Procesy jądrowe w skorupie gwiazdy neutronowej i nowe zjawiska w astronomii rentgenowskiej

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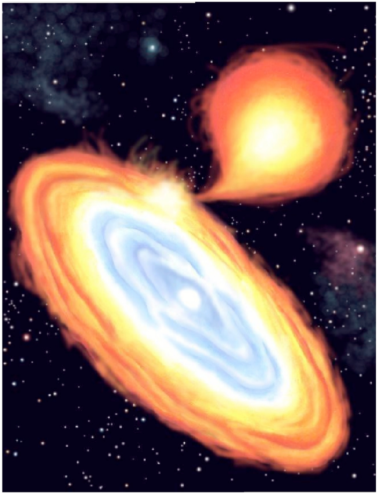
X-ray astronomy and neutron stars

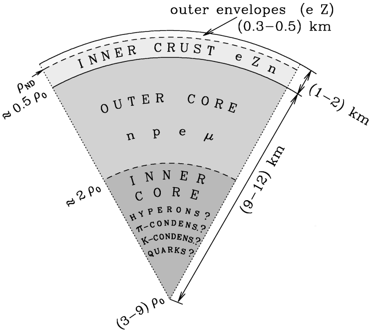
- X-ray detectors outside Earth atmosphere (Giacconi et at. 1962 - detectors on rockets). Then detectors on satellites. Discovered many point-like strong X-ray sources in Galaxy. Most of them - neutron stars. Nobel prize for R. Giacconi in 2002 for pioneer work on X-ray astronomy.
- neutron stars younger than 100 000 years have $T_{\rm surf} \sim 10^6$ K - radiate mostly in X-rays.
  $T_{\rm surf} \gtrsim 10^6$ K $\quad L_\gamma \sim 4\pi R^2 \sigma_{\rm SB} T_{\rm surf}^4 \sim 10^{33} (R/10\ {\rm km})^2 T_6^4\ {\rm erg\ s^{-1}}$
- accreting neutron stars in close binary systems - heated by accretion to $T_{\rm surf}$ above 10^7 K ($\dot{M} \sim 10^{-10} - 10^{-9}\ M_\odot/year$)
- **X-ray bursters** - thermonuclear explosions of accreted plasma. X-ray bursts: duration - a few 10 seconds, quasi-periodicity $\sim$ hour. $L_{\rm burst} \sim 10^{38}\ {\rm erg\ s^{-1}}$. **Soft X-ray transient**: active days-weeks, quiet - months-years. **Persistent transients**: active years, quiescence - decades, very rare. **Superbursts**: duration few - twelve hours, very rare.
- X-ray pulsars - heated polar caps radiate X-rays. Rotation implies pulsation of the detected signal.

Low mass X-ray binaries (LMXBs)



The artists view of a low-mass X-ray binary. The companion of a neutron star fills its Roche lobe and looses its mass via plasma flow through the inner Lagrangian point. Due to its angular momentum, plasma orbits around neutron star, forming an accretion disk. Gradually loosing the angular momentum due to viscosity within the accretion disk, plasma approaches neutron star and falls eventually onto neutron star surface. Figure by T. Piro.

Neutron star crusts



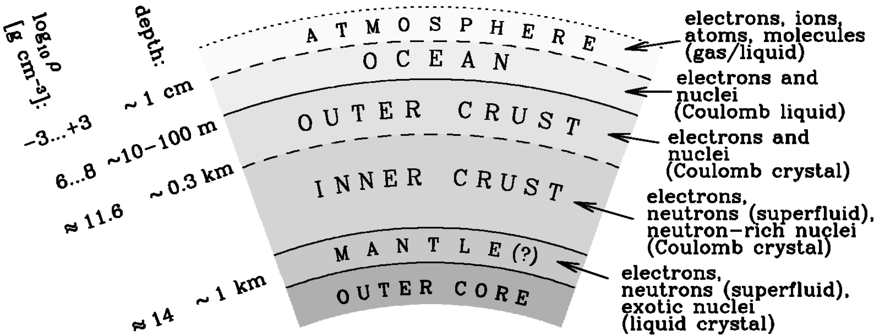
Standard reference: S.L. Shapiro, S.A. Teukolsky *Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects* (Wiley, 1983).

Problems and Methods

- Plasma and nuclear physics $(10^4 - 10^{14}\ \mathrm{g\ cm^{-3}}$ (atoms crushed, unstable neutron-rich nuclei, nuclear many-body problem). Basic constituents - n p e - like in "terrestrial physics".
- Extreme physical conditions: density of the matter, high neutron excess due to dense electron gas, neutron gas outside nuclei.

