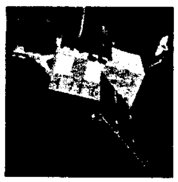
Understanding Neutron Stars using Thermonuclear X-ray Bursts

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Outline

Neutron Stars: why do we care?

Thermonuclear Bursts: why do we care?

Neutron Stars: Mass, Radius and Spin:

- a. Continuum Spectroscopy of Bursts
- b. Spectral Lines from Bursts
- c. Timing Properties of Bursts

Neutron Star Atmosphere: Thermonuclear Flame Spreading

Future Prospects and Conclusions

Neutron Star

Neutron star vs. a city

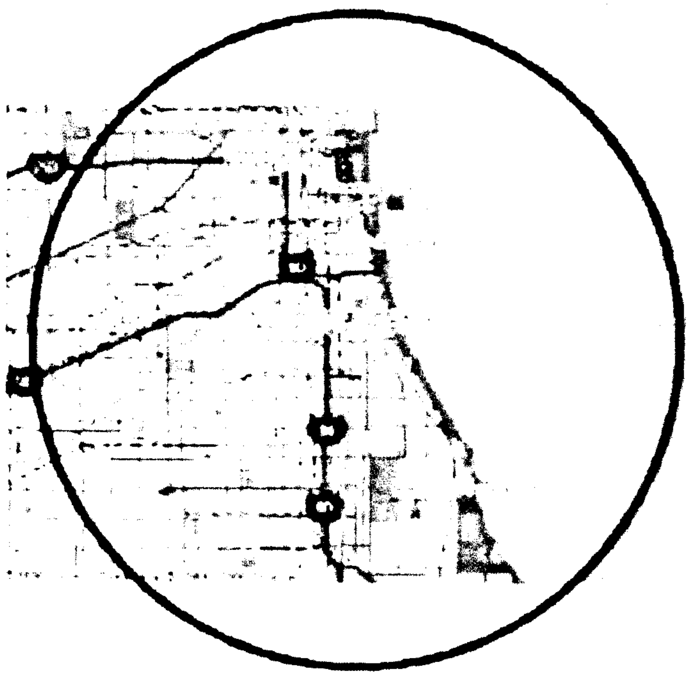


Figure courtesy M. Coleman Miller

Radius ~ 10 - 20 km

Mass ~ 1.4 - 2.0 solar mass

Core density ~ 5 -10 times the nuclear density

Magnetic field ~ 10^7 - 10^{15} G

Spin frequency (in some binary stellar systems) ~ 300 - 600 Hz

Some of the most extreme conditions of the universe exist in neutron stars.

Neutron Star: Surface and Interior

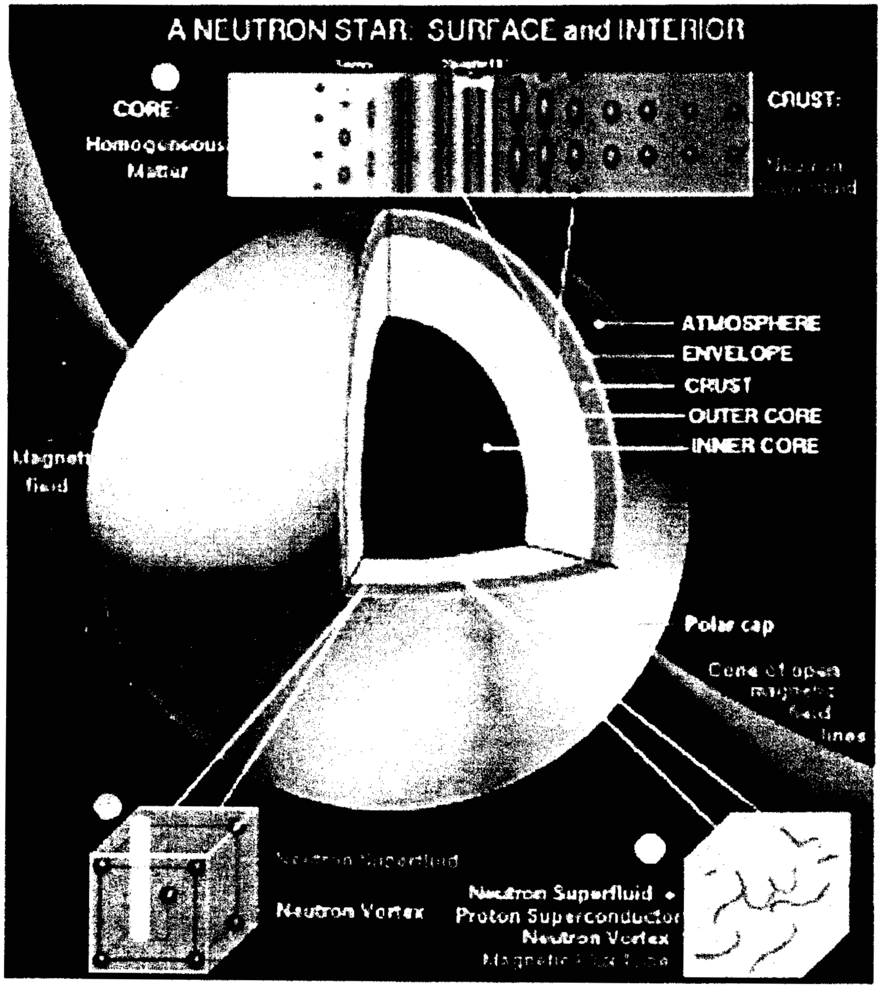


Figure courtesy D. Page.

Core density ≥ nuclear density

⇓

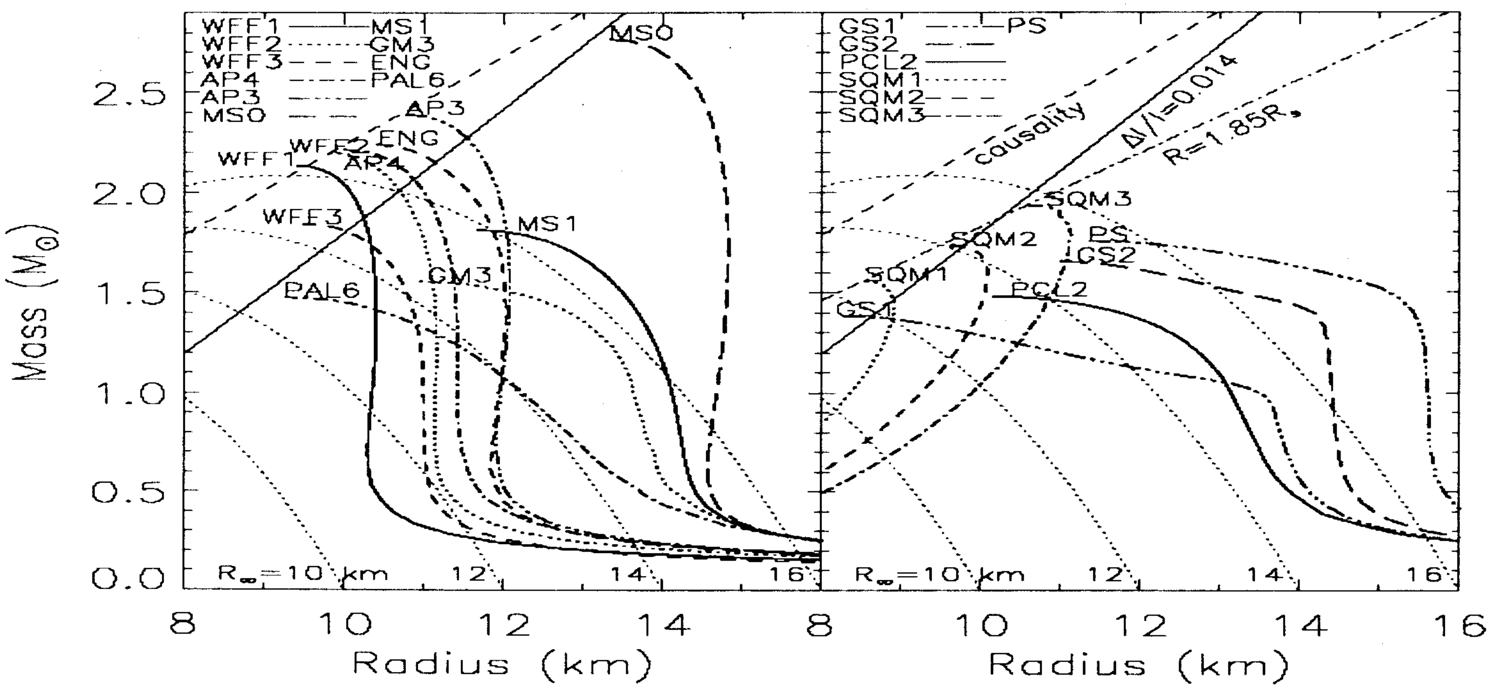
Exotic matter???

