst oscillation method
5. Accretion-powered pulsation method
6. Kilo-Hz QPO method
7. Broad relativistic iron line method
8. Quiescent emission method
9. Mass measurement: binary orbital motion method

Many complementary methods may be required to overcome the systematic effects.

SB, AdSpR, 45, 949 (2010)

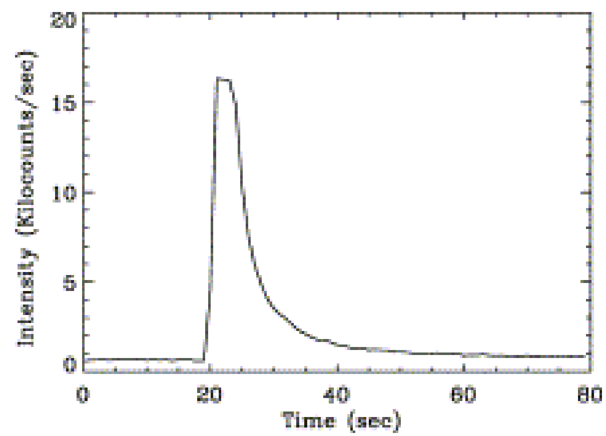
Thermonuclear X-ray Bursts



Accretion on neutron star

Unstable nuclear burning of accreted matter on the neutron star surface causes type I (thermonuclear) X-ray bursts.

Burst light curve



Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release in 10 seconds
≈ 10^{39} ergs

↓

Sun takes more than a week to release this energy.

Why is *unstable* burning needed?

Energy release:
Gravitational ≈ 200 MeV / nucleon
Nuclear ≈ 5 MeV / nucleon

Accumulation of accreted matter for hours → Unstable nuclear burning for seconds ⇒ Thermonuclear X-ray burst.

Thermonuclear X-ray Bursts

Bursts provide complementary methods to measure parameters of neutron stars in low-mass X-ray binaries

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1. Continuum spectrum method

Burst spectra are normally well fit with a blackbody model.

In principle, neutron star radius can be measured from the observed bolometric flux (F_{obs}) and blackbody temperature (T_{obs}), and the known source distance (d):

$$R_{obs}=d.(F_{obs}/(\sigma T^4_{obs}))^{1/2}$$

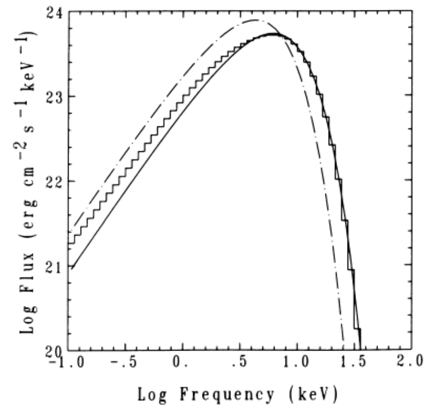
But there are systematic uncertainties:

(1) unknown amount of spectral hardening;
(2) effect of unknown gravitational redshift;
(3) unknown distance;
(4) if part of the surface emits.

$$T = T_{obs}.(1+z)/f \qquad R = R_{obs}.f^2/(1+z) \qquad \left\{ \begin{array}{l} z > 0;\ f \sim 1.0 - 2.0 \\ 1+z = [1 - (2GM/Rc^2)]^{-1/2} \end{array} \right.$$

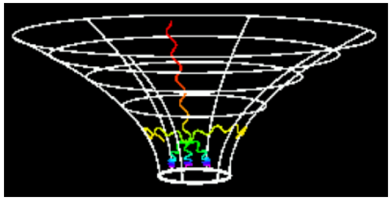
Atmospheric chemical composition, surface gravity, temperature $\Rightarrow$ f (primary problem)

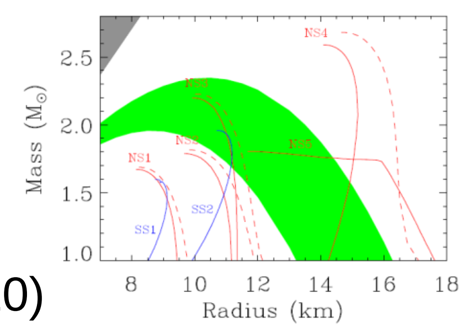
Burst spectra



London, Taam & Howard (1986)

Gravitational redshift





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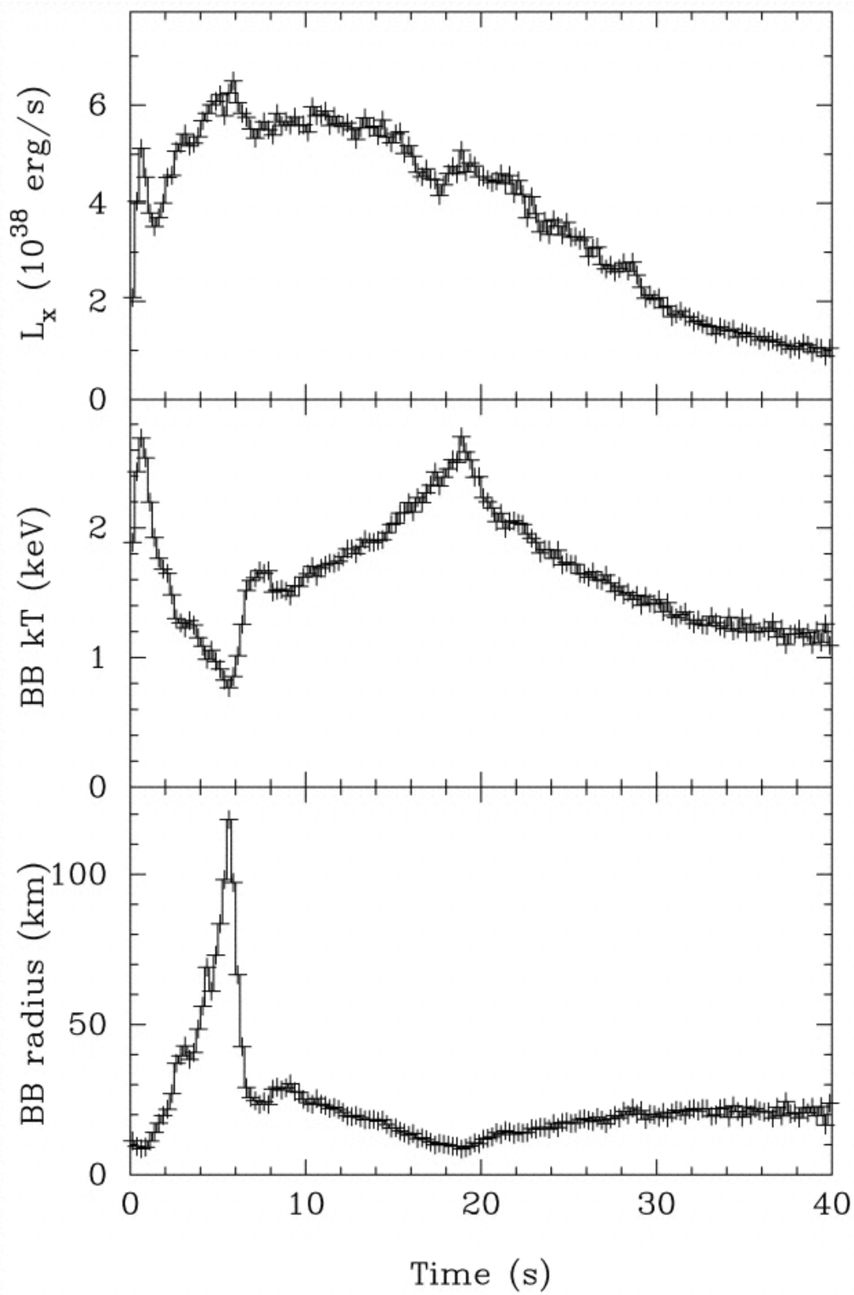
2. PRE burst method



