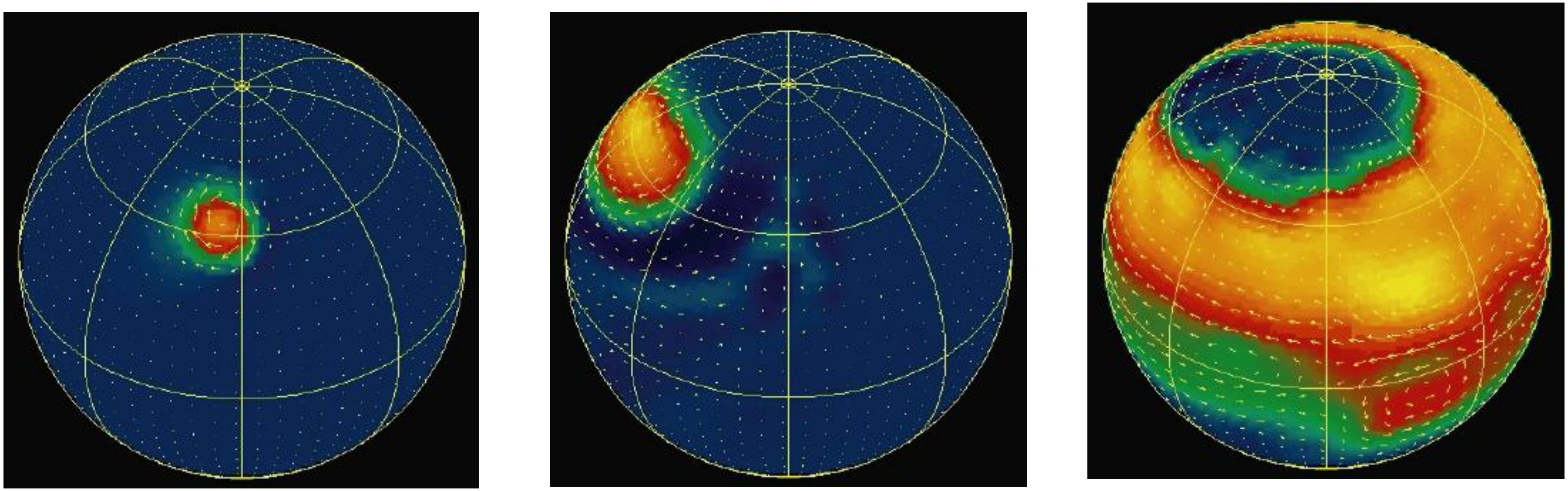
Thermonuclear flame propagation on neutron stars

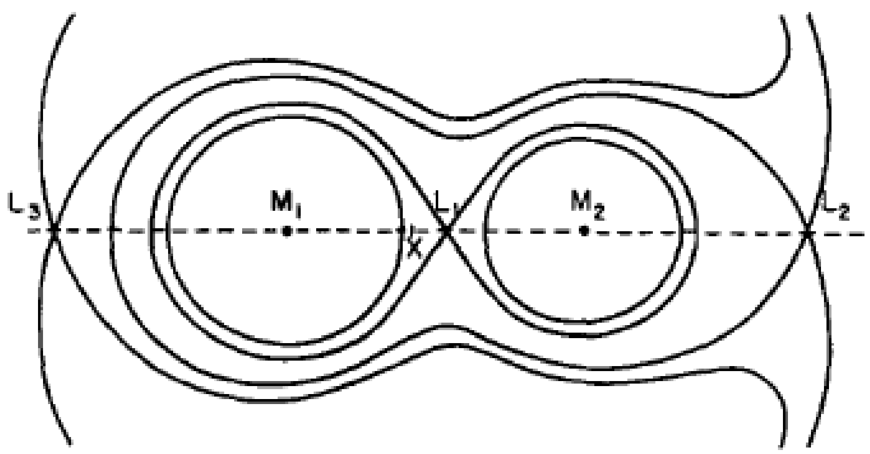


Courtesy: A. Spitkovsky

Sudip Bhattacharyya

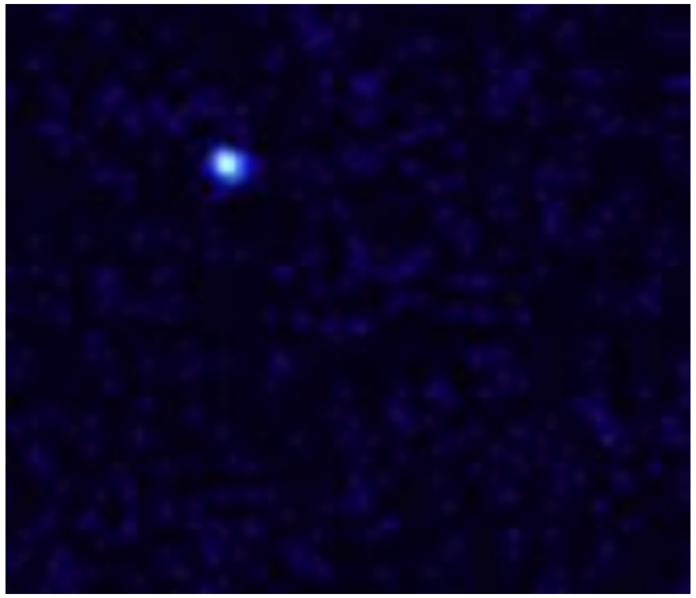
Tata Institute of Fundamental Research (TIFR), Mumbai

Neutron Star Low-mass X-ray Binary (LMXB)



Equipotential surfaces in a binary system
Figure courtesy: Bhattacharya & van den Heuvel, PHR, 203, 1 (1991)

Artist's impression of a low-mass X-ray binary
Courtesy: NASA website



***Chandra* image of KS 1731-260**
Courtesy: NASA website

X-rays from inner accretion disk and neutron star surface.

Orbital period: minutes to days

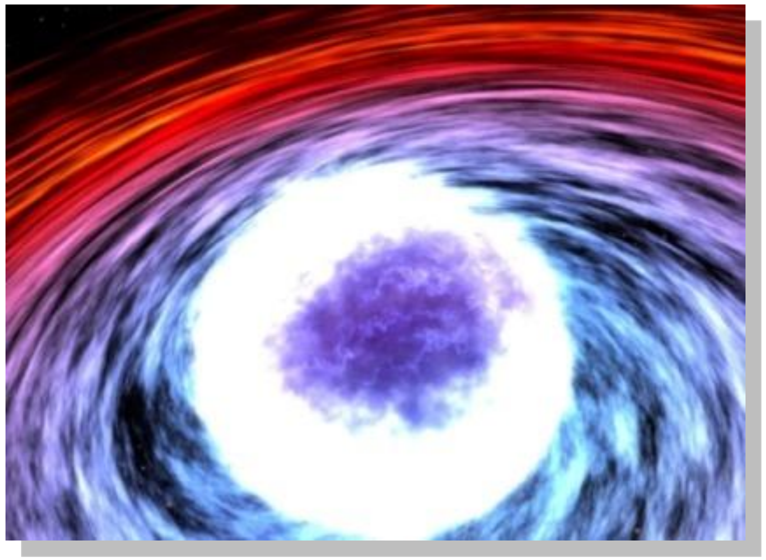
Age ~ Billion years

Neutron star magnetic field ~ 10^7 to 10^9 G

Neutron star spin ~ 300 to 600 Hz

Thermonuclear X-ray Bursts

What is a thermonuclear X-ray burst?



Accretion on neutron star

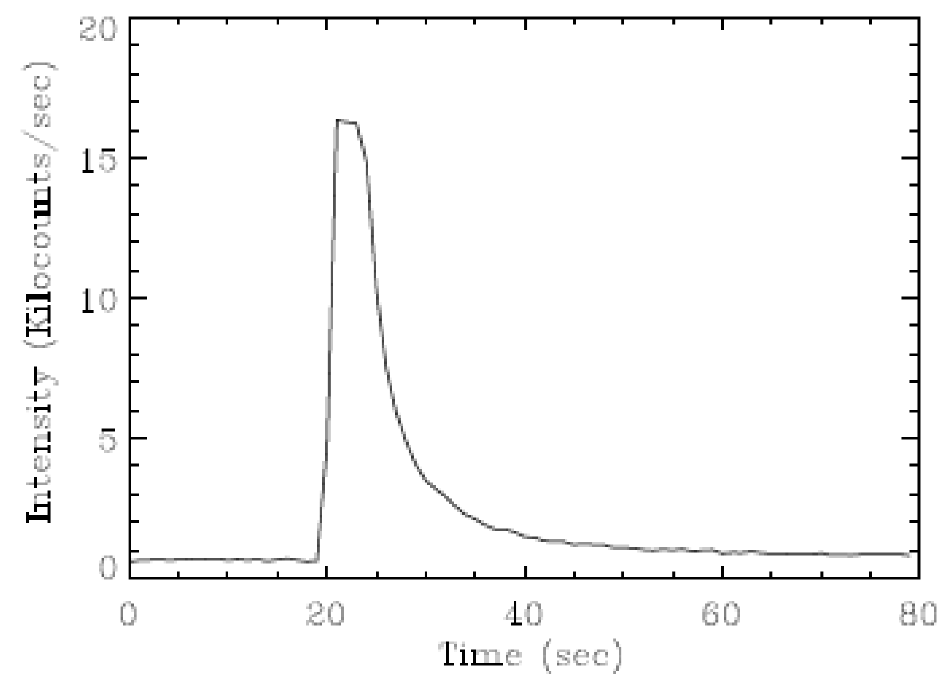
Rise time ≈ 0.5 - 5 seconds
Decay time ≈ 10 - 100 seconds
Recurrence time ≈ hours to day
Energy release in 10 seconds
≈ 10^{39} ergs

↓

Sun takes more than a week to release this energy.

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

Burst light curve



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.

Thermonuclear X-ray Bursts

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

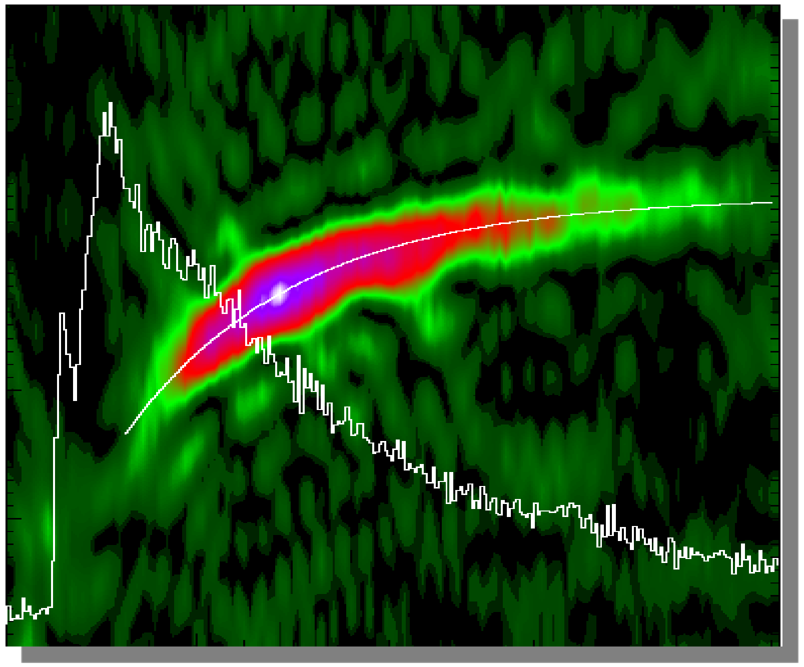
What are burst oscillations?

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

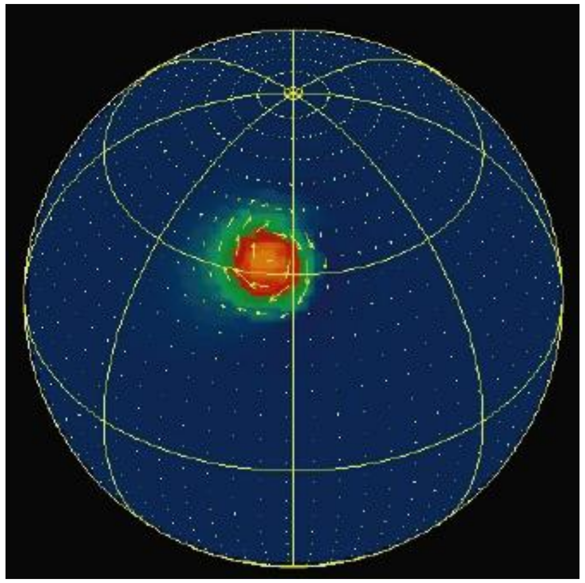
What is their origin?

Asymmetric brightness pattern on the spinning neutron star surfaces.

Burst light curve and colour-coded power



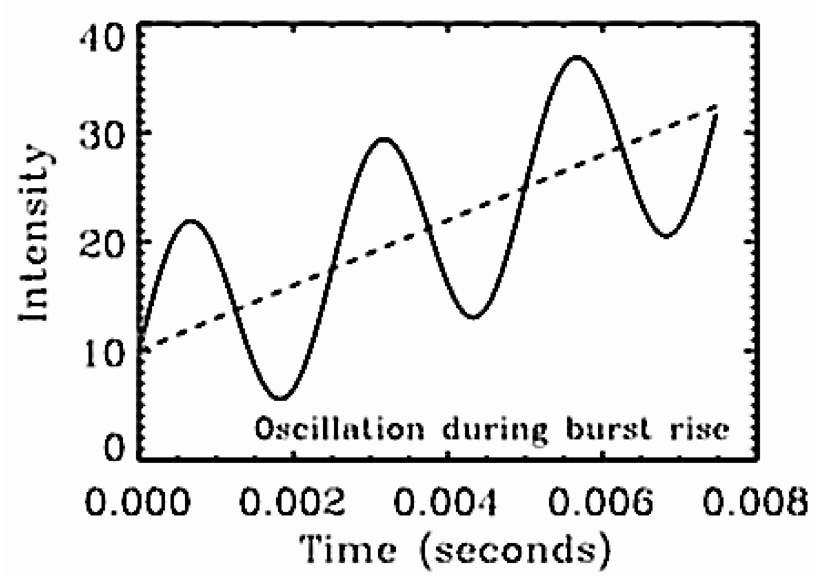
Courtesy: Tod Strohmayer



Courtesy: A. Spitkovsky

Spinning neutron star

Neutron star spin frequency = Burst oscillation frequency



The main question we ask:

Does thermonuclear flame spread during burst rise and does such flame-spreading cause burst oscillations during rise?

