Nuclear reactions in neutron star crusts
Implications for superbursts and cooling transients

Edward Brown

- “Possible Resonances in the $^{12}$C + $^{12}$C Fusion Rate and Superburst Ignition,” Cooper, Steiner, & Brown 2009, Astrophys. Jour. 702: 660
Approximately a solar mass star

$P_{\text{orb}} = \text{minutes–hours}$

Each accreted H releases

$\approx \frac{GMm_H}{R} \approx 200 \text{ MeV.}$

Fusing H to He releases

$\approx 7 \text{ MeV}$

per nucleon.
n, p, e\(^{-}\), \(\mu\)

\(\Lambda, \Sigma, K, \pi?\)

uds?
rp-process (hours–days)

unstable $^{12}\text{C} + ^{12}\text{C}$ (years)

deep crust electron captures, pycnonuclear reactions (centuries–millenia)
crust reactions important for...

magnetic field evolution
(from Brown & Bildsten 98)

\[ \dot{m} = 5 \dot{m}_{\text{Edd}} \]

\[ \tau_{\text{gr}}, t_{\text{n}} \]

quiescent thermal emission
from transients

ignition depth of long X-ray bursts
(from Kuulkers '01)

\[ \dot{m} = 1 \dot{m}_{\text{Edd}} \]

\[ \tau_{\text{gr}}, t_{\text{n}} \]

\[ \dot{m} = 0.5 \dot{m}_{\text{Edd}} \]

\[ \tau_{\text{gr}}, t_{\text{n}} \]

crust mountains
(plot from Ushomirsky et al. '00)

Ocean

\[ \Delta z_i \]

\[ (A_1, Z_1), X_{n1} \]

\[ (A_2, Z_2), X_{n2} \]

Core
Rapid Burster
66 bursts (cont.)
62 shown

KS 1731–260
26 bursts

SLX 1735–269
1 burst

4U 1735–44
11 bursts

A sample of 1187 X-ray bursts from 48 sources
neutronization

Sato, Haensel & Zdunik, Gupta et al.

\[ E \approx -a_V(N + Z) + a_A \frac{(N - Z)^2}{N + Z} \]

In \( \beta \)-equilibrium, \( \mu_e = \mu_n - \mu_p \), with

\[ \mu_n = \left( \frac{\partial E}{\partial N} \right)_Z, \quad \mu_p = \left( \frac{\partial E}{\partial Z} \right)_N. \]

\[ \frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A} \]
connection to mechanical structure

In the outer crust, $\mu_e$ sets the pressure,

$$p \approx \frac{1}{4} n_e \mu_e = \frac{\mu_e^4}{12\pi^2 (hc)^3}$$

and the density is

$$\rho \approx \frac{m_u}{3\pi^2} \left( \frac{\mu_e}{hc} \right)^3.$$

In a planar geometry, a useful coordinate is the column,

$$y \equiv \int \rho \, dz \approx \frac{P}{g}.$$
neutronization
Sato, Haensel & Zdunik, Gupta et al.

\[ E \approx -a_V (N + Z) + a_A \frac{(N - Z)^2}{N + Z} \]

In \( \beta \)-equilibrium, \( \mu_e = \mu_n - \mu_p \), with

\[ \mu_n = \left( \frac{\partial E}{\partial N} \right)_Z, \quad \mu_p = \left( \frac{\partial E}{\partial Z} \right)_N. \]

\[ \frac{Z}{A} \approx \frac{1}{2} - \frac{\mu_e}{8a_A} \]
neutron drip; pycnonuclear reactions
Sato, Haensel & Zdunik, Gupta et al.

\[ E \approx -\alpha_V (N + Z) + \alpha_A \frac{(N - Z)^2}{N + Z} \]

At neutron drip,

\[ \mu_n = \left( \frac{\partial E}{\partial N} \right)_{Z} \rightarrow 0 \]

\[ \mu_e \approx 2\alpha_V \approx 30 \text{ MeV} \]
$E_{\text{Fermi}} = 0.4 \text{ MeV}$

$Y_e = 0.45$
$E_{\text{Fermi}} = 21.0$ MeV

$Y_e = 0.34$
electron capture reactions, outer crust

Each electron capture has density change: mountains made by variations in composition

(Bildsten 98, Ushomirsky et al. 00)

