CONSTRAINTS ON THE NATURE OF THERMONUCLEAR BURST OSCILLATIONS

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Many thanks to Duncan Galloway
Pavlin Savov
Dimitrios Psaltis
Neutron Star Self-Lensing

The Schwarzschild metric:

$$ds^2 = dt^2 - \frac{2M}{r} dr^2 - \frac{2M}{r} f (\square, \square)$$

A perfect ring of radiation:

$$\Rightarrow R/M = 3.52$$
General Relativistic Effects
Pulse Amplitudes

* Normalized to average
What if the star is rotating rapidly?

$v \sim 0.1 \, c$

$\frac{\omega}{2\pi} \sim 600 \, \text{Hz}$

$E = E_0 (1 + \omega R/c)$

Doppler Boosts

Time delays

$t = \sqrt{\frac{\omega}{2\pi}} \frac{R}{c}$

Light travel time

NS half period
Lensed Lightcurves

Non-sinusoidal lightcurves
Higher amplitude oscillations
What does this have to do with bursts?

- Thermonuclear bursts occur on the surface → GR effects important
- Oscillations are one of the most powerful probes
- Use pulse profiles to constrain the burst or neutron star properties

Weinberg, Miller, & Lamb 01
Nath, Strohmayer, & Swank 02
Burst Oscillations

Oscillations observed during tails of thermonuclear bursts

Strohmayer 98; Muno et al. 02
Pulse Profiles

Muno et al. 02
Harmonics?

Muno et al. 02
Not really...

Muno, Özel, & Chakrabarty 02

Stringent upper limits on harmonic amplitudes
Effects of Emitting Area Size of Hot Region (degrees)

\[ A_1, A_2 \]

- \( m=1 \)
- \( m=2 \)

Size of Hot Region (degrees)
Where Does the Emission Come from?

Harmonic/Fundamental

$A_n / A_1$

Size of Hot Region (degrees)

- $\Omega = 0$ Hz
- $\Omega = 300$ Hz
- $\Omega = 600$ Hz

Muno, Özel, & Chakrabarty 02
Constraining Location on the Neutron Star

![Graph showing the ratio of model moments to the observer's angle and viewing angle.](image)
Possibilities

One hot region must be localized near the rotational pole

or

Two hot regions must be centered on the equator

or

Half of the neutron star or equatorial band must be hotter than the other half

➢ A highly organized pattern or mode on the stellar surface
Energy Dependence of Amplitudes

Muno, Özel, & Chakrabarty 03
What affects the Energy Dependence?

\[ T_{\text{star}} \ll T_{\text{hot}} \]

Rest of the star must emit within the PCA band

\[ T_{\text{star}} \sim T_{\text{hot}} \]
for $\Theta = 90$, $\theta = \phi = 90$

Further Constraints

Muno, Özel, & Chakrabarty 03
Time Lags

Muno, Özel, & Chakrabarty 03
- Expect soft lags from Doppler boosts
- Observed: hard or no lags

→ A scattering corona may induce hard lags
Conclusions

✓ Bursts excite a (non-radial) mode on the NS

✓ m=1, m=2 patterns seem to match the observations

  Photon diffusion time \(\sim 1\) s.
  Higher frequency modes trapped in burning layer filtered out?

And many questions:

✓ Need models of a scattering corona during bursts

✓ Modes, but which modes? (Spitkovsky, Lamb)

✓ How does the frequency evolution fit in with modes?
Thoughts on Scattering Coronae

• Need $\frac{A_n}{A_1}$ to reduce $A_n / A_1$ to observed levels but this also reduces the fundamental significantly

• Harmonic ratios don’t change with photon energy band but different energy photons should undergo different number of scatterings