The role of the rp-process in accreting neutron stars

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Why are we interested in neutron stars in low mass X-ray binaries?

**astrophysics**
- what is the neutron star spin and magnetic field?
- how to make these binaries?
- fluids: dynamics of reactive flow, turbulent mixing, angular momentum transport…

**nuclear physics**
- rp-process burning at high temperatures and densities
- crust reactions
- nuclear equation of state above nuclear density
How can we probe the rp-process using observations? OR What effect does the rp-process have on observable properties of nuclear burning?

- **Energetics**
  - Global bursting behavior
    - recurrence times as function of accretion rate
    - transition to stable burning

- **Duration**
  - Burst lightcurves
    - long burst tails powered by rp-process burning

- **Ashes**
  - Superbursts
    - extremely energetic flashes that occur when the rp-process ashes reignite

- **Crust transport and mechanical properties**
Type I (Thermonuclear) X-ray bursts

thin shell flashes driven by unstable He burning

typical properties

recurrence times ~ hours to days
durations ~ 10 - 100 seconds
energies ~ $10^{39}$-$10^{40}$ ergs
spectral softening during the tail

energetics

$$\alpha \equiv \frac{\int L_{\text{accr}} dt}{E_{\text{burst}}} \approx \frac{GM/R}{E_{\text{nuc}}} \approx \frac{200 \text{ MeV per nucleon}}{(1 - 5) \text{ MeV per nucleon}}$$

History of a fluid element

- Atmosphere: accreted H/He
- Ocean: heavy elements + carbon
- Heavy elements
- Crust: electron captures, pycnonuclear reactions

Density:
- $\sim 10^5 \text{ g cm}^{-3}$
- $10^{-12} M_\odot$
- 5 m

Mass:
- $10^9 \text{ g cm}^{-3}$
- $10^{-8} M_\odot$
- 30 m

Mass:
- $10^{10} \text{ g cm}^{-3}$
- $10^{-6} M_\odot$
- 100 m
Burning regimes


\[
\dot{M} > 2.6 \times 10^{-8} \, M_\odot \, \text{yr}^{-1}
\]

\[
2.6 \times 10^{-8} > \dot{M}/(M_\odot \, \text{yr}^{-1}) > 10^{-9}
\]

\[
10^{-9} > \dot{M}/(M_\odot \, \text{yr}^{-1}) > 2 \times 10^{-10}
\]

\[
2 \times 10^{-10} \, M_\odot \, \text{yr}^{-1} > \dot{M}
\]
The Sn-Sb-Te cycle

SnSbTe cycle sets the endpoint (Schatz et al. 2001)

Sn-Sb-Te cycle

rp process:

\[ ^{41}\text{Sc} + p \rightarrow ^{42}\text{Ti} \]
\[ + p \rightarrow ^{43}\text{V} \]
\[ + p \rightarrow ^{44}\text{Cr} \]
\[ ^{44}\text{Cr} \rightarrow ^{44}\text{V} + e^+ + n_e \]

ap process:

\[ ^{14}\text{O} + a \rightarrow ^{17}\text{F} + p \]
\[ ^{17}\text{F} + p \rightarrow ^{18}\text{Ne} \]
\[ ^{18}\text{Ne} + a \rightarrow \cdots \]

3a reaction

\[ a + a + a \rightarrow ^{12}\text{C} \]

Wallace & Woosley (1981)
Schatz et al. (1998)
Effect of rp-process on burst lightcurves

one zone
Brown et al. (2002)
(see also Koike et al. 1999, Schatz et al. 2001)

multizone

Woosley, Heger et al. (2004)

Fisker & Thielemann (2004)
Multizone models of X-ray bursts


1D stellar evolution (e.g. prescription for convection)

+ adaptive nuclear network to follow rp-process in detail at each depth
The “textbook” burster: GS 1826-24

Cocchi et al. (2001)

Galloway et al. (2003)
Galloway et al. (2003)

\[ t_{\text{recur}} \propto \dot{M}^{-1.11} \]

...a variations indicate
\[ \sim \text{solar metallicity} \]
Galloway et al. (2004) long tails powered by hydrogen burning

Woosley et al. (2004)
Change in the burst lightcurves with accretion rate

Galloway et al. (2003, 2006)

Heger et al. (2007)
Spreading during the rise?

