Deep Crustal Heating in Accreting Neutron Stars

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INT Seattle
July 11th, 2007

Introduction - 1

Older work:

- Non-catalyzed matter ($T < 10^9$ K) slowly compressed under the weight of accreted outer layer $\Longrightarrow$ non-equilibrium reactions $\Longrightarrow$ changing composition, heating (Vartanyan & Ovakimova 1976, Bisnovatyi-Kogan & Chechetkin 1979, Sato 1979, Haensel & Zdunik 1990a,b)
- Total crustal heating is ~ 1.5 MeV per one accreted nucleon, mostly deposited at $\rho \sim 10^{12} - 10^{13}$ g cm^{-3} (Haensel & Zdunik 1990b, Haensel & Zdunik 2003). Crucial rôle of pycnonuclear reactions.
- Soft X-ray transients: crustal heating necessary to explain thermal radiation in quiescence (Brown, Bildsten & Rutledge 1998)

Introduction - 2

Recent work:

- pycnonuclear processes - might be so slow that they have no sufficient time to proceed at $\sim 10^{12}\ g\ cm^{-3}$ (Yakovlev, Gasques, Wiescher 2006)
- electron captures proceed to excited states of daughter nuclei, which de-excite and heat the matter $\Longrightarrow$ non-equilibrium neutrino losses are negligible (Gupta et al. 2006)
- non-steady stage (initial cooling) detected after a long accretion period (Cackett et al. 2006)

Plan

- Basic processes leading to crustal heating
- Dependence on the initial nuclear ashes
- The rôle of excited nuclear states and neutrino losses
- Dependence on pycnonuclear fusion: remarkable constancy of total Q
- Initial cooling in quasi persistent X-ray transients

Soft X-Ray Transients - 1

Soft X-ray Transients (SXTs) - a sub-group of Low Mass X-Ray Binaries (LMXB) $=$ NS $+$ low mass companion filling its Roche lobe

Standard picture:

Quiescent state

$t_{\rm q} \sim years - decades$ of negligible accretion - $L_X < 10^{34}\ erg\ s^{-1}$

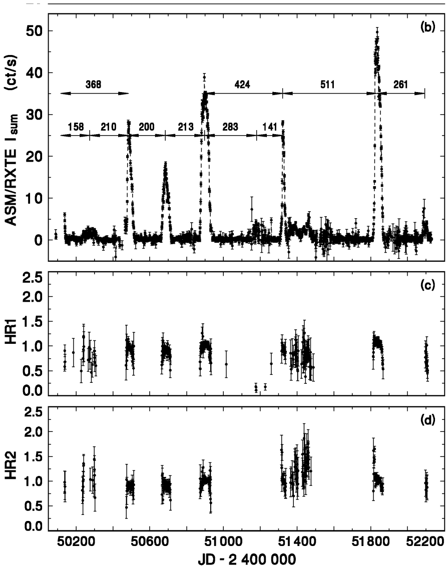
Active state - outburst

$t_{\rm a} \sim weeks - months$ - strong accretion - $L_X \sim 10^{36} - 10^{39}\ erg\ s^{-1}$

Soft X-Ray Transients - 2

Quasi-periodic heating $t_{\rm a} \ll t_{\rm q}$ - after a few thousands of cycles a steady thermal state is reached for a system $core + crust + surface$

Example: Aquila X-1
RXTE All Sky Monitor
(Šimon 2002) $\Longrightarrow$



Heating - outer crust - 1

One-component plasma: a single nuclear species (A, Z) is present at each pressure. Due to the nucleon pairing, stable nuclei in dense matter have even $N = A - Z$ and Z (even-even nuclides). In the outer crust, in which free neutrons are absent, the electron captures which proceed in two steps after the threshold $\mu_e = \Delta_1$ is reached:

quasi equilibrium

$$(A, Z) + e^- \longrightarrow (A, Z-1) + \nu_e$$

off equilibrium

$$(A, Z-1) + e^- \longrightarrow (A, Z-2) + \nu_e + Q$$

Q - total; Q_d - deposited in the matter; Q_ν - taken away by neutrinos

$$Q = Q_\mathrm{d} + Q_\nu$$

Heating - outer crust - 2

Total heat release

$$Q = Q_{\rm d} + Q_\nu$$

The effective heat deposited in matter is

$$Q_{\rm d} = \eta(\mu_e - \Delta_2)$$

Older calculations: GS-GS transition, $\eta \simeq 1/6 - 1/4$, but Gupta et al. 2006 have shown that off equilibrium process goes via GS-ES transitions, and $\eta \simeq 1$ (capture leads to an excited state, which then γ - deexcites).