Why do we care?

1. Modeling of burst oscillation light curve can be useful to measure neutron star mass and radius, which is possibly the only way to address the fundamental physics of super-dense degenerate core matter of neutron stars.

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How?

Probing super-dense matter from neutron star parameters

Neutron Star: Surface and Interior

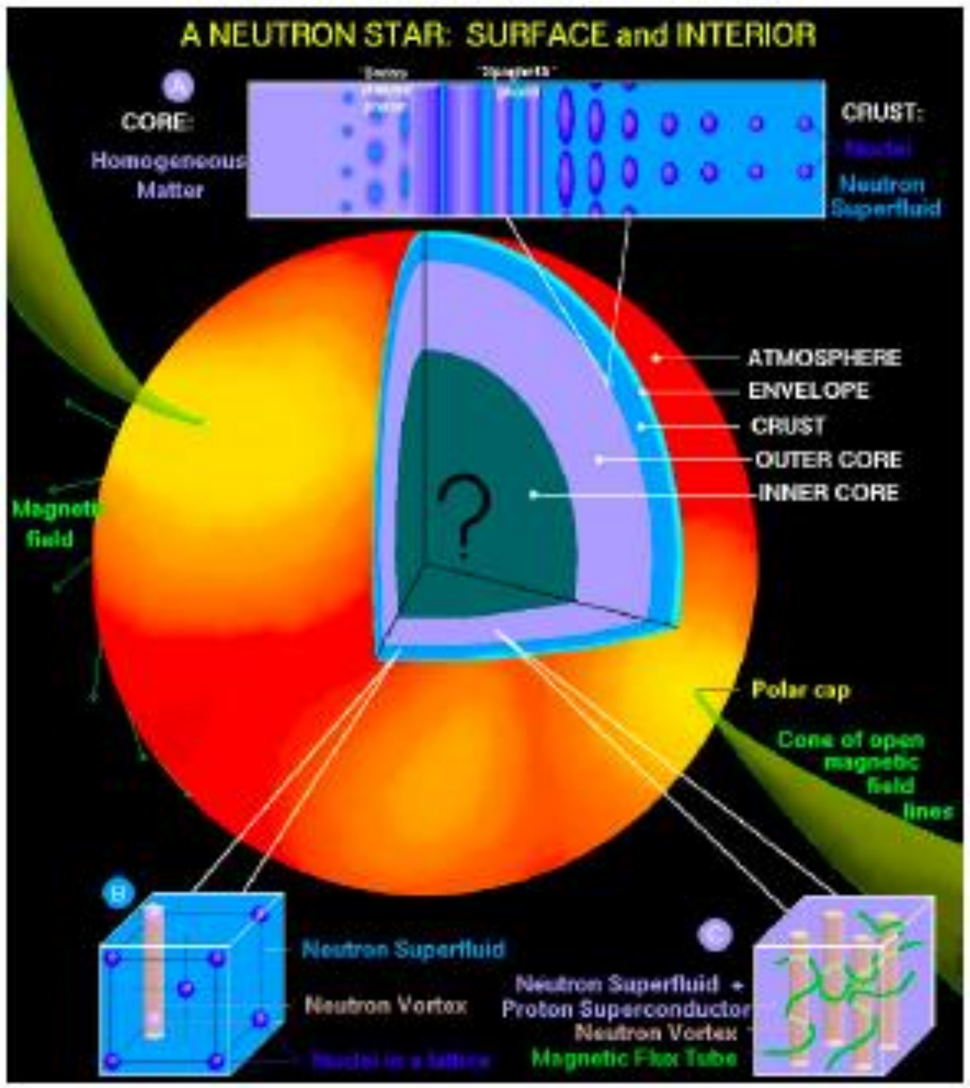
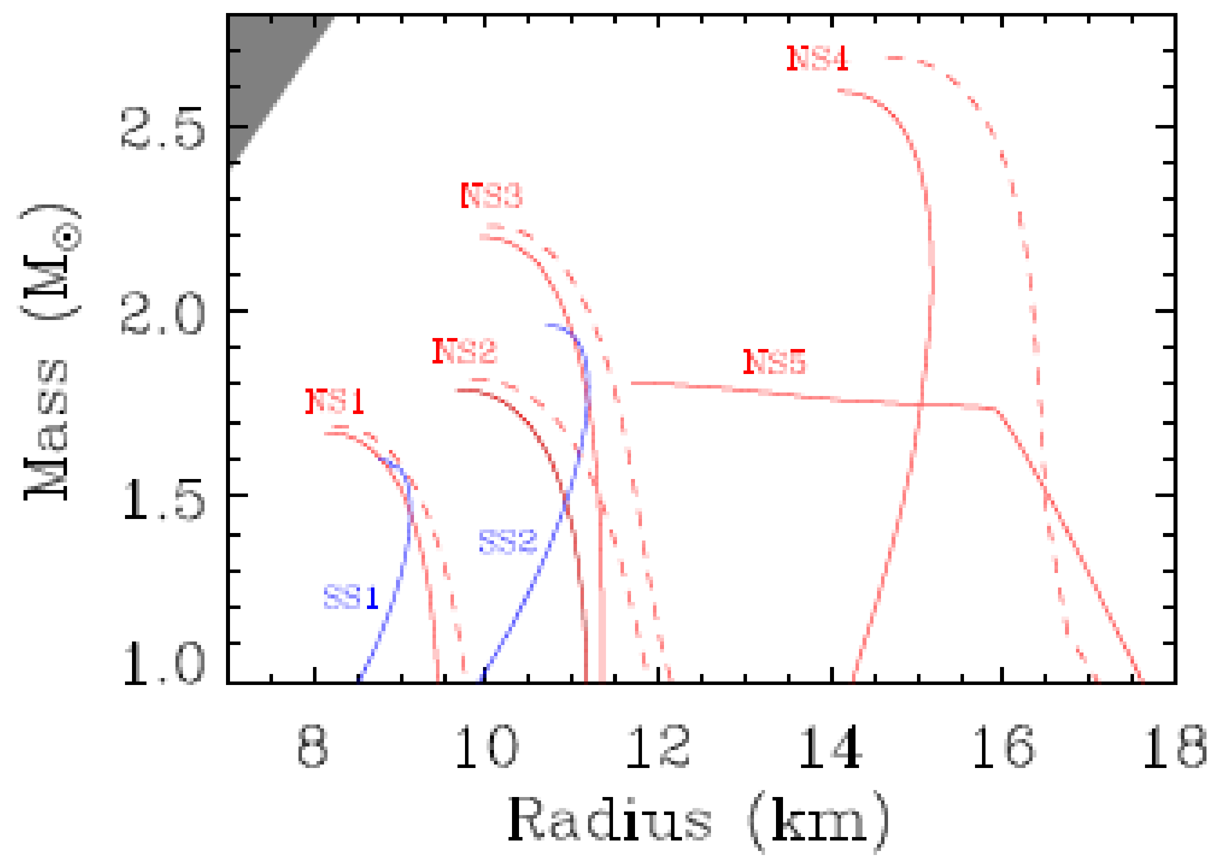


Figure courtesy: D. Page

How to constrain theoretically proposed equation of state models of neutron star core?



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.

The main question we ask:

Does thermonuclear flame spread during burst rise and does such flame-spreading cause burst oscillations during rise?

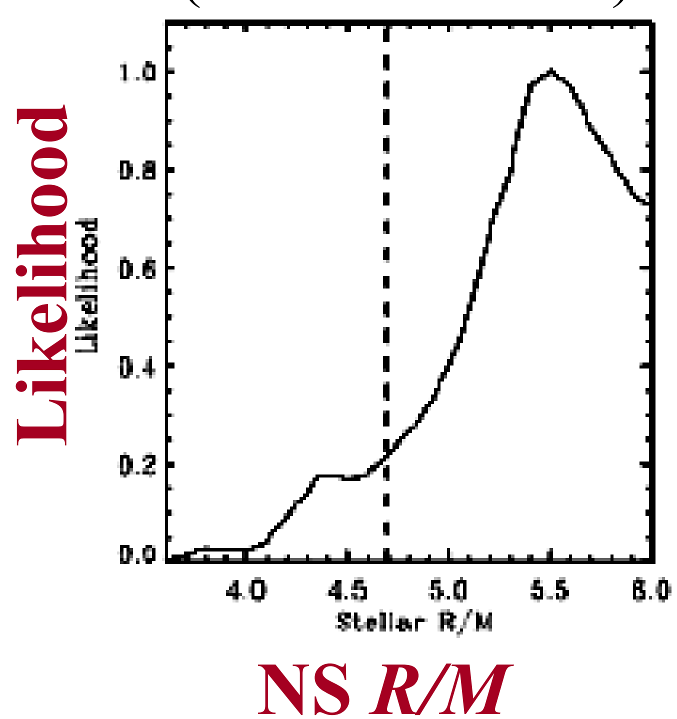
Why do we care?

1. **Modeling of burst oscillation light curve** can be useful to measure neutron star mass and radius, which is possibly the only way to address the fundamental physics of super-dense degenerate core matter of neutron stars. Here are two examples of **this tool**:

1

***RXTE* PCA data fitting**

(XTE J1814-338)

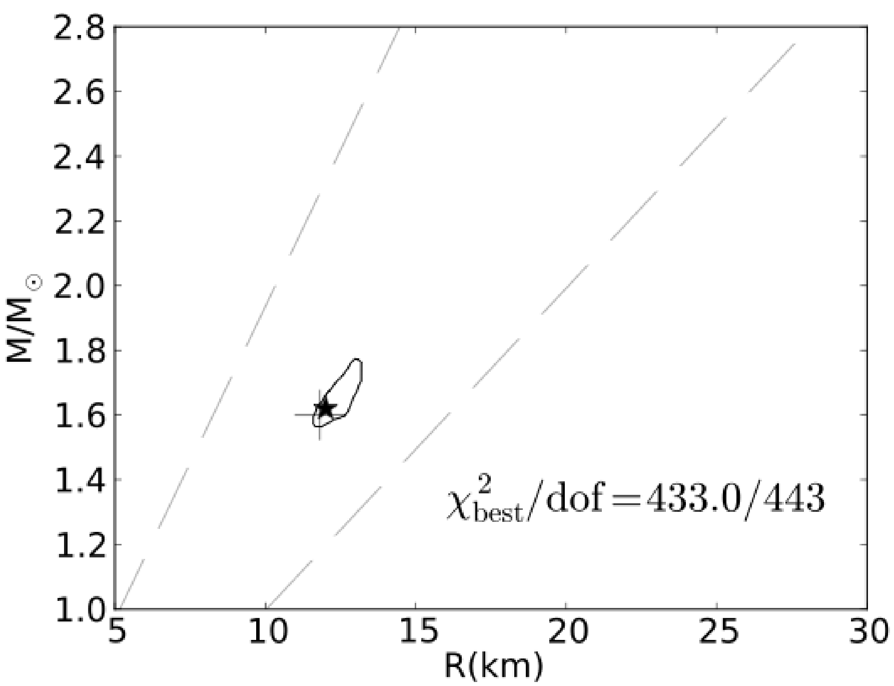


The vertical dashed line gives the lower limit of the stellar radius-to-mass ratio with 90% confidence.

SB, Strohmayer, Miller, Markwardt, ApJ, 619, 483 (2005)

2

Simulated data fitting



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

Lo, Miller, SB, Lamb, ApJ, 776, 19 (2013)

The main question we ask:

Does thermonuclear flame spread during burst rise and does such flame-spreading cause burst oscillations during rise?

Why do we care?

1. Modeling of burst oscillation light curve can be useful to measure neutron star mass and radius, which is possibly the only way to address the fundamental physics of super-dense degenerate core matter of neutron stars.

   And this science goal is a driver for future large area timing X-ray space missions, such as **LOFT**.

   But in order to use burst oscillation as a tool of any reliability, it is essential to know about its details, for example, whether during burst rise such oscillation originates from expanding hot spot due to flame spreading.

The main question we ask:

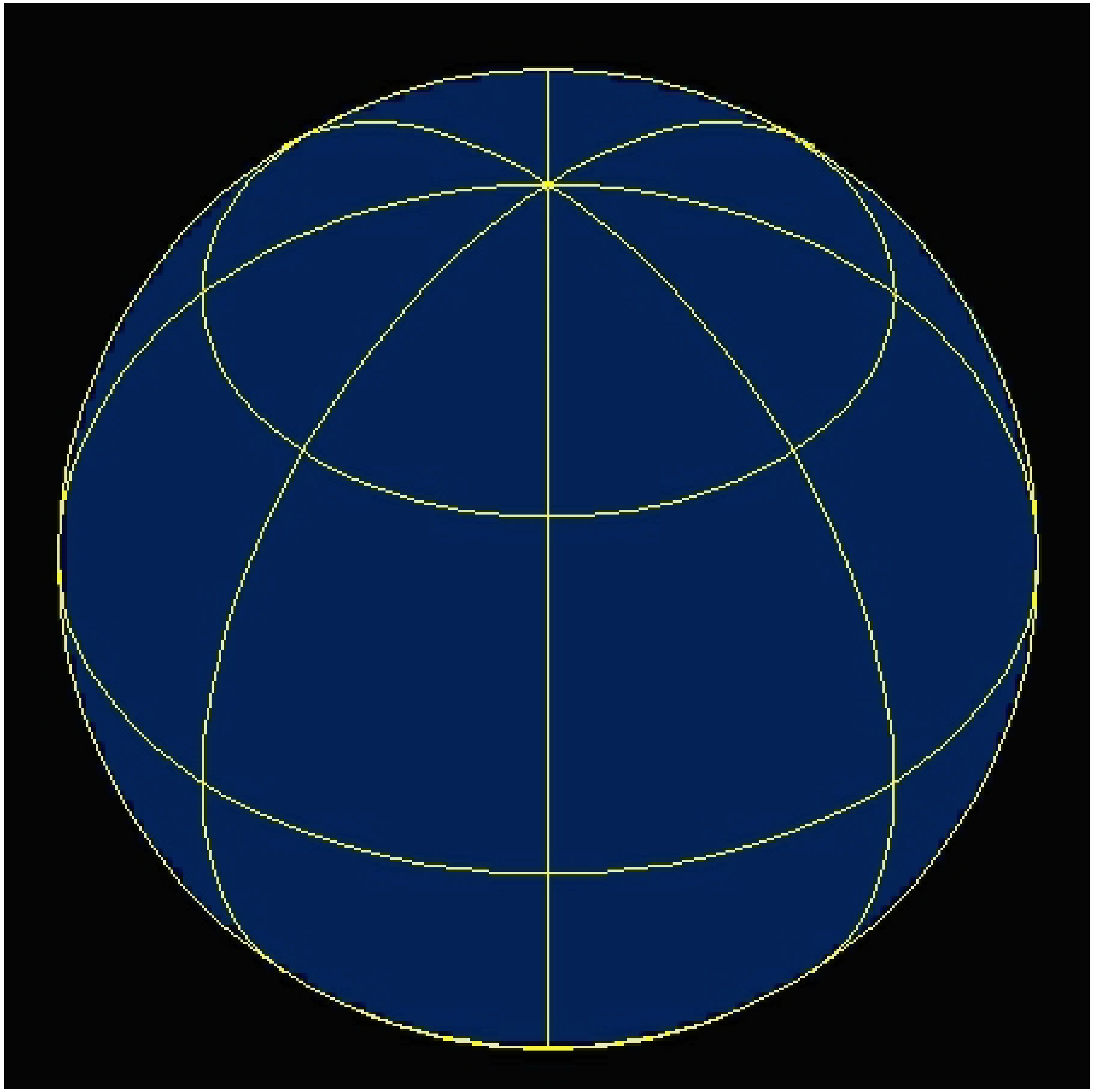
Does thermonuclear flame spread during burst rise and does such flame spreading cause burst oscillations during rise?