New advanced up-to-date reference: P. Haensel, A.Y. Potekhin, and D.G. Yakovlev *Neutron Stars 1. Equation of state and structure* (Springer, 2007)

Structure of envelope and crust



Schematic structure of an envelope of a neutron star with the internal temperature $\sim 10^8$ K.

Two scenarios of formation of neutron star crust

- **Collapse of stellar core** - birth of neutron star at $T \sim 10^{11}$ K, nuclear equilibrium, then cooling to $< 10^9$ K in few months. Crust matter in "nuclear equilibrium" (ground state of the matter = "cold catalyzed matter"). No exothermic reactions possible.

- **Slow accretion** of plasma onto NS surface. Typical in close binaries: $10^{-10} - 10^{-9}\ M_\odot$/year. X-ray bursts $\Longrightarrow$ Fe ... ashes. For $M < M_\odot$ companions accretion can last $> 10^9$ years. For $\rho > 10^9\ \mathrm{g\ cm^{-3}}\ T < 10^9$ K, Coulomb barriers for nuclei $\Longrightarrow$ only nuclear reactions: electron capture, neutron emission/absorption, pycnonuclear fusion. *Accreted crust* vastly different from the *ground-state crust*. Accreted crust is a *reservoir of energy*.

Deep crustal heating and observed phenomena

THEORY

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; Sato 1979; Bisnovatyi-Kogan & Chechetkin 1979, Haensel & Zdunik 1990). **Total crustal heating is $\sim 1.5 - 2$ MeV per one accreted nucleon, mostly deposited at $\rho \sim 10^{12} - 10^{13}$ g cm^{-3}** (Haensel & Zdunik 1990, Haensel & Zdunik 2003, 2008).

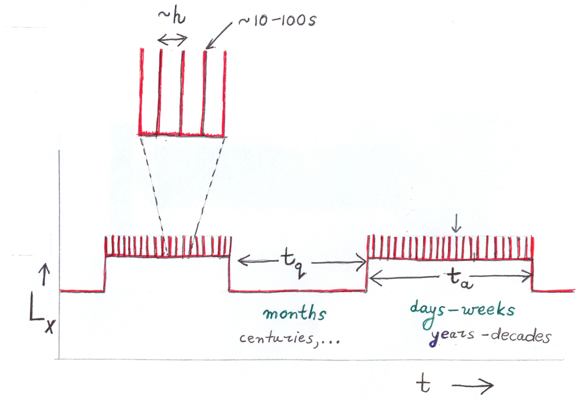
OBSERVATIONS

- Soft X-ray transients: deep crustal heating necessary to explain thermal radiation in quiescence (Brown, Bildsten & Rutledge 1998)

NEW ↓

- Superbursts: they seem to result from an explosive ^{12}C ignition - deep crustal heating necessary to explain their frequency (years, not decades) (Brown, Bildsten & Rutledge 2005)
- **Initial cooling in persistent SXTs: internal overheating by deep crustal heating during active (accreting) episode followed by observed thermal relaxation (Cackett et al. 2006)**

Soft X-ray transients - SXTs - theoretical picture



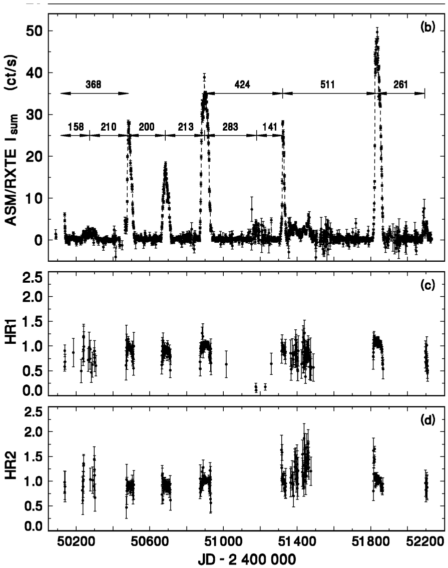
Type I X-ray bursts during accretion ($t_{\rm a}$, $\dot{M}_{\rm a}$) - explosive He burning. Steady accreting state - stable H burning, cumulation of He.

SXTs in quiescence - $t_{\rm q} \gg t_{\rm a}$, surface heated due to cumulated deep crustal heating.