Here: $\mu_e =$ electron Fermi energy (including the rest energy), Δ_2 is the GS-GS energy threshold for the capture on the odd-odd nucleus (nonequilibrium process).

Heating - inner crust - 1

Above the neutron-drip point ($\rho > \rho_{\rm ND}$), electron captures trigger neutron emissions

quasi equilibrium

$$(A,Z) + e^- \longrightarrow (A,Z-1) + \nu_e$$

off equilibrium

$$(A,Z-1) + e^- \longrightarrow (A-{\rm k},Z-2) + {\rm k}\,n + \nu_e + Q$$

Then the rate of pycnonuclear fusion of a pair of $(A,Z'=Z-2)$ nuclei $1/t_{\rm pyc}$ is calculated, and compared with local compression rate $1/t_{\rm comp} = \dot{\rho}/\rho$.

Heating - inner crust - 2

Pycnonuclear fusion

$$(A, Z') + (A, Z') \longrightarrow (2A, 2Z') + Q_1$$

is followed by neutron emission

$$(2A, 2Z') \longrightarrow (2A - \mathrm{k}', 2Z') + \mathrm{k}'\, n + Q_2$$

and further electron captures and neutron emissions

$$\ldots \qquad \ldots \qquad \ldots \qquad \ldots + Q_3$$

where "…" correspond to some not specified chain of the electron captures accompanied by neutron emissions. The total heat deposition in matter, resulting from a chain of reactions involving a pycnonuclear fusion, is $Q = Q_1 + Q_2 + Q_3$.

A model: $A_{\rm i} = 106$ (*Haensel & Zdunik 2003*) - corrected HZ2007

Table: X-ray bursts ashes - $^{106}\mathrm{Pd}$. P, ρ - at which the reaction takes place. $\Delta\rho/\rho$ - relative density jump connected with reaction, q - heat, X_n - fraction of free neutrons among nucleons, in the layer just above the reaction surface. Nuclei - compressible liquid drop model *Mackie & Baym 1977*.

P (dyn cm^{-2})	ρ (g cm^{-3})	reactions	X_n	$\Delta\rho/\rho$ %	q (keV)
9.235×10^{25}	3.517×10^{08}	$^{106}\mathrm{Pd} \rightarrow {}^{106}\mathrm{Ru} - 2e^- + 2\nu_e$	0	4.4	22.9
3.603×10^{27}	5.621×10^{09}	$^{106}\mathrm{Ru} \rightarrow {}^{106}\mathrm{Mo} - 2e^- + 2\nu_e$	0	4.6	22.7
2.372×10^{28}	2.413×10^{10}	$^{106}\mathrm{Mo} \rightarrow {}^{106}\mathrm{Zr} - 2e^- + 2\nu_e$	0	4.9	22.4
8.581×10^{28}	6.639×10^{10}	$^{106}\mathrm{Zr} \rightarrow {}^{106}\mathrm{Sr} - 2e^- + 2\nu_e$	0	5.1	22.2
2.283×10^{29}	1.455×10^{11}	$^{106}\mathrm{Sr} \rightarrow {}^{106}\mathrm{Kr} - 2e^- + 2\nu_e$	0	5.4	22.1
5.025×10^{29}	2.774×10^{11}	$^{106}\mathrm{Kr} \rightarrow {}^{106}\mathrm{Se} - 2e^- + 2\nu_e$	0	5.7	22.0
9.713×10^{29}	4.811×10^{11}	$^{106}\mathrm{Se} \rightarrow {}^{106}\mathrm{Ge} - 2e^- + 2\nu_e$	0	6.1	22.0

