Long Type I X-Ray Bursts and Neutron Star Interior Physics

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Superbursts (SBs)
- A new regime of nuclear burning on accreting NSs
- 1000 x more energetic and duration of normal Type I X-ray bursts
- Otherwise look very similar, spectral softening during decay
- They directly affect the Type I bursting behavior

Initial interest - nuclear physics
- Carbon production in rp-process $\Rightarrow 10\% 1^2C$
- $\approx 90\%$ heavy

showed that such a mixture would ignite unstably to give a burst with roughly the right properties

showed that ignition is much more sensitive to the interior thermal properties

A new way to study NS interiors
Complementary to isolated cooling NSs and accreting NSs in quiescence
This talk

What are the ignition conditions for SBs?

What does that tell us about interior properties?

We find that to get ignition at the shallow depths inferred from SB properties, need to adjust parameters so that as much heat flux as possible comes out.

Any kind of efficient neutrino emission (eg. from neutron Cooper pairing in the crust) makes it difficult to reproduce observed ignition conditions.
Superburst Energetics

Observed energy is \( \approx 10^{42} \text{erg} \)

\[
\frac{10^{18} \text{erg/g}}{10^{18} \text{erg/g}} \Rightarrow 10^{24} \text{g of fuel}
\]

Recurrence time estimates 0.5 – 4 years
(Wijnands 2001; in’ t Zand 2003)

Accretion rates \( \frac{L_x}{GM/R} \approx (1-3) \times 10^{17} \text{g/s} \)

\( \approx (0.1-0.3) \dot{M}_{\text{Edd}} \)

\( \Rightarrow \Delta M = \dot{M} \Delta t \approx (0.2-3.6) \times 10^{25} \text{g} \)

Column depth \( y = \frac{\Delta M}{4\pi R^2} \approx (0.2-3.6) \times 10^{12} \text{g/cm}^2 \)

Energy release \( \frac{10^{42} \text{ergs}}{\Delta M} \approx (0.3-5.0) \times 10^{17} \text{erg/g} \)
Cooling models for SB light-curves

assume the fuel burns very rapidly

\[ \int C_p \, dT = E_{nu} \]

\[ T_i \approx (3-8) \times 10^8 \, K \quad T_f \approx 4 \times 10^9 K \sqrt{E_{17}} \]

then follow the cooling

\[ C_p \frac{dT}{dt} = -\frac{1}{\varepsilon} \nabla \cdot \mathbf{F} - \varepsilon \nu \]

\[ \mathbf{F} = -K \nabla T \]

Electrons + ions

\[ E_f \approx 3 \text{ MeV} \quad \rho \approx 10^8 - 10^9 \text{ g/cm}^3 \]

Neutrino cooling with e-ion

\[ \Gamma = \frac{Z^2 e^2}{a k_B T} \approx 70 \left( \frac{T_8}{5} \right)^{-1} \quad \text{(pairs)} \]

Scattering

Important for \( E_{17} \approx 2 \)

Radiative at peak \( T \)'s

Two parameters: energy release \( E_{17} \) \((10^{17} \text{ erg/g})\)

Ignition depth \( Y_{12} \) \((10^{12} \text{ g/cm}^2)\)

See also Eichler & Cheng (1989)
at late times

\[ F \propto t^{-4/3} \]
A simple model

Constant thermal conductivity

eg. a metal

\[ T(x,t) = \frac{\sinh \left( \frac{ax}{2D\tau} \right)}{\sqrt{\pi D\tau}} e^{\frac{-x^2+a^2}{4D\tau}} \]

flux at the surface \((x=0)\) is

\[ F \propto t^{-3/2} e^{\tau/t} \]

where \( \tau = \frac{4a^2}{D} \) thermal time

(1) DELTA FUNCTION

(2) TOP HAT

this time

\[ F \propto \left( \frac{\tau}{t} \right)^{1/2} \left[ 1 - e^{\tau/t} \right] \]
Neutrino “thermostat” sets characteristic energy of $10^{42}$ ergs

Cumming & Macbeth (2004)
Fits to SB lightcurves...

KS 1731-254 (BeppoSAX/WFC)

4U 1636-54 (RXTE/PCA)

$y_{12} = 1.3$

$y_{12} = 0.48$

AC, Macbeth, in 't Zand, Page (2005)
Fits to SB lightcurves

<table>
<thead>
<tr>
<th>Source</th>
<th>$f_{\text{peak}}^a$</th>
<th>$d/R^b$</th>
<th>$E_{17}^c$</th>
<th>$y_{12}^c$</th>
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<tr>
<td>4U 1254-690</td>
<td>0.22</td>
<td>13</td>
<td>1.5</td>
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<td>2.6</td>
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<td>KS 1731-260</td>
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<td>GX 17+2 burst 2</td>
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<td>8</td>
<td>1.8</td>
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<td>Ser X-1</td>
<td>1.9</td>
<td>6</td>
<td>2.3</td>
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<td>4U 1636-54</td>
<td>2.4</td>
<td>5.9</td>
<td>2.6</td>
<td>0.48</td>
</tr>
</tbody>
</table>

$E_{17}=2 \quad y_{12}=0.5-3$
Ignition Models

- steady state \[ \frac{dF}{dy} = -\varepsilon \quad \frac{dT}{dy} = \frac{F}{4\pi c T^3/3k} \]