Gupta et al. ‘07
deep crustal heating
Sato; Haensel & Zdunik; Gupta et al.
Heating from electron captures

For a liquid-drop model,

\[ W = a_V + a_S A^{-1/3} + a_A (1 - 2Y_e)^2 + a_C \frac{Z^2}{A^{4/3}} + a_P \frac{\delta}{A^{1/2}}. \]

The heating is mainly set by the odd-even staggering of masses: per capture pair, the heating per nucleon is

\[ 4a_P A^{-3/2} \]

and there are \( A \Delta Y_e / 2 \) pairs of electron captures, giving

\[ Q_{\text{max}} \approx \frac{a_P \mu_e}{4a_A A^{1/2}} \approx 0.35 \text{ MeV} \left( \frac{\mu_e}{20 \text{ MeV}} \right) \left( \frac{60}{A} \right)^{1/2}. \]
between of dance. In contrast, the OCP essentially does not evolve expands to \[ E \] concentrated along a single \[ E \] event-even nuclei is the same as in the OCP calculation of wards. The product undergoes up to (EC, emissions. The OCP trajectories of \[ 28 \text{MeV} \] for an MCP calculation starting with pure reactions begin to cycle material out of the PRL at \[ 101 \], \[ 95 \], \[ 98 \], \[ 101 \] Wednesday, January 27, 2010.

Electron Chemical Potential

Distribution of \( N \) and \( Z \)

Heat deposited per accreted nucleon

\[ \text{no } \nu \text{ losses} \]
\[ \text{maximal } \nu \text{ losses} \]
\[ Z_{\text{min}}=4 \]

Integrated heat / baryon [MeV]

\[ \log(\rho) \text{ [g cm}^{-3}\text{]} \]

Gupta et al. ‘08, Haensel & Zdunik ’08
• *RXTE* monitoring observations discovered *quasi-persistent* transients

• Rutledge et al. ‘02 suggested looking for thermal relaxation of crust during quiescence

• observations (Wijnands, Cackett) detect this cooling
Quasi-persistent sources discovered

accrete for several years, then
accretion “turns off”

look for thermal relaxation of crust in
*quiescence*

MXB 1659-29, KS 1731-260;
Cackett et al. ‘06, ’08

fits from Brown & Cumming ’09;
cf. Shternin et al. ‘07
crust models

solve thermal evolution equation on fixed hydrostatic grid

\[
\frac{\partial}{\partial t} \left( T \epsilon_c^2 \right) = e^{2 \epsilon_c^2} C \left( \epsilon_{\text{nuc}} - \epsilon_v \right) - \frac{1}{4\pi r^2 \rho(1+z)} \frac{\partial}{\partial r} \left( L e^{2 \epsilon_c^2} \right),
\]

\[ L e^{2 \epsilon_c^2} = -\frac{4\pi r^2 K e^{2 \epsilon_c^2}}{1+z} \frac{\partial}{\partial r} \left( T e^{2 \epsilon_c^2} \right), \]

\[ Q_{\text{imp}} \equiv n_{\text{ion}}^{-1} \sum_i n_i (Z_i - \langle Z \rangle)^2 \]

\[ K = \frac{\pi^2 n_e k_B^2 T}{3 m_e^* \nu}, \]

\[ \nu_e Q = \frac{4\pi Q_{\text{imp}} e^4 n_{\text{ion}}}{p_F^2 v_F} \Lambda_{\text{imp}}, \]
Core temperature during outburst, recurrence cycle (1H1905)

\[ \langle \dot{M} \rangle = 6 \times 10^{-11} \, M_\odot \, \text{yr}^{-1} \]

\[ \langle \dot{M} \rangle = 10^{-12} \, M_\odot \, \text{yr}^{-1} \]
Lightcurve from cooling crust