Kong et al. (2000)

calculation by Michael Zamfir
EXO 0748-676

Boirin et al. (2007)
EXO 0748-676

exponential decay times ~15, ~50 seconds

Boirin et al. (2007)
“normal”
Type I burst

E $\sim 10^{39}$ ergs
10 s

superburst

E $\sim 10^{42}$ ergs
10 hours
Some properties of superbursts

- they are **rare**
  - 13 superbursts from 9 sources
  - recurrence times ~ 1-2 years

- they are **long duration** and **energetic**
  - 1000 times “normal” Type I bursts
  - energies ~ $10^{42}$ ergs
  - exponential decay times 1-3 hours

- they “**interact**” with normal Type I bursts
  - they “quench” normal bursting for ~ 3 weeks
  - normal bursts are seen as “precursors”
Type I bursts

superburst

KS 1731-260  Kuulkers et al. (2002)

Ser X-1  Cornelisse et al. (2002)
Ashes from steady-state H/He burning

Schatz et al. (1999)
Carbon ignition in a heavy element ocean

Predict ignition at $\Delta M \sim 10^{25}\text{g}$

$\Rightarrow$ Energy $\sim 10^{42}\text{ergs}$

Heavy elements are important because they make the layer **opaque**

$\Rightarrow$ steeper temperature gradient

$\Rightarrow$ early ignition

Cumming & Bildsten (2001)
Ed Brown (2004) and Cooper & Narayan (2005) pointed out that constant outwards flux is not a good assumption, instead you should look at the entire T profile of the star.

A new way to study NS cooling!
Modelling superb burst lightcurves

- Fits to observed lightcurves

\[ y \approx 10^{12} \text{ g cm}^{-2} \]
\[ E \approx 2 \times 10^{17} \text{ erg g}^{-1} \]
\[ (X_C = 0.1 - 0.2) \]
Photodisintegration

\[ T_{\text{peak}} > 2.5 \times 10^9 \, \text{K} \]

Energetics
photodisintegration
~ 0.1 MeV/nucleon
carbon burning
~ 1 MeV/nucleon

Photodisintegration dominates for small \( X_c \)!

Carbon production in rp process burning

- protons rapidly capture on carbon (carbon “poison”)
  ⇒ make carbon after the hydrogen runs out
  ⇒ anti-correlation between $X_C$ and heavy element mass

- **stable burning needed** to make $> \text{few} \%$ $^{12}\text{C}$ by mass
  consistent with observed burst energetics in superburst sources!

BUT stable burning at accretion rates $\sim 0.1 \text{ Eddington}$ not understood!

Schatz, Bildsten, Cumming, Ouellette (2003)
Superbursts occur when (some) hydrogen/helium is burning stably

in ‘t Zand (2003)

<table>
<thead>
<tr>
<th>Object name</th>
<th>$T_c^{(a)}$</th>
<th>$\alpha^{(b)}$</th>
<th>$\alpha^{(c)}$</th>
<th>$\tau^{(d)}$ [s]</th>
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<tbody>
<tr>
<td>4U 1254-69</td>
<td>4.6</td>
<td>4800</td>
<td></td>
<td>6 ± 2 (15)</td>
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<tr>
<td>4U 1636-536</td>
<td>0.6</td>
<td>440</td>
<td>44–336$^{[1]}$</td>
<td>6.2 ± 0.1 (67)</td>
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<td>KS 1731-260$^{(c)}$</td>
<td>0.8</td>
<td>780</td>
<td>30–690$^{[2]}$</td>
<td>5.6 ± 0.2 (37)</td>
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<td>4U 1735-444</td>
<td>2.4</td>
<td>4400</td>
<td>220–7728$^{[3]}$</td>
<td>3.2 ± 0.3 (34)</td>
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<tr>
<td>GX 3+1</td>
<td>1.2</td>
<td>2100</td>
<td>1700–21000$^{[4]}$</td>
<td>4.6 ± 0.1 (61)</td>
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<td>4U 1820-303</td>
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<td>2200</td>
<td></td>
<td>4.5 ± 0.2 (47)</td>
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<td>Ser X-1</td>
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<td>5800</td>
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<td>5.7 ± 0.9 (7)</td>
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<td>EXO 0748-676</td>
<td>1.0</td>
<td>140</td>
<td>18-34$^{[5]}$</td>
<td>12.8 ± 0.4 (155)</td>
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<td>4U 1702-429</td>
<td>0.3</td>
<td>58</td>
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<td>7.7 ± 0.2 (107)</td>
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<tr>
<td>4U 1705-44</td>
<td>1.1</td>
<td>1600</td>
<td>55–1455$^{[6]}$</td>
<td>8.7 ± 0.4 (74)</td>
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<td>GX 354–0</td>
<td>0.2</td>
<td>97</td>
<td>105–140$^{[7]}$</td>
<td>4.7 ± 0.1 (417)</td>
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<tr>
<td>A 1742-294</td>
<td>0.4</td>
<td>130</td>
<td></td>
<td>16.8 ± 1.0 (141)</td>
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<tr>
<td>GS 1826-24</td>
<td>0.2</td>
<td>32</td>
<td>41$^{[8]}$</td>
<td>30.8 ± 1.5 (248)</td>
</tr>
</tbody>
</table>
Carbon production in steady burning

Schatz et al. (2007)
Carbon production in steady burning

Schatz et al. (2007)
Summary

• **lightcurves:** need to systematically explore the dependence of multizone model lightcurves on input rp-process data

• **superbursts:** how is the carbon made? how to make the crust hot enough?

• **other questions:** transition to stable burning, mHz qpos, transport of rp-process elements to the photosphere (and beyond...?)
  - are the “ten minute” bursts coming from nuclear physics?