Generation of Type I X-ray Burst Oscillations

Randall Cooper
Harvard University
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

Mass donor star loses matter via tidal stripping

Accretion disk forms around neutron star

Neutron star accretes matter lost from disk

Piro 2005
Type I X-ray Bursts

Thermonuclear explosions on accreting neutron stars

Burst properties

• $t_{\text{recur}} \sim \text{hours - days}$
• $t_{\text{rise}} \sim 1 \text{ s}$
• $t_{\text{decay}} \sim 10 - 100 \text{ s}$
Burst Oscillations

During the rise (hot spot)  
During the decay (surface mode)

Strohmayer et al. (1998)  
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_{\text{rise}} \ll t_{\text{recur}} \rightarrow \text{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 $\lambda$ (Spitkovsky et al. 2002):

\[ v_{\text{flame}} \propto \frac{1}{\sin \lambda} \]

Need to know ignition latitude!
Burst Ignition Latitude

Assumption: fuel spreads to minimize gravitational potential energy

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

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

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

Spitkovsky et al. (2002)
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 $\Sigma$ 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!

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

Cooper & Narayan (2007)
Burst Rise Oscillations

\[ v_{\text{flame}} \propto \frac{1}{\sin \lambda} \]

Low \( \dot{M} \):
- Axisymmetric belt: no oscillations
- Ignition point

High \( \dot{M} \):
- 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 $\sim 10\%$ flux variations $\Rightarrow$ mode must be driven unstable!
Surface Mode Driver: $\varepsilon$-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) \[ P \propto \rho T \quad S \propto \ln \left( \frac{T}{\rho^{\gamma-1}} \right) \]

Stable!

Unstable!
Mode Instability Criterion

For $\varepsilon_{\text{nuc}} \propto T^\nu$: if \[
\frac{\text{Heating rate}}{\text{Cooling rate}} \geq \frac{2}{4 + \nu}
\] \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 $\rightarrow$ no hot spot $\rightarrow$ no oscillations
• High $\dot{M}$: nonequatorial ignition $\rightarrow$ hot spot $\rightarrow$ oscillations

Oscillations during burst decay due to unstable surface mode

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

Burst oscillations may help constrain NS equation of state