Brown & Cumming ‘09
basic physics of the lightcurve

For a cooling crust,

$$\rho C_P \frac{\partial T}{\partial t} = \frac{\partial}{\partial r} \left( K \frac{\partial T}{\partial r} \right),$$

and a cooling front propagates into crust on a timescale

$$\tau \approx \frac{1}{4} \left[ \int \left( \frac{\rho C_P}{K} \right)^{1/2} dr \right]^2.$$

$$\tau \propto \left( \frac{R^2}{GM} \right)^2 \left( 1 - \frac{2GM}{Re^2} \right)^{1/2}.$$
\[ \tau \approx \frac{1}{4} \left[ \int \left( \frac{\rho C_P}{K} \right)^{1/2} \, dr \right]^2. \]

\[ C_P \sim \left( \frac{T}{T_D} \right)^3. \]
heat flux in outer crust
≈0.5 MeV/u•dM/dt
from density < 3•10^{10} g/cm^{-3}

thermal diffusivity in
inner crust: \( K, C_P, \Delta r \)

\[
\frac{d \ln T_{\text{eff}}^\infty}{d \ln t} \approx 0.03 \left( \frac{F}{10^{21} \text{ ergs s}^{-1} \text{ cm}^{-2}} \right),
\]

\( T_{\text{core}} \)
Mapping $T_{\text{eff}}$ to $T_{\text{core}}$

Gudmundsson et al., Potekhin et al., Brown et al.
heat flux in outer crust 
\( \approx 0.5 \text{ MeV/u} \cdot \text{dM/dt} \)
from density \(< 3 \cdot 10^{10} \text{ g/cm}^3\)

thermal diffusivity in inner crust: \( K, C_P, \Delta r \)

\[
\frac{\text{d} \ln T_\text{eff}^\infty}{\text{d} \ln t} = \left( \frac{\text{d} \ln T_\text{eff}^\infty}{\text{d} \ln T} \right) \left( \frac{\text{d} \ln T}{\text{d} \ln y} \right) \left( \frac{\text{d} \ln y}{\text{d} \ln \tau} \right) \\
\approx 0.03 \left( \frac{F}{10^{21} \text{ ergs s}^{-1} \text{ cm}^{-2}} \right),
\]

\( T_{\text{core}} \)
How impure is the crust?

\[ \frac{\partial T}{\partial t} = D \frac{\partial^2 T}{\partial x^2}, \]

\[ D \propto \nu (n\sigma)^{-1} \]

\[ \sigma \propto \langle (Z - \langle Z \rangle)^2 \rangle \]

for this mixture, \( \langle (Z - \langle Z \rangle)^2 \rangle \approx 100 \)
constraints on $Q_{\text{imp}}$

- explore with Markov Chain Monte Carlo
- $Q_{\text{imp}} < 10$
- agrees with Shternin et al.
- fit degenerate with surface gravity, accretion rate
  - crust thickness (Lattimer et al. '94)

$$\tau \propto \left( \frac{R^2}{GM} \right)^2 \left( 1 - \frac{2GM}{Rc^2} \right)^{1/2}$$
crust impurities

rp-process ashes: $Q_{imp} \approx 23$ (Horowitz & Berry 2009)

$\langle Z^2 \rangle - \langle Z \rangle^2 = 10$

pure lattice

Observations
- $Q = 0, T_{b,8} = 3.8$
- $Q = 1, T_{b,8} = 3.8$
- $Q = 4, T_{b,8} = 3.8$
- $Q = 10, T_{b,8} = 3.8$

Observations
- $Q = 0, T_{b,8} = 4.5$
- $Q = 1, T_{b,8} = 4.2$
- $Q = 4, T_{b,8} = 3.8$
- $Q = 10, T_{b,8} = 3.5$
heat flux in outer crust
$\approx 0.5 \text{ MeV/u}\cdot\text{dM/dt}$
from density $< 3\cdot10^{10} \text{ g/cm}^3$

thermal diffusivity in inner crust: $K, C_P, \Delta r$

$\frac{d\ln T_\text{eff}^\infty}{d\ln t} = \left( \frac{d\ln T_\text{eff}^\infty}{d\ln T} \right) \left( \frac{d\ln T}{d\ln y} \right) \left( \frac{d\ln y}{d\ln \tau} \right)$

$\approx 0.03 \left( \frac{F}{10^{21} \text{ ergs s}^{-1} \text{ cm}^{-2}} \right)$,

$T_{\text{core}}$
\[ T_b = 3.8 \times 10^8 \text{ K}, \dot{M} = 10^{17} \text{ g s}^{-1}, Q_{\text{imp}} = 4 \]

\[ \dot{M} = 5 \times 10^{17} \text{ g s}^{-1}, Q_{\text{imp}} = 1 \]

\[ \dot{M} = 9 \times 10^{17} \text{ g s}^{-1}, Q_{\text{imp}} = 0 \]

Cackett et al. (2008) **MXB1659 data**
Fig. 5.— Effective neutron star surface temperature as a function of time with best-fit cooling curves shown. The solid and short-dashed curves are broken power laws fitted to data points 1–5 plus 8–12, and data points 1–5, respectively. The gray long-dashed curve is the best-fit exponential decay curve with a constant offset—also shown in Fig. 4).

