Layers of electron captures in the crust of accreting neutron stars

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IReNA-INT Joint Workshop on Thermal and Magnetic Evolution of Neutron Stars

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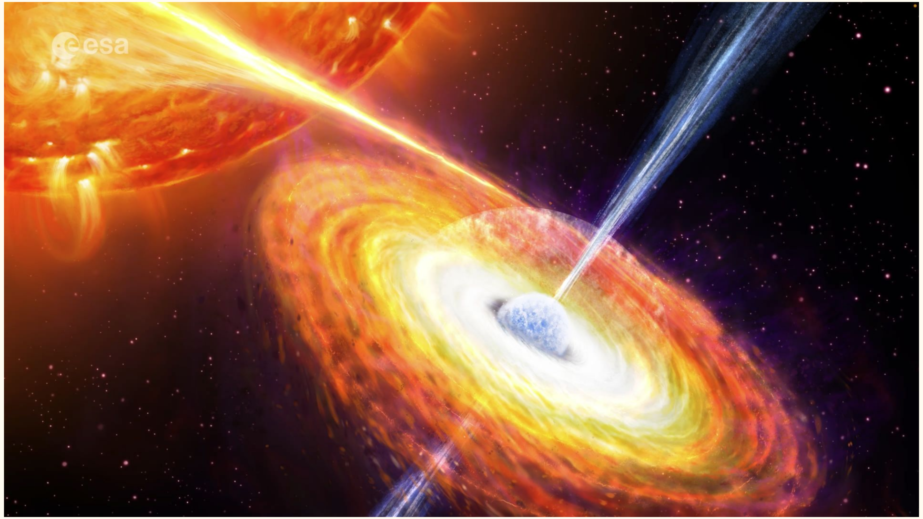
Quick deep crustal heating summary

Low mass X-ray binaries:

- Neutron Star (NS) subject to **accretion** when the companion star has filled its Roche lobe.
- Accreted matter falls from the accretion disk to the NS surface.
- Thermonuclear burning deposit ashes at the crust surface.



Credit: ESA website

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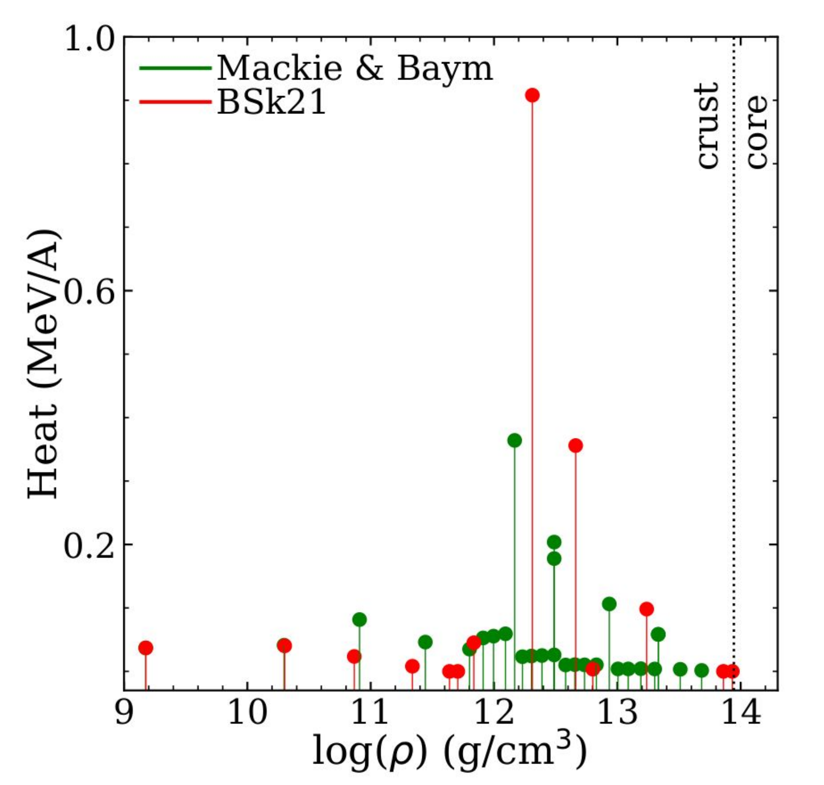
- Thermonuclear burning deposit ashes at the crust surface.
- Continuous accretion pushes ashes towards the NS core, triggering **exothermic reactions**: deep crust heating.
- The heat diffuses, and translates into a **surface luminosity**.
- **Observed thermal relaxation** during quiescent phases of accretion can inform on the equation of state and composition of the NS crust.



Infinite reaction rate assumption in deep crustal heating

Common approach of **instantaneous** reactions:

- Compression triggered exothermic reactions are assumed to have **infinite rates**.
- All nuclei in a piece of matter are instantaneously changed from parent to daughter nuclei once $\mathbf{P_{th}}$ has been reached.