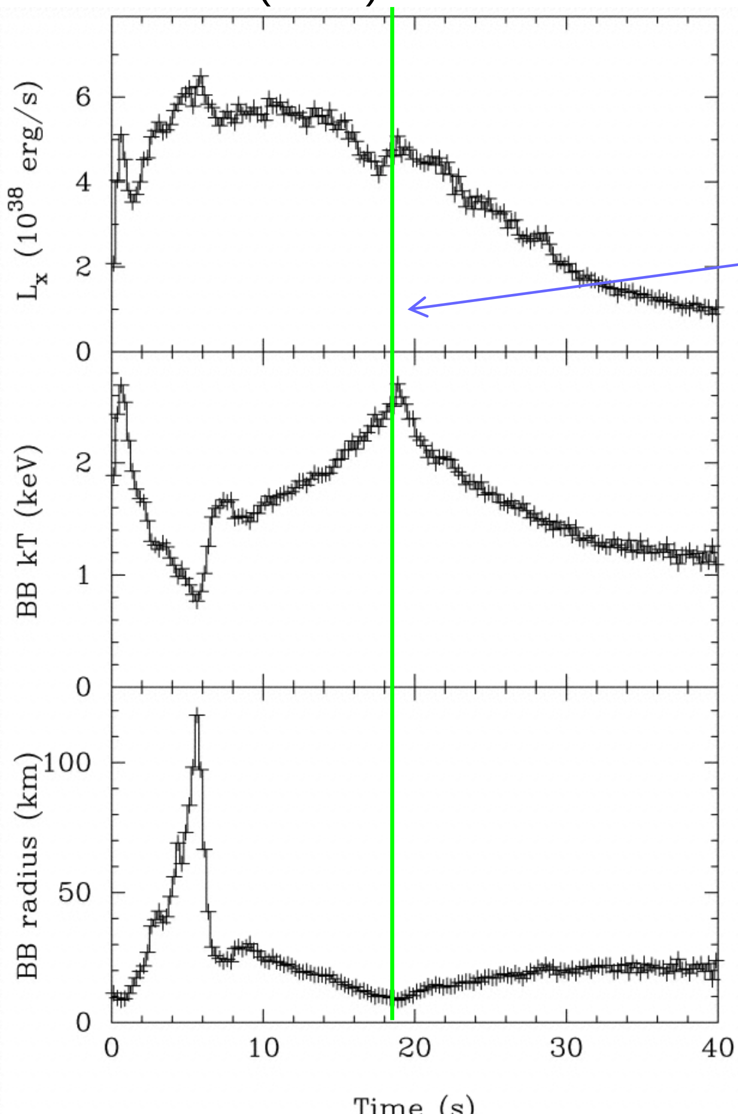
Photospheric Radius Expansion (PRE) bursts

The burst is so strong that the radiative pressure pushes the photosphere or the neutron star atmosphere away from the stellar surface temporarily.

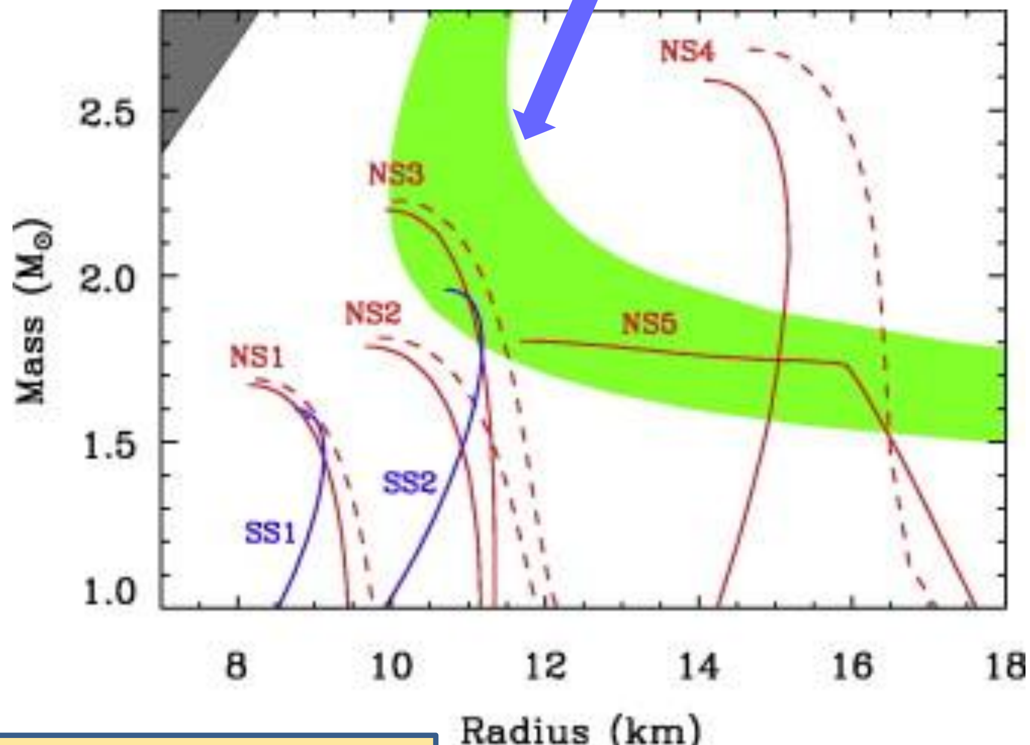
Smale (2001)

2. PRE burst method

Smale (2001)



Eddington flux = Touch-down flux



$$F_{Edd} = (1/4\pi d^2)(4\pi GMc/\kappa)(1-2GM/Rc^2)^{1/2}$$

SB, AdSpR, 45, 949 (2010)

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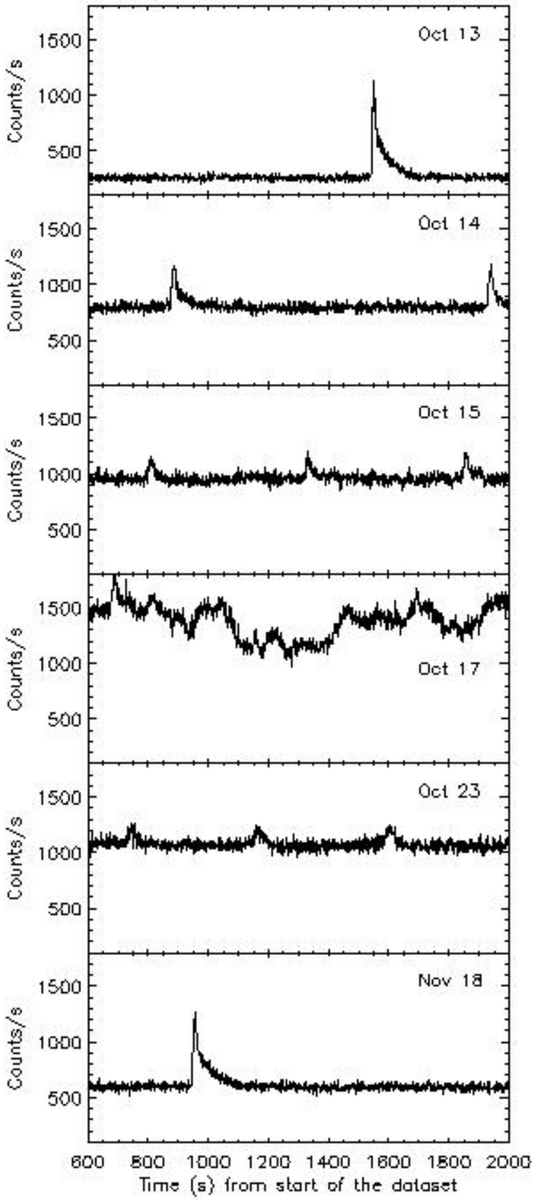
SB, AdSpR, 45, 949 (2010)