No terrestrial experiments seem possible at such high densities and low (comparatively) temperatures.

Many equation of state (EOS) models for the neutron star core matter are available in the literature. We need to constrain these models by observing neutron stars.

The constituents of neutron star interiors remain a mystery after 40 years.

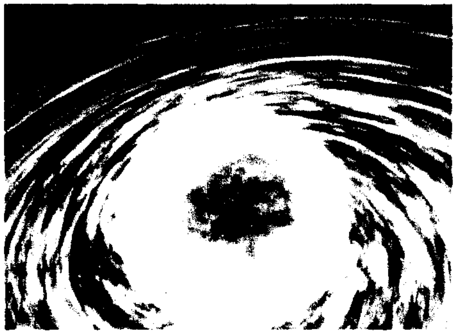
How to constrain EOS models?



Lattimer & Prakash (2001)

Mass, radius and **spin frequency** of a neutron star are to be measured in order to constrain **equation of state** models.

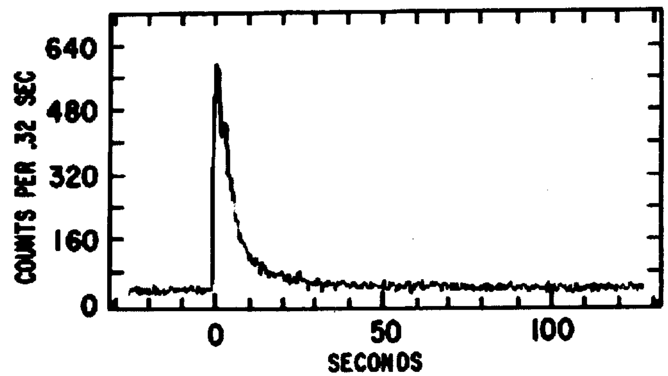
Thermonuclear X-ray Bursts



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 ≈ 7 MeV / nucleon

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

Why are the thermonuclear X-ray bursts important for understanding neutron stars?

(1) They originate from neutron star surfaces.

(2) Their intensities are ~ 10 times higher than the non-burst emission intensity. This gives higher signal-to-noise ratio.

(3) They show timing and spectral features, that can be used to constrain the *mass*, *radius* and *spin frequency* of a neutron star.

(4) They provide the unique opportunity to understand the thermonuclear flame spreading on neutron star surfaces.

(5) Many bursts are observed from the same neutron star.

(6) Comparatively lower magnetic fields (~ 10^7-10^9 G) of the bursting neutron stars simplify the modeling.

Procedures to constrain neutron star parameters analyzing thermonuclear X-ray bursts:

(1) Spectral studies:

(a) continuum spectroscopy *(RXTE-PCA)*,

(b) line spectroscopy *(Chandra, XMM-Newton, Suzaku)*.

(2) Studies of fast (millisecond period) timing properties *(RXTE-PCA)*.

Continuum Burst Spectroscopy

★ Burst spectra are normally well fitted with a blackbody model.

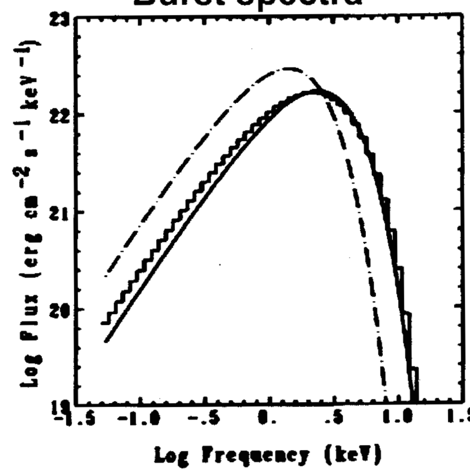
★ In principle, neutron star radius can be measured from the observed bolometric flux (F_{obs}) and blackbody temperature (T_{obs}), and the known source distance (d):

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

★ But there are systematic uncertainties:
(1) unknown amount of spectral hardening due to electron scattering;
(2) effect of unknown gravitational redshift.

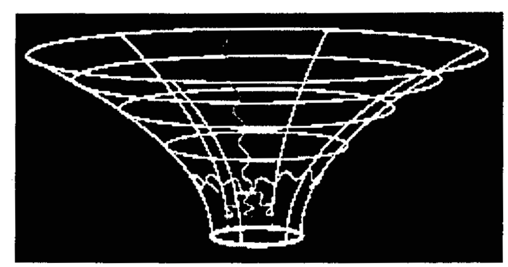
$$T = T_{obs}.(1+z)/f \qquad R = R_{obs}.f^2/(1+z) \qquad \begin{cases} z > 0;\ f \sim 1.0 - 2.0 \\ 1+z = [1 - (2GM/Rc^2)]^{-1/2} \end{cases}$$

Burst spectra



London, Taam & Howard (1986)

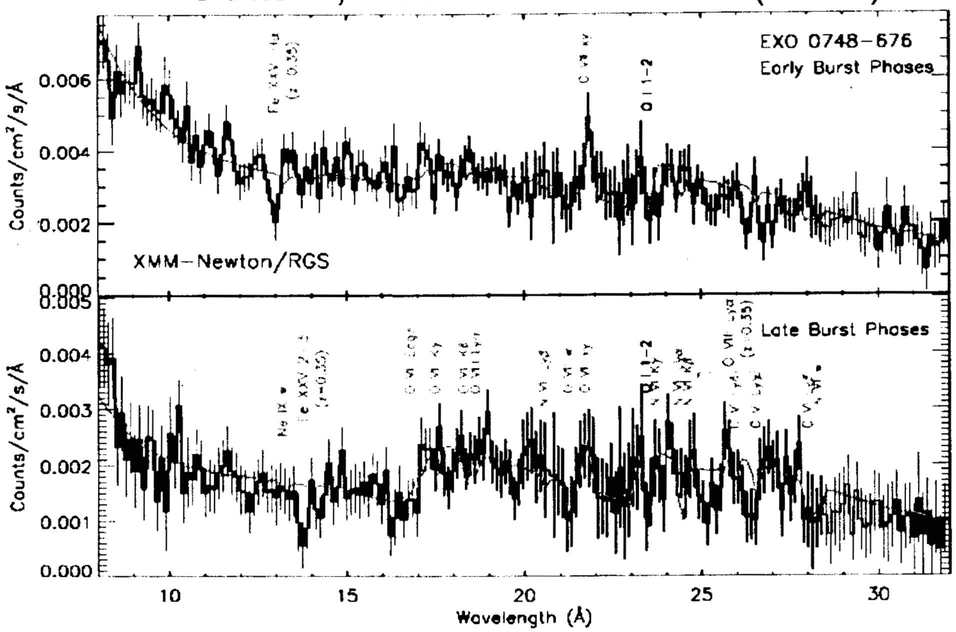
Gravitational redshift



Chemical composition of neutron star atmosphere ⇒ f
Neutron star radius-to-mass ratio ⇒ 1+z