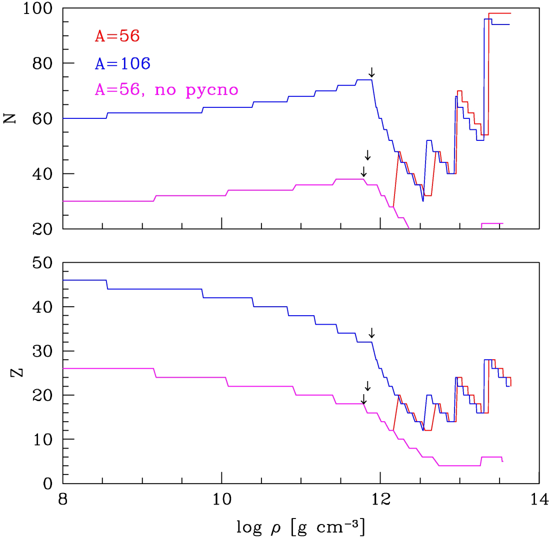
A model: $A_\mathrm{i} = 106$ - corrected (*H2003*) - HZ2007 - cont.

Table: Continuation - inner crust. Nuclei - *Mackie & Baym 1977*

P (dyn cm^{-2})	ρ (g cm^{-3})	reactions	X_n	$\Delta\rho/\rho$ %	q (keV)
1.703×10^{30}	7.785×10^{11}	$^{106}\mathrm{Ge} \rightarrow {}^{92}\mathrm{Ni} + 14n - 4e^- + 4\nu_e$	0.13	13.2	110.8
1.748×10^{30}	8.989×10^{11}	$^{92}\mathrm{Ni} \rightarrow {}^{86}\mathrm{Fe} + 6n - 2e^- + 2\nu_e$	0.19	6.9	53.2
1.924×10^{30}	1.032×10^{12}	$^{86}\mathrm{Fe} \rightarrow {}^{80}\mathrm{Cr} + 6n - 2e^- + 2\nu_e$	0.25	7.3	57.5
2.135×10^{30}	1.197×10^{12}	$^{80}\mathrm{Cr} \rightarrow {}^{74}\mathrm{Ti} + 6n - 2e^- + 2\nu_e$	0.30	7.7	62.1
2.394×10^{30}	1.403×10^{12}	$^{74}\mathrm{Ti} \rightarrow {}^{68}\mathrm{Ca} + 6n - 2e^- + 2\nu_e$	0.36	8.1	67.2
2.720×10^{30}	1.668×10^{12}	$^{68}\mathrm{Ca} \rightarrow {}^{62}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.42	8.5	72.9
3.145×10^{30}	2.016×10^{12}	$^{62}\mathrm{Ar} \rightarrow {}^{56}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.47	9.0	79.2
3.723×10^{30}	2.488×10^{12}	$^{56}\mathrm{S} \rightarrow {}^{50}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.53	9.4	86.0
4.549×10^{30}	3.153×10^{12}	$^{50}\mathrm{Si} \rightarrow {}^{42}\mathrm{Mg} + 8n - 2e^- + 2\nu_e$	0.61	8.8	94.5
4.624×10^{30}	3.472×10^{12}	$^{42}\mathrm{Mg} \rightarrow {}^{36}\mathrm{Ne} + 6n - 2e^- + 2\nu_e$ $^{36}\mathrm{Ne} + {}^{36}\mathrm{Ne} \rightarrow {}^{72}\mathrm{Ca}$	0.66	10.6	268.2
5.584×10^{30}	4.399×10^{12}	$^{72}\mathrm{Ca} \rightarrow {}^{66}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.69	4.8	31.6
6.883×10^{30}	5.355×10^{12}	$^{66}\mathrm{Ar} \rightarrow {}^{60}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.72	4.7	33.5
8.749×10^{30}	6.655×10^{12}	$^{60}\mathrm{S} \rightarrow {}^{54}\mathrm{Si} + 6n - 2e^- + 2\nu_e$	0.75	4.6	35.2
1.157×10^{31}	8.487×10^{12}	$^{54}\mathrm{Si} \rightarrow {}^{46}\mathrm{Mg} + 8n - 2e^- + 2\nu_e$ $^{46}\mathrm{Mg} + {}^{46}\mathrm{Mg} \rightarrow {}^{92}\mathrm{Cr}$	0.79	4.0	145.3
1.234×10^{31}	9.242×10^{12}	$^{92}\mathrm{Cr} \rightarrow {}^{86}\mathrm{Ti} + 6n - 2e^- + 2\nu_e$	0.80	2.0	11.4
1.528×10^{31}	1.096×10^{13}	$^{86}\mathrm{Ti} \rightarrow {}^{80}\mathrm{Ca} + 6n - 2e^- + 2\nu_e$	0.82	1.9	11.4
1.933×10^{31}	1.317×10^{13}	$^{80}\mathrm{Ca} \rightarrow {}^{74}\mathrm{Ar} + 6n - 2e^- + 2\nu_e$	0.83	1.8	11.2
2.510×10^{31}	1.609×10^{13}	$^{74}\mathrm{Ar} \rightarrow {}^{68}\mathrm{S} + 6n - 2e^- + 2\nu_e$	0.85	1.7	10.6
3.363×10^{31}	2.003×10^{13}	$^{68}\mathrm{S} \rightarrow {}^{62}\mathrm{Si} + 6n - 2e^- + 2\nu_e$ $^{62}\mathrm{Si} + {}^{62}\mathrm{Si} \rightarrow {}^{124}\mathrm{Ni}$	0.86	1.7	70.5
4.588×10^{31}	2.520×10^{13}	$^{124}\mathrm{Ni} \rightarrow {}^{120}\mathrm{Fe} + 4n - 2e^- + 2\nu_e$	0.87	0.8	3.0
5.994×10^{31}	3.044×10^{13}	$^{120}\mathrm{Fe} \rightarrow {}^{118}\mathrm{Cr} + 2n - 2e^- + 2\nu_e$	0.88	0.9	2.7
8.408×10^{31}	3.844×10^{13}	$^{118}\mathrm{Cr} \rightarrow {}^{116}\mathrm{Ti} + 2n - 2e^- + 2\nu_e$	0.88	0.8	2.5