3. Milli-Hz QPO method

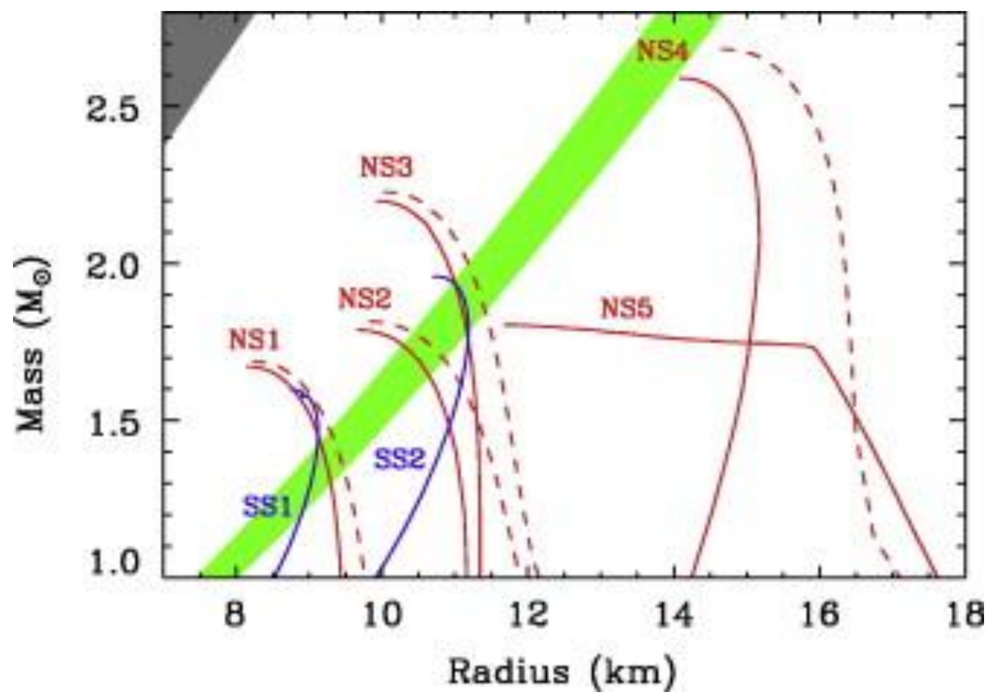
IGR J17480-2446



Chakraborty & SB (2011)

From the marginal burning stability condition, the oscillation frequency is a strong function of the surface gravity:

$g \cong GM/R^2[1 - 2GM/RC^2]^{-1/2}$



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SB, AdSpR, 45, 949 (2010)

4. Burst oscillation method

Fast Timing Properties of X-ray Bursts (Burst Oscillations)

What are burst oscillations?

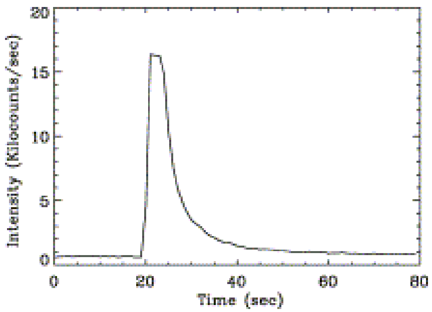
These are millisecond period variations of observed intensity during thermonuclear X-ray bursts.

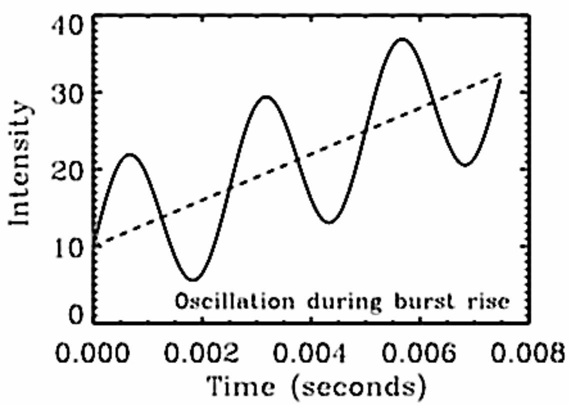
What is their origin?

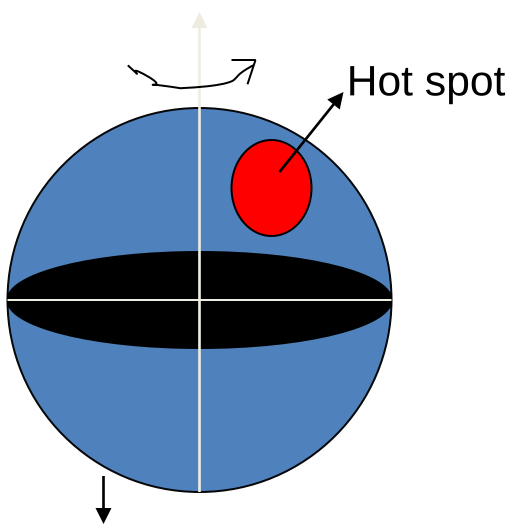
Asymmetric brightness pattern on the spinning neutron star surfaces.

Neutron star spin frequency
= Burst oscillation frequency

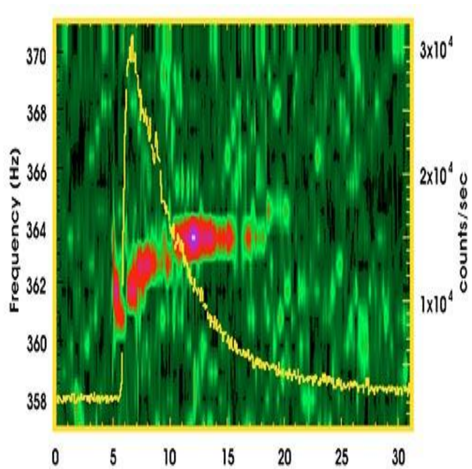
Burst light curve







Spinning neutron star



NASA website

4. Burst oscillation method

Burst oscillation method to measure neutron star parameters:
SB, Strohmayer, Miller, Markwardt, ApJ, 619, 483 (2005)

Physical effects included in the model:

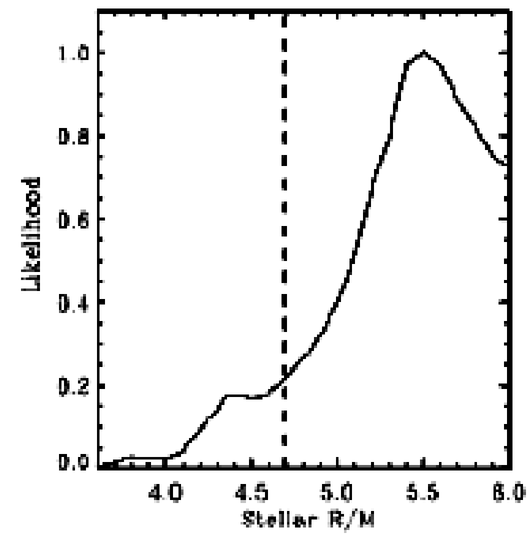
(1) Doppler boosts; (2) special relativistic beaming; (3) gravitational red-shift; (4) light bending; (5) frame dragging.

