Compression and heat sources in neutron star's crusts

ECT* - NS As Multi-Messenger Laboratories For Dense Matter

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Astrophysical context for crust compression

Partially accreted crusts

- Beyond the assumption of a fully accreted crust (FAC)
- Example: IGR J17480−2446 [Bonanno & Urpin 2015]
  - observed pre-accretion, during a 2-month outburst, 2 months post-accretion,
  - low spin [Degenaar 2015],
  - not recycled.
- Not accreted enough matter to be considered FAC.
- Hybrid, time dependent crust
  - accumulating accreted material,
  - original crust compressed underneath.

[LS, J.L. Zdunik, P. Haensel & M. Fortin 2022]

Spinning down NS

- Rotating star has an oval shape,
- Decrease of rotation
  - from oblate to spherical shape,
  - relative compression [Iida & Sato 1997].
- Compression of a FAC [Gusakov et al. 2015]

Decaying B in magnetars

- Increase in X-ray flux [Zelati et al. 2018]
- Decrease of the magnetic field
  - Magnetic VS self-gravitation pressure
  - relative compression [N. Chamel, et al. (LS) 2021]

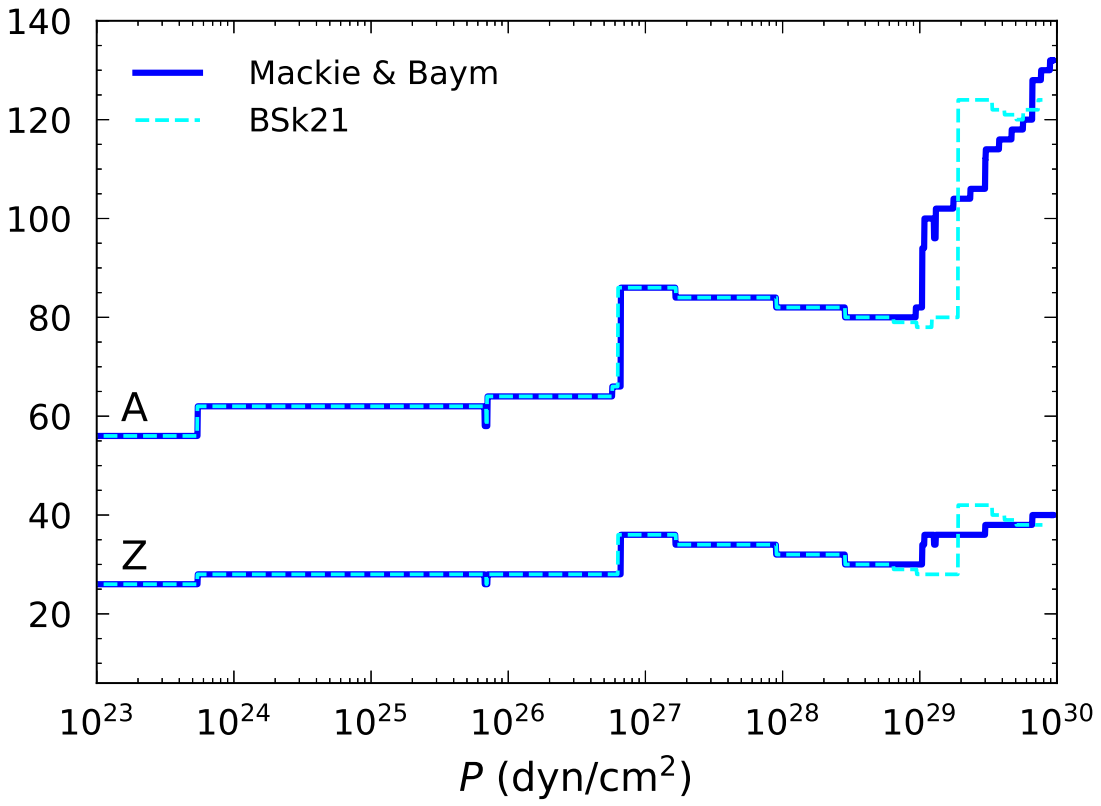
Simple nuclear model I

Cold Compressible Liquid Drop Model