- criterion for ignition \[ \frac{dE_{\text{heat}}}{dT} > \frac{dE_{\text{cool}}}{dT} \]

sets thickness of the fuel layer

- physics input
  - neutrino cooling in crust and core
  - crust composition 56Fe or 104Pd
    \[ Q = 100 \text{ or amorphous} \]
  - fixed core EOS \[ f(r) = f_c (1 - \left(\frac{r}{R}\right)^2) \]
  - energy deposition \[ Q_{\text{nuc}} = 1.4 \text{ MeV/nucleon} \]
<table>
<thead>
<tr>
<th>Label</th>
<th>Type(^a)</th>
<th>Prefactor(^b) (erg cm(^{-3}) s(^{-1}))</th>
<th>Comment</th>
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<tbody>
<tr>
<td>a</td>
<td>fast</td>
<td>(10^{26})</td>
<td>fast cooling</td>
</tr>
<tr>
<td>b</td>
<td>slow</td>
<td>(3 \times 10^{21})</td>
<td>enhanced</td>
</tr>
<tr>
<td>c</td>
<td>slow</td>
<td>(10^{20})</td>
<td>mURCA</td>
</tr>
<tr>
<td>d</td>
<td>slow</td>
<td>(10^{19})</td>
<td>nn Bremsstrahlung</td>
</tr>
<tr>
<td>e</td>
<td>slow</td>
<td>(10^{17})</td>
<td>suppressed</td>
</tr>
</tbody>
</table>

\(^a\)Fast and slow cooling laws are of the form \(Q_\nu = Q_f(T_c/10^9 \text{ K})^6\) and \(Q_\nu = Q_s(T_c/10^9 \text{ K})^8\) respectively.

\(^b\)Either \(Q_s\) or \(Q_f\) for slow or fast cooling, respectively.
1. CORE NEUTRINO EMISSIVITY

Cumming et al. (2005)
2. CRUST COMPOSITION

![Graph showing temperature vs. log column depth with various lines and markers indicating different compositions and states such as disordered, $^{104}\text{Pd}$, disordered, $^{56}\text{Fe}$, and Q=100, $^{56}\text{Fe}$. There is an observed range highlighted in green.](image-url)
3. COOPER PAIR NEUTRINOS IN CRUST

![Graph showing temperature vs. log column depth with observed range indicated.]

- **Temperature ($10^9$ K)**
- **Log Column Depth (g cm$^{-2}$)**

- **SF**
- **no SF**

- **Observed range**

The graph illustrates the relationship between temperature and column depth, highlighting the observed range and comparing scenarios with and without superfluidity (SF).
Limiting temperature of the crust from neutrino cooling

1. Bremsstrahlung

\[ Q_\nu \approx 0.3 \text{ erg/g/s} \ T_8^6 \ \mathcal{L} \ (1-Y_\nu) \frac{Z^2}{A} \]

\[ \Rightarrow \ L_\nu \approx 3 \times 10^{30} \text{ erg/s} \ T_8^6 \]

Set equal to the heating rate \( L_{\text{crust}} \approx 10^{36} \text{ erg/s} \left( \frac{\dot{m}}{\dot{m}_{\text{Edd}}} \right) \)

\[ \Rightarrow \ T_8 \approx 8 \left( \frac{\dot{m}}{\dot{m}_{\text{Edd}}} \right)^{\frac{1}{6}} \]

2. Cooper pairs

\[ Q_\nu \approx 7 \times 10^{20} \text{ erg/cm}^3/\text{s} \ T_8^7 \left( \frac{k_F}{\text{fm}^{-1}} \right) \]

\[ \Rightarrow \ L_\nu \approx 3 \times 10^{31} \text{ erg/s} \ T_8^7 \]

\[ \Rightarrow \ T_8 \approx 4.4 \left( \frac{\dot{m}}{\dot{m}_{\text{Edd}}} \right)^{\frac{1}{7}} \]
Pure Helium Accretion

Ultracompact binaries (orbital periods < 80 mins)

4U 1820-30  2S0918-549

ignition depth \( \approx 10^8 \text{ g/cm}^2 \)  \( \approx 10^{10} \text{ g/cm}^2 \)

\( \dot{M} \approx 0.3 \text{ M}_{\text{Edd}} \)  \( \approx 0.01 \text{ M}_{\text{Edd}} \)

in't Zand, AC, et al. (2005)  2S0918-549
long burst with duration 40 minutes
energy \( \approx 10^{41} \text{ ergs} \)

Ignition of pure He at a depth \( y \approx 10^{10} \text{ g/cm}^2 \) matches energetics and lightcurve
— but need most of the energy released in the crust to flow OUT!
Most sensitive to core physics

Most sensitive to crust physics
Summary

- Ignition conditions for both superbursts (\(^{12}\text{C}\)) and "intermediate duration" bursts (\(^{4}\text{He}\)) are sensitive to the thermal state of the NS interior.

- Lightcurves usefully constrain the ignition depth and energetics

- Cooper pairing of neutrons in the crust \(\Rightarrow T_{\text{crust}} \leq 5 \times 10^8 \text{ K}\)
  - gives SB ignition depths ten times larger than observed

- Solution — additional heating?
  - Strange star?

- Problem even worse for transients (we assumed steady state)