Free parameters for a chosen EoS model:

(1) NS radius-to-mass ratio: ***R/M***;
(2) θ-position of the centre of the hot spot: θ_c;
(3) angular radius of the spot: $\Delta\theta$;
(4) observer's inclination angle w.r.t. NS spin axis: ***i***;
(5) beaming (due to NS atmosphere) parameter: ***n*** [specific intensity as a function of angle ψ (in emitter's frame) from surface normal is given by $I(\psi) \propto \cos^n(\psi)$];
(6) background.

XTE J1814-338
(RXTE-PCA data)

Likelihood



NS *R/M*

The vertical dashed line gives the lower limit of the stellar radius-to-mass ratio with 90% confidence.

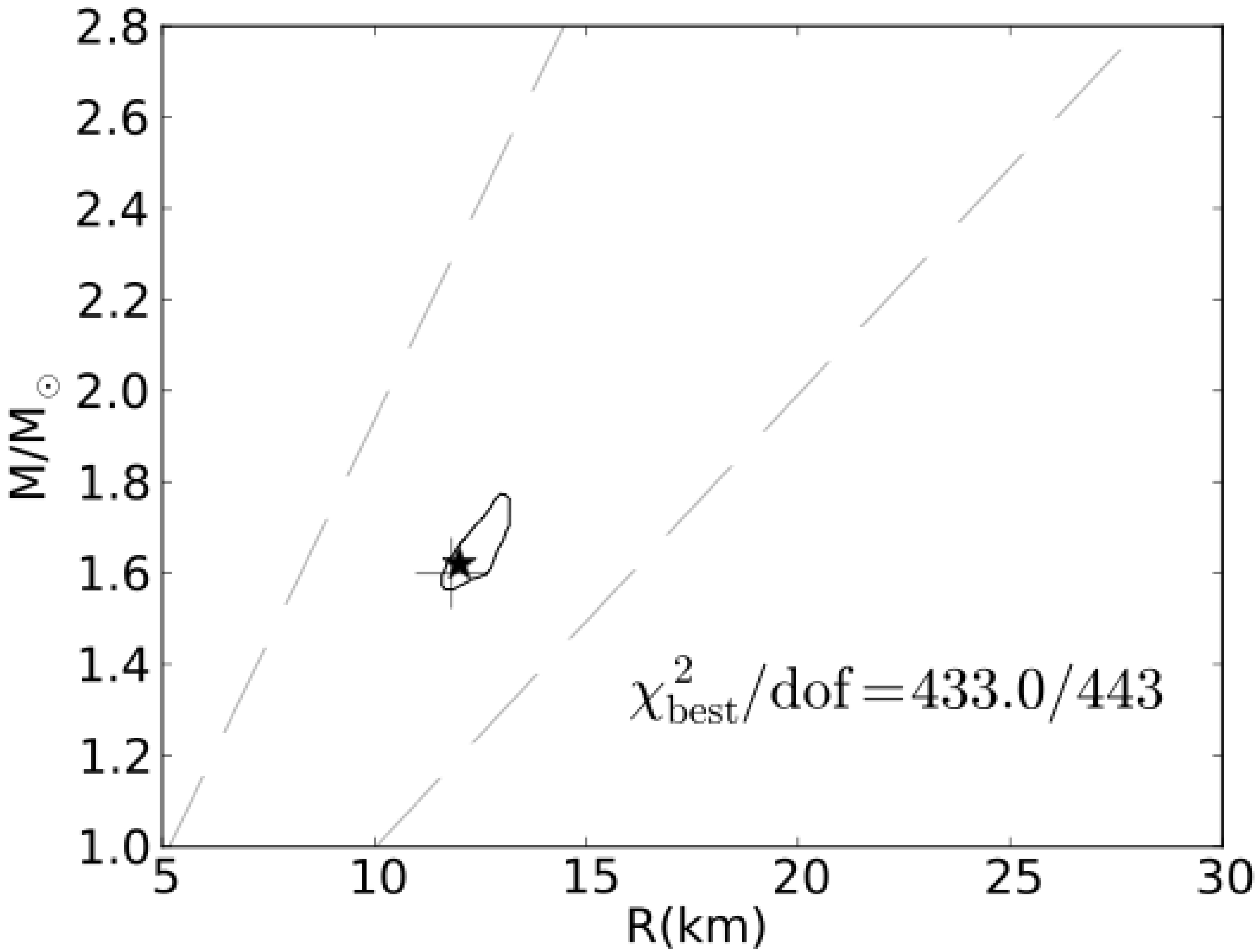
$$q(\theta_k) = \int d\theta_1 \ldots d\theta_{k-1} d\theta_{k+1} \ldots d\theta_n \, p(\theta_1 \ldots \theta_n). \quad (1)$$

Integration over "nuisance" parameters.
$p \rightarrow$ posterior probability density

4. Burst oscillation method

Burst oscillation method to measure neutron star parameters:

Simulated data fitting



A 10 square metres future timing X-ray instrument (originally done for LOFT) is considered for simulation.

Same method is being used for NICER, and may be used for other satellites (e.g., eXTP).

Ka Ho Lo, Cole Miller, SB, Fred Lamb, ApJ, 776, 19 (2013)