We studied the impact of **finite reaction rates**:

- Applied to **electron captures**
- Kinetics of the first EC is of interest

Equation of state:

- Outer crust only (T=0)
- Mixture of nuclei: $\mathbf{X = N_{parent} / N_{total}}$
- Degenerate gas of e⁻ + lattice contribution

Composition:

- Threshold energy **W** defined at P_{th}
- Masses determined by *AME2020* or *HFB-21*

[Wang et al. 2021] *[Goriely et al. 2010]*

$$(A,Z) + e^- \rightarrow (A,Z-1) + \nu \qquad \text{Slow}$$

$$(A,Z-1) + e^- \rightarrow (A,Z-2) + \nu \qquad \text{Fast}$$

$$P = \frac{(m_e c^2)^4}{(\hbar c)^3}\phi\left(\alpha(X) n^{1/3}\right) + \beta(X) n^{4/3}\,,$$

Mixed layer approach

$$W_1 = \mathcal{M}_{\rm at}(A,Z-1)c^2 - \mathcal{M}_{\rm at}(A,Z)c^2 + m_e c^2 + B_{\rm el}(Z-1) - B_{\rm el}(Z) + E_{\rm exc}(A,Z-1)$$

$$W_2 = \mathcal{M}_{\rm at}(A,Z-2)c^2 - \mathcal{M}_{\rm at}(A,Z-1)c^2 + m_e c^2 + B_{\rm el}(Z-2) - B_{\rm el}(Z-1)$$

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Electron capture rates: *[Wang et al. 2021]* *[Goriely et al. 2010]*

- Half-life from *National Nuclear Data Center*

Solve the continuity equation for X(P,t)

Mixed layer approach

$$R_{\rm ec} = \frac{1}{\tau_{\rm ec}} G(\bar{E}_F, \bar{W}_1)$$

$$G(\bar{E}_F, \bar{W}) = \int_{\bar{W}}^{\bar{E}_F} \bar{E}\sqrt{\bar{E}^2 - 1}\,(\bar{E} - \bar{W})^2 \mathrm{d}\bar{E}$$

$$\frac{\partial}{\partial t} \ln\left(n\big(X(P,t), P\big)\ X(P,t)\right) + \frac{1}{\tau_{\rm acc}(t)} \frac{\partial \ln X(P,t)}{\partial \tilde{P}} = -R_{\rm ec}\big(X(P,t), P\big)$$

$$\tau_{\rm acc}(t) = \frac{4\pi R^4 P_{\rm th}}{G M \dot{M}(t)}$$

Reaction	$\tau_{\rm ec}$ (in s)	$\tau_{\rm acc}$ (in s)
$Z = 26 \rightarrow 25$	8.67×10^6	9.50×10^7
$Z = 24 \rightarrow 23$	1.37×10^4	2.40×10^9
$Z = 22 \rightarrow 21$	7.34×10^3	1.21×10^{10}
$Z = 20 \rightarrow 19$	1.59×10^5	5.67×10^{10}

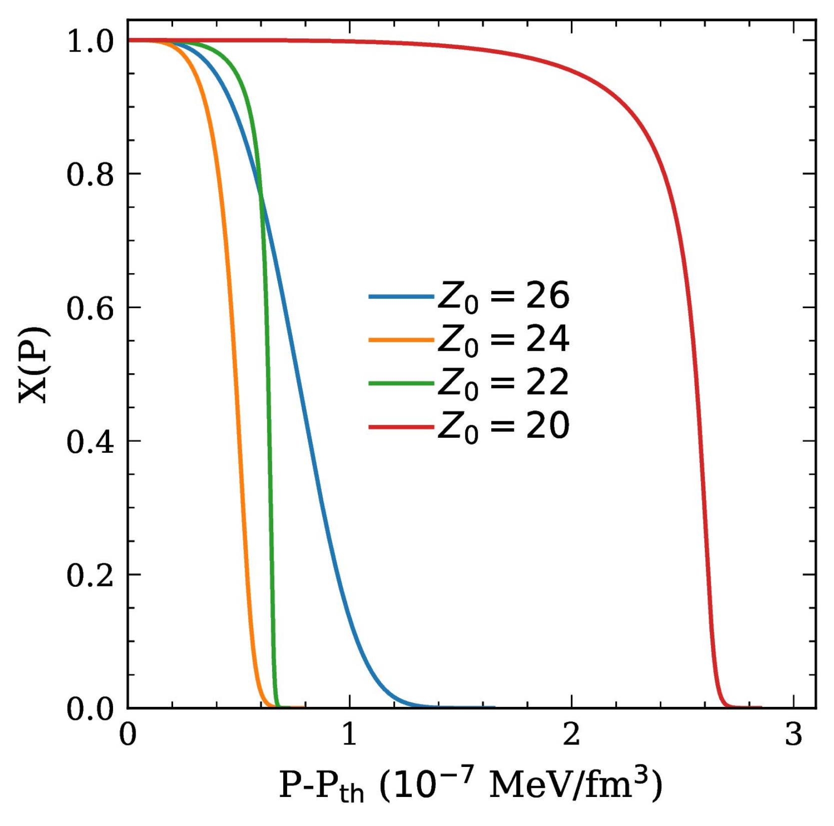
Stationary solution during active accretion