Line Burst Spectroscopy

Cottam, Paerels & Mendez (2002)



Observation of surface atomic spectral line at the energy E_{obs}

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Identification: original line energy = E_0

⇓

Gravitational redshift 1+z = E_0/E_{obs}

⇓

Neutron star "radius to mass" ratio from $1+z = [1-(2GM/Rc^2)]^{-1/2}$

XMM-Newton grating observations of surface atomic spectral absorption lines during X-ray bursts from an LMXB (EXO 0748-676): measured gravitational redshift 1+z = 1.35, and hence $Rc^2/GM = 4.4$.

But why LMXBs and X-ray bursts?

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These Fe absorption lines could be produced in the upper atmosphere of the neutron star, and the continuous accretion might supply the Fe ions.

Line Burst Spectroscopy

Why LMXBs and X-ray bursts?

* For LMXBs, and during bursts, continuous accretion and radiative pressure may keep heavy elements in the atmosphere for the time required for spectral line detection.

* Comparatively lower magnetic field (10^7-10^9 G):
  (1) magnetic splitting is negligible: line identification is easier;
  (2) magnetic field does not complicate the modeling of neutron star atmosphere and photon emission.

* During the bursts, neutron star surface emission dominates the total X-ray emission.

* During the bursts, high photon flux from the neutron star surface provides good signal-to-noise ratio.

Line Burst Spectroscopy

❊ But the neutron stars in LMXBs normally spin very fast (ν_{spin} ~ 300-600 Hz) due to accretion induced angular momentum transfer.

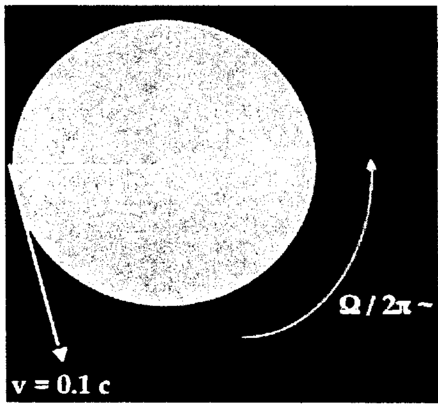


Figure courtesy F. Ozel.

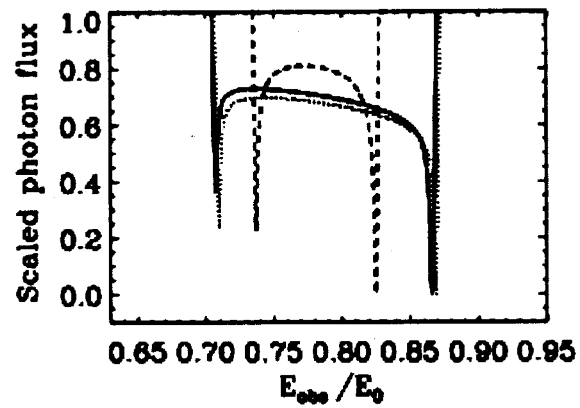
→ *Spinning neutron star:* surface speed is ~ 0.1c; Doppler effect will make the spectral line broad and asymmetric.

How do we measure Rc^2/GM from a broad and skewed line?

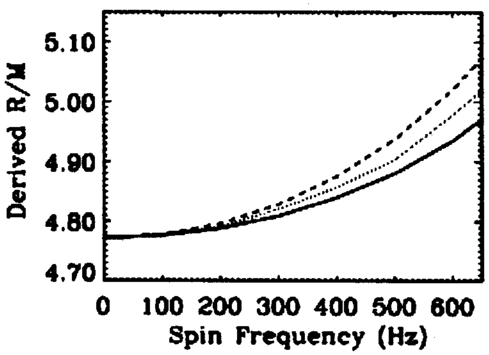
⇓

$$\begin{cases} E_{obs} = (E_1 E_2)^{1/2} \\ 1+z = E_0/E_{obs} \\ Rc^2/GM = 2.(1 - (1+z)^{-2})^{-1} \end{cases}$$

⇓



Bhattacharyya, Miller & Lamb (2006)



Bhattacharyya, Miller & Lamb (2006)

← Better than 2% estimate!

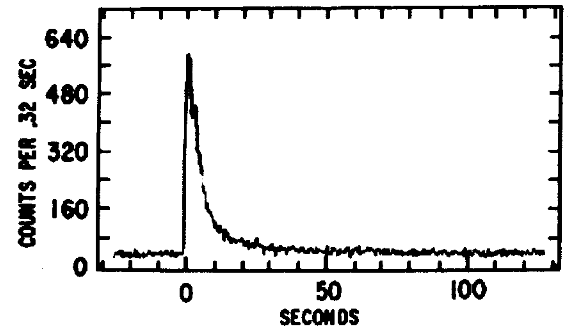
Modeling of the shapes of the spectral lines will be useful to constrain other neutron star parameters.

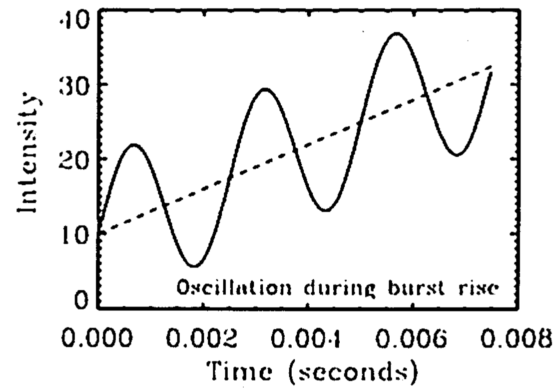
Fast Timing Properties of X-ray Bursts (Burst Oscillations)

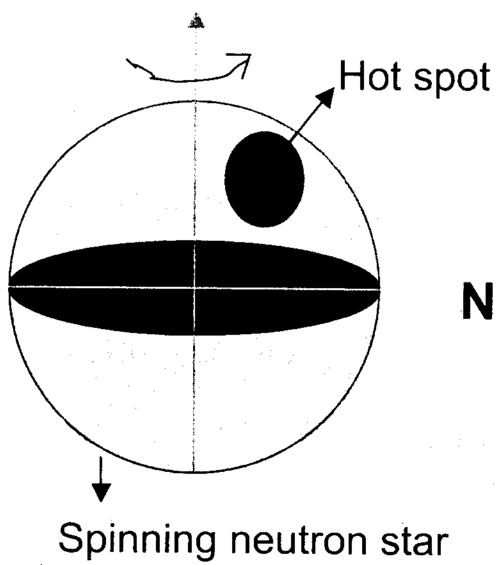
- What are burst oscillations?
  These are millisecond period variations of observed intensity during thermonuclear X-ray bursts.