Why do we care?

1. Modeling of burst oscillation light curve can be useful to measure neutron star mass and radius, which is possibly the only way to address the fundamental physics of super-dense degenerate core matter of neutron stars.

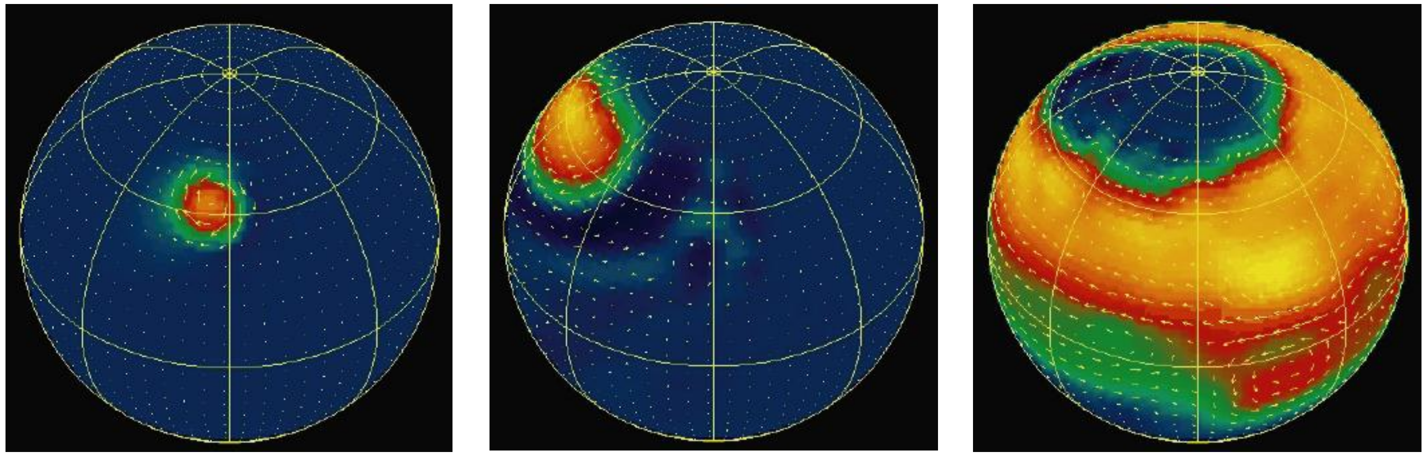
2. Thermonuclear flame spreading is an interesting science on its own; it combines various fields, such as, astrophysics, nuclear physics, fluid dynamics, gravitational physics, etc., and can be useful to constrain neutron star surface parameters, such as the turbulent viscosity for flame spreading.

Burst oscillation during rise: thermonuclear flame spreading?



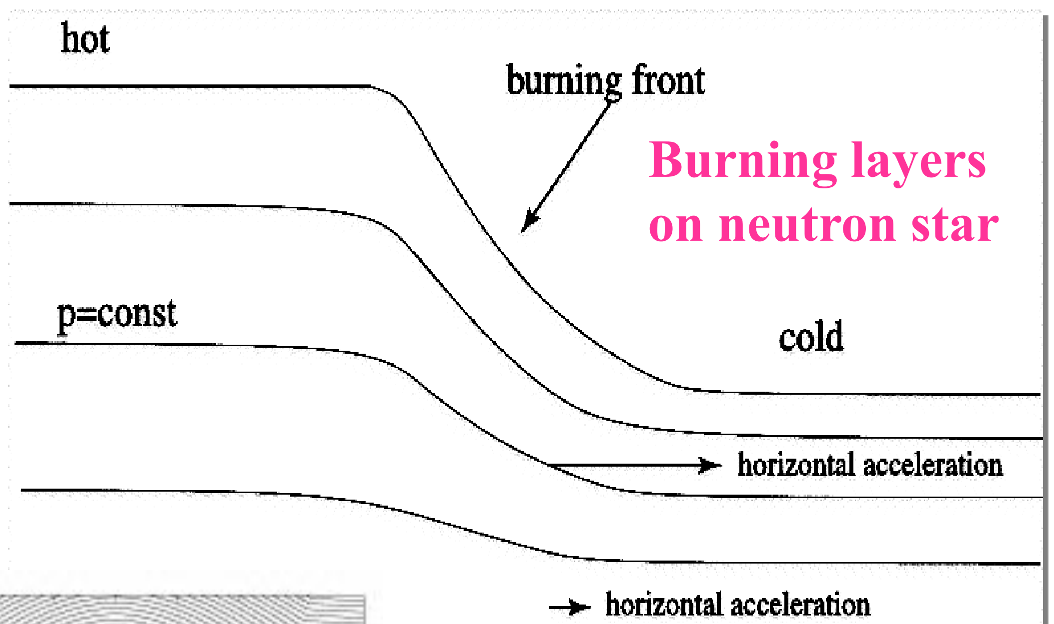
Courtesy: Anatoly Spitkovsky

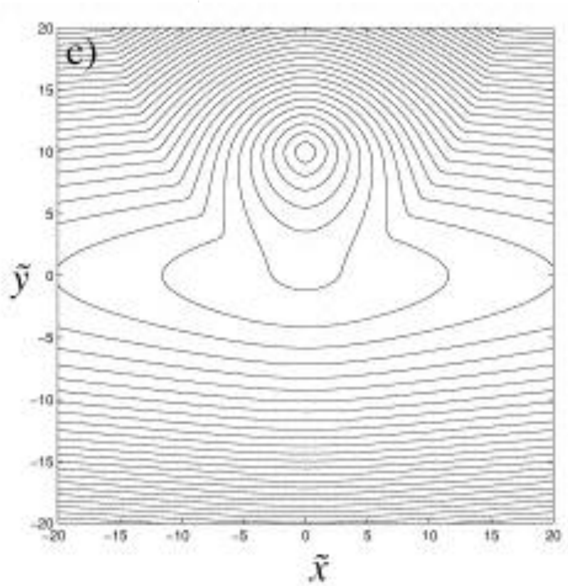
Burst oscillation during rise: thermonuclear flame spreading?



Courtesy: A. Spitkovsky

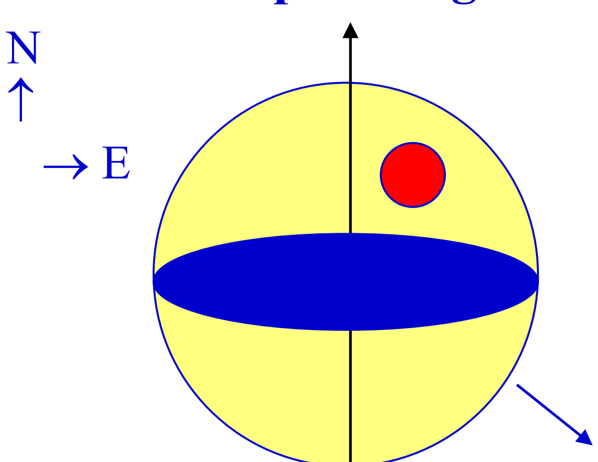
Spitkovsky, Levin & Ushomirsky (2002)





Contours showing an expanding burning region

Flame spreading



Spinning neutron star

Burst should be ignited at a certain point on the neutron star surface, and then the thermonuclear flame should spread to ignite the whole stellar surface.

Spin frequency of bursting neutron stars ≈ 300-600 Hz ⇒ Coriolis force important.

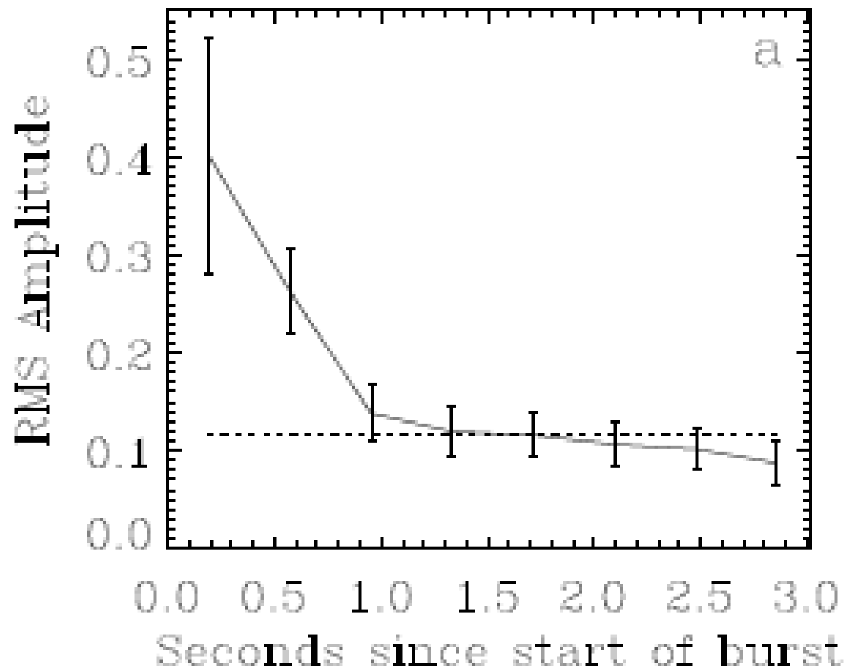
Theoretical expectation:

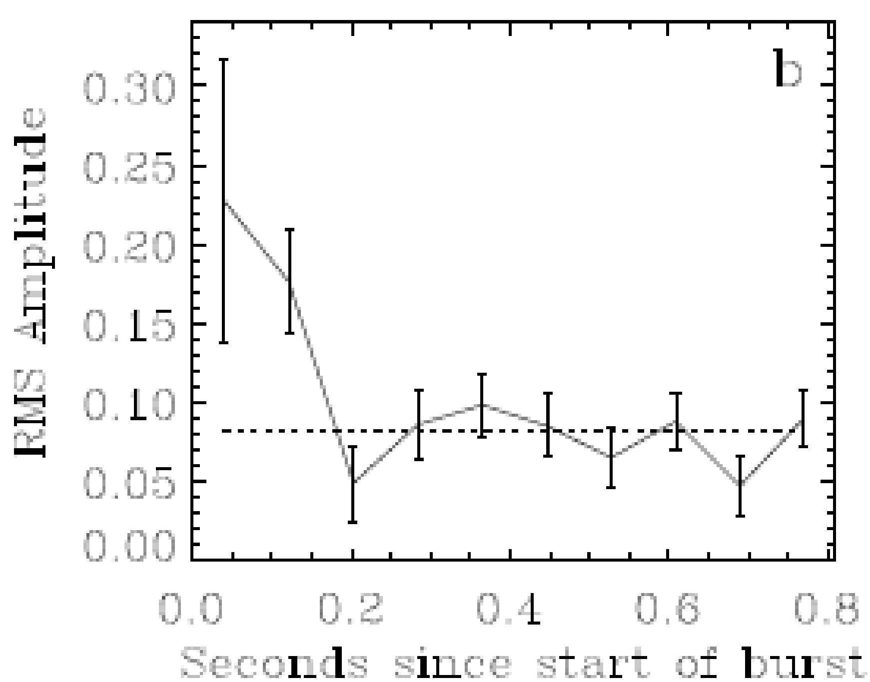
Flame spreads faster near the equator than near the pole (effect of Coriolis force). Hence the burning region should expand asymmetrically, as shown on the left (Spitkovsky, Levin & Ushomirsky 2002).

Burst oscillation during rise: thermonuclear flame spreading?

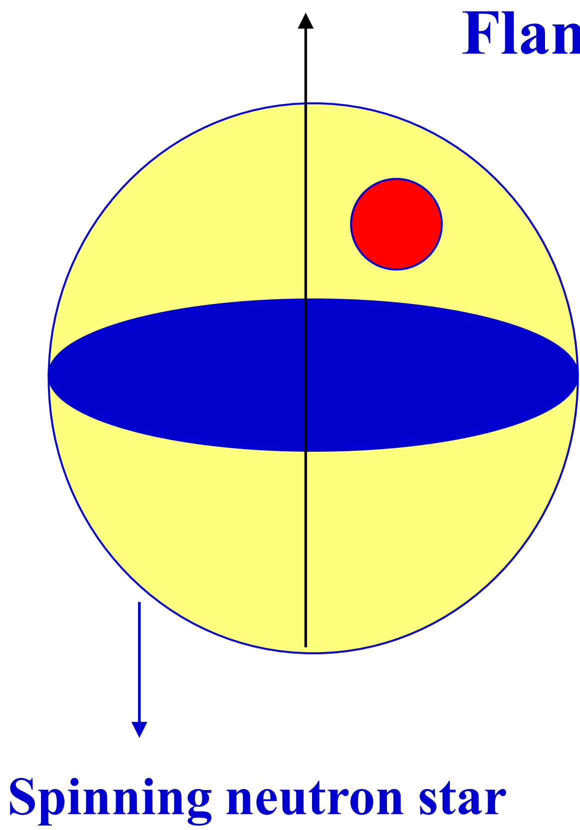
Observed burst oscillation amplitude evolution during burst rise (*RXTE* data).