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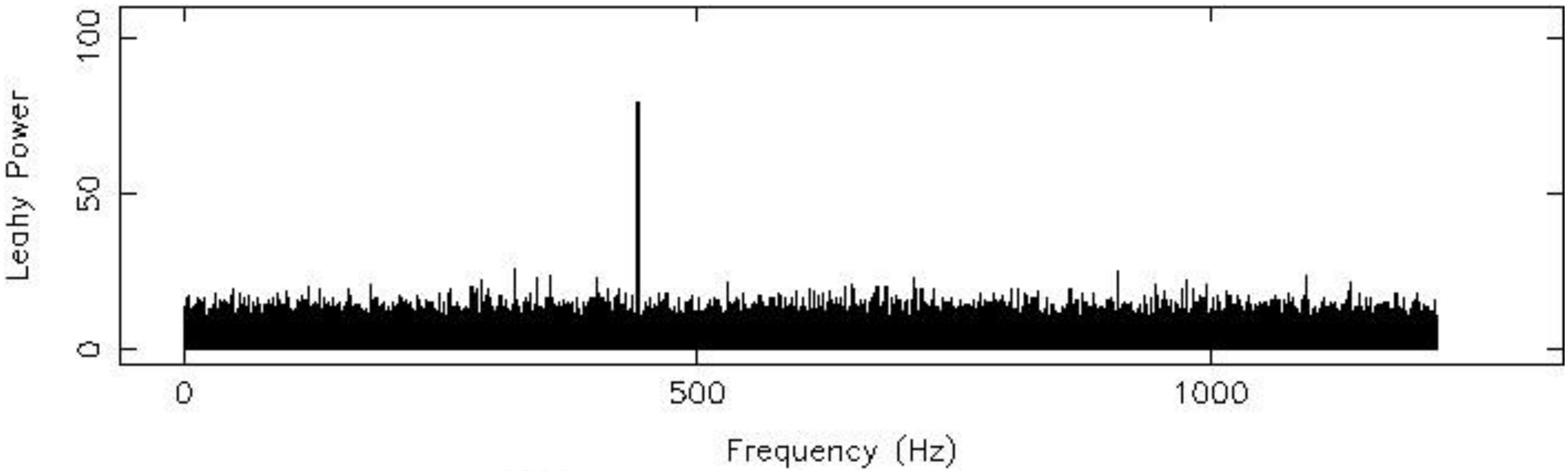
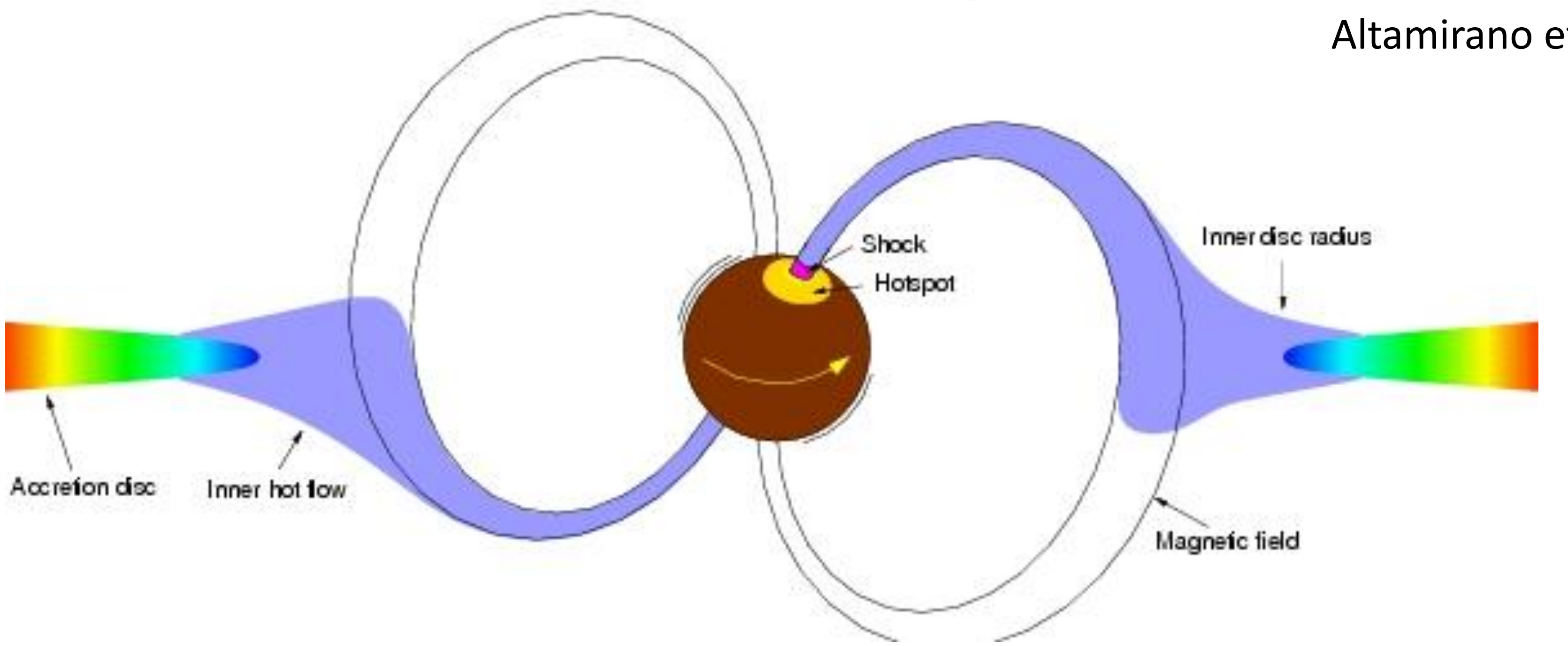
SB, AdSpR, 45, 949 (2010)

Accretion-powered pulsars



Altamirano et al. (2008)



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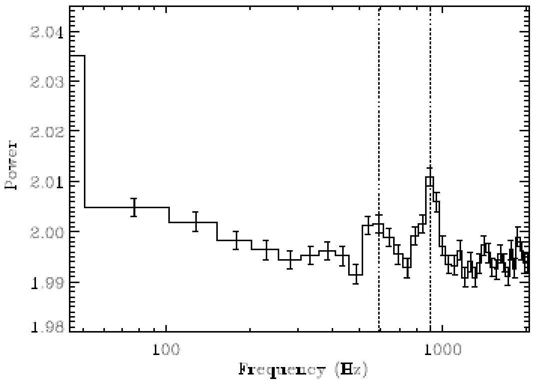
Kilohertz quasi-periodic oscillations (kHz QPOs)



KHz QPOs often appear in a pair in the power spectrum, in the 200-1200 Hz frequency range.

Fourier Transform

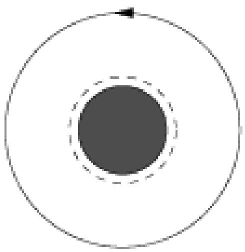
$$\hat{f}(\xi) := \int_{-\infty}^{\infty} f(x)\, e^{-2\pi i x \xi}\, dx$$

$$f(x) = \int_{-\infty}^{\infty} \hat{f}(\xi)\, e^{2\pi i x \xi}\, d\xi$$

Power is the Fourier transform of the spectrum intensity vs. time curve.

This observationally robust timing feature have been detected from many neutron star LMXBs.

According to almost all the models, the uniquely high kHz QPO frequencies are either the following accretion disk frequencies, or the beating or resonances among them, or with the neutron star spin frequency ν_{spin}.



- ν_ϕ : **Orbital frequency**
- ν_r : **Radial epicyclic frequency**
- ν_θ : **Vertical epicyclic frequency**
- $\nu_\phi - \nu_r$: **Periastron precession frequency**
- $\nu_\phi - \nu_\theta$: **Nodal or `Lense-Thirring' precession frequency**

Kilohertz quasi-periodic oscillations (kHz QPOs)

Accretion disk frequencies:

$$\nu_\phi = \frac{\sqrt{GM/r^3}/2\pi}{1 + j(r_g/r)^{3/2}} = \nu_K(1 + j(r_g/r)^{3/2})^{-1}$$

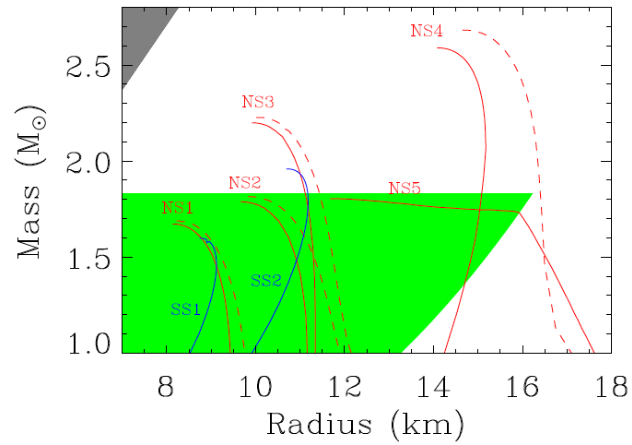
$$r_g \equiv GM/c^2$$

$$\nu_r = \nu_\phi \left(1 - 6(r_g/r) + 8j(r_g/r)^{3/2} - 3j^2(r_g/r)^2\right)^{1/2}$$

$$j \equiv Jc/GM^2$$

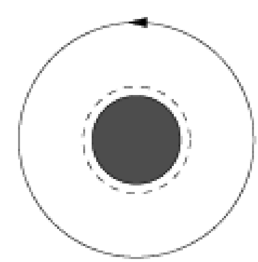
$$\nu_\theta = \nu_\phi \left(1 - 4j(r_g/r)^{3/2} + 3j^2(r_g/r)^2\right)^{1/2}$$

Miller et al. (1998)



So when the correct model is identified, kHz QPOs can be used to measure the neutron star parameters M and J.