- What is their origin?
  Asymmetric brightness pattern on the spinning neutron star surfaces.

Burst light curve







Neutron star spin frequency
= Burst oscillation frequency

Burst Oscillations: Stellar Mass and Radius

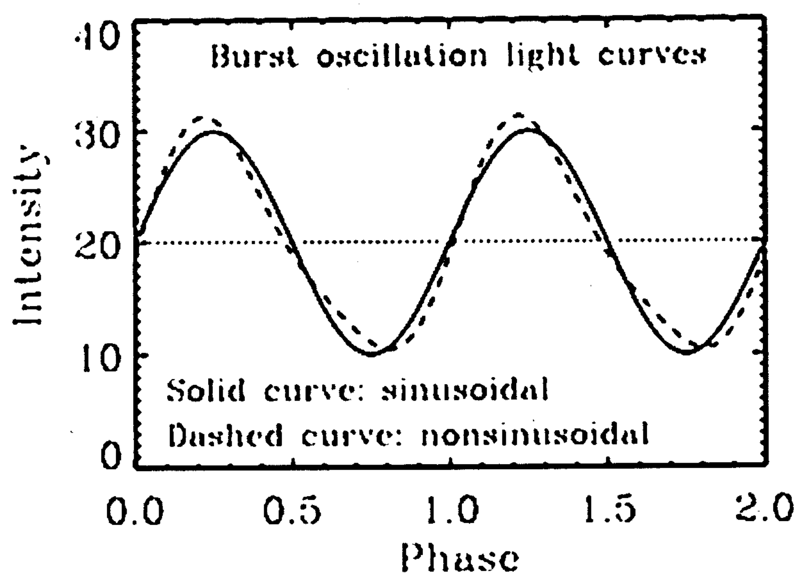
- Modeling of burst oscillation amplitudes and light-curve-shapes :

  ⇓

  Neutron star mass and radius-to-mass ratio.

- Models should include the following physical effects: Doppler effect, special relativistic beaming, gravitational redshift, gravitational light bending, frame dragging, etc.

- However non-sinusoidal burst oscillation light curves are required to fully utilize this procedure.



Modeling Burst Oscillation Light Curves

Non-sinusoidal light curves from the decay portions of the X-ray bursts from the LMXB XTE J1814-338.

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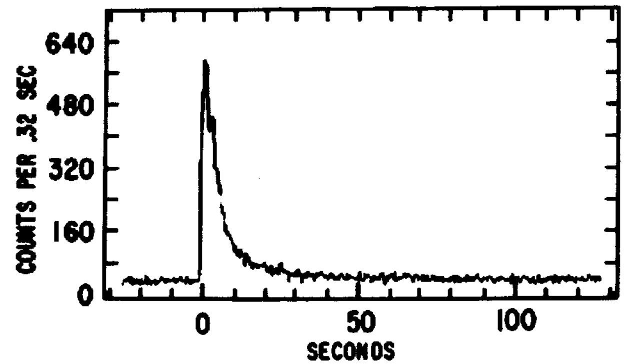
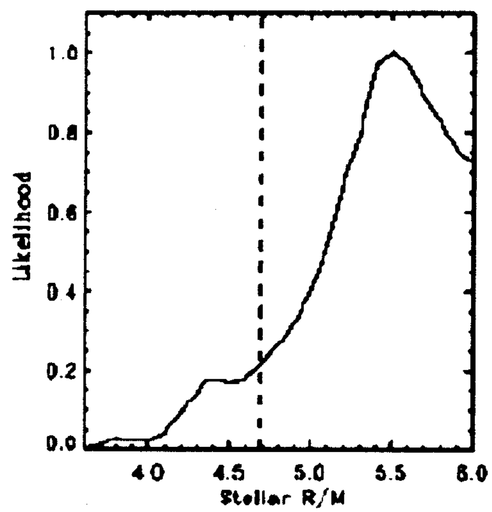
Fitting the observed burst oscillation light curves with our theoretical model (assuming a hot spot on the spinning neutron star surface), we have constrained a few parameters, including stellar radius-to-mass ratio.

Burst light curve

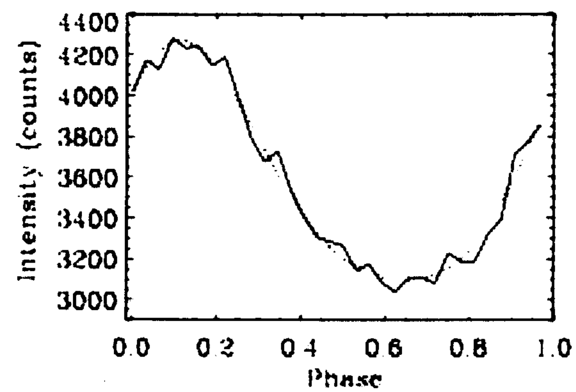


The vertical dashed line gives the lower limit of the stellar radius-to-mass ratio with 90% confidence.

XTE J1814-338
(RXTE-PCA data)



XTE J1814-338
(RXTE-PCA data)



Bhattacharyya et al. (2005)

Summary of constraining neutron star EOS models

EOS $\Leftarrow$ spin, mass and radius of a neutron star.

Thermonuclear X-ray bursts give the opportunity of three types of studies: *continuum spectroscopy*, *line spectroscopy* and *fast timing study*.

Burst oscillations $\Rightarrow$ Neutron star **spin frequency**

Surface atomic spectral line or burst oscillations $\Rightarrow$ stellar **Rc^2/GM**
Study of bursts and accretion flow $\Rightarrow$ chemical composition of stellar atmosphere

$\Downarrow$

Continuum spectroscopy $\Rightarrow$ Stellar **radius**

Example: LMXB EXO 0748-676:
Spin frequency = 45 Hz (burst oscillations)
Rc^2/GM = 4.4 (line spectroscopy)
R or M = ?

Complementary methods for neutron stars in LMXBs (i.e., bursters):
(1) kHz QPOs; (2) quiescent emissions of neutron stars; and
(3) broad relativistic iron lines (Bhattacharyya & Strohmayer 2007a).

Thermonuclear Flame Spreading on Neutron Stars

When does it happen?

During the thermonuclear X-ray bursts (mostly during burst rise).

Why should we care?