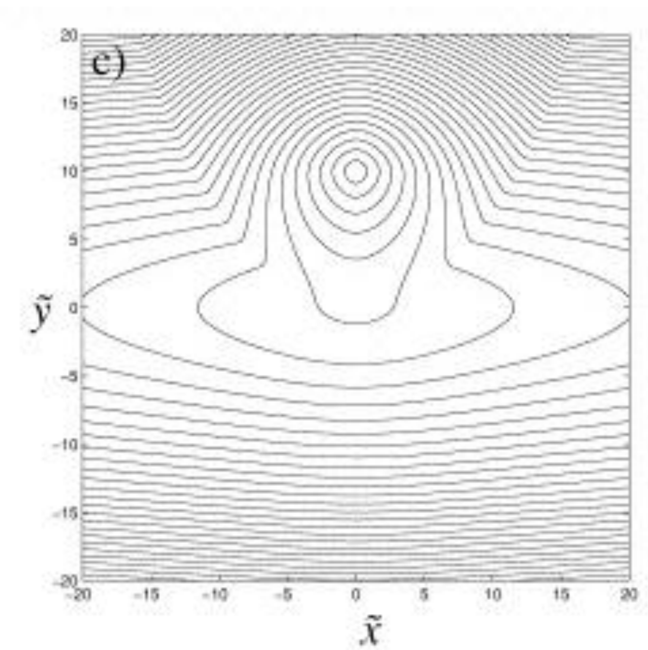
4U 1636-536 and SAX J1808.4-3658





SB & Strohmayer, ApJ, 666, L85 (2007)





Spitkovsky, Levin & Ushomirsky (2002)

Plausible theoretical explanation of the observation shown on the left using the expected asymmetric spreading due to Coriolis force:

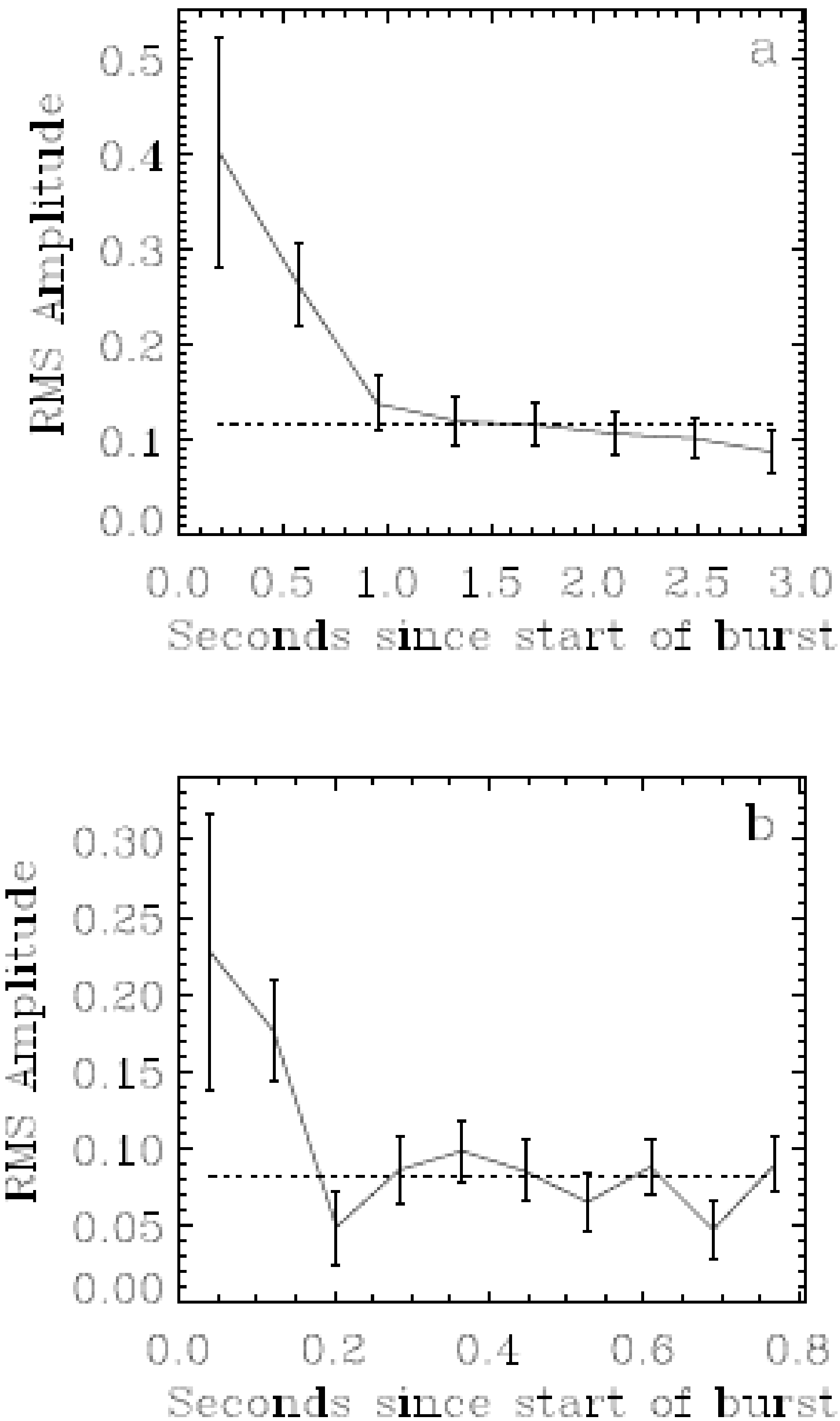
(1) Initial large amplitude is due to a small hot spot.

(2) As the burning region grows, amplitude decreases quickly.

(3) The persistent low amplitude after some time is due to the residual asymmetry (shown above).

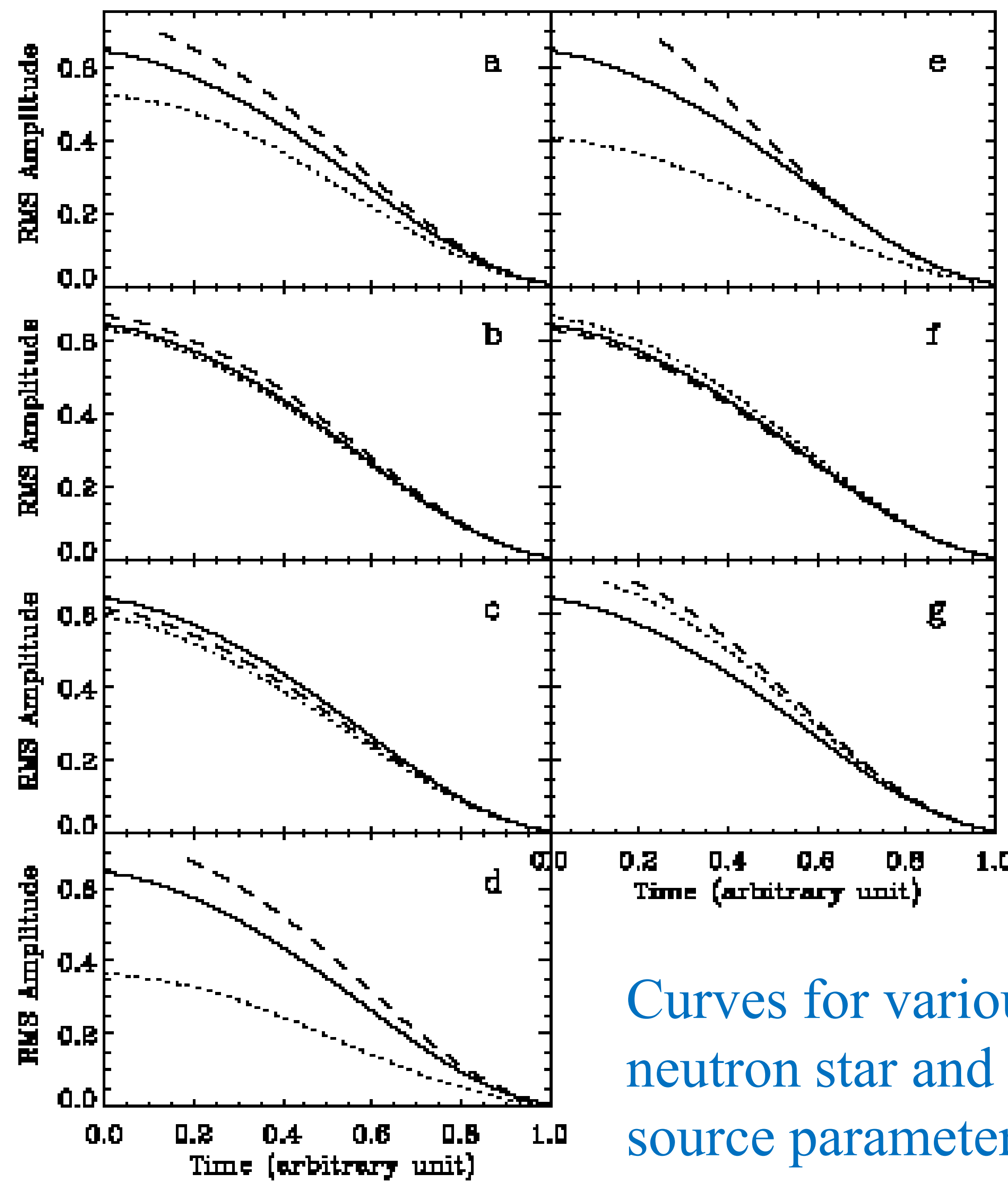
Burst oscillation during rise: thermonuclear flame spreading?

Burst oscillation amplitude evolution:
RXTE observation
4U 1636-536 and SAX J1808.4-3658



SB & Strohmayer, ApJ, 666, L85 (2007)

Burst oscillation amplitude evolution:
Model: uniform expansion of a circular burning region (effect of Coriolis force is not included).

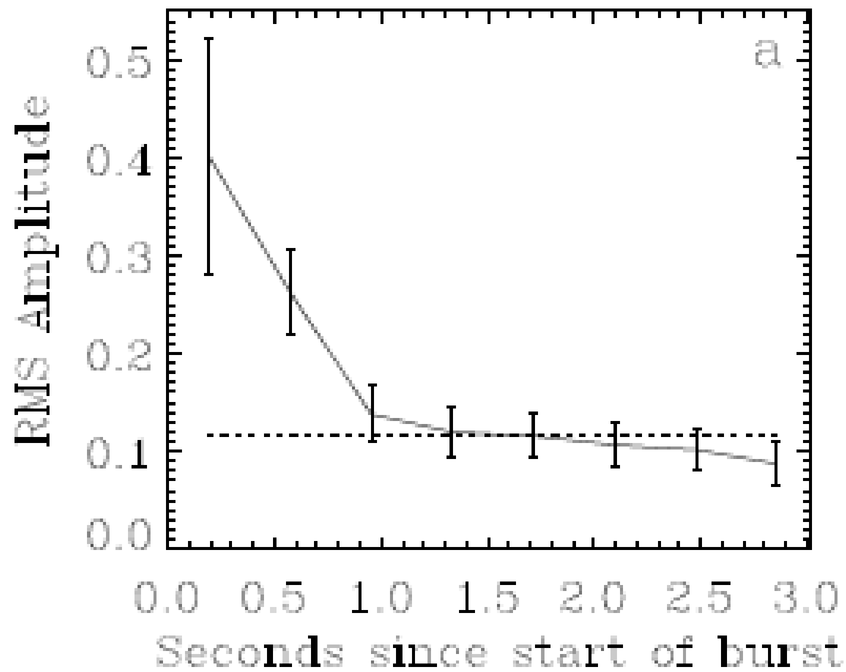


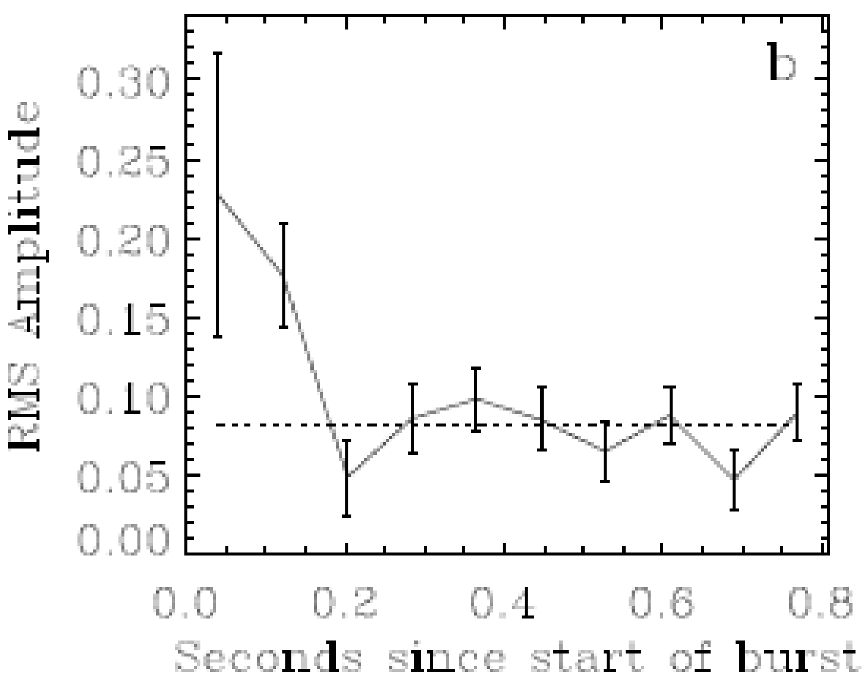
Curves for various neutron star and other source parameters.

Model without the Coriolis force effect on flame spreading cannot explain the observations.

Burst oscillation during rise: thermonuclear flame spreading?

