Thermonuclear X-ray bursts and the rp-process

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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
- nuclear equation of state above nuclear density
History of a fluid element

- atmosphere
  - accreted H/He
- ocean
  - heavy elements + carbon
- heavy elements
- crust

Properties:

- density
- mass
- depth

Values:

- $\sim 10^5 \text{ g cm}^{-3}$
- $10^{-12} M_\odot$
- 5 m
- $\sim 10^9 \text{ g cm}^{-3}$
- $10^{-8} M_\odot$
- 30 m
- $\sim 10^{10} \text{ g cm}^{-3}$
- $10^{-6} M_\odot$
- 100 m
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

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

hydrostatic balance

\[ P = \frac{GM \Delta M}{R^2 \ 4\pi R^2} \]

entropy

\[ c_P \frac{\partial T}{\partial t} = \varepsilon - \varepsilon_v - \frac{1}{\rho} \frac{\partial F}{\partial r} \]

heat flux

\[ F = F_C - \frac{4acT^3 \partial T}{\kappa \rho} \frac{\partial r}{dr} \]
The Sn-Sb-Te cycle
 sets the endpoint
 (Schatz et al. 2001)

rp process:
$^{41}\text{Sc} + p \rightarrow ^{42}\text{Ti}$
$+ p \rightarrow ^{43}\text{V}$
$+ p \rightarrow ^{44}\text{Cr}$

$^{44}\text{Cr} \rightarrow ^{44}\text{V} + e^+ + \nu_e$

$^{44}\text{V} + p$ ...

Wallace & Woosley (1981)
Schatz et al. (1998)

$^{3\alpha}$ reaction
$\alpha + \alpha + \alpha \rightarrow ^{12}\text{C}$
Nuclear data needs:
- Masses (proton separation energies)
- β-decay rates
- Reaction rates (p-capture and α,p)

Some recent mass measurements
β-endpoint at ISOLDE and ANL
Ion trap (ISOLTRAP)

Separation energies
Experimentally known up to here

Many lifetime measurements at
radioactive beam facilities
(for example at LBL,GANIL, GSI, ISOLDE, MSU, ORNL)
- Know all β-decay rates (earth)
- Location of drip line known (odd Z)

Indirect information about rates
from radioactive and stable beam experiments
(Transfer reactions, Coulomb breakup, …)

Direct reaction rate measurements
with radioactive beams have begun
(for example at ANL, LLN, ORNL, ISAC)

slide from H. Schatz
Recent mass measurements of rp-process waiting point nuclei

$^{72}$Kr; Rodriguez et al. (2004)
ISOLTRAP/ISOLDE

$^{68}$Se; Clark et al. (2004)
CPT/ATLAS

$^{74}$Sr $\beta$ $^{73}$Rb $\beta$ $^{72}$Kr $T_{1/2}=17.2\text{s}$

$^{72}$Kr($p,\gamma$) rate $(x1,5,100,10^4)$
How can we probe the rp-process using observations? OR What effect does the rp-process have on observable properties of nuclear burning?

- **Energetics**
- **Duration**
- **Ashes**

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

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

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

**Crust transport and mechanical properties**
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

Galloway et al. (2003)

Cocchi et al. (2001)
Galloway et al. (2003)

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

\( \alpha \) variations indicate
\( \sim \) solar metallicity
Galloway et al. (2004)

long tails powered by hydrogen burning

Woosley et al. (2004)
“normal”
Type I burst

\[ E \sim 10^{39} \text{ ergs} \]

superburst

\[ E \sim 10^{42} \text{ ergs} \]

10 s

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”
KS 1731-260   Kuulkers et al. (2002)

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

A flammable mixture!

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

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

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

Heavy elements are important because they make the layer opaque

$\Rightarrow$ steeper temperature gradient

$\Rightarrow$ early ignition

Cumming & Bildsten (2001)
Ed Brown (2004) 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!**

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[Graph showing temperature vs. log column depth with various curves labeled mURCA, mURCA/10, mURCA/1000, and observed range.]

*Cumming et al. (2005)*
Neutrino Cooling

1. direct URCA
   \[ n \rightarrow p + e^- + \bar{\nu} \]
   \[ p + e^- \rightarrow n + \nu \]

2. modified URCA
   \[ n + n \rightarrow p + e^- + \bar{\nu} \]
   \[ p + e^- \rightarrow n + \nu + n \]
   spectator particle
   suppressed by \( \sim (kT/E_F)^2 \sim 10^{-6} \) at \(10^9\)K

3. superfluidity suppresses neutrino emission
   suppressed by \( \sim \exp(-T_C/T) \)

but 4. Cooper pair emission for \( T \sim T_C \)
EFFECT OF COOPER PAIR NEUTRINOS IN CRUST

AC, Macbeth, in 't Zand, Page (2005)
nuclear heating
Superbursts: current state of ignition models

- upper limits 1-2 months limited by BeppoSAX total exposure
- planned Brazilian mission MIRAX will do much better (continuous exposure of GC for ~ 2 yrs)

Keek, in 't Zand, & Cumming (2005)

models with Cooper pair cooling in the crust are too cold... extra heating?
Superbursts from strange stars

Strange stars have no inner crust => no Cooper pair neutrinos!

Alcock, Farhi, & Olinto 1986

Page & Cumming 2005
Modelling superburst 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
  > few % $^{12}$C by mass

consistent with observed burst energetics in superburst sources!

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

Schatz, Bildsten, Cumming, Ouellette (2003)
• 7-9 mHz oscillations in the persistent flux

• mostly in soft photons

• only observed when $L_X$ is in a narrow range near $10^{37}$ erg/s
van der Pol oscillator
One zone model

energy

\[ c_p \frac{dT}{dt} = \epsilon - \frac{F}{y} \]

composition

\[ \frac{dy}{dt} = \dot{m} - \frac{\epsilon}{E_*} y \]

linear perturbations =>

\[
\frac{\partial^2 f}{\partial t^2} + \left( \frac{4 - \alpha}{t_{\text{therm}}} - \frac{1}{t_{\text{accr}}} \right) \frac{\partial f}{\partial t} + \frac{2\alpha}{t_{\text{accr}} t_{\text{therm}}} f = 0
\]

oscillation period = (thermal time x accretion time)\(^{1/2}\)~100 s
Heger, AC, & Woosley 2005
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?

- **mHz QPOs**: just beginning to explore this.. how does the frequency depend on nuclear physics input?

- **other questions**: transport of rp-process elements to the photosphere (and beyond…?) are the “ten minute” bursts coming from nuclear physics?
Summary

• several new observational phenomena involving nuclear burning on accreting neutron stars have been discovered in recent years
  (burst tails, mHz QPOs, superbursts)

• they are promising new probes of spin, magnetism, neutron star interior, dynamics of burning fronts…

• to understand them we need to understand the details of the rp-process (masses, lifetimes, reaction rates)