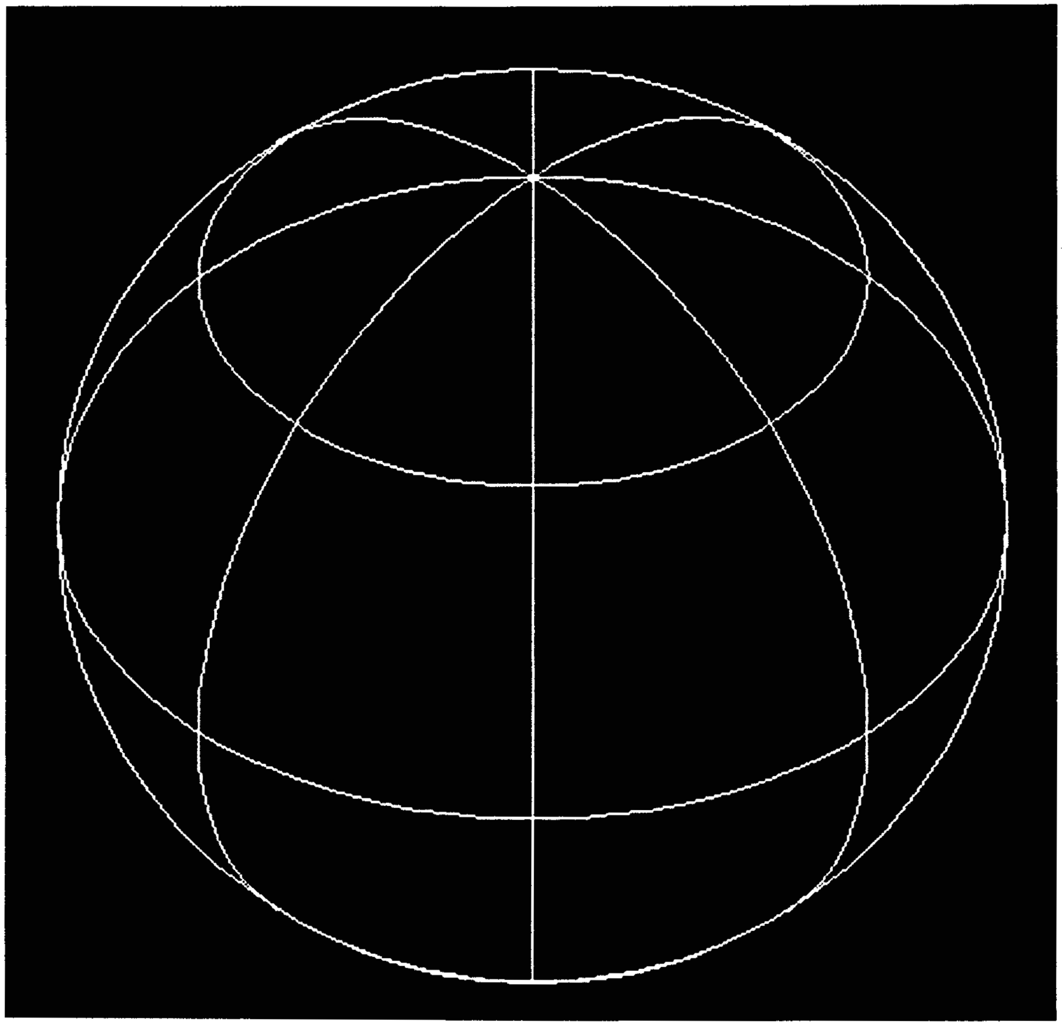
(1) It is an interesting research field on its own. It is basically atmospheric physics under extreme conditions: extreme gravity, high density (10^5-10^6 gm/cc), high magnetic field, huge energy generation and radiation pressure, large stellar spin (and hence Coriolis force), etc.

(2) It can be useful to understand the neutron star atmosphere, and to constrain surface magnetic field, chemical composition of matter, etc. It is also useful to model burst rise oscillations.

Theoretical study:

Not yet done taking all the main physical effects into account. Until recently, observations could not provide enough motivation. Our recent observational findings may provide this motivation.

Thermonuclear Flame Spreading on Neutron Stars

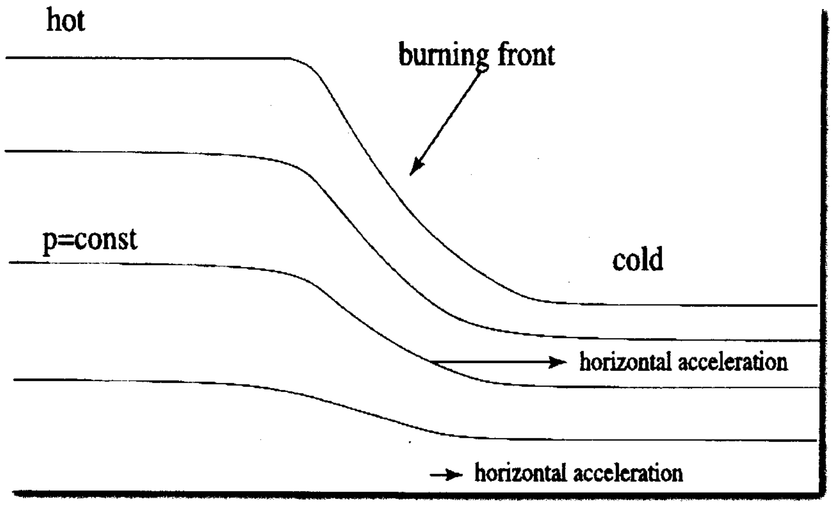


A simulation considering Coriolis force, but ignoring several other physical effects (such as surface magnetic field).

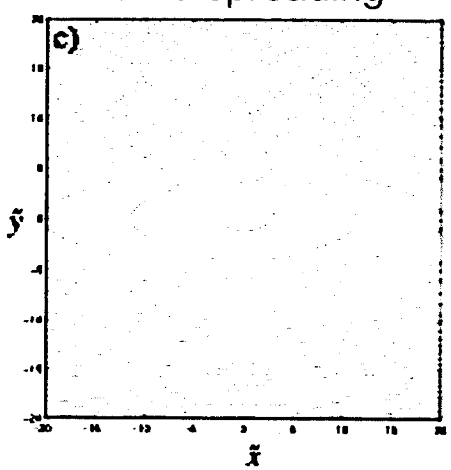
Thanks to Anatoly Spitkovsky!

Theoretical modeling of thermonuclear flame spreading

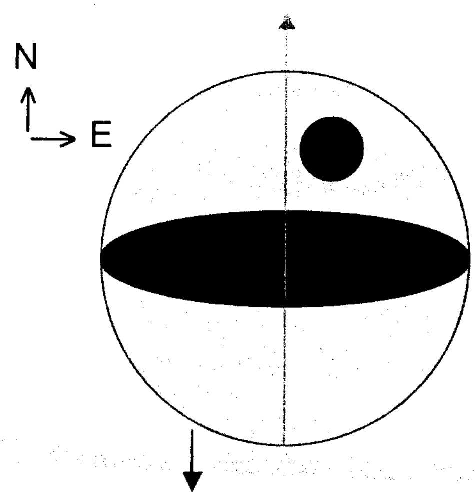
Spitkovsky et al. (2002)



Flame spreading



Spitkovsky et al. (2002)



Spinning neutron star

Neutron star spin frequency 300-600 Hz ⇒ Coriolis force important.

Thin burning layer ⇒ Geostrophic approximation.

Flame speed ~ Ageostrophic speed.

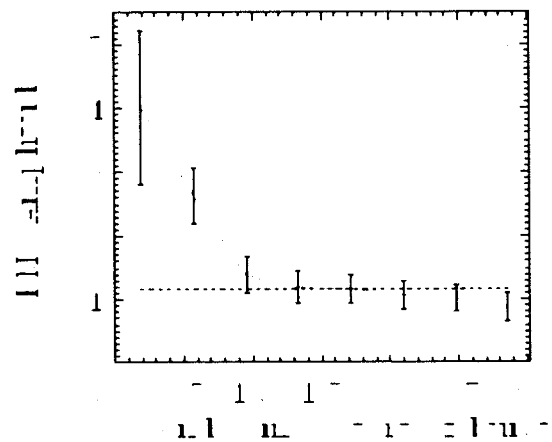
For weak turbulent viscosity, flame speed $\vartheta \sim 5 - 20$ km/s.