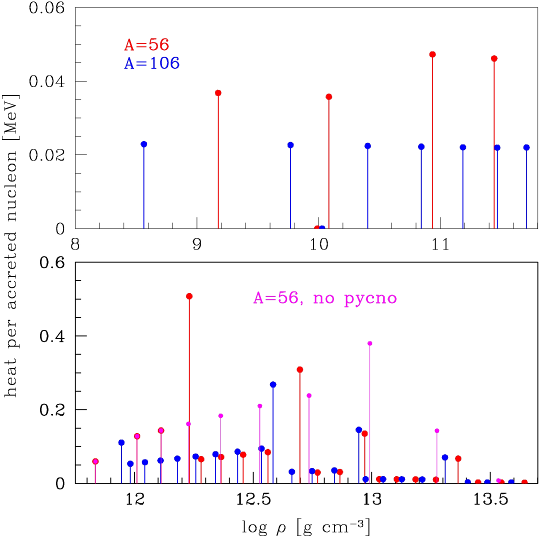
Compression of a layer of crustal matter - (N, Z)

Z and N versus matter density in an accreting neutron-star crust. Blue line: $A_\mathrm{i} = 106$; red - magenta line: $A_\mathrm{i} = 56$ (magenta - pycno delayed till $Z_\mathrm{min} = 4$). Change of N and Z - accompanied by a jump in density. Small steep segments connect the top and the bottom density of a thin reaction shell. Arrows - neutron drip point.



Compression of a layer of crustal matter - heating

Heat per one accreted nucleon [MeV], deposited in the crust, for two models with different initial $A = A_\mathrm{i}$. Blue vertical lines (ended with circles): $A_\mathrm{i} = 106$; red lines (ended with circles): $A_\mathrm{i} = 56$ with pycnonuclear fusions; magenta - pycnonuclear fusion delayed. Vertical lines are positioned at the densities at the bottom of the reaction shell.