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

$$L_{\rm dh} = Q_{\rm tot} \langle \dot{M} \rangle / m_{\rm u}$$

Example: Aquila X-1 *RXTE* All Sky Monitor (1996-2001). Points: one day means. (b) - counts. (c)+(d) - hardness ratio. (Šimon 2002) $\Longrightarrow$



Newtonian theory for simplicity

L_r - heat per second through sphere of radius r

S - entropy/volume; Q_ν - energy emitted with neutrinos per unit volume per second; Q_h - heat produced per unit volume per second

Thermal structure equations in order to get $L_r(r,t)$ and $T(r,t)$ in diffusion approximation:

$$\frac{1}{4\pi r^2}\frac{\partial L_r}{\partial r} = -Q_\nu + Q_\mathrm{h} - T\frac{\partial S}{\partial t} \quad ,$$

$$\frac{L_r}{4\pi r^2} = -\kappa\frac{\partial T}{\partial r} \quad .$$

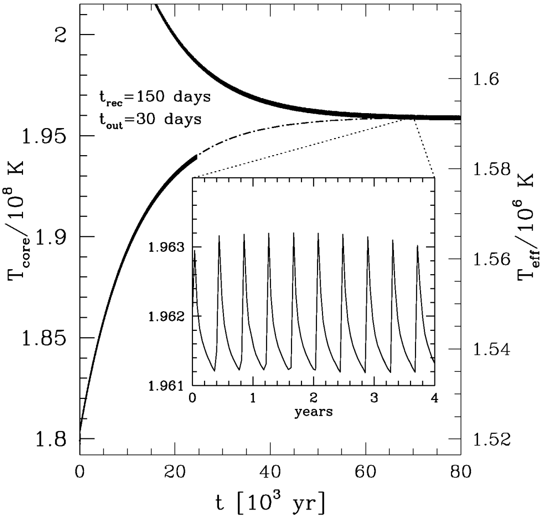
Impose boundary conditions (may be time-dependent). Assume initial $T(r,0)$, integrate in r and evolve in t.

Reaching a steady state

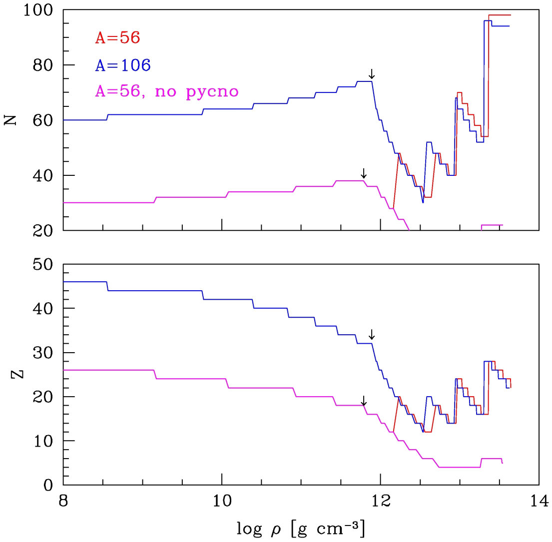
Space-time metric $ds^2 =$
$c^2 dt^2 e^{2\Phi} - e2\lambda dr^2 - r^2(d\theta^2 + \sin^\theta d\phi^2)$

Redshifted $T_{\rm core} = e^\Phi T(r,t) = const.$ vs. time. Onset of accretion at $t = 0$. Star $1.4\ M_\odot$, superfluid core. Transient a accretion of $\Delta M = 6 \times 10^{-11}\ M_\odot$ during 30 d, with recurrence time $t_{\rm rec} = 150$ d. Dot-dash line: continuous accretion at $\dot{M} = \langle \dot{M} \rangle = 1.46 \times 10^{-10}\ M_\odot/{\rm y}$.

(Colpi, Geppert, Page, Possenti 2001)



Composition of accreted crust

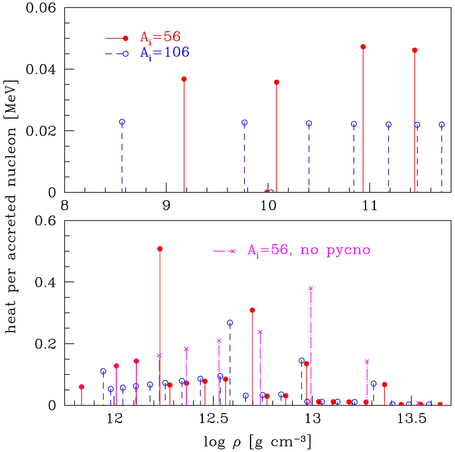


Z and N of nuclei, versus matter density in an accreting neutron-star crust. Arrows indicate positions of the neutron drip point.