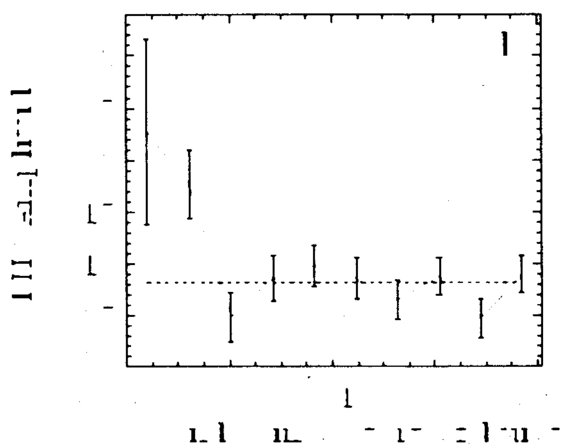
For strong turbulent viscosity, flame speed $\vartheta \leq 300$ km/s.

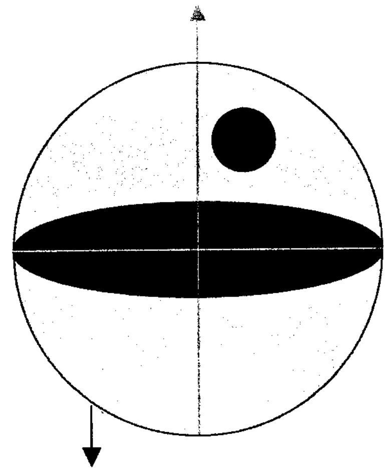
$\vartheta_{pole} < \vartheta_{equator}$

Burst Oscillation Amplitude Evolution

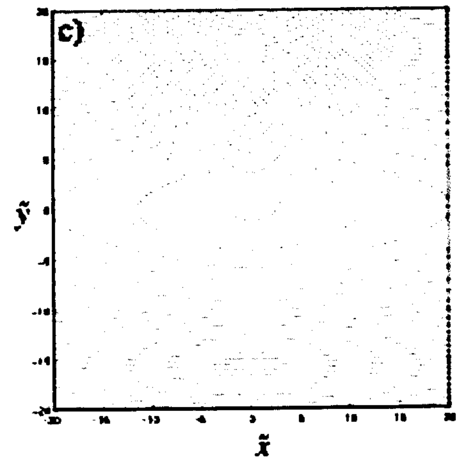
4U 1636-536 and SAXJ1808.4-3658







Flame spreading



Spitkovsky et al. (2002)

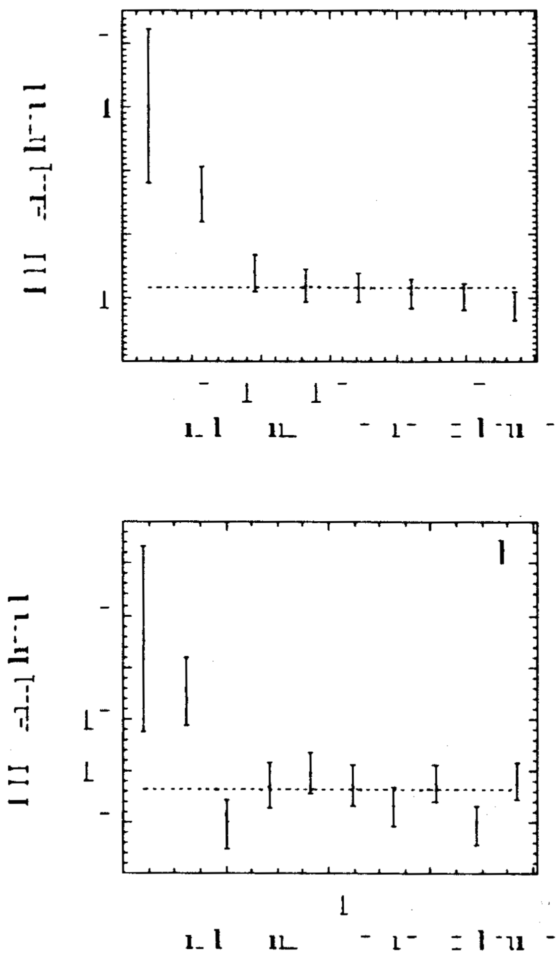
Neutron star spin frequency 300-600 Hz $\Rightarrow$
Coriolis force important $\Rightarrow \vartheta_{pole} < \vartheta_{equator}$

(1) Initial large amplitude is due to small hot spot.
(2) As the burning region grows, amplitude decreases and radius increases quickly.
(3) The low amplitude after some time is due to the residual asymmetry.

Bhattacharyya & Strohmayer (2007b)

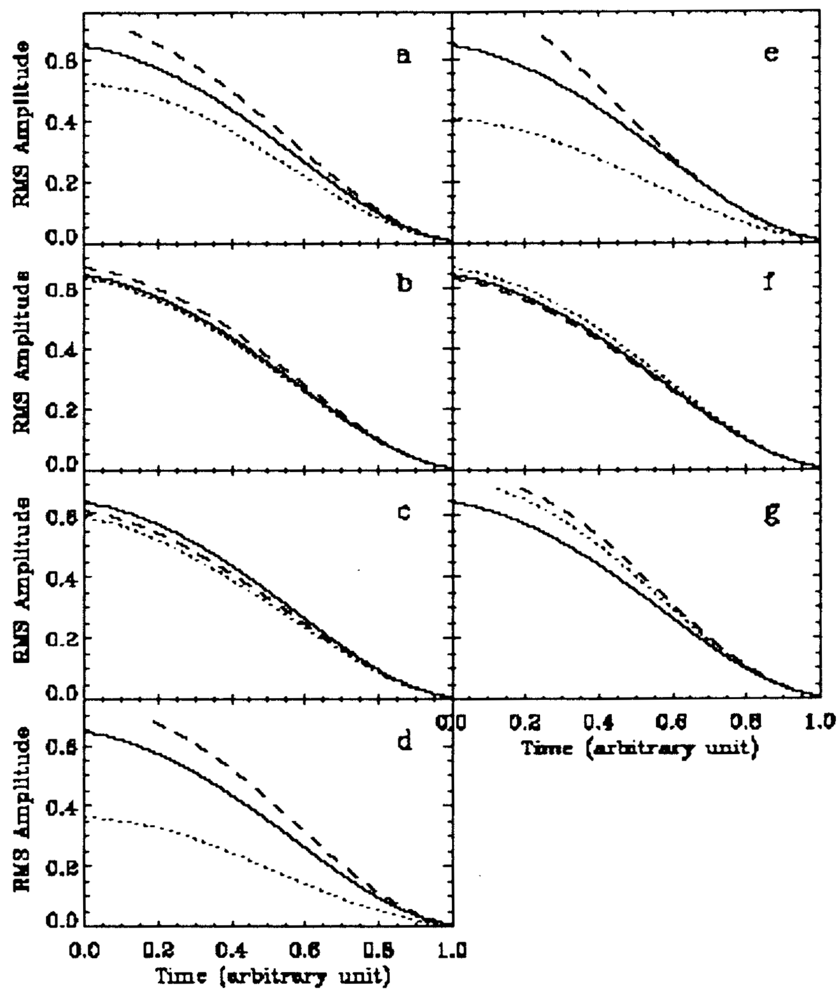
Burst Oscillation Amplitude Evolution

4U 1636-536 and SAX J1808.4-3658



Bhattacharyya & Strohmayer (2007b)