XTE J1701-462

Fridriksson et al., submitted to ApJ

slope ≈ 0.03; similar to MXB 1659

spectrally “hard” flare: accretion spurt?

break at ~ 50 d, but large uncertainty in fit
KS 1731–260 superburst
Kuulkers 2002

Superbursts are ≈1000 times more energetic, longer-lasting, and infrequent than regular X-ray bursts.
superburst ignition

- $^{12}\text{C}$ likely cause of superbursts (Cumming & Bildsten 01, Strohmayer & Brown 02)
- Hot crust required to match inferred ignition depth (Brown 04; Cooper & Narayan 05; Cumming et al. 06)
- This is at odds with measurements of surface temperature during quiescence, when accretion turns off!

![Graph showing temperature vs. log column depth with annotations and labels.](Image)

*Inferred ignition depth from cooling timescale*

*Plot from Cumming et al. 06*
shallow crustal heating?

Implications for superburst ignition (unstable $^{12}$C fusion)?

$\frac{0.5 \text{ MeV/u \cdot (dM/dt)}}{\text{at } y = 10^{12} \text{ g cm}^{-2}}$
\[ ^{12}\text{C} + ^{12}\text{C} \]

Cooper, Steiner, & Brown 2009

- Electron captures: at \( E_{\text{Fermi}} < 6 \) MeV, captures are thermally stable
- Light element reactions (e.g., \( ^4\text{He} + ^{12}\text{C} \)): nuclides with \( Z < 6 \) are depleted at too shallow a depth; \( Z > 6 \) are depleted at too great a depth
- Screening: corrections to lowest order (linear mixing) expression are small in this regime
12C + 12C cross-section

12C + 12C → \{ 23\text{Mg} + n, \quad Q = -2.59 \text{ MeV} \\
23\text{Na} + p, \quad Q = 2.24 \text{ MeV} \\
20\text{Ne} + \alpha, \quad Q = 4.62 \text{ MeV} \}

Resonances predicted below 2 MeV (Perez-Torres et al. ’06)

Cooper, Steiner, & Brown 2009

\[ T_{\text{ign}} (\text{GK}) \]

- CF88
- \((\omega \gamma)_R = 3.4 \times 10^{-8} \text{ eV}\)
- \((\omega \gamma)_R = 3.4 \times 10^{-7} \text{ eV}\)

\[ \Gamma_R < 100 \text{ keV} \]
\[ S_R < S_{\text{exp}}, \text{ for } E > 2.1 \text{ MeV} \]

Typical superburst ignition depth

\[ P/g \ (\text{g cm}^{-2}) \]

\[ 10^{11} \quad 10^{12} \quad 10^{13} \]

Wednesday, January 27, 2010
implications for other astrophysical sites

massive star evolution; affects production of $^{60}\text{Fe}$ and $^{26}\text{Al}$ (Gasques et al. '07)

ignition of type Ia supernovae

\[ \rho (\text{g cm}^{-3}) \]

\[ T_{\text{ign}} (10^8 \text{ K}) \]

- CF88
- \( E_R = 1.5 \text{ MeV}, (\omega\gamma)_R = 3.4 \times 10^{-8} \text{ eV} \)
- \( E_R = 1.5 \text{ MeV}, (\omega\gamma)_R = 3.4 \times 10^{-7} \text{ eV} \)
summary

- two ways of constraining internal temperature
- cooling of quiescent transients (high thermal conductivity, cool crust)
- superbursts (hot crust or enhanced $^{12}\text{C} + ^{12}\text{C}$ cross-section)
- nuclear physics input crucial
  - $^{12}\text{C} + ^{12}\text{C}$ at $E \sim 1.5$ MeV
  - reaction kinetics of neutron drip, inner crust
  - EOS (symmetry energy)
Astrophysical Transients: Multi-messenger Probes of Nuclear Physics

Institute for Nuclear Theory (INT-11-2b)

July 11–August 5, 2011

Organizers

Sanjay Reddy
Chris Fryer
Bennet Link
Ed Brown