In this talk

- Overview of accreting neutron stars
- Building the crust from the ashes of X-ray bursts
- The effect on “surface” phenomena
Low-mass X-ray binaries (LMXBs)

- Neutron star primary with ≈ solar mass companion in short (< 1 day orbit)
- Mass transfer through Lagrange point
- Drop 1 H atom onto neutron star, receive

\[ E \approx \frac{GMm_H}{R} \approx 200 \text{ MeV} \]
Crust structure

Crust: region where density $< \text{nuclear saturation}$

$\rho < 2 \times 10^{14} \text{ g cm}^{-3}$

$M_{\text{NS}} = 1.6 \, M_{\text{sun}}$
Mass transfer cycle of a LMXB

- Parameters giving a final configuration matching PSR1855+09
  - $\langle \dot{M} \rangle = 5 \times 10^{-10} \, M_\odot \, \text{yr}^{-1}$
  - The mass-transfer (LMXB) phase lasts for 0.4 Gyr
  - The neutron star accumulates $\approx 0.2$ solar masses
  - Most LMXBs should have replaced the original crust

![Diagram showing the mass transfer cycle of a LMXB](image)
Journey of an accreted fluid element

Envelope: accreted H, He

Outer crust: nuclei, e

Inner crust: nuclei, n, e

Outer core: npe

Inner core: ?

\[ Q \approx 1 \text{ MeV}/m_u \]

rp-process
C ignition

e capture

pycnocarbon

C ignition

rp-process
Products of X-ray bursts

![Graphs showing abundance vs. mass number for X-ray bursts and steady-state burning.](image-url)
Journey of an accreted fluid element

Envelope: accreted H, He

Outer crust: nuclei, e

Inner crust: nuclei, n, e

$Q \approx 1 \text{ MeV}/m_u$

Inner core: ?

Outer core: npe

rp-process

C ignition

e capture

pycnuclear

C ignition

rp-process

Inner core: ?

Inner crust: nuclei, n, e

Outer crust: nuclei, e

Envelope: accreted H, He
Crust structure

Crust: region where density < nuclear saturation
$\rho < 2 \times 10^{14} \text{ g cm}^{-3}$

$M_{NS} = 1.6 \ M_{\text{sun}}$
Path to neutron drip

\[ \log_{10}(y) \]

\[ \log_{10}(\rho) \]

\[ \bar{h} \omega_{p,e} \]

\[ \mu_e \text{ (MeV)} \]

\[ \log_{10}(y) \]

\[ \log_{10}(\rho) \]

\[ \bar{h} \omega_{p,e} \]

0 5 10 15 20
Fig. 2. Heat per one accreted nucleon, deposited in the crust, for two models with different initial $A$. Solid vertical lines (ended with circles): $A_i = 106$; dotted lines (ended with crosses): $A_i = 56$. Vertical lines are positioned at the densities at the bottom of the reaction shell.

$(e,\nu)$

$(e,n)$

$^{(A}Z + ^{(A}Z \rightarrow ^{(2A)}(2Z)$

Coupled thermal structure code with reaction network
- Include strength distribution for excited states (Möller)
- Analytical approximation to phase space integration (Gupta)
- Starts from distribution of rp-process nuclei (Schatz et al., *PRL*)
Composition set by rising Fermi energy

Consider the symmetry term in the mass fmla.,

\[ \frac{E}{A} = \ldots + E_s \left( \frac{N-Z}{N+Z} \right)^2 = \ldots + E_s (1-2Y_e)^2. \]

The electron Gibbs energy, per nucleon is

\[ \frac{1}{n_b} (E + PV) = Y_e \mu_e \]

and minimizing the total energy with respect to \( Y_e \) gives

\[ Y_e \approx \frac{1}{2} - \frac{\mu_e}{8E_s} . \]

NB. This fmla. also follows from \( \mu_e = \mu_n - \mu_p \)
With Coulomb term included

\[ \langle A \rangle = \begin{cases} 30 & A = 30 \\ 60 & A = 60 \\ 90 & A = 90 \end{cases} \]

\[ \langle Z \rangle = \begin{cases} 10 & \mu_e \text{ (MeV)} \\ 20 & \mu_e \text{ (MeV)} \\ 30 & \mu_e \text{ (MeV)} \end{cases} \]
\[ E_{\text{thr,gs-gs}}^{Z} + E_{\text{exc}} = E_{\text{thr,gs-gs}}^{Z-1} \]
With captures into excited states

Approximate model—ignore rates, capture into lowest state with significant strength

HZ 2003

Network

$Q$ (keV/u)

$\mu_e$ (MeV)
Nuclear Structure Effects
Composition matters!
The heating sets

- the quiescent luminosity of transients (previous talks)
- ignition depth of superbursts (Brown, Cooper & Narayan, Cumming et al.)
- X-ray bursts at low accretion rates (Cumming et al., Peng et al.)

The composition sets

- transport properties
Can this heating be observed?

For steady accretors, no
\[ E_{\text{grav}} \sim 200 \text{ MeV/nucleon} \]
\[ Q_{\text{nuc}} \sim 1 \text{ MeV/nucleon} \]

But many sources accrete transiently—observe heated crust in quiescence (Brown, Bildsten & Rutledge 1998)

Plot from Rutledge et al. 2001

Cen X-4: Chandra ACIS-S/BI, June 23 2000
from Heinke et al. 2007, following Yakovlev et al. 2004

\[ T_{\text{core}} \approx 2 \times 10^8 K \left( \frac{\langle \dot{M} \rangle}{10^{-10} M_\odot \text{yr}^{-1}} \right)^{1/8} \]

"slow" neutrino emissivity

\[ T_{\text{core}} \approx 2 \times 10^7 K \left( \frac{\langle \dot{M} \rangle}{10^{-10} M_\odot \text{yr}^{-1}} \right)^{1/6} \]

"fast" neutrino emissivity

\[ L_A = Q \langle \dot{M} \rangle \]

Standard cooling

\[ \log L_{NS} \text{ (erg s}^{-1}) \]

\[ \log \dot{M} \text{ (} M_\odot \text{ yr}^{-1}) \]
Superburst profiles in ‘t Zand et al. 2003
Variation of crust temperature

\[ \dot{M} \approx 0.3 \dot{M}_{\text{Edd}} \]

Gupta, Brown, Schatz, Möller, & Kratz 2007
Ignition columns

Gupta, Brown, Schatz, Möller, & Kratz 2007
Ignition at very low accretion rates

\[ \frac{\dot{m}}{\dot{m}_{\text{Edd}}} = 5.7 \times 10^{-3}, \, 0.011 \]
Composition at base of accreted layer

$\dot{m} = 5.7 \times 10^{-3} \dot{m}_{\text{Edd}}$

diffusion off
Composition at base of accreted layer

\[ \dot{m} = 5.7 \times 10^{-3} \dot{m}_{\text{Edd}} \]

\[ \frac{\dot{m}}{X/X(t=0)} \]
Simulations find weak flashes!

$L_{\text{acc}} = 0.002 L_{\text{Edd}}$

Multi-zone simulation by Alexander Heger
He flashes at large depth

- Repeated flashes build up massive He layer
- Eventually $3\alpha$ ignites, produces more energetic burst
- Ignition depth sensitive to heat flux from reactions in crust
  (Brown 2004, Cooper & Narayan 2005, Cumming et al. 2006)

Summary

- Deep crustal heating
  - In the outer crust, nuclear structure & composition matters!
  - Amount of outer crust heating affects ignition of superbursts, long X-ray bursts (Cumming et al. 2006, Peng et al. 2007)
- Pay attention to all phenomena