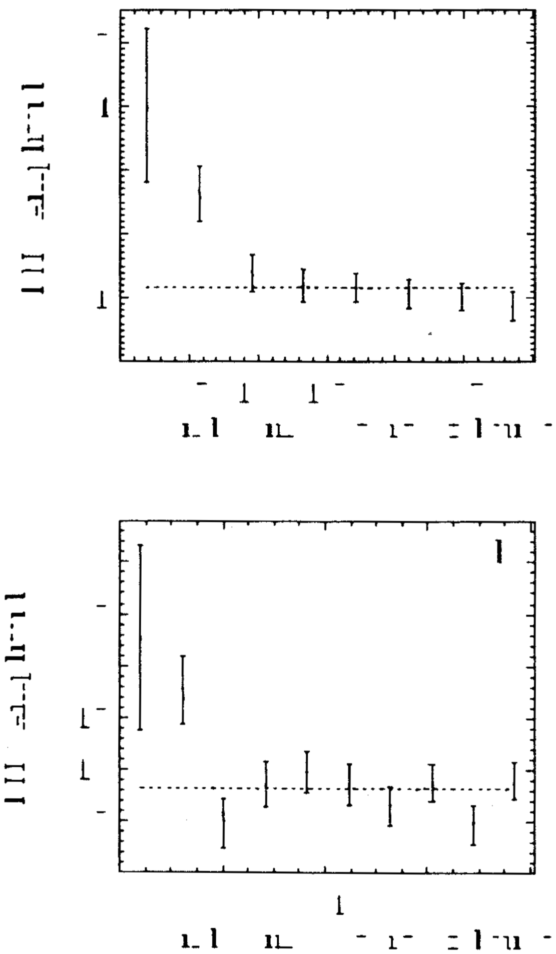
Model: uniform expansion of circular burning region



Bhattacharyya & Strohmayer (2007b)

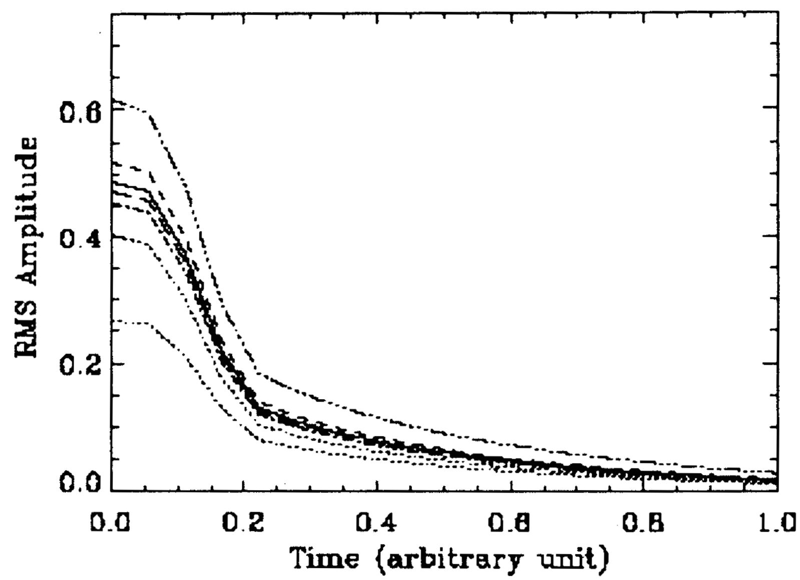
Burst Oscillation Amplitude Evolution

4U 1636-536 and SAX J1808.4-3658



Bhattacharyya & Strohmayer (2007b)

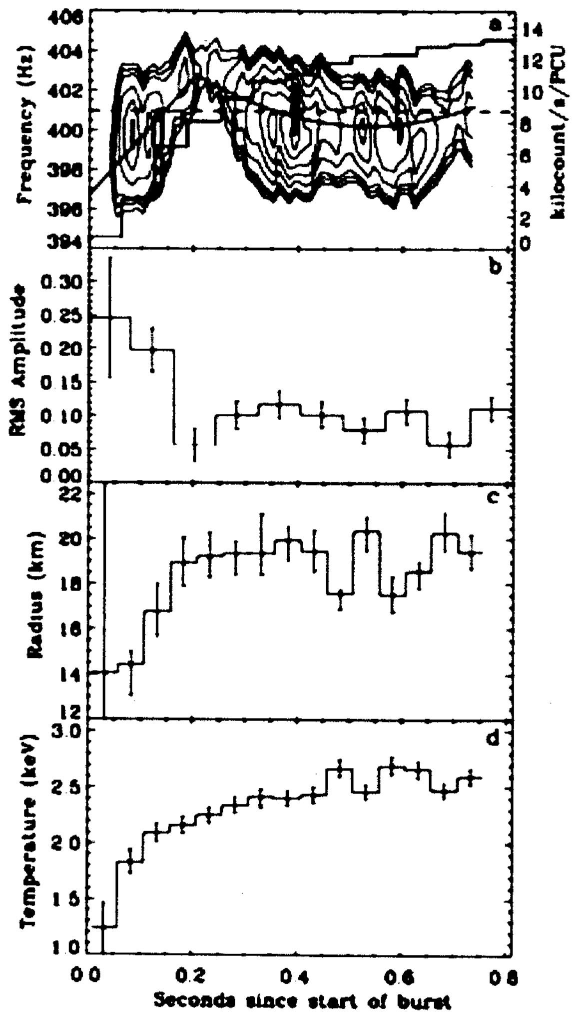
Model: expansion of burning region considering some salient features of the effects of Coriolis force.



Bhattacharyya & Strohmayer (2007b)

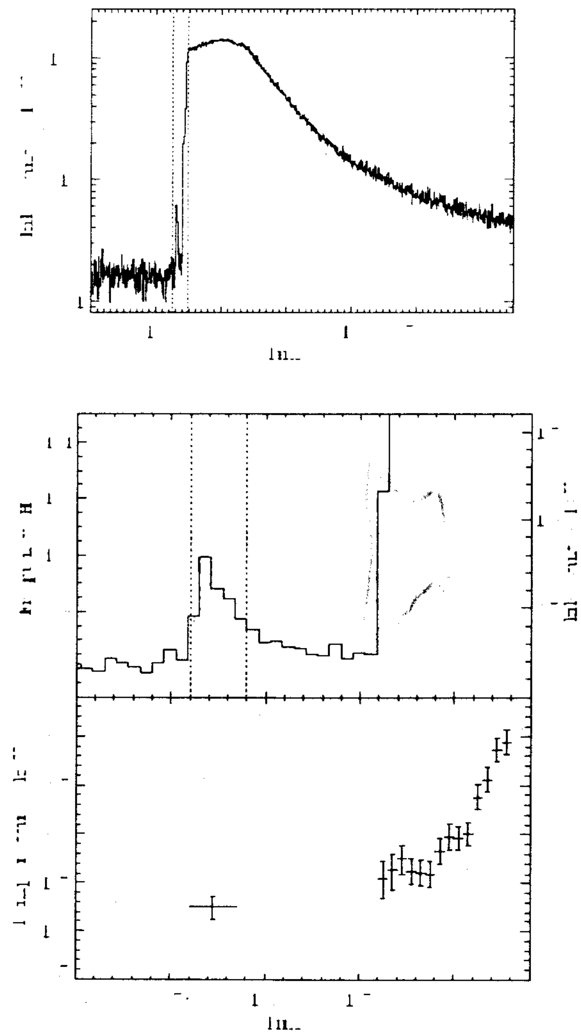
Thermonuclear Flame Spreading on Neutron Stars