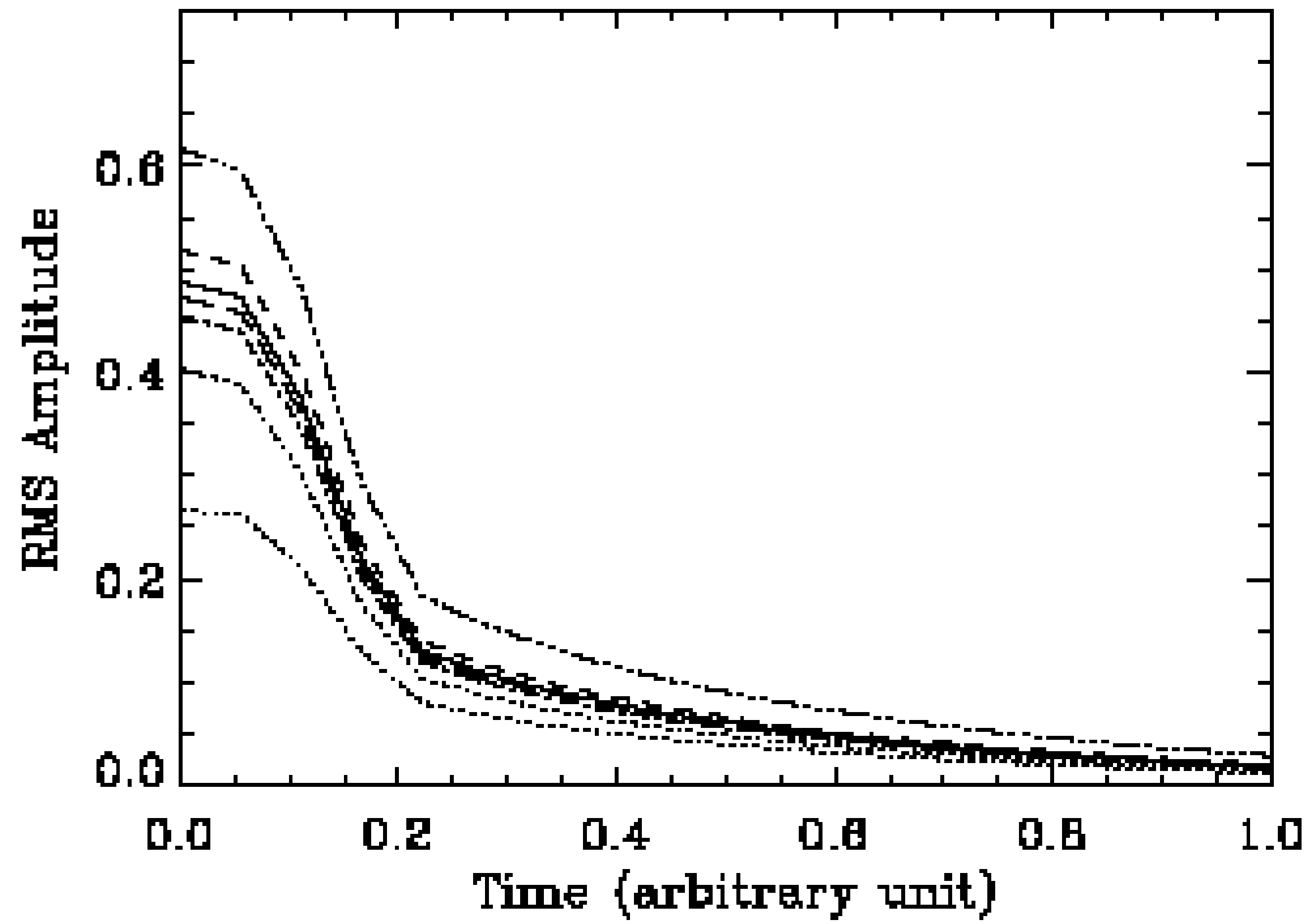
Burst oscillation amplitude evolution:
RXTE observation
4U 1636-536 and SAX J1808.4-3658





SB & Strohmayer, ApJ, 666, L85 (2007)

Burst oscillation amplitude evolution:
Model: expansion of burning region considering some salient features of the effects of Coriolis force.



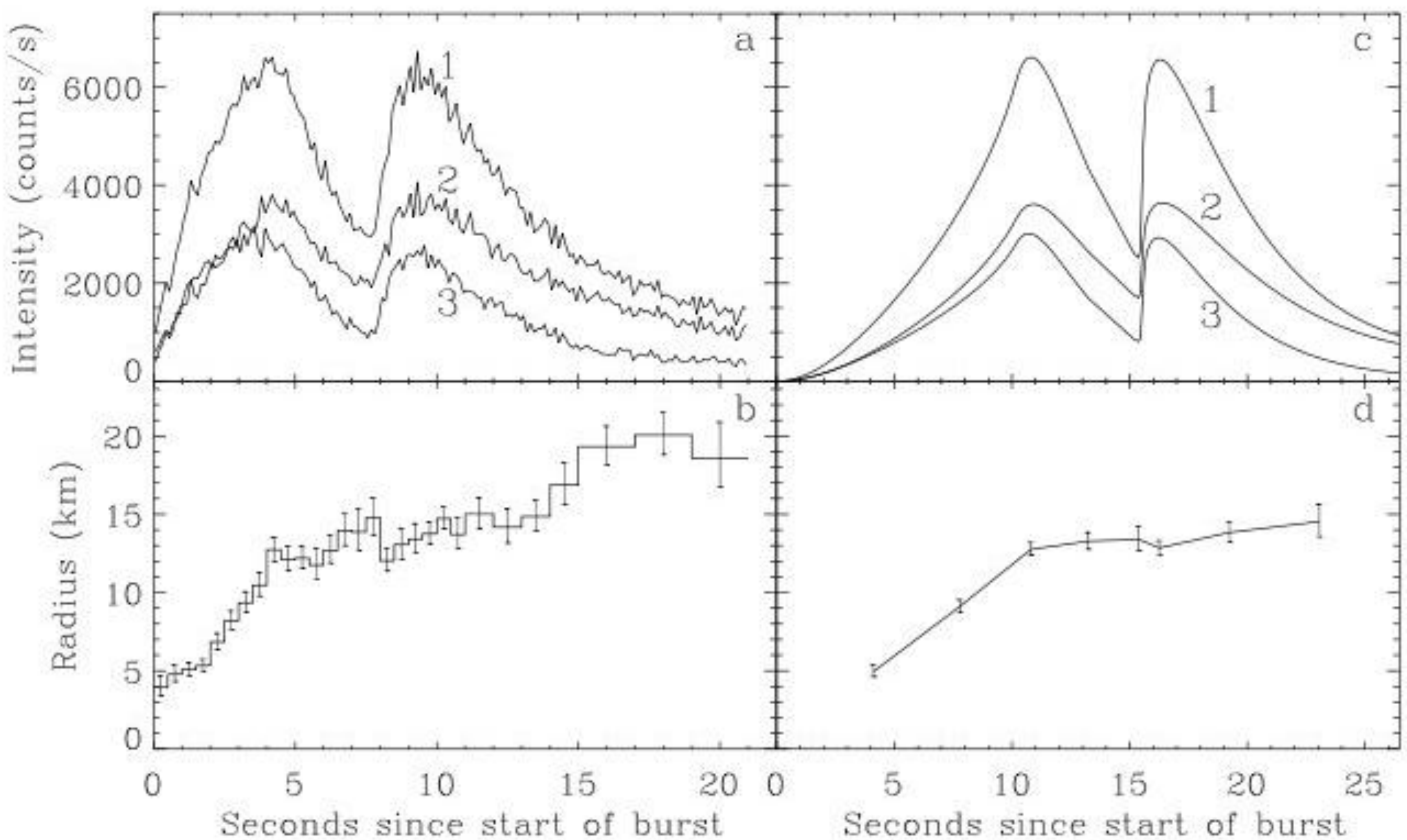
Curves for various neutron star and other source parameters.

Model with the salient features of the Coriolis force effects on flame spreading can qualitatively explain the observations.

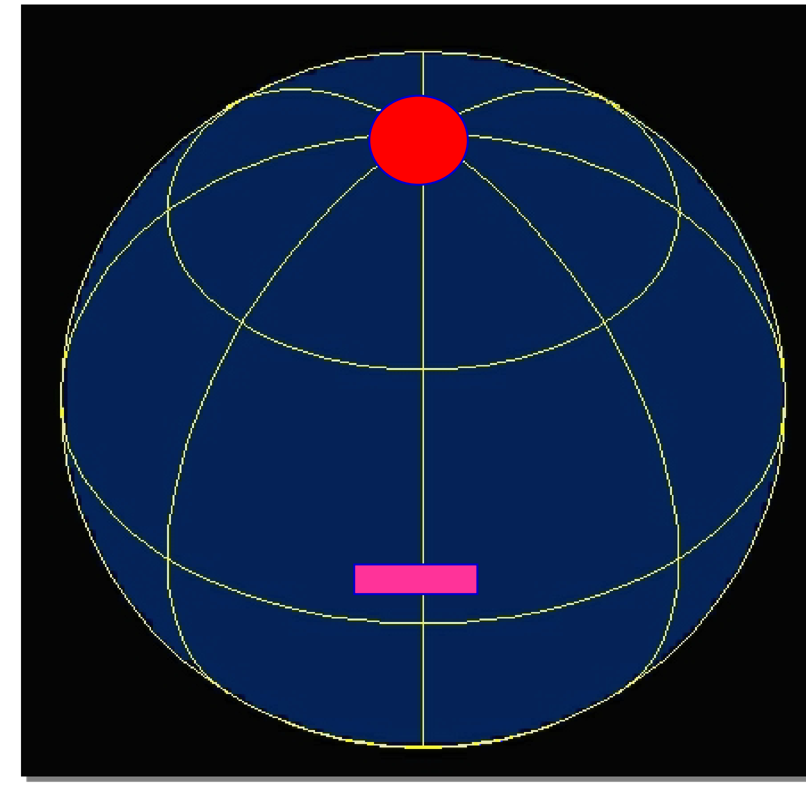
Other observational indications of flame spreading

Rare Weak Double-peaked X-ray Bursts

Data 4U 1636-536 Model



SB & Strohmayer, ApJ, 636, L121, 2006; *RXTE data*



Neutron star with polar ignition

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

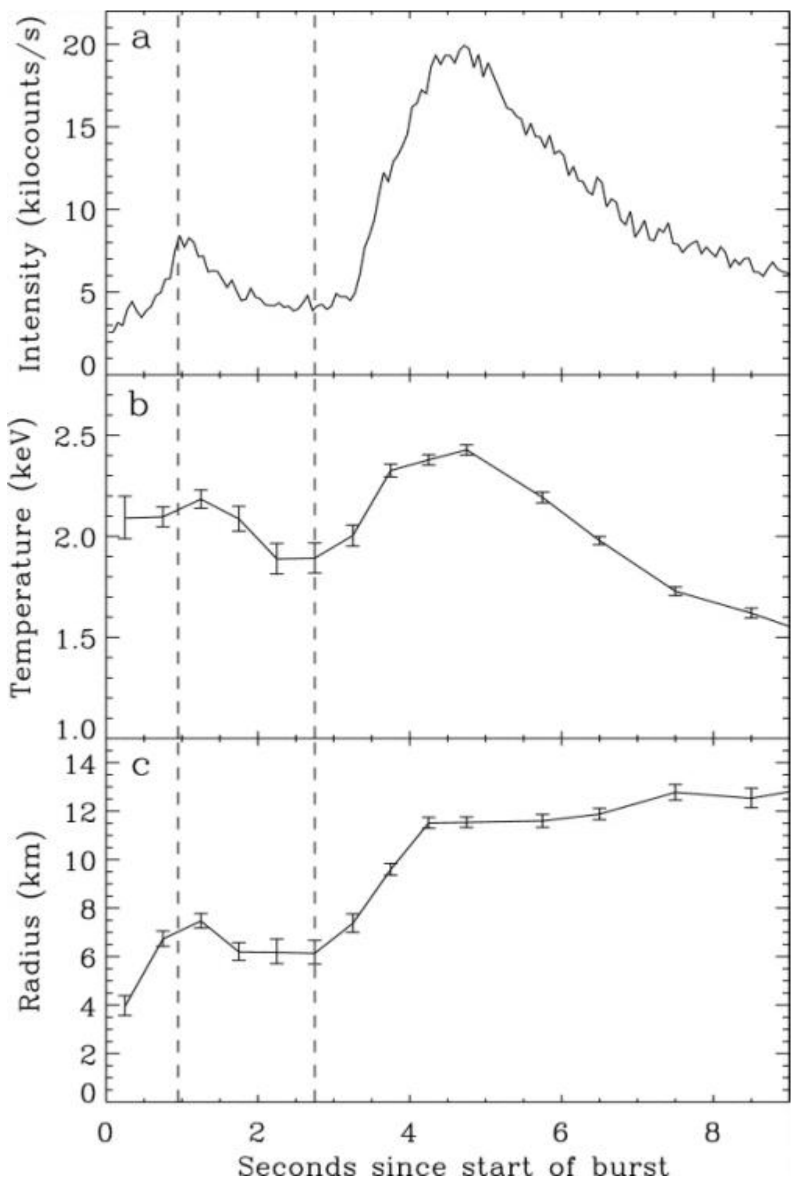
(2) Azimuthally symmetric temporary burning front stalling cools the burning region for a few seconds, while keeping the burning area unchanged. This can explain the intensity and temperature drop during the dip.

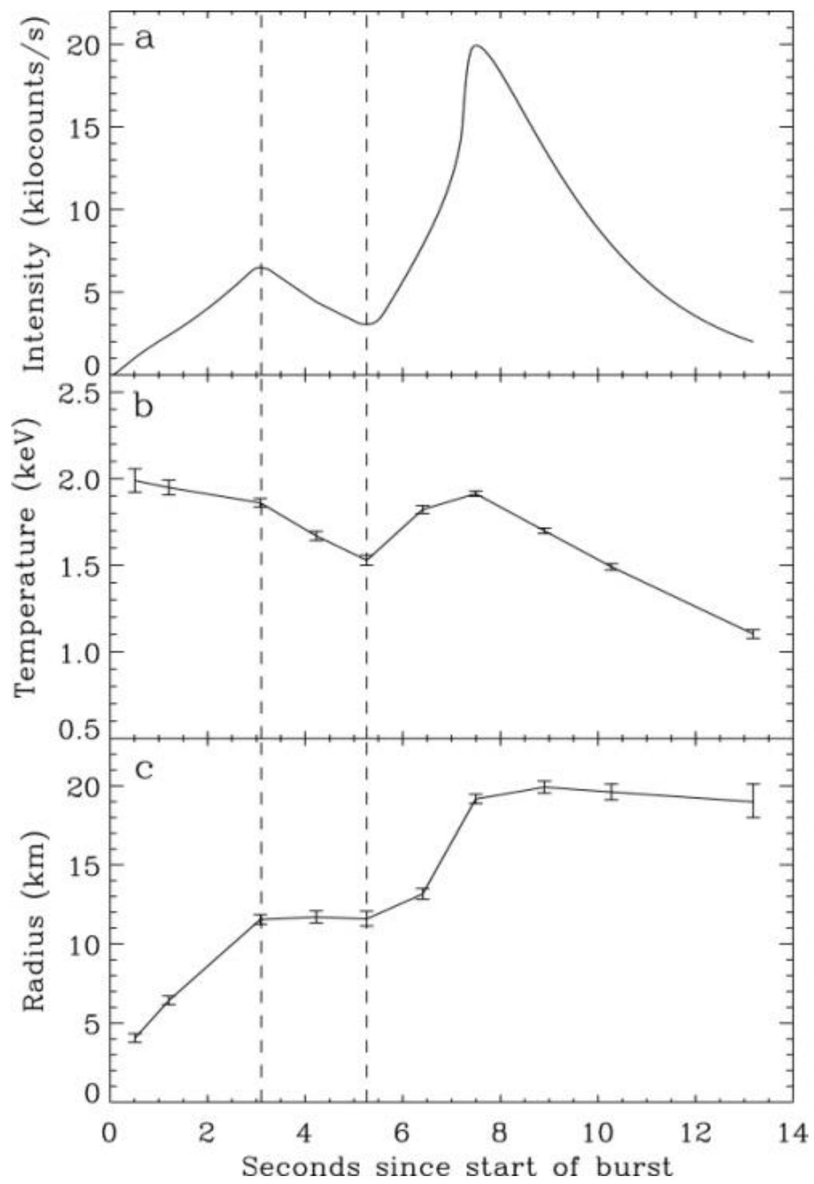
(3) The subsequent expansion of burning region explains the second intensity peak.

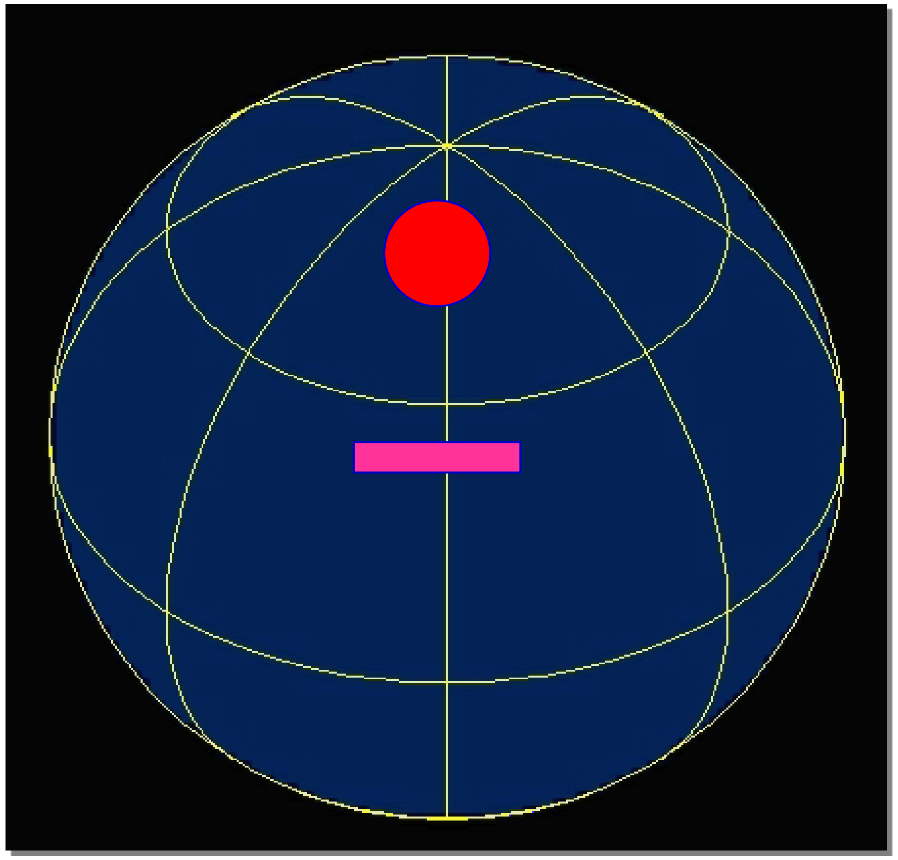
Other observational indications of flame spreading

Rare Weak Double-peaked X-ray Bursts

Data 4U 1636-536 Model







Neutron star with high latitude ignition

SB & Strohmayer, ApJ, 641, L53, 2006; *RXTE 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.

Burst oscillation during rise: thermonuclear flame spreading?

So the previous results suggested that burst rise oscillations originate from the expanding hot spot due to thermonuclear flame spreading.

However, this suggestion was made from a few bursts. A quantitative study with a large sample, to check whether the fractional amplitude of burst rise oscillation decreases with time for all bursts, was not done.

Burst oscillation during rise: thermonuclear flame spreading?

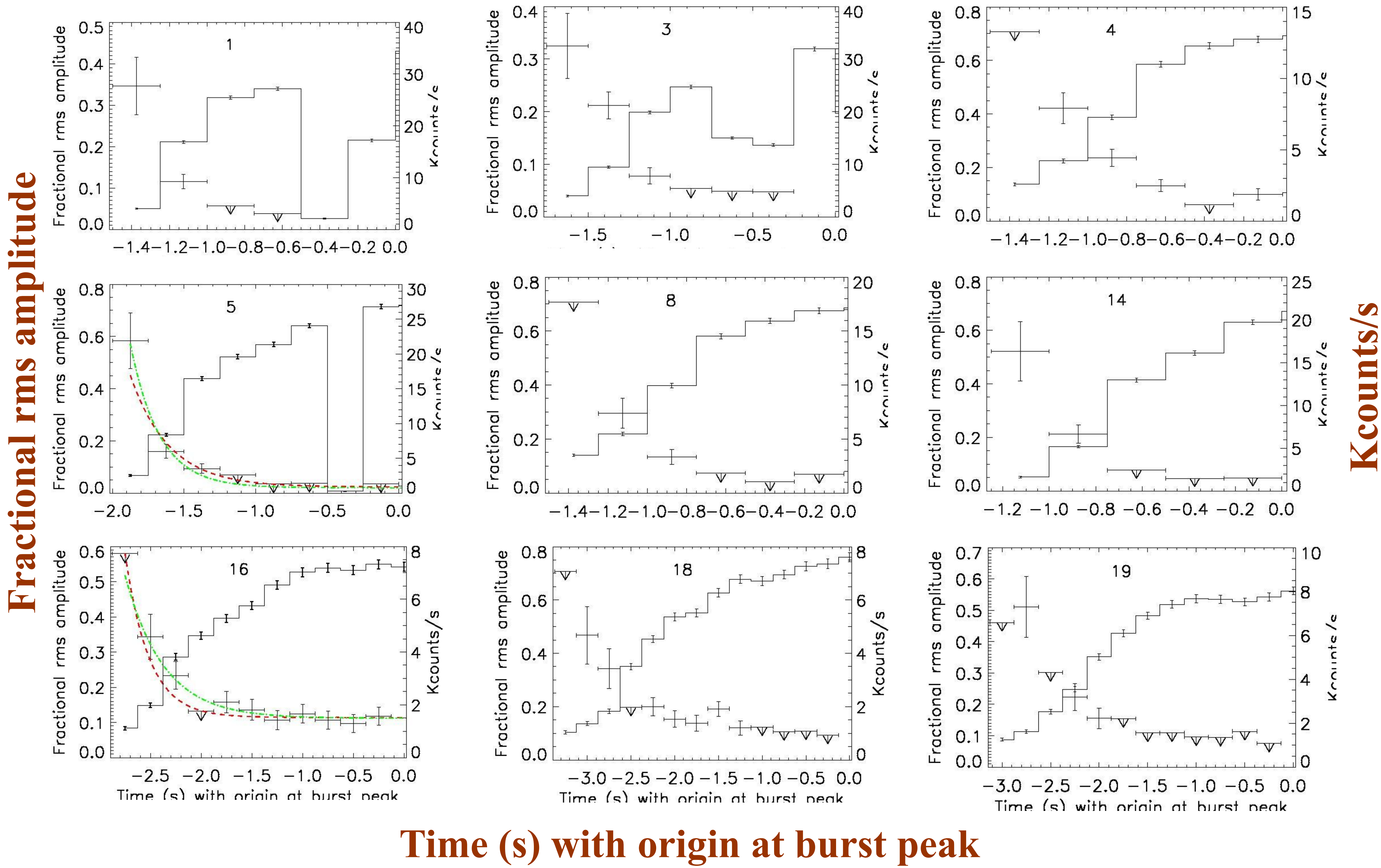
So the previous results suggested that burst rise oscillations originate from the expanding hot spot due to thermonuclear flame spreading.

However, this suggestion was made from a few bursts. A quantitative study with a large sample, to check whether the fractional amplitude of burst rise oscillation decreases with time for all bursts, was not done.

We have addressed this problem in Chakraborty, **SB**, ApJ, 792, 4 (2014)

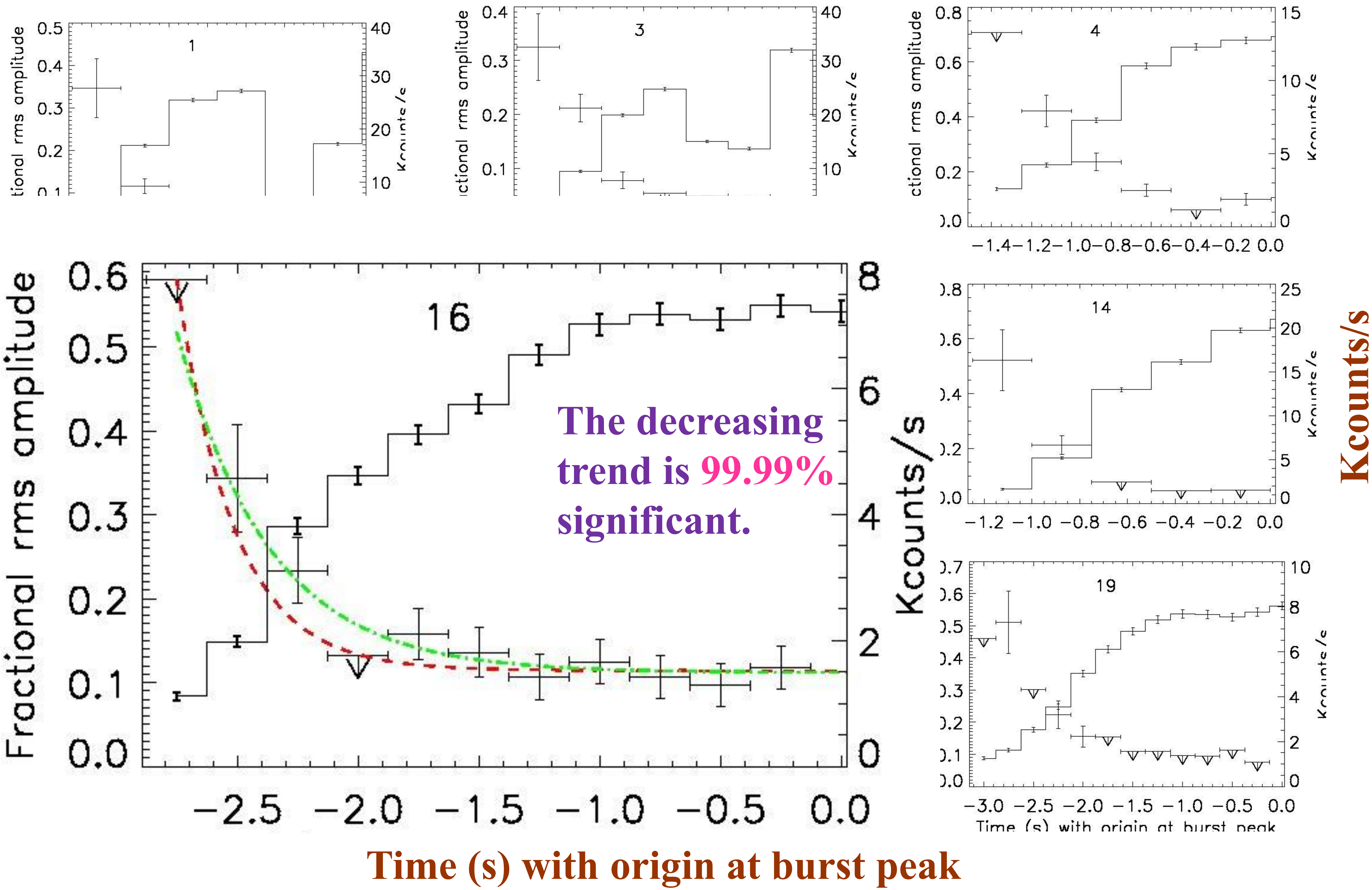
We used the data of 161 *RXTE* PCA bursts from the neutron star LMXB 4U 1636-536 and bursts from nine other sources. We divided the rise time of each burst into 0.25 sec bins, and identified the bins in which oscillations were detected with at least 3σ significance. 51 (27 from 4U 1636-536) of these bursts had detection in at least one 0.25 sec time bin, and we studied fractional amplitude evolution for these 51 bursts.

All bursts show a decreasing trend for fractional rms amplitude for burst rise oscillations: examples of nine bursts from 4U 1636-536 are shown.



Chakraborty, SB, ApJ, 792, 4 (2014)

All bursts show a decreasing trend for fractional rms amplitude for burst rise oscillations: no burst from any source shows an opposite trend.



Chakraborty, SB, ApJ, 792, 4 (2014)

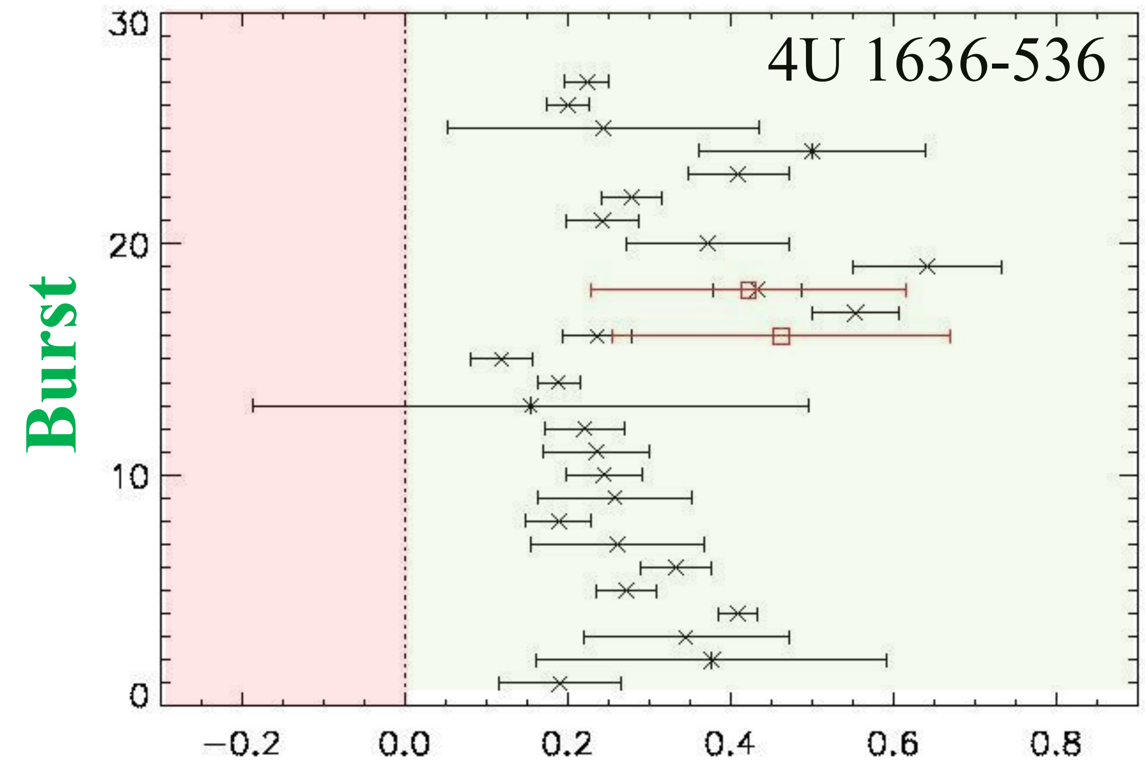
Latitude-dependent flame speeds, possibly due to Coriolis force

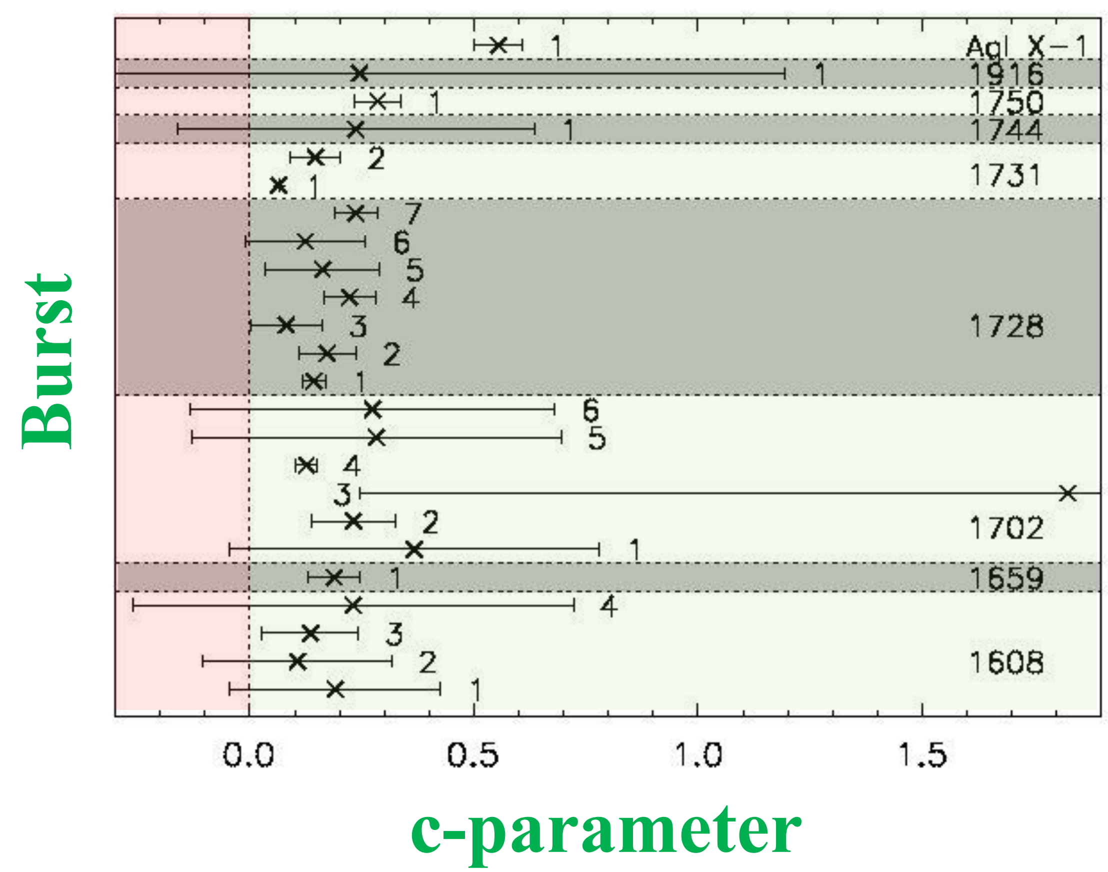
We fit the fractional rms amplitude (R) vs. time (t) curve during burst rise with an empirical model of the form:

$$R = a - bc(1 - \exp(-t/c))$$

with the parameters **a > 0, b > 0** and **c**. A positive value of **c** implies an upward concave fractional rms amplitude (**R**) vs. time (**t**) curve, while a negative value implies a convex curve.

Best-fit values of the **c-parameter** for all the 51 bursts from ten sources are **positive**, implying latitude-dependent flame speeds, possibly due to Coriolis force. **This further supports the thermonuclear flame spreading origin of burst rise oscillations.**





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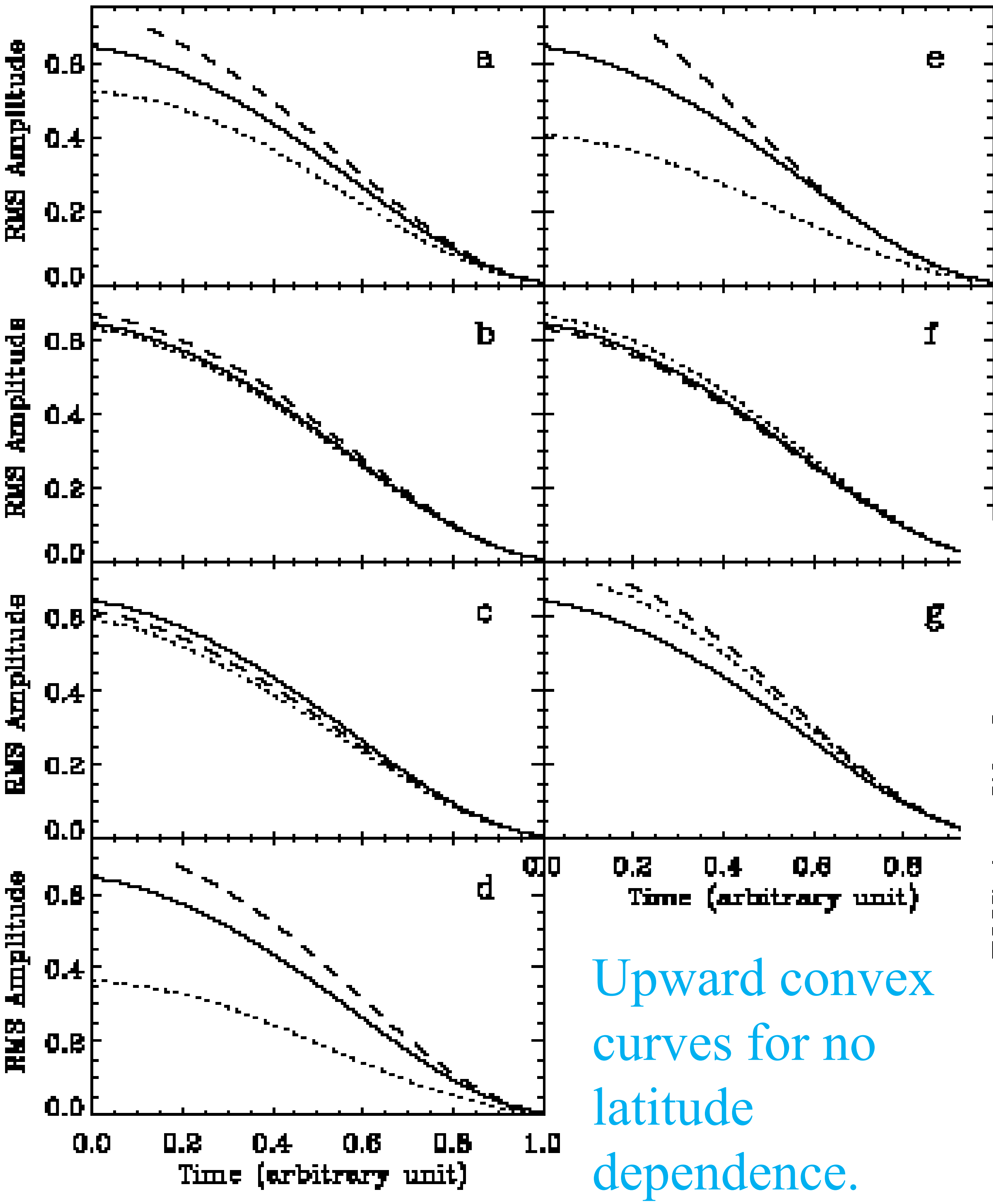
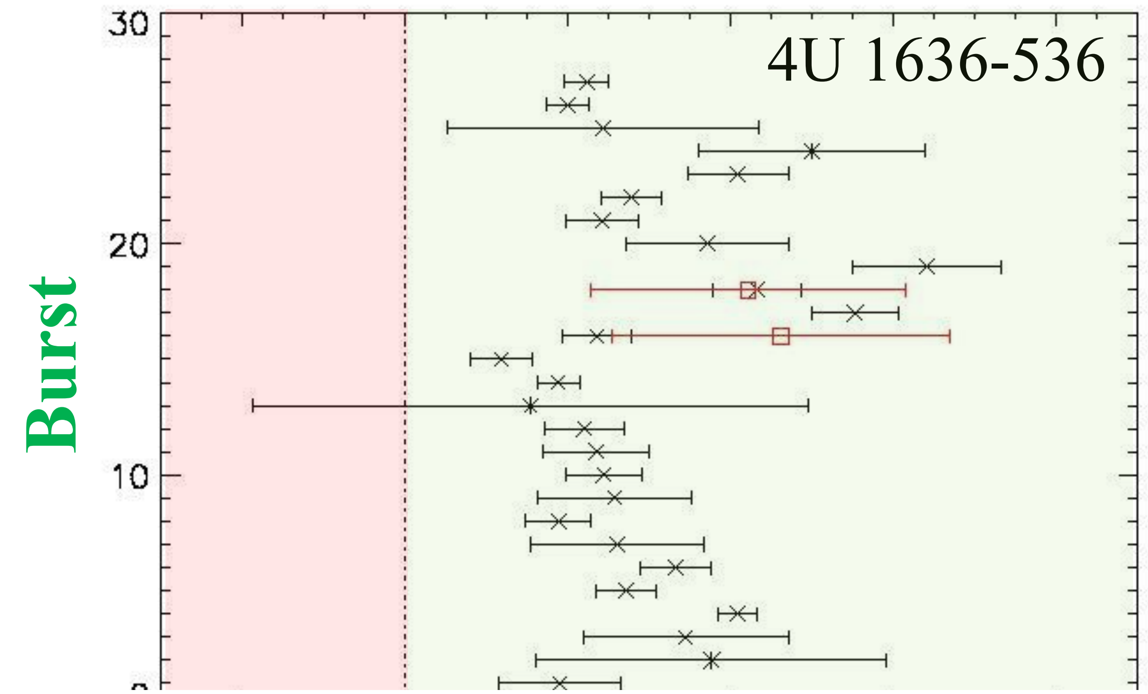
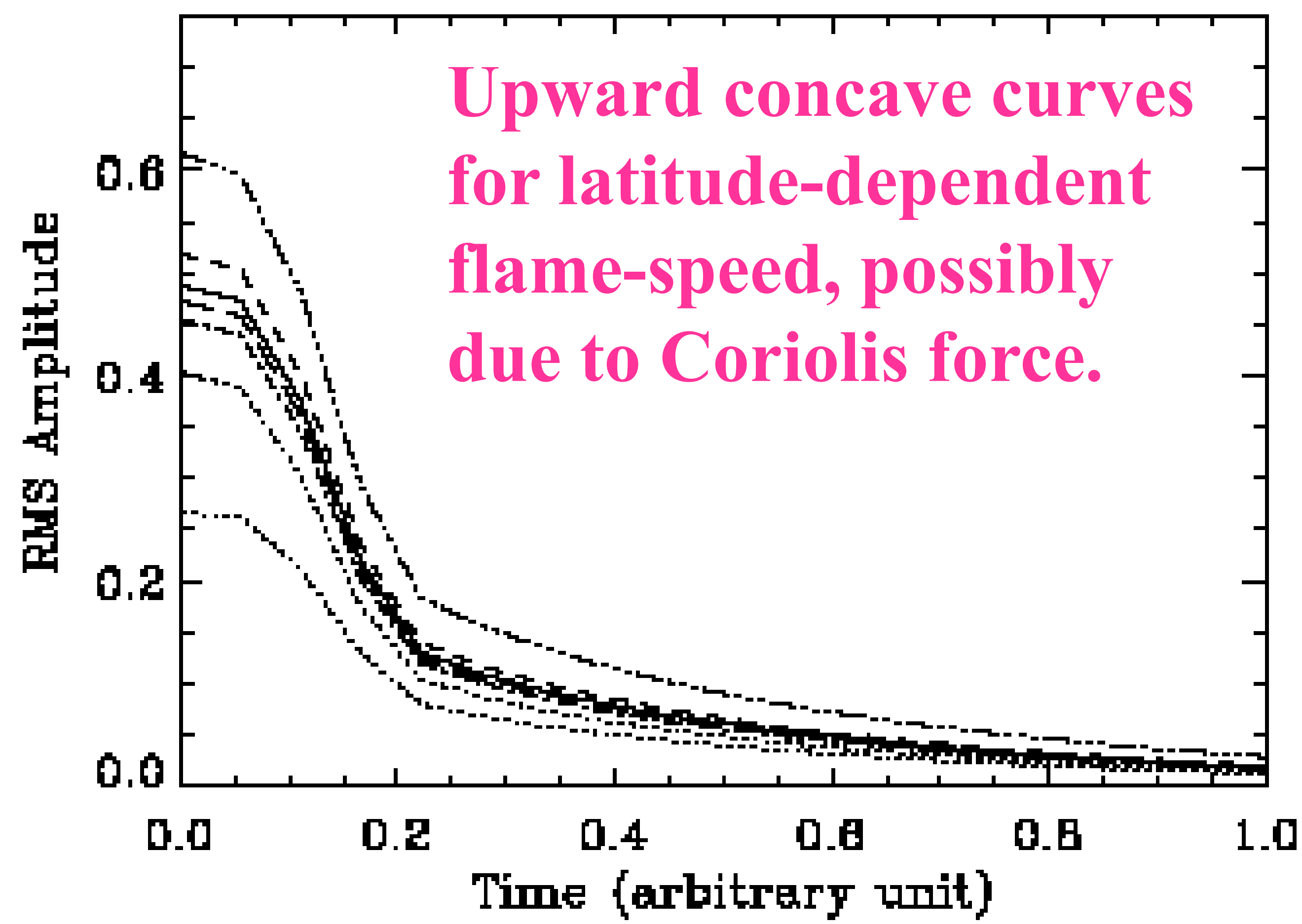


Upward convex curves for no latitude dependence.





Upward concave curves for latitude-dependent flame-speed, possibly due to Coriolis force.

SB & Strohmayer, ApJ, 666, L85 (2007)

Latitude-dependent flame speeds, possibly due to Coriolis force

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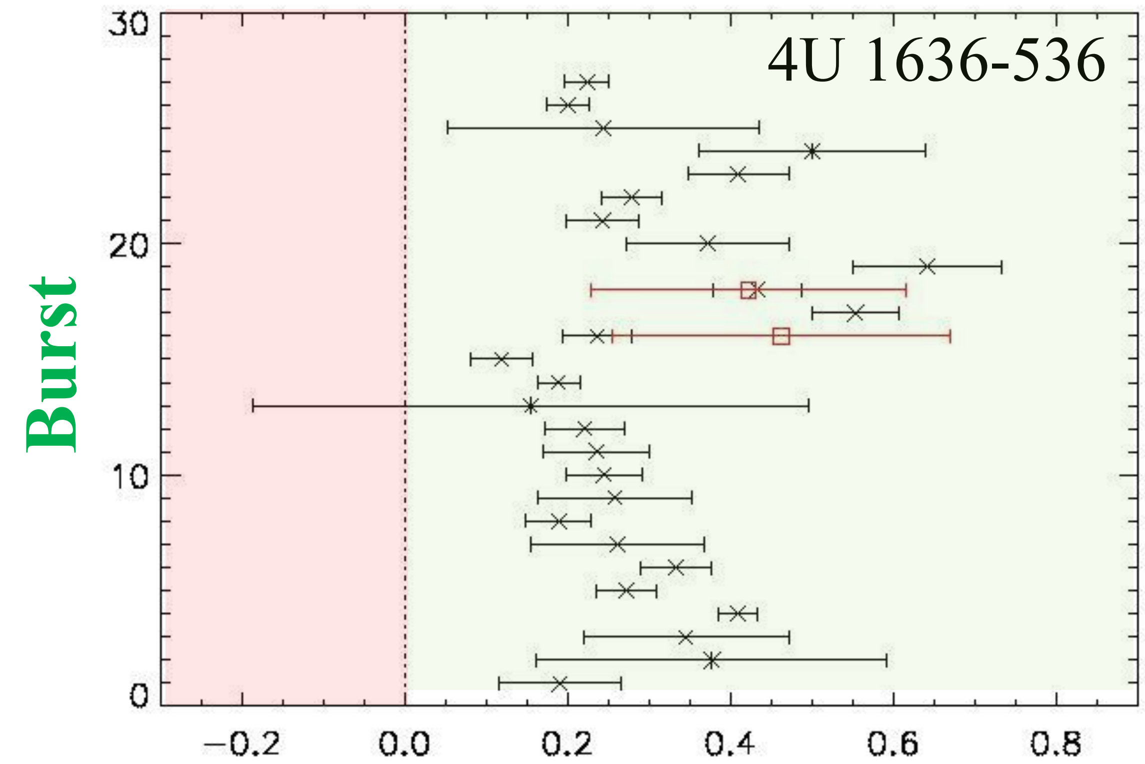
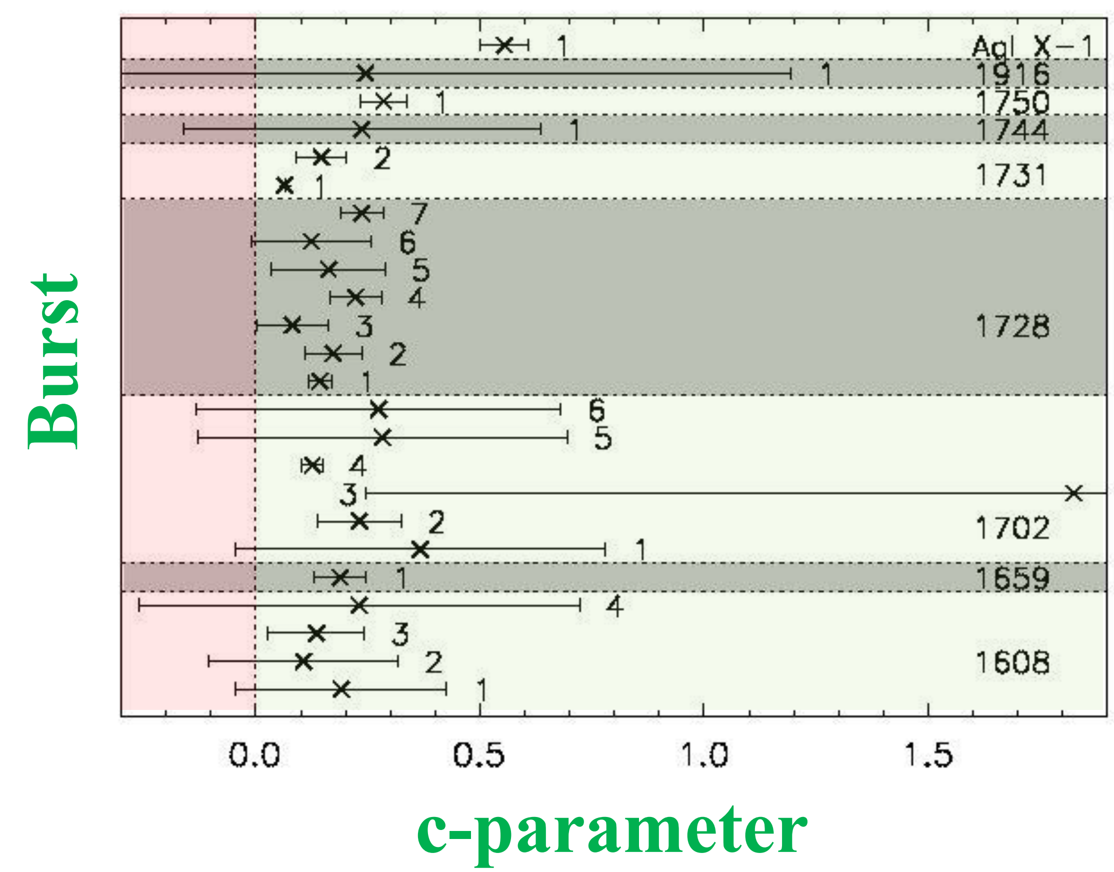




Chakraborty, SB, ApJ, 792, 4 (2014)

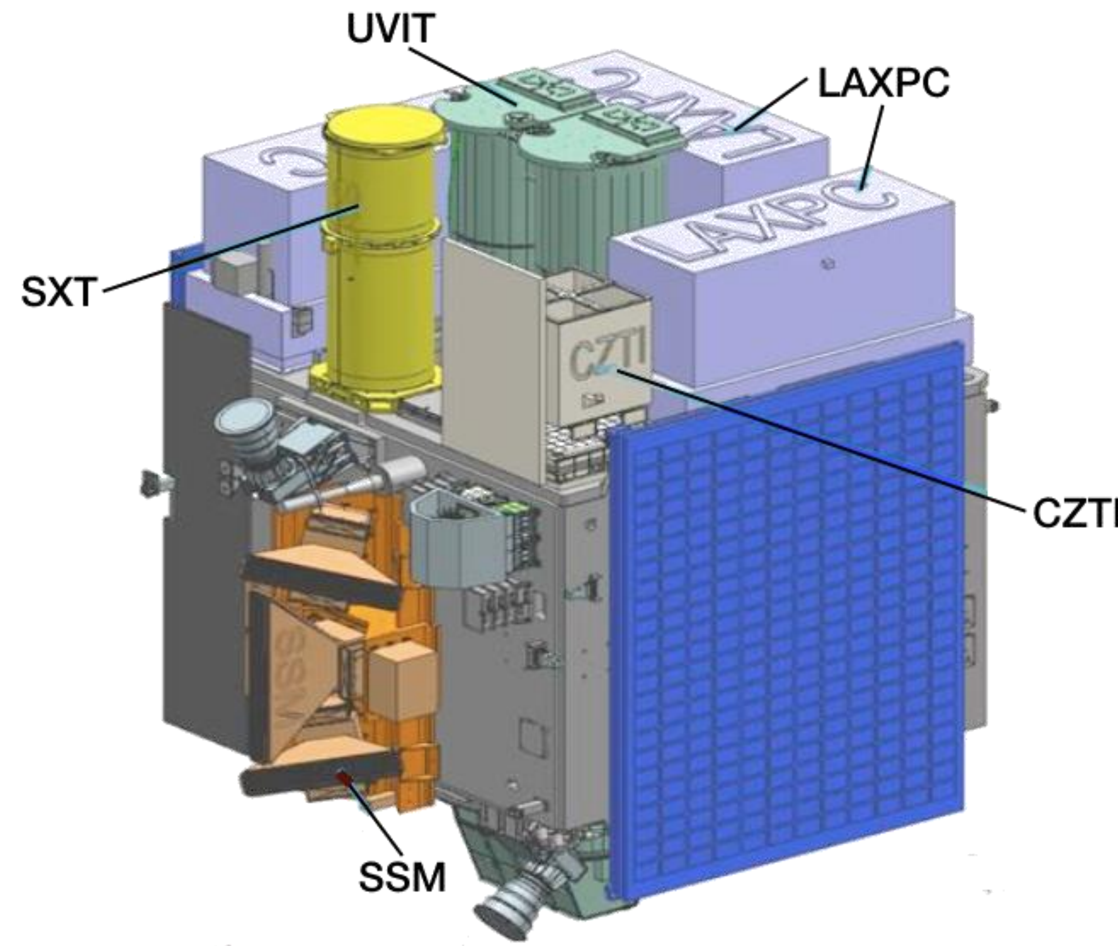
Conclusions

1. Burst rise oscillation is an important tool to measure neutron star mass and radius, which is a science driver for future large area timing X-ray space missions. But to have any reliability of this tool, it is essential to check whether such oscillations originate from an expanding hotspot due to thermonuclear flame spreading.

2. Our recent detailed and uniform analysis of an unprecedented large sample of bursts (for this purpose) supports the flame spreading origin, making this tool more reliable.

Burst oscillation: a tool to measure neutron star parameters

Spectral and timing study of burst rise



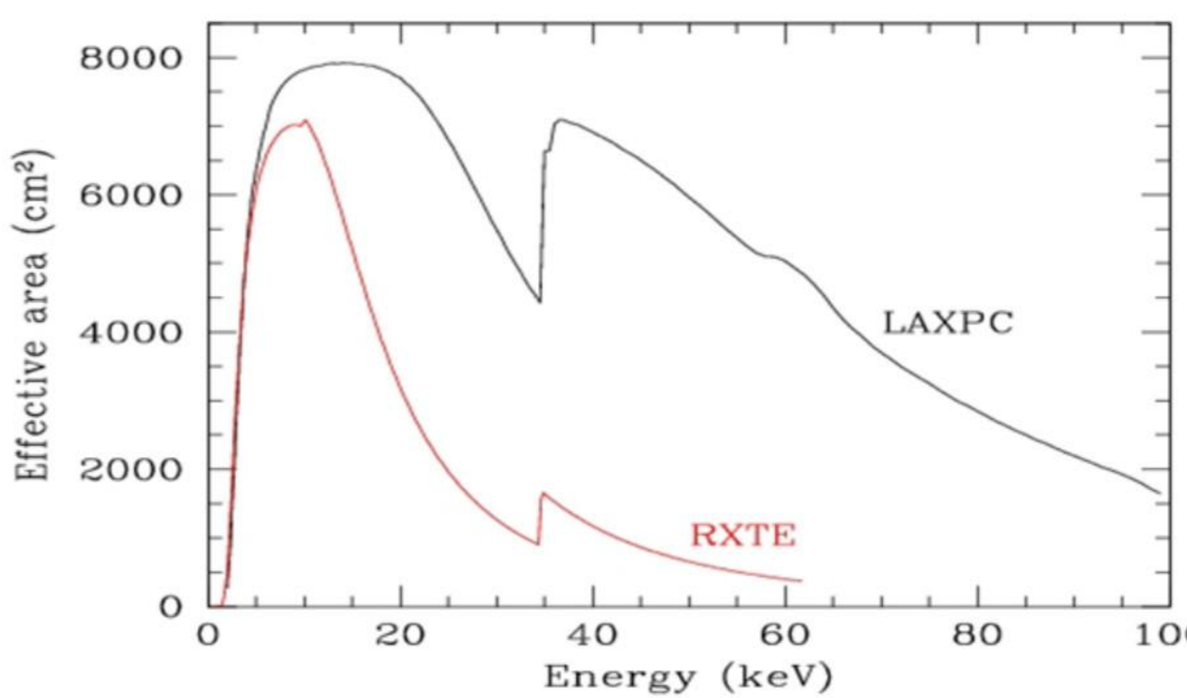
What can *Astrosat* do?

(1) In its time, only *Astrosat* will have the capability to study burst oscillations.

(2) Full LAXPC area will be important to increase the signal-to-noise for both burst oscillations and X-ray spectrum. Note that *RXTE*-PCA operated with much lesser area during most of its lifetime.

(3) Most promising sources are known from *RXTE* observations.

(4) *Astrosat* will model the burst and non-burst emissions in a much larger (than *RXTE*) photon-energy range, which will be important to accurately model the energy-dependent burst oscillation profiles.



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2. **Our recent detailed and uniform analysis of an unprecedented large sample of bursts (for this purpose) supports the flame spreading origin,** making this tool more reliable.

3. **This inference implies that flame spreading on a rapidly spinning neutron star happens in ~2.5 sec, and not in a much smaller (say, < 0.25 sec) time. This implies a flame speed of $\sim$ 12 km s^{-1}, rather than a flame speed of $\sim$ 120 km s^{-1}. This, considering the calculations of Spitkovsky et al. (2002), supports a weak turbulent viscosity for flame spreading.**

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Thank you!