Accretion adding parent nuclei and reactions transforming them have come to an ***equilibrium****.*

Layers of electron capture:

- Mix of parent nuclei + grand daughter nuclei
- Layers are small compared to the shell thickness
- A few meters to 0.2m thick

Reaction	$\delta P(X = 0.95)$ MeV/fm^3	ΔP_{layer} MeV/fm^3
$Z_0 = 26$	3.86×10^{-8}	1.24×10^{-7}
$Z_0 = 24$	3.18×10^{-8}	6.20×10^{-8}
$Z_0 = 22$	5.53×10^{-8}	6.71×10^{-8}
$Z_0 = 20$	2.31×10^{-7}	2.68×10^{-7}



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$$q(P,X) = 2\mu_e(P,X) - (W_1 + W_2) + E_{\text{exc}}$$

$$q_{\text{th}}(P,X) = W_1 - W_2 + E_{\text{exc}}$$

$$\dot{q}(P,t) = q(P,X) R_{\text{ec}}(P,X) \frac{n(P,X)}{A} X(P,t)$$

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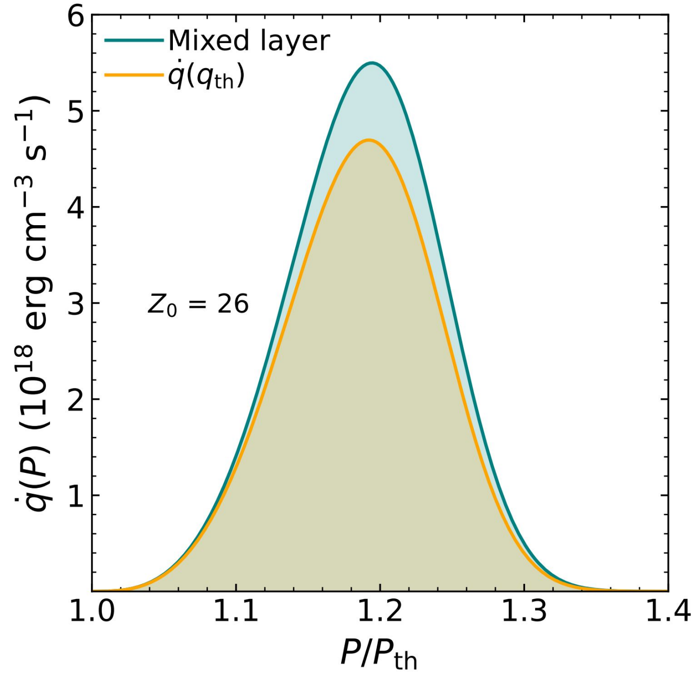

Impact on the **heat release**:

- Parent nuclei found deeper in the shell
- **Heat release depends on the pressure**
- Heat release is increased: up to ~20%

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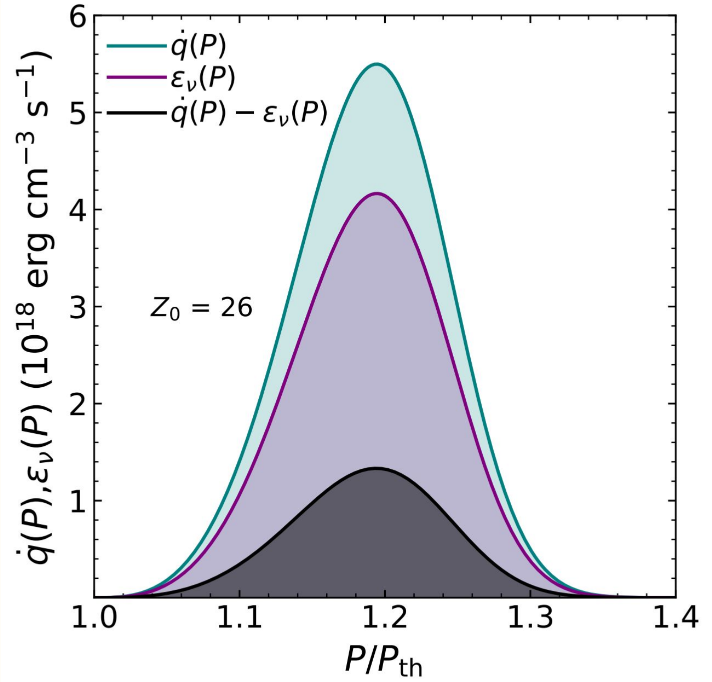