Cumulated crustal heating

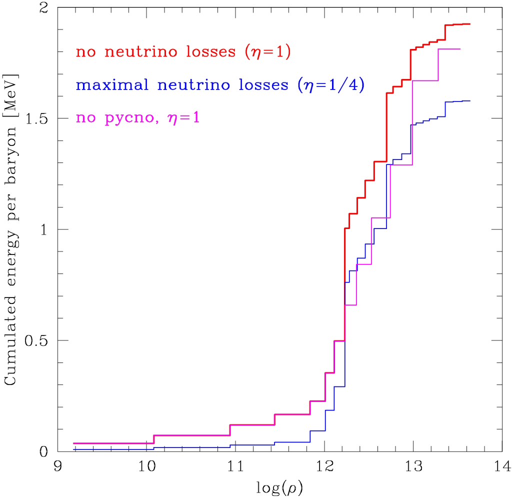
$A_{\rm i} = 56$, pycno, GS+ES - GS+ES ν-losses neglected

$A_{\rm i} = 56$, no pycno till $Z_{\rm min} = 4$, ν-losses neglected

$A_{\rm i} = 56$, pycno, GS-GS, ν-losses

Integrated heating per one accreted nucleon [MeV], deposited in the crust, $Q(\rho) = \sum_{\rm j}^{\rho_{\rm j}<\rho} Q_{\rm j}$, three models $\longrightarrow$

Pycnos at $\sim 10^{12}\ g\ cm^{-3}$ are not crucial



Total crustal heat/nucleon

Table: Total crustal heating - Haensel & Zdunik 2007

model	η	A_i	Q_dh
pycno	1/4	56	1.58 MeV
pycno	1	56	1.92 MeV
pycno	1/4	106	1.16 MeV
pycno	1	106	1.48 MeV
$Z_\mathrm{min} = 6$	1	56	1.87 MeV
$Z_\mathrm{min} = 4$	1	56	1.82 MeV
$Z_\mathrm{min} = 6$	1	106	1.43 MeV
$Z_\mathrm{min} = 4$	1	106	1.20 MeV

A_i **more important than pycno at** $\sim 10^{12}\ g\ cm^{-3}$

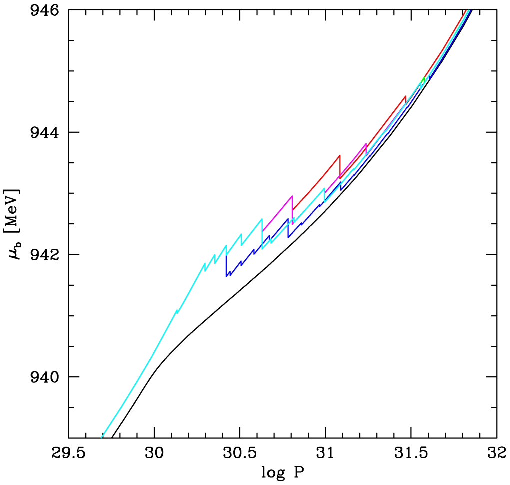
Weak dependence of Q on the path - 1

Example: different pycno threshold. Scenarios (paths) α

$$\mu_{\rm b}^{(\alpha)}(P) \simeq \overline{\mu}_{\rm b}(P)$$

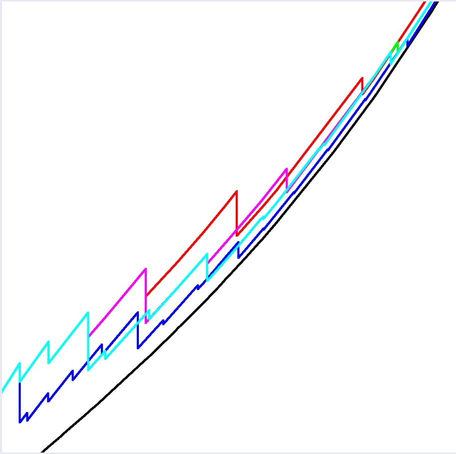
$$-\sum_j \Theta(P - P_j^{(\alpha)}) Q_j^{(\alpha)}$$

Function $\overline{\mu}_{\rm b}(P)$ is continuous, with very slow change of derivative. All $\mu_{\rm b}^{(\alpha)}(P)$ tend to cold catalyzed matter for $P > 10^{32}\ dyne\ cm^{-2}$



Weak dependence of Q on the path - 2

Derivatives with respect to P are nearly independent on α. Function $\overline{\mu}_{\rm b}(P)$ is continuous, with very slow change of derivative.