Such a constraint on the neutron star mass-radius space is possible, if one of the kHz QPO frequencies is ν_ϕ, and the corresponding radial distance r is greater than or equal to the neutron star and the ISCO radius.



Apart from neutron star parameter measurement, KHz QPOs can be useful to study the matter flow in strong gravity region, and to test a law of gravitation.

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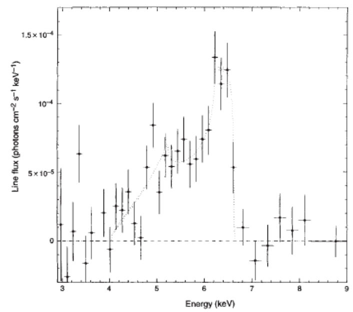
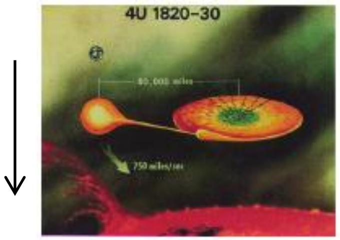
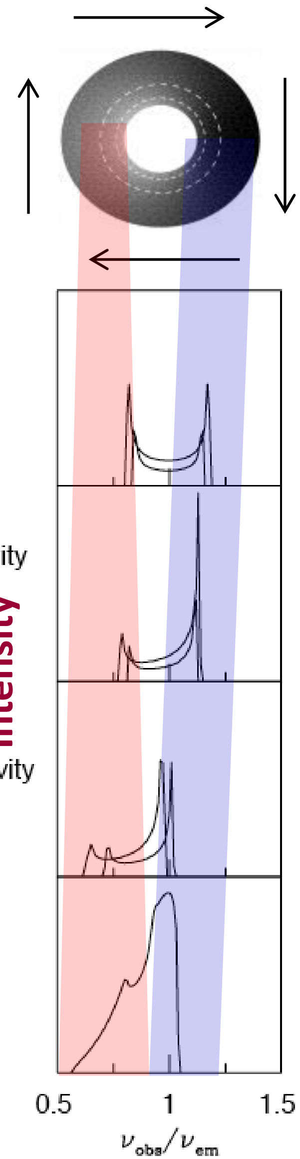
Broad relativistic spectral line and its use

Broad asymmetric iron Kα emission lines are observed from accreting super-massive black hole (AGN) and stellar-mass black hole (black hole LMXB) systems. They originate from the inner part of the accretion disk.



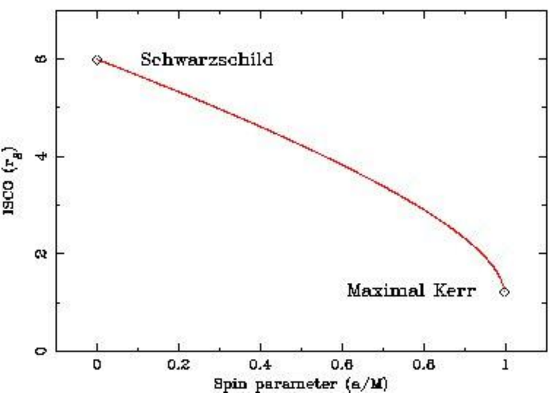
Tanaka et al. (1995)

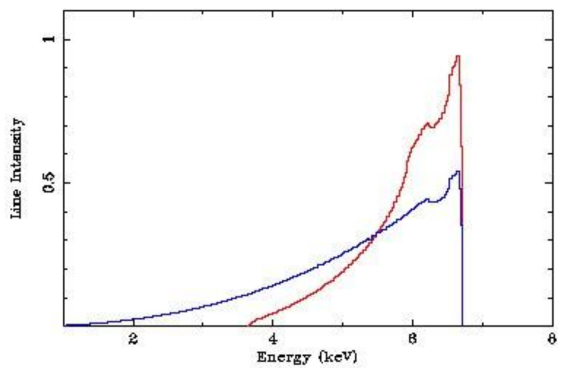




Fabian et al. (2000)

They are a nature-given tool to measure the black hole spin and to probe the strong gravity regime.





Theoretical models of broad line for two BH spin parameter ($a/M \equiv Jc/GM^2$) values. (Miller 2007)

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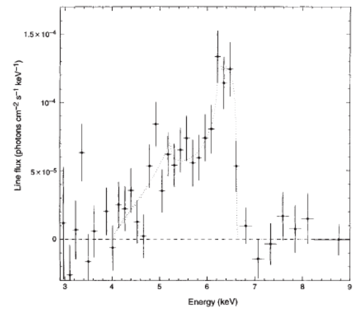

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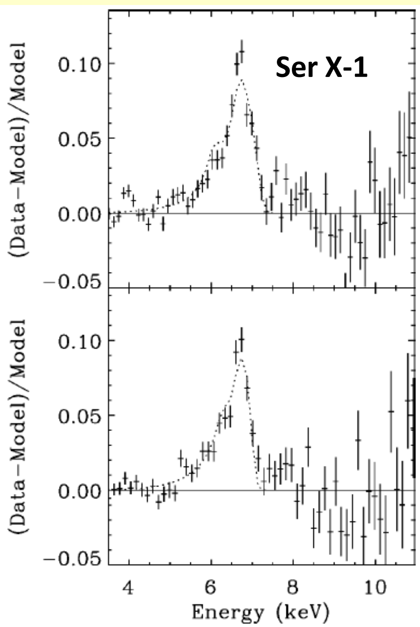
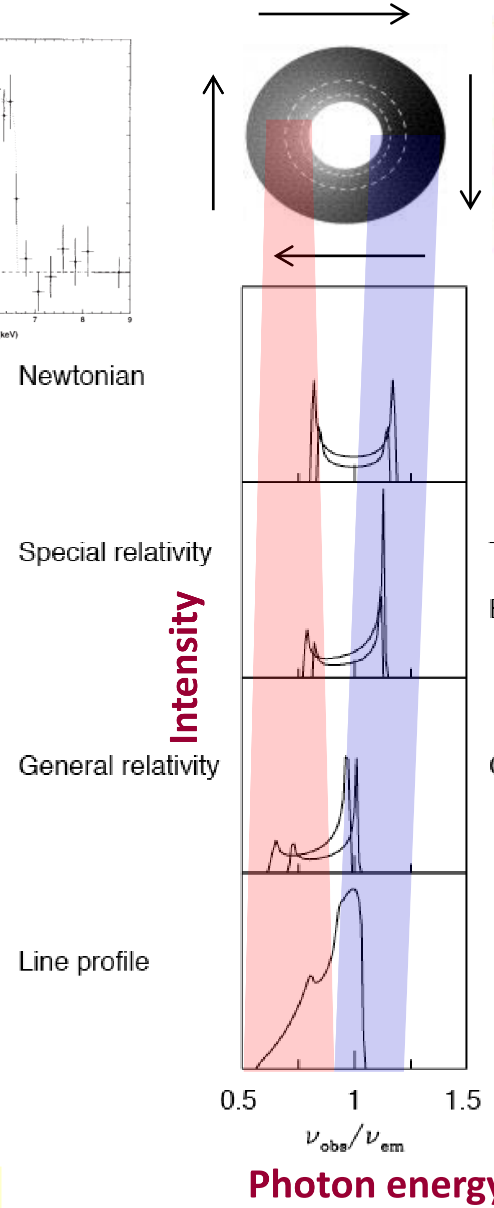


The first relativistic iron line from a neutron star LMXB was discovered by Bhattacharyya & Strohmayer, ApJ, 664, L103 (2007).