“no pycno” - pycnonuclear reactions blocked until $Z = 4$

(Haensel & Zdunik 2008)

Deep heat sources



Heat sources in the outer (upper panel) and inner (lower panel) crust.

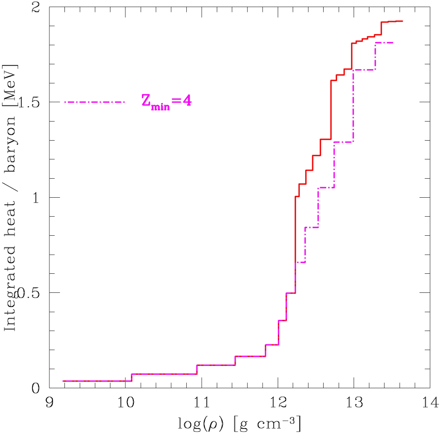
Vertical lines, positioned at the density at the bottom of the reaction shell, represent the heat per one accreted nucleon (Haensel & Zdunik 2008).

Important quantity: integrated heat deposited in the crust in the layer with density $< \rho$. It is given by

$$Q^{(\alpha)}(\rho) = \sum_{j(\rho_j<\rho)} Q_j^{(\alpha)} \ , \qquad (1)$$

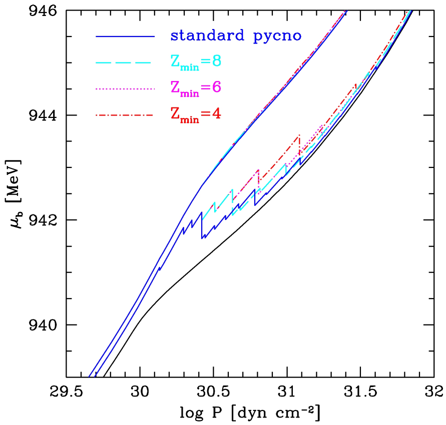
where (α) is the label characterizing a specific crust heating model (specific $A_{\rm i}, Z_{\rm i}$, etc.). The quantity $Q^{(\alpha)}(\rho)$, for two specific models of compressional evolution, is plotted in next slide.

Integrated heat - 2



Integrated heat released in the crust, $Q(\rho)$ (per one accreted nucleon) versus ρ, assuming initial ashes of pure $^{56}\mathrm{Fe}$. Solid line: HZ* model of (Haensel & Zdunik 2008) with $A_\mathrm{i} = 56$. Dash-dot line: with pycnonuclear fusion blocked until $Z = Z_\mathrm{min} = 4$.

Constancy of $Q_{\rm tot}$



Gibbs free energy per nucleon (baryon chemical potential) $\mu_{\rm b} = (\mathcal{E} + P - T\mathcal{S})/n_{\rm b}$

$\mu_{\rm b}(P)$ for different versions of blocking of pycnonuclear fusion. "Standard pycno" corresponds to HZ* model with $A_{\rm i} = 56$. Three other curves - pycnonuclear fusion suppressed until $Z = Z_{\rm min} = 8, 6, 4$ (Haensel & Zdunik 2008).

The upper continous curves, *which nearly coincide*, are defined as

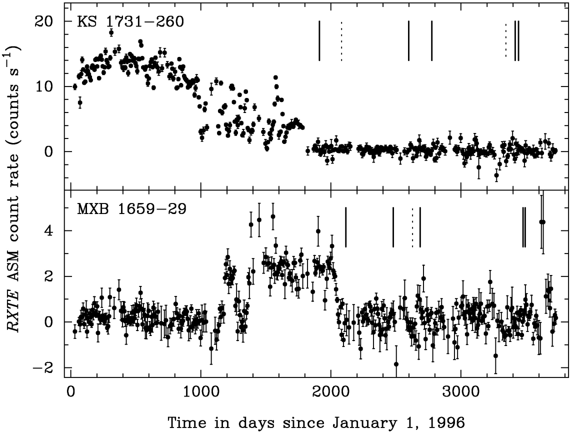
$$\overline{\mu}_{\rm b}^{(\alpha)}(P) \equiv \mu_{\rm b}^{(\alpha)}(P) + \sum_{j(P_j<P)} Q_j^{(\alpha)}.$$

Dependence of $\overline{\mu}_{\rm b}^{(\alpha)}(P)$ on (α) is negligible, and index (α) can be removed. The lowest smooth solid curve - cold catalyzed matter.

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.