Application: Soft X-ray Transients in quiescence

X-ray luminosity in quiescence (after reaching a steady state) depends on the time-averaged accretion rate

$$\langle \dot{M} \rangle = t_{\rm a} \dot{M}_{\rm a}/(t_{\rm a} + t_{\rm q}) \ll \dot{M}_{\rm a}$$

Full deep heating power

$$L_{\rm dh} = Q \times \frac{\langle \dot{M} \rangle}{m_{_N}} = 6.03 \times 10^{33} (\langle \dot{M} \rangle / 10^{-10}\ M_\odot/y)(Q/MeV)\ {\rm erg\ s}^{-1}$$

Thermal balance equation in the steady state

$$L_{\rm dh}(\langle \dot{M} \rangle) = L_\nu(T_{\rm in}) + L_\gamma(T_{\rm eff})$$

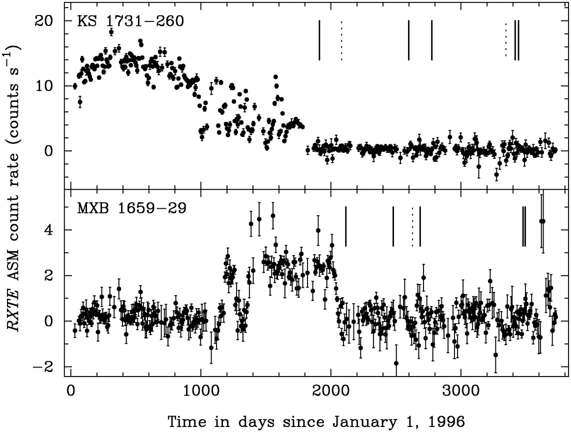
$$T_{\rm eff} = T_{\rm eff}(T_{\rm in})$$

Soft X-Ray Transients

Special type of SXRTs: with $t_a \sim years - decades$ (instead of $weeks - months$) **-quasi-persistent X-ray transients.**

Examples: KS 1731-260 and MXB 1659-29. Observations by RXTE, Chandra, XMM Newton (Cackett et al. 2006).

During t_a, the crust is heated well beyond the thermal equilibrium.



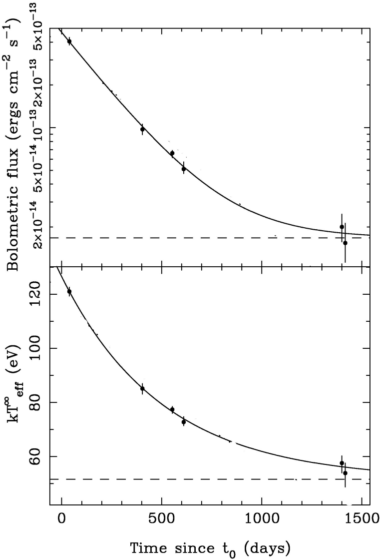
Thermal relaxation after accretion episode - 1

After $t_{\rm a}$, crust cools by X-ray emission until it reaches thermal equilibrium with core corresponding to the quiescent state.

Crust heat content is so small that it can cool significantly after the outburst (**initial cooling**).

First observation - in MXB 1659-29 Cackett et al. 2006

$\Longrightarrow$



Thermal relaxation after accretion episode - 2

Crust heat content is so small that it can cool significantly after the outburst $\Longrightarrow$ non-steady stage of **initial cooling**.

Surface cooling curve:

$$L_X^{\infty}(t) = 4\pi\sigma_{\rm SB} R_{\infty}^2 (T_{\rm eff}^{\infty})^4$$

depends on:

- internal (core, crust) cooling mechanisms
- crust properties such as thermal conductivity (composition, purity)
- heat sources distribution within the crust

Last item - very important for localizing the main heat sources within the crust (Shternin, Haensel & Yakovlev 2007, in preparation)