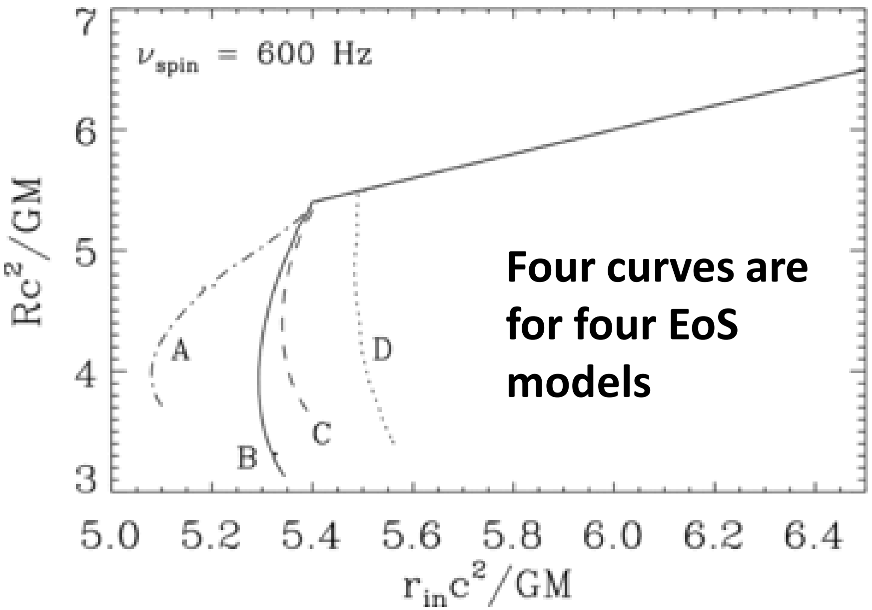
This opened up a new way to probe the strong gravity regime around neutron stars and to measure the stellar parameters.



Fabian et al. (2000)

Broad relativistic spectral line and its use

Rapidly spinning neutron star structures have been calculated with full GR effects using the formalism of Cook, Shapiro & Teukolsky.



SB, MNRAS, 415, 3247 (2011)

Conclusion: $r_{in}c^2/GM$ is to be measured with better than an accuracy of 0.1 to effectively constrain EoS models.

A section of the White Paper (Watts, Yu, Poutanen, Zhang, SB, et al., Science China PMA, 2019) of eXTP's Science Working Group 1 on Dense Matter was written based on this work.

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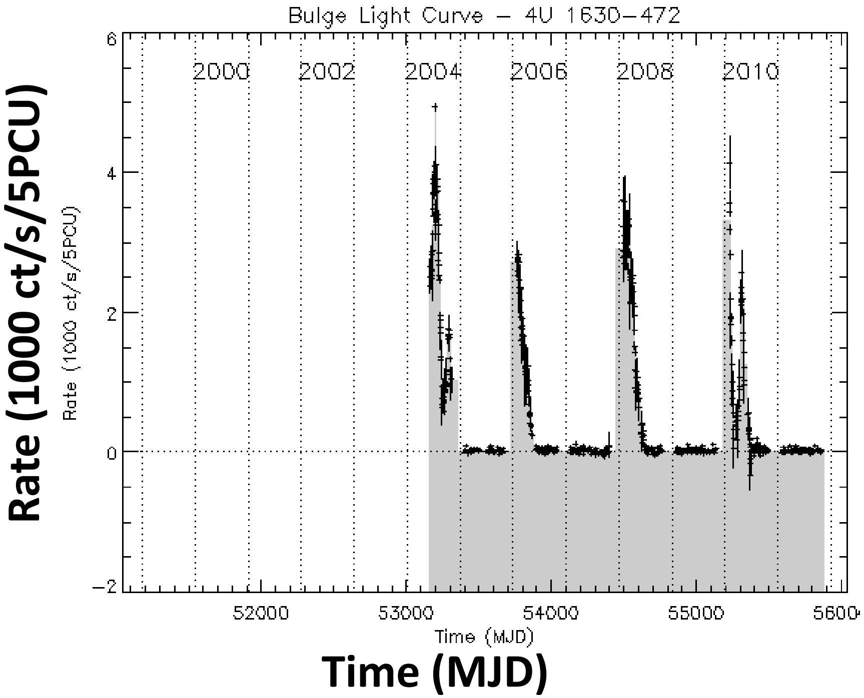
Quiescent emission method



Transient sources show big outbursts, and quiescent periods between two subsequent outbursts.

RXTE/PCA light curve of 4U 1630-472 from Galactic bulge scan

Courtesy: http://asd.gsfc.nasa.gov/Craig.Markwardt/galscan/

In the quiescent period, the neutron star surface emits almost like a blackbody.

So, in principle, neutron star radius can be measured from the observed bolometric flux (F_{obs}) and blackbody temperature (T_{obs}), and the known source distance (d):