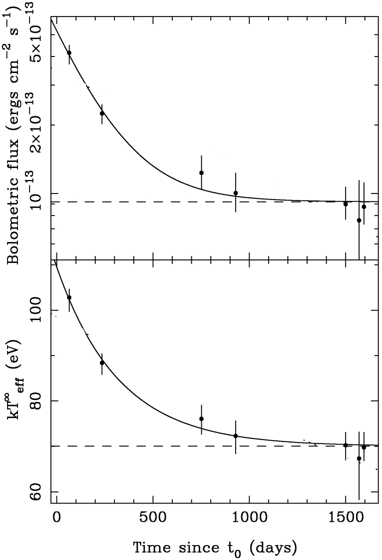
Thermal relaxation after accretion episode

After t_a, crust cools by X-ray emission until it reaches thermal equilibrium with core corresponding to the quiescent state.

Surface cooling curve:
$L_X^\infty(t) = 4\pi\sigma_{SB} R_\infty^2 (T_{\rm eff}^\infty)^4$
depends on: internal cooling mechanisms and crust properties (thermal conductivity: composition, purity). Crust heat content is so small that it can cool significantly after the outburst (**initial cooling**).

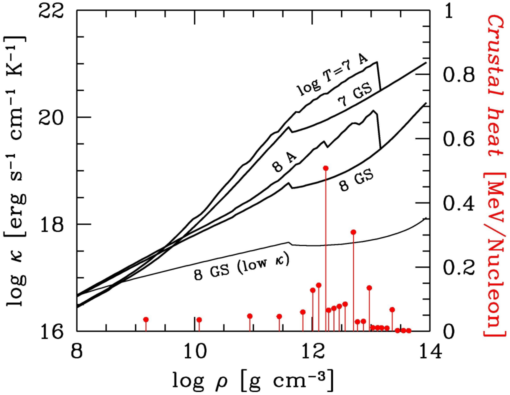
MXB 1659-29 Cackett et al. 2006

$\Longrightarrow$



Theory vs. observations - 1

Shternin,Yakovlev,Haensel,Potekhin(2007) **KS 1937 - 260**. Thermal relaxation after 12.5 y of deep crustal heating. Interpreting results of Cackett et al. (2006). Preliminary interpretation - Rutledge et al. (2002). More detailed models of the crust: composition, deep crustal heating and thermal conductivity.



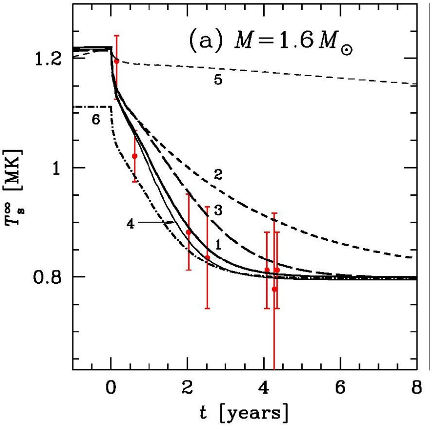
Crust physics. A - accreted crust. GS - ground-state crust.

Deep heating: Haensel & Zdunik 2007, $A_{\rm i} = 56$.

low κ - amorphous crust, remaining - pure crystal.

Theory vs. observations - 2

Shternin,Yakovlev,Haensel,Potekhin(2007) **KS 1937 - 260**. Thermal relaxation after 12.5 y of deep crustal heating. Interpreting results of Cackett et al. (2006).



APR EOS for the core.
$M_{\max} = 1.92\ M_\odot$,
$M_{\rm Durca} = 1.83\ M_\odot$. **1** - best.
Accreted crust, pure - normal κ.
$M = 1.6\ M_\odot$ (no Durca, but massive - to have thin crust).
Amorphous crust (5) ruled out.

Summary and conclusion

- The value of $Q_{\rm tot} \approx 1.5 - 1.9$ MeV/nucleon does not depend on uncertainties of the details of deep crustal heating.
- $Q_{\rm tot} \approx 1.5 - 1.9$ MeV/nucleon is just what is needed to explain $T_{\rm surf}$ of soft X-ray transients in quiescence (0.15 MeV/nucleon - too cold).
- Deep crustal heating with proper thermal conductivity explains thermal relaxation of a persistent X-ray transient KS 1731-260 after accretion (12.5 years !) stopped (Shternin,Yakovlev,Haensel,Potekhin 2007). Quite pure crystal, $1.6\ M_\odot$, 1.5 MeV/nucleon
- *Future: modeling of observed thermal relaxation of persistent soft X-ray transients could hopefully shed light on the distribution of heat sources with depth & density*