SAX J1808.4-3658
(RXTE-PCA data)



Bhattacharyya & Strohmayer (2006a)

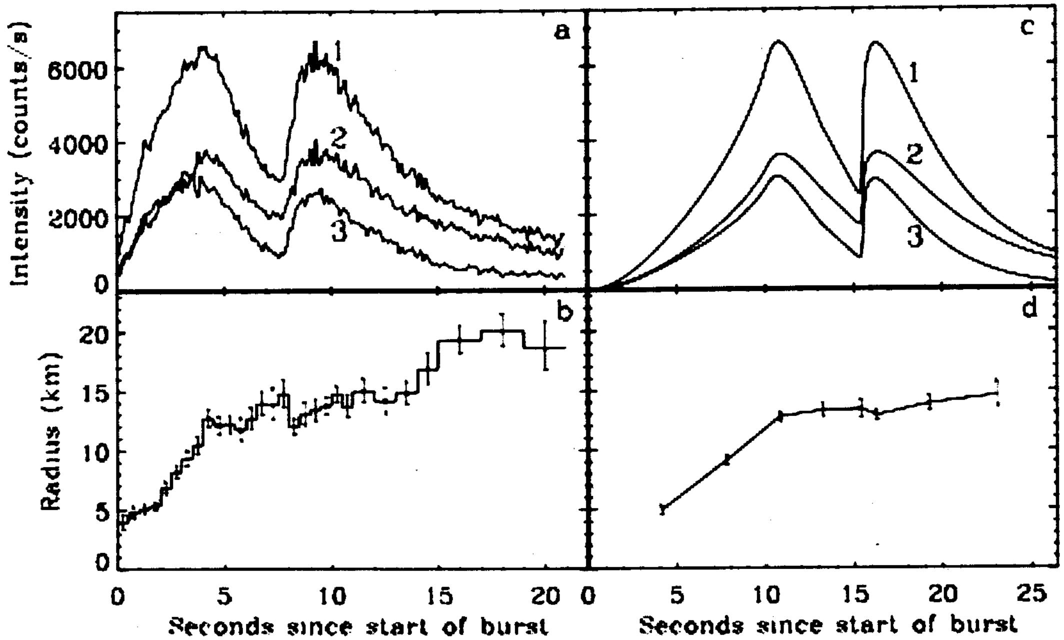
SAX J1808.4-3658
(RXTE-PCA data)



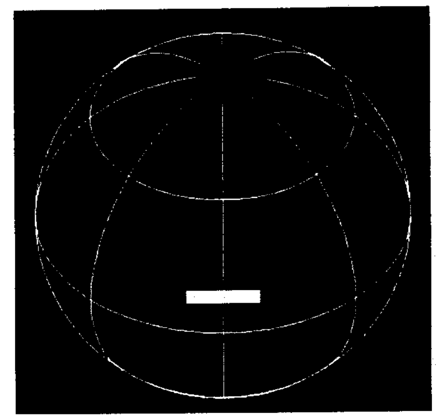
Bhattacharyya & Strohmayer (2007c)

Thermonuclear Flame Spreading on Neutron Stars: Weak Double-peaked X-ray Bursts

Data — 4U 1636-536 — Model



Bhattacharyya & Strohmayer (2006b); *RXTE-PCA data*



Neutron star with polar ignition

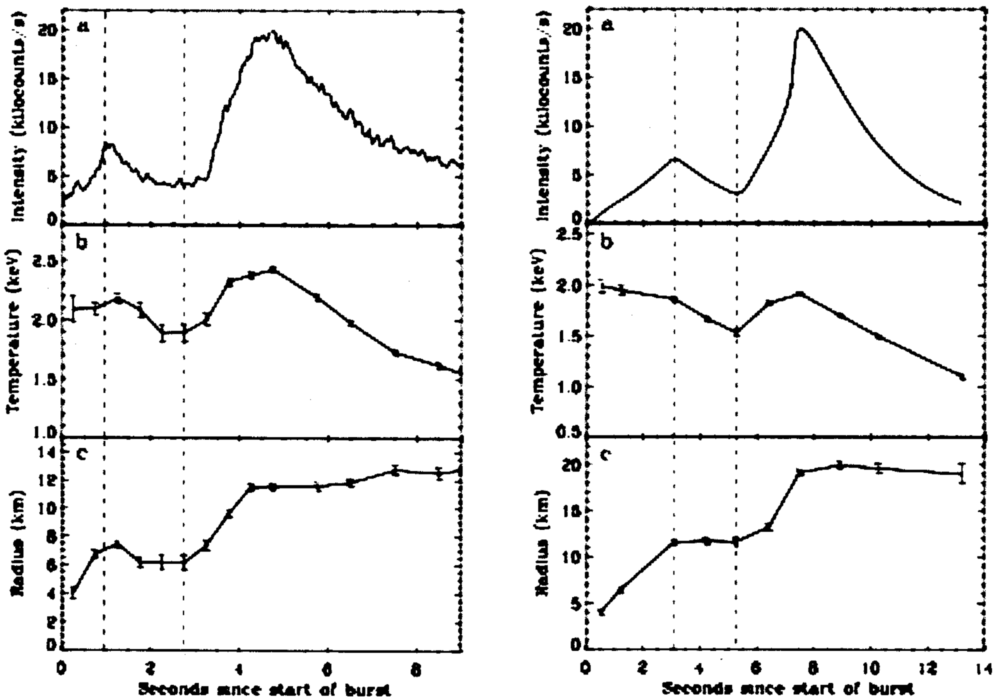
(1) Burst ignition at a pole, which explains the lack of oscillations and the rarity of the burst.

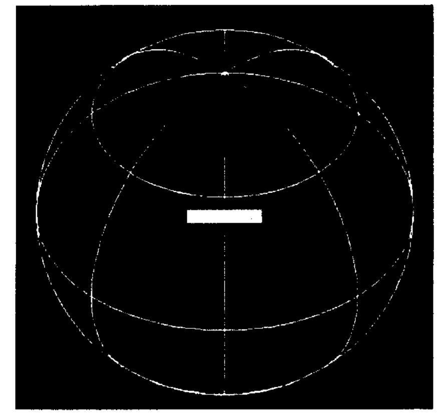
(2) Azimuthally symmetric temporary burning front stalling cools the burning region for a few seconds, while keeping the burning area unchanged. This can explain the intensity and temperature drop during the dip.

(3) The subsequent expansion of burning region explains the second intensity peak.

Thermonuclear Flame Spreading on Neutron Stars: Weak Double-peaked X-ray Bursts

Data　　　4U 1636-536　　　Model





Neutron star with high latitude ignition

Bhattacharyya & Strohmayer (2006c); *RXTE-PCA data*

Vertical dashed lines give the time interval in which the radius (and hence the burning region area) does not change much and the temporary burning front stalling occurs.

Conclusions

- ✷ Studies of thermonuclear X-ray bursts can be very useful to constrain the spin rate, mass and radius of a neutron star ⇒ **EOS model** of high density cold matter in the neutron star cores.

- ✷ Extensive observation and analysis of the data from the rising portions of the bursts ⇒ modeling of burst oscillations and thermonuclear flame spreading.

- ✷ Theoretical study of thermonuclear flame spreading on the rapidly spinning neutron stars should be done considering all the main physical effects (including magnetic field, nuclear energy generation, Coriolis effect, strong gravity, etc.).

❉❉❉ *Thank you!* ❉❉❉