Generation of Type I X-ray Burst Oscillations

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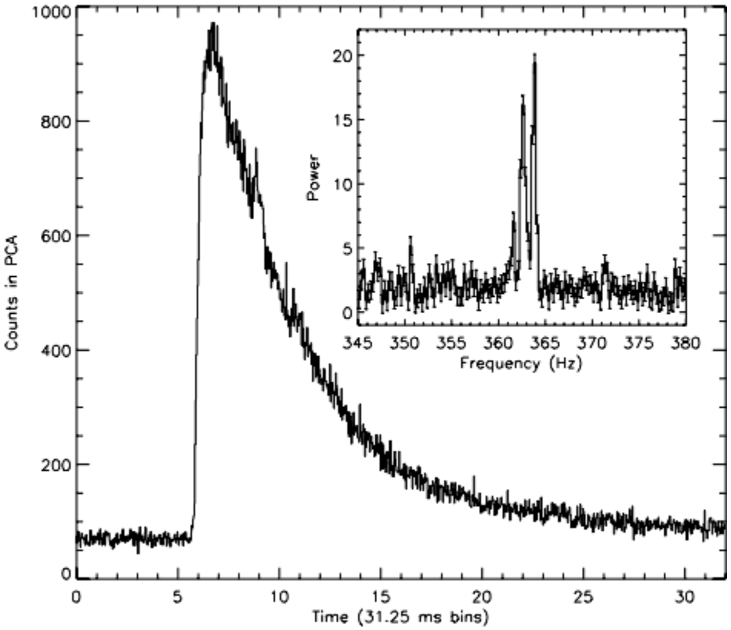
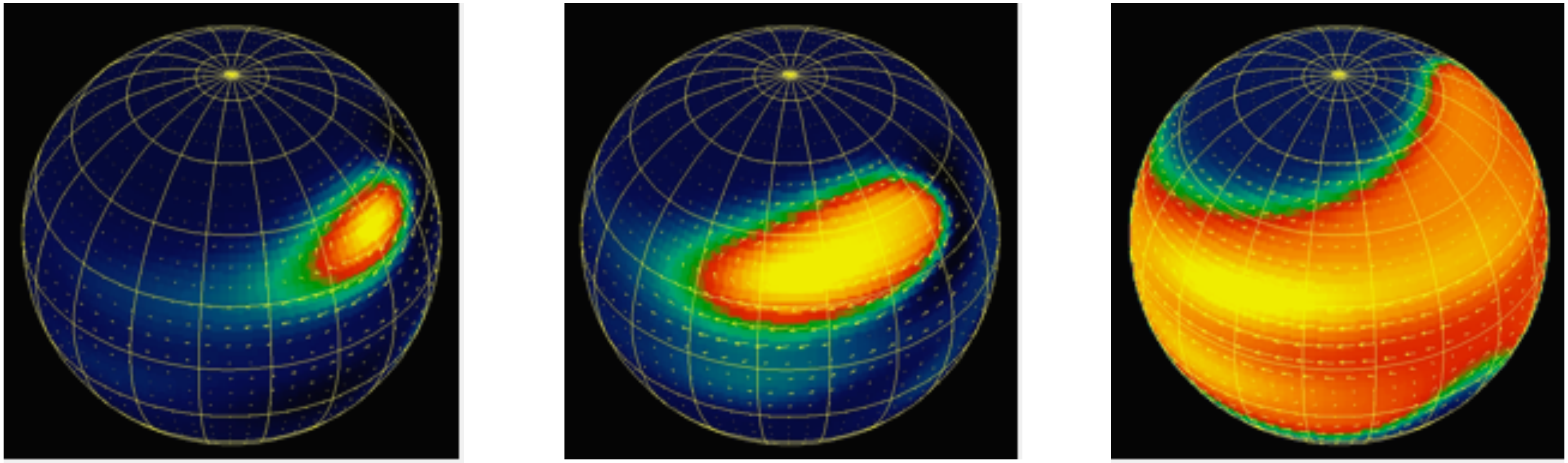