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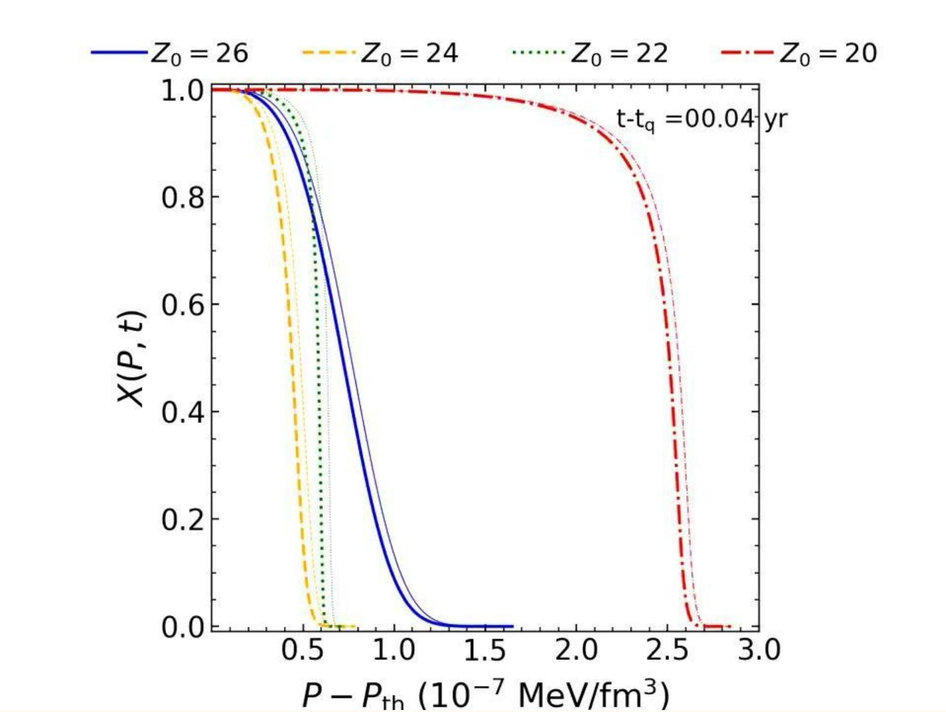
- Heat release is increased: up to ~20%
- We also added neutrino loss in our results

Heat sources during quiescence

What happens if the accretion is stopped after some period of our stationary solution ?

$$\frac{\partial}{\partial t} \ln \left(n\big(X(P,t),P\big)\; X(P,t)\right) + \frac{1}{\tau_{\rm acc}(t)} \frac{\partial \ln X(P,t)}{\partial \tilde{P}} = -R_{\rm ec}\big(X(P,t),P\big)$$

- Reactions **during quiescence**
- Nuclei far from P_{th} react first
- Active accretion can start before all nuclei have reacted
- Number of **reacting** != number of **accreted** nuclei over one accretion cycle



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	Solution	$Z_0 = 26$	$Z_0 = 24$	$Z_0 = 22$	$Z_0 = 20$
Stationary active phase		Heat release			
	Instantaneous	38.9	41.8	34.0	24.3
	Mixed layer	47.5	42.5	34.5	25.1
		Neutrino emission			
	Mixed layer	36.0	32.7	26.2	19.0
		Heat deposited			
	Mixed layer	11.5	9.8	8.3	6.1
Quiescence following stationary		Heat release			
	Instantaneous	0.0	0.0	0.0	0.0
	Mixed layer	6.5	4.2	4.4	12.1
		Neutrino emission			
	Mixed layer	4.9	3.2	3.3	9.1
		Heat deposited			
	Mixed layer	1.6	1.0	1.1	3.0

What about time dependence in the active phase ?

- Some shells **do not reach the stationary state** (depends on accretion rate and time)
- Less nuclei reacted = **decrease Q/accreted baryon**, yet increase Q/reactive baryon.
- Reaction rate vs Accretion rate/time

$$\frac{\partial}{\partial t} \ln \left(n\left(X(P,t),P\right)\ X(P,t)\right) + \frac{1}{\tau_{\mathrm{acc}}(t)} \frac{\partial \ln X(P,t)}{\partial \tilde{P}} = -R_{\mathrm{ec}}\left(X(P,t),P\right)$$

Conclusion

Layers of electron captures affect the heat release from exothermic reactions in the crust.

Including nuclear informed reaction rates, paired with astro informed accretion rates and time affects the heat deposition in the crust.

This in turn will impact thermal relaxation from deep crust heating.

Prospects:

- Extend to inner crust
- Including complete excitation states
- Assess the impact on thermal relaxation

Thank you for your attention !