$$R_{obs}=d.(F_{obs}/(\sigma T^4_{obs}))^{1/}$$

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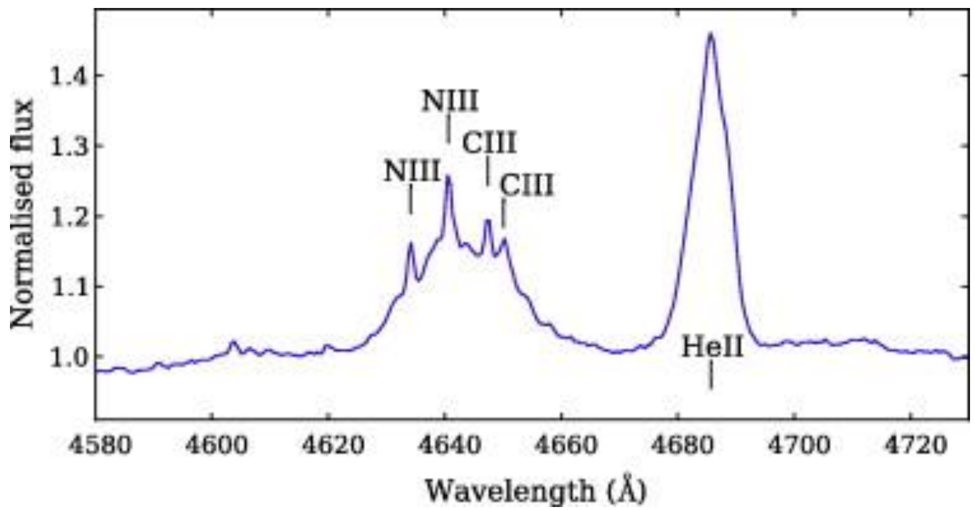
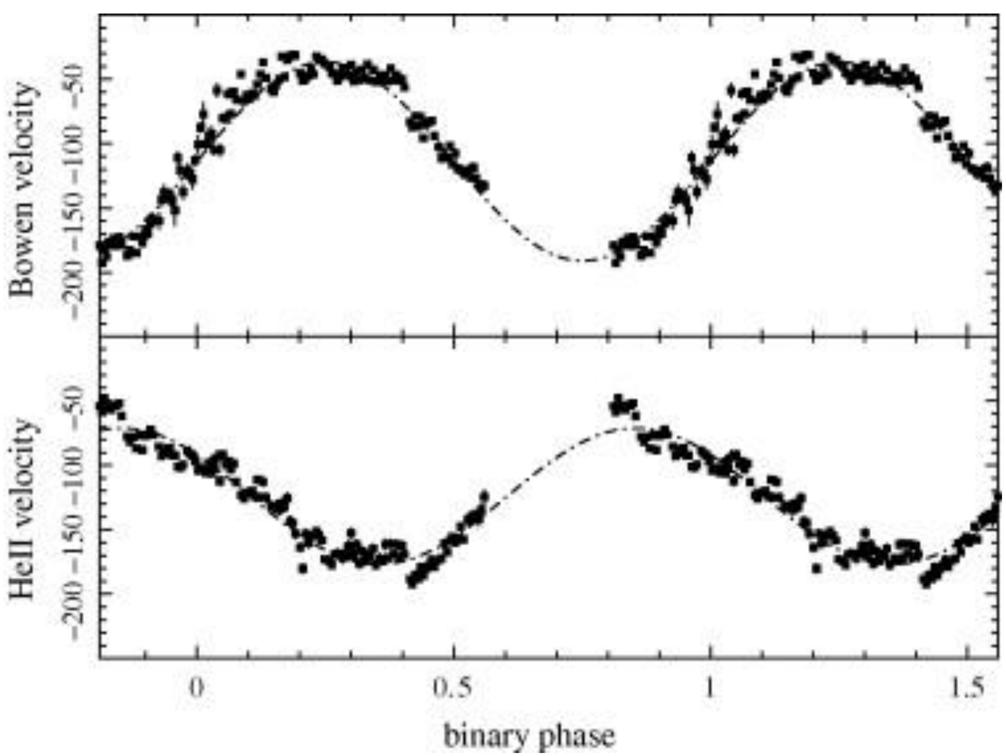
5. Accretion-powered pulsation method
6. Kilo-Hz QPO method
7. Broad relativistic iron line method
8. Quiescent emission method
9. Mass measurement: binary orbital motion method

Many complementary methods may be required to overcome the systematic effects.

SB, AdSpR, 45, 949 (2010)

Mass measurement: binary orbital motion method

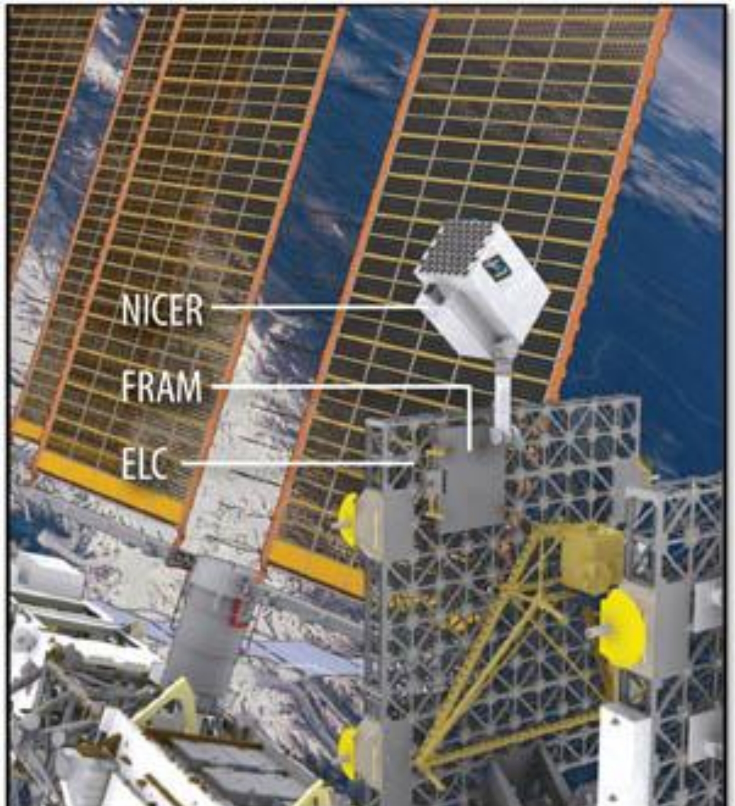


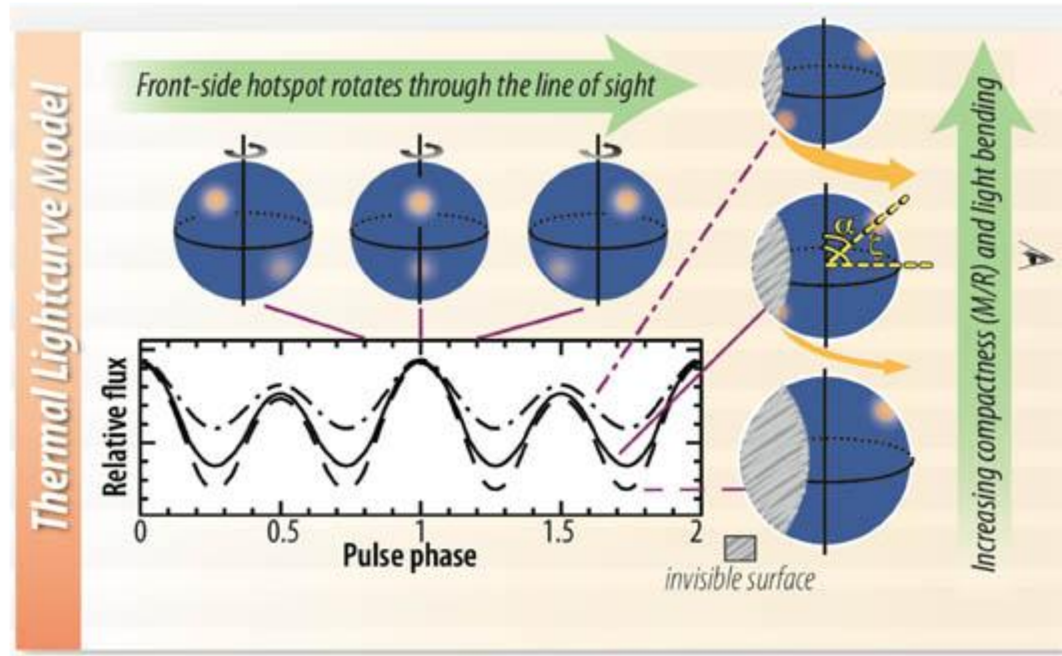


Velocity curves can be measured from the Doppler shifts of the spectral lines.
Mass can be estimated from the velocity curves and Kepler's 3rd law.

Steeghs and Casares (2002)
SB, AdSpR, 45, 949 (2010)

Neutron star parameters from the measurement of spin-phase folded X-ray light curves of millisecond radio pulsars





https://heasarc.gsfc.nasa.gov/docs/nicer/nicer_about_merged.html

NICER satellite

Millisecond pulsars: Equation of state

NICER should tightly constrain the neutron star mass-radius space for a few millisecond pulsars.

For many equation of state (EoS) models, we numerically compute the rapidly spinning neutron star structures (considering the full effect of GR) for the known stellar spin frequencies, and we will try to constrain the EoS models from NICER results.

We particularly consider the possibility of transition from a neutron star to a strange (or to a hybrid) star.

SB, Bombaci, Logoteta, Thampan, ApJ, 848, 65 (2017)