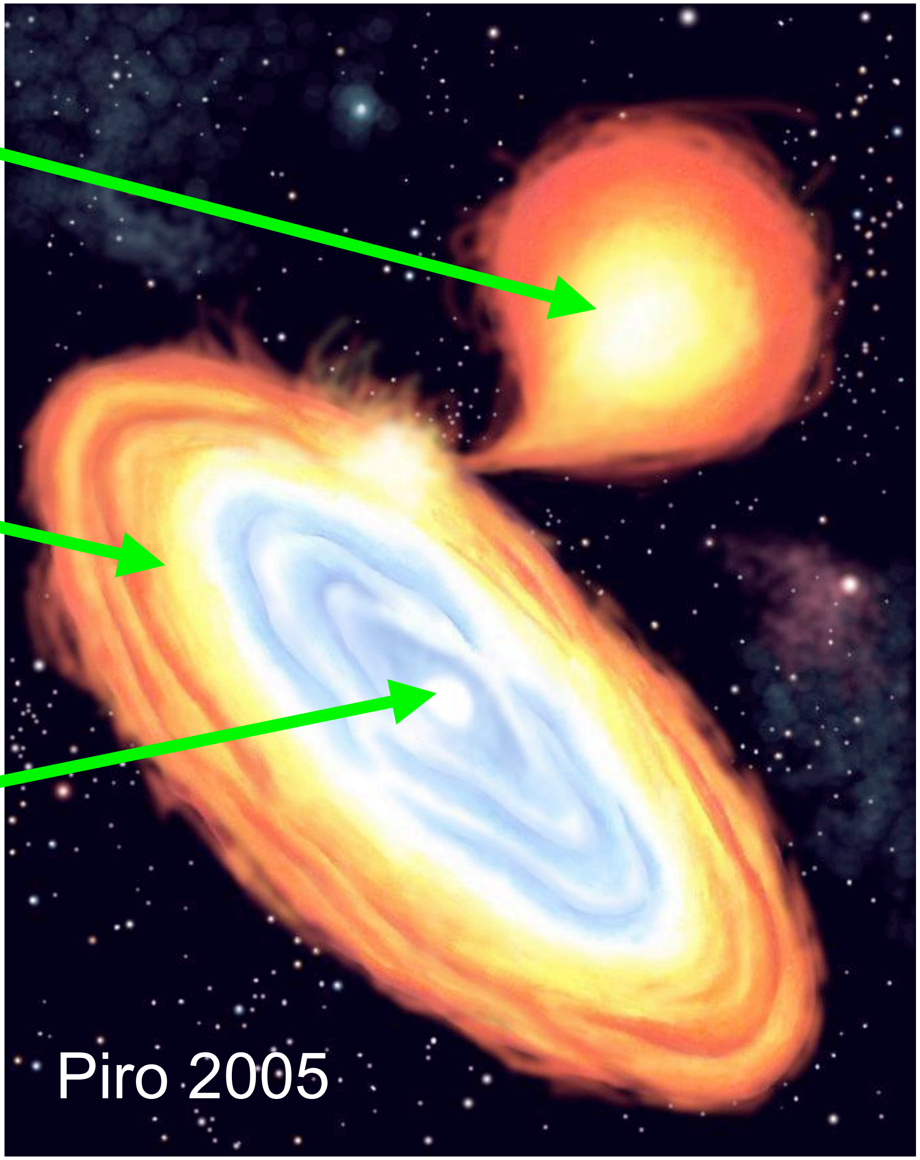
Outline

1. Introduction to bursts and oscillations
2. Oscillations during the burst rise
3. Oscillations during the burst decay

What mechanism generates each type of oscillations?

Why are both types detected only at high $\dot{M}$?

Low-Mass X-ray Binaries



Piro 2005

Mass donor star
loses matter via
tidal stripping

Accretion disk
forms around
neutron star

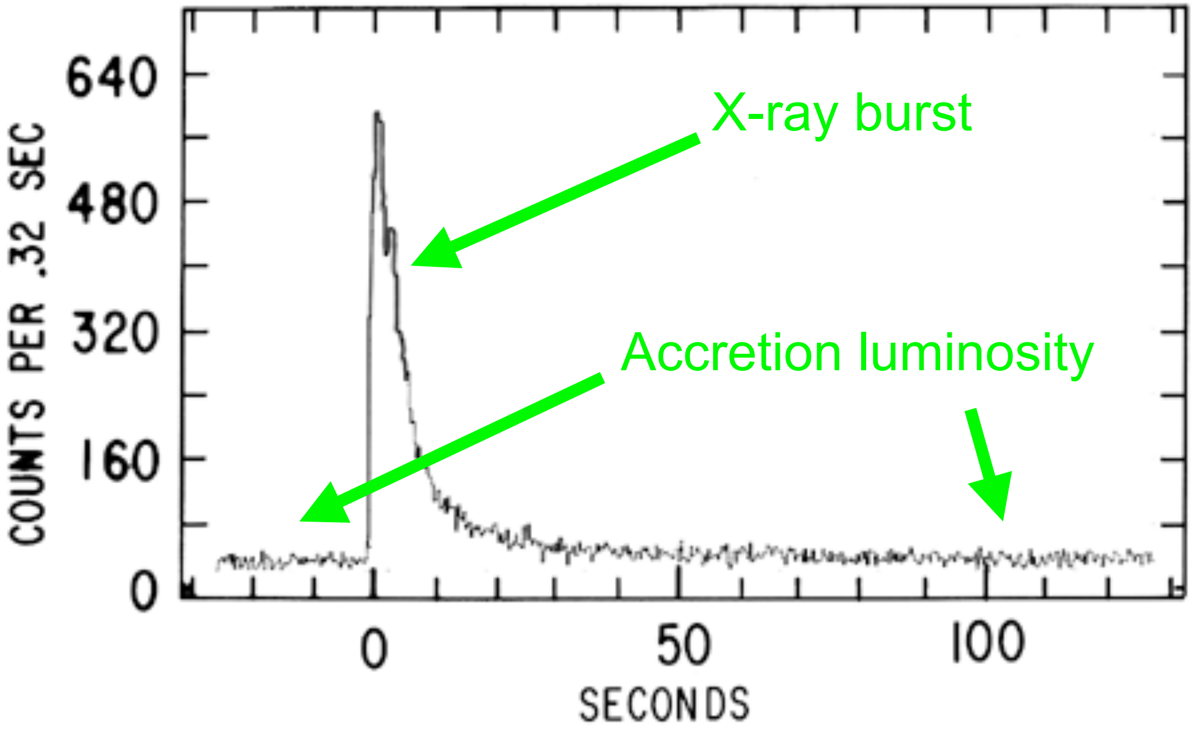
Neutron star
accretes matter
lost from disk

Type I X-ray Bursts

Thermonuclear explosions on accreting neutron stars

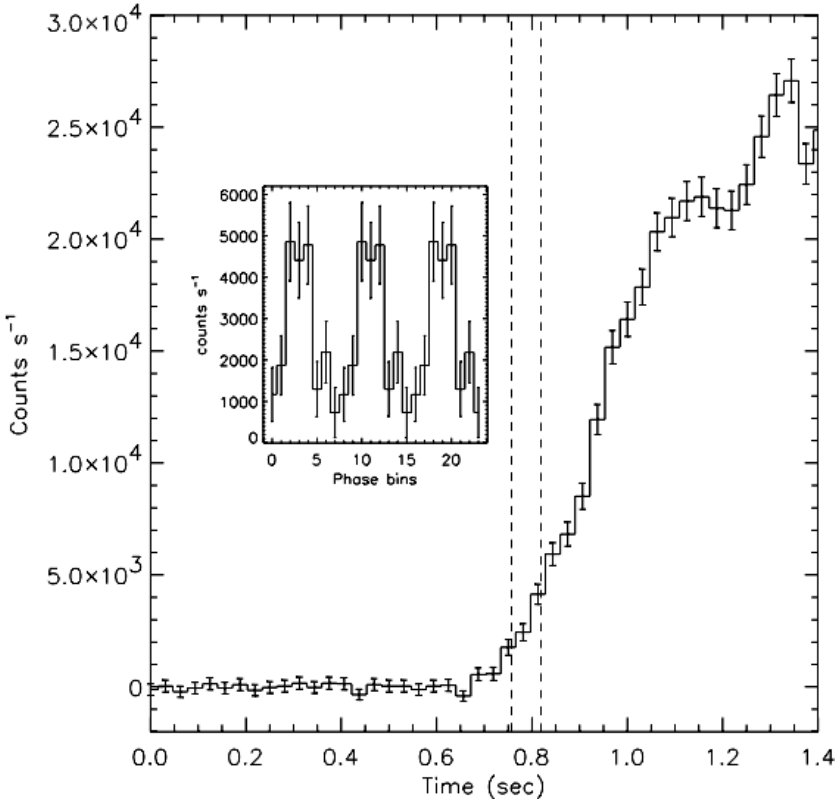
Burst properties

- t_{recur} ~ hours - days
- t_{rise} ~ 1 s
- t_{decay} ~ 10 - 100 s



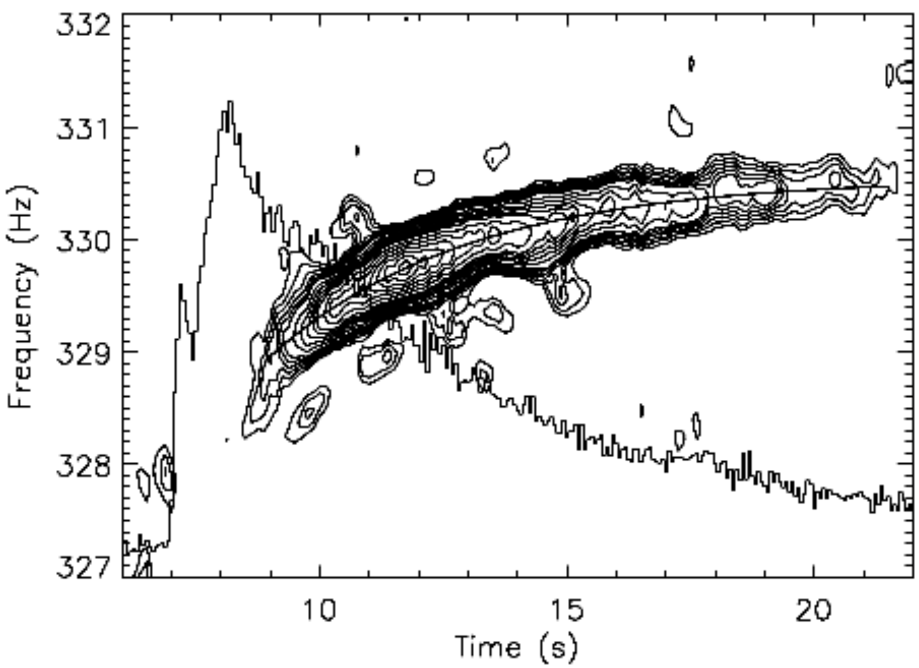
Burst Oscillations

During the rise (hot spot)



Strohmayer et al. (1998)

During the decay (surface mode)



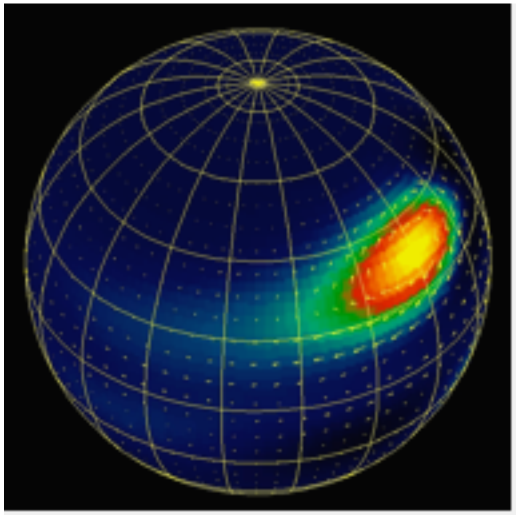
Strohmayer & Markwardt (1999)

Burst Oscillations are Cool!

Observations can tell us about:

- Neutron star spin frequency (largest is 1122 Hz!?)
- Equation of state of ultra-dense matter (e.g. Strohmayer et al. 1998, Miller & Lamb 1999)
- Flame propagation over stellar surface (recent work by Bhattacharyya & Strohmayer)
- Ocean/crust interface (Piro & Bildsten 2005)

Generation of Burst Rise Oscillations



Rotationally modulated hot spot

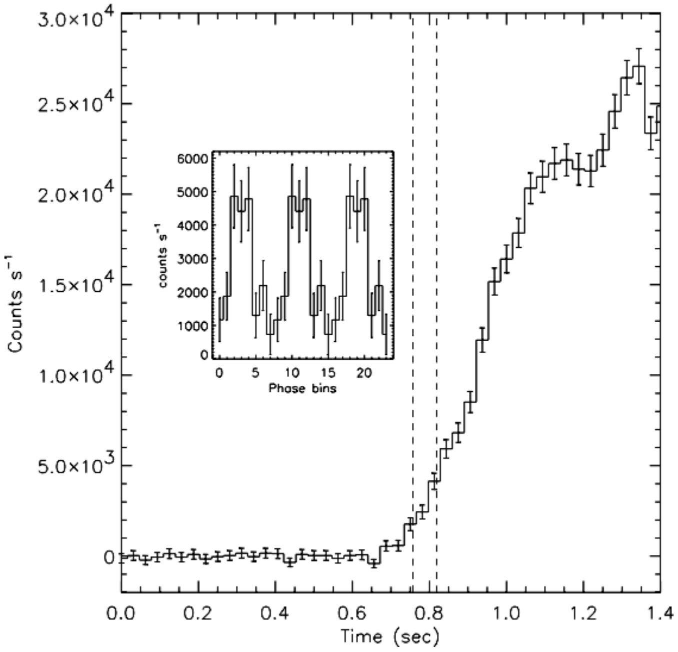
$t_{rise} << t_{recur}$ → ignition must occur at a point!

Need to “confine” flame front around ignition point to make a long-lasting hot spot

Flame speed depends on latitude λ (Spitkovsky et al. 2002):

$$v_{flame} \propto \frac{1}{\sin \lambda}$$

Need to know ignition latitude!



Burst Ignition Latitude

Assumption: fuel spreads to minimize gravitational potential energy

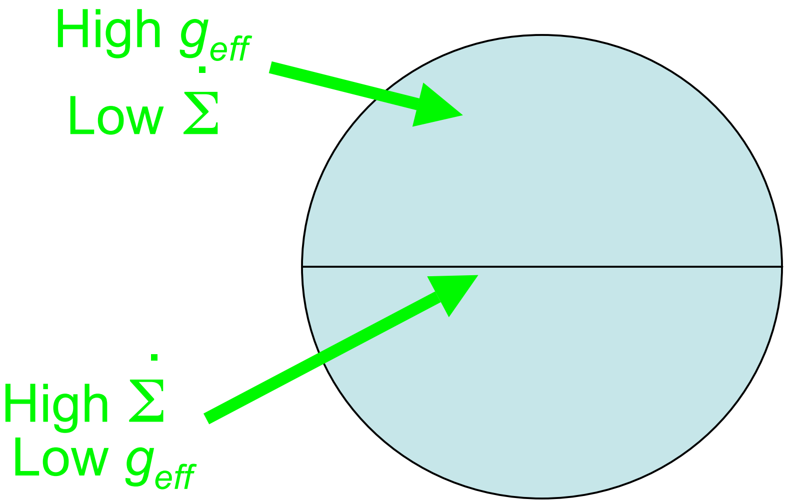
pressure $P = \Sigma g_{eff}$ (Σ = column depth) at base of accreted layer is *independent of latitude*!

Local accretion rate $\dot{\Sigma} \propto 1/g_{eff}$

$\dot{\Sigma}$ highest at equator ➔ fuel ignites at equator!

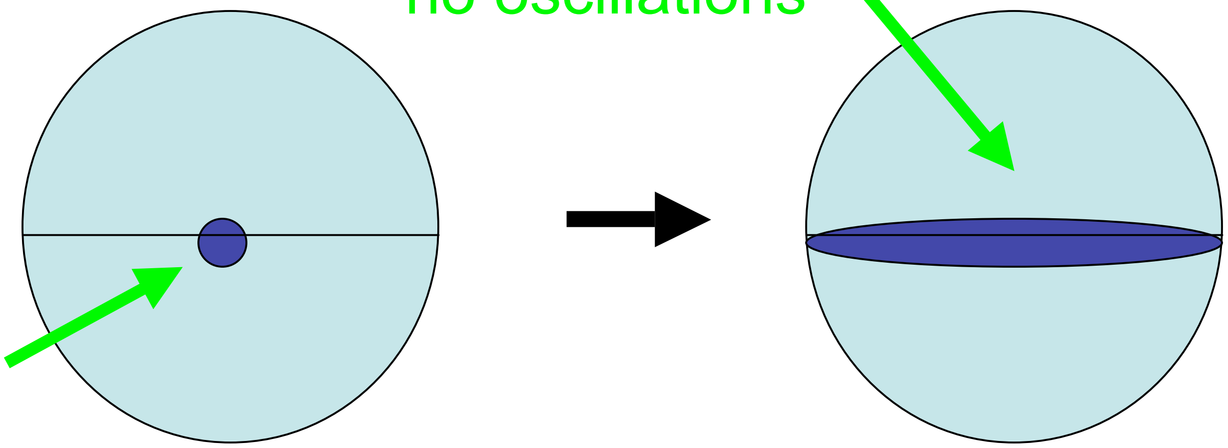
Spitkovsky et al. (2002)

Rapidly rotating neutron star



Burst Rise Oscillations

$$v_{\text{flame}} \propto \frac{1}{\sin \lambda}$$



Axisymmetric belt: no oscillations

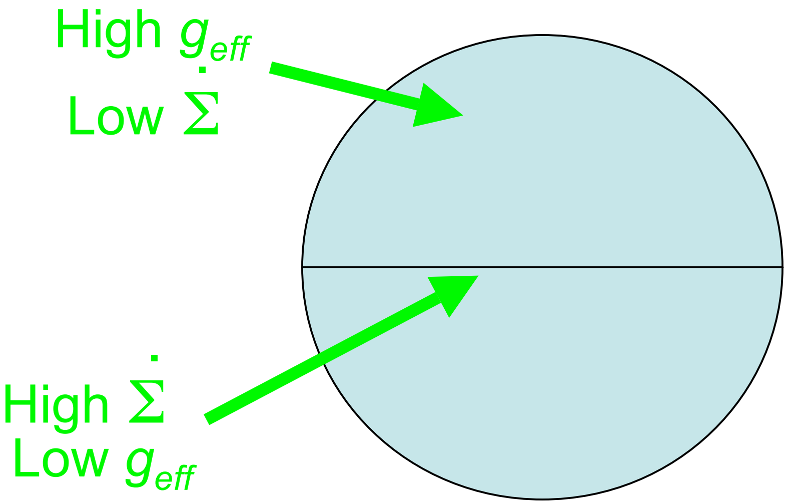
Ignition point

Burst Ignition Latitude

BUT… both theory and observations imply that there is a critical $\dot{\Sigma}$ above which bursts don't occur!

So there is a range of high $\dot{M}$ in which nuclear burning is stable at equator but unstable off equator!

Rapidly rotating neutron star



High g_{eff}
Low $\dot{\Sigma}$

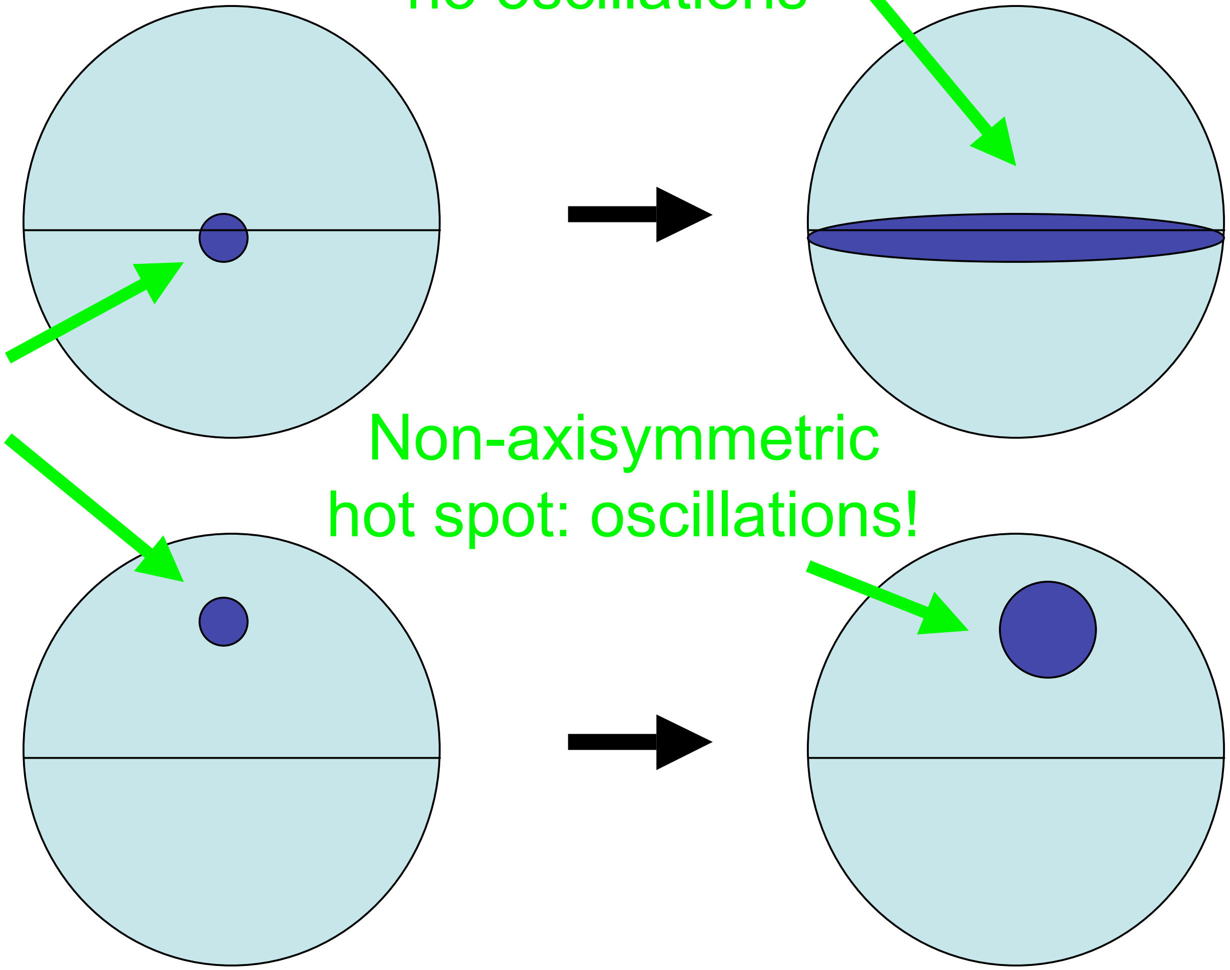
High $\dot{\Sigma}$
Low g_{eff}

$\dot{\Sigma}$ highest at equator ➔ nonequatorial ignition at high $\dot{M}$!

Cooper & Narayan (2007)

Burst Rise Oscillations

$$v_{\text{flame}} \propto \frac{1}{\sin \lambda}$$



Low $\dot{M}$:

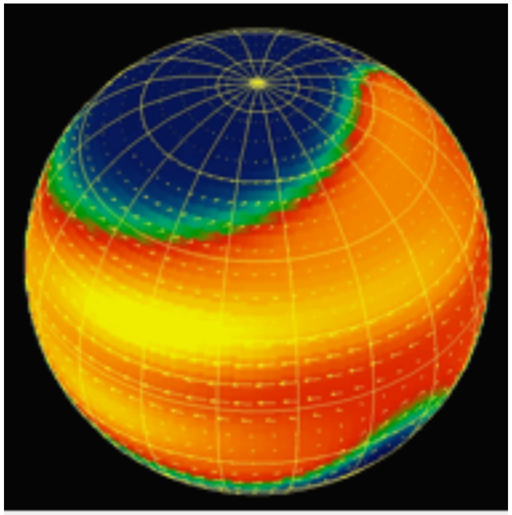
High $\dot{M}$:

Ignition point

Axisymmetric belt:
no oscillations

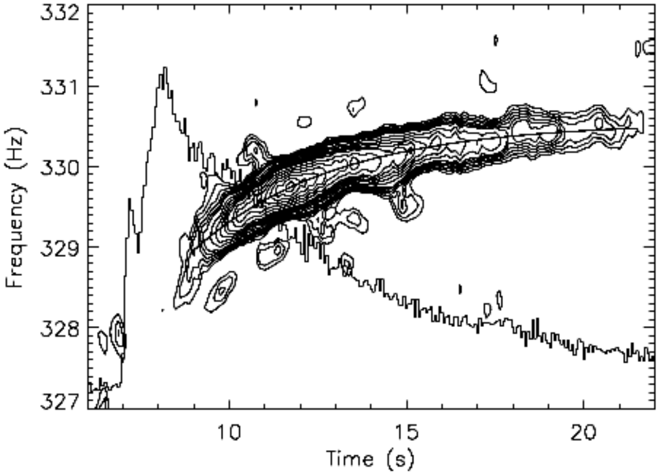
Non-axisymmetric
hot spot: oscillations!

Generation of Burst Decay Oscillations



Hot spot doesn't work: probably flux modulations from surface modes (e.g. *r*-mode, Heyl 2004)

Surface modes can explain frequency drift (Heyl 2004) and amplitude energy dependence (Piro & Bildsten 2006)



Need large amplitude oscillations to produce ~ 10% flux variations ➔ mode must be driven unstable!

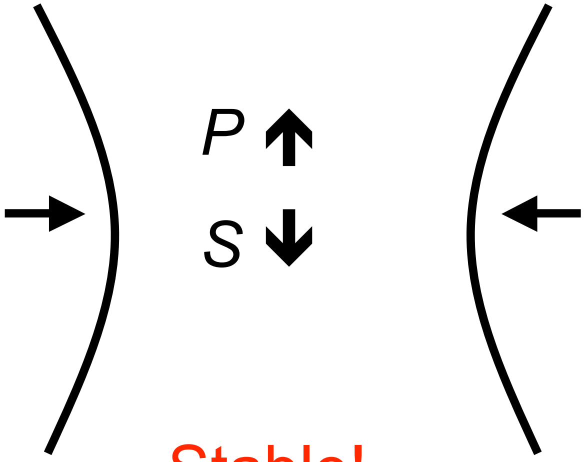
Surface Mode Driver: ε-mechanism

A region that gains heat when compressed is a driving region;
A region that loses heat when compressed is a damping region

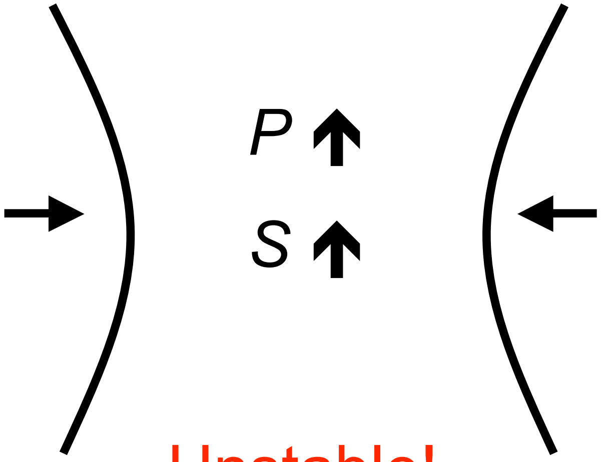
Heating is due to nuclear reactions during burst.

Consider lateral compression of a column of matter:

(ideal gas) $P \propto \rho T$ $S \propto \ln (T/\rho^{\gamma-1})$



Stable!



Unstable!

Mode Instability Criterion

For $\varepsilon_{nuc} \propto T^{\nu}$: if $$\frac{\text{Heating rate}}{\text{Cooling rate}} \gtrsim \frac{2}{4+\nu} \Rightarrow \text{unstable!}$$

Criterion is *less restrictive* than thermal instability criterion…

Surface modes can be unstable during the burst decay, when nuclear burning is thermally stable!

Favors:

1) Powerful bursts
2) *T*-sensitive nuclear reactions

Narayan & Cooper (2007)

Burst Decay Oscillations

Thus, oscillations expected in short, He-rich bursts and not in long, H-rich (rp-process) bursts

All bursts that show oscillations in the decay phase are short, He-rich bursts (except those from pulsars)!

Burst decay oscillations from accreting ms pulsars probably due to another mechanism (Piro & Bildsten 2005, Watts & Strohmayer 2006)

Short bursts occur at high $\dot{M}$: explains why burst decay oscillations are detected only at high $\dot{M}$!

Conclusions

Oscillations during burst rise due to rotationally modulated growing hot spot

- Low $\dot{M}$: equatorial ignition ➔ no hot spot ➔ no oscillations
- High $\dot{M}$: nonequatorial ignition ➔ hot spot ➔ oscillations

Oscillations during burst decay due to unstable surface mode

- Driven by ε-mechanism
- Favored in short, He-rich bursts that occur at high $\dot{M}$

Burst oscillations may help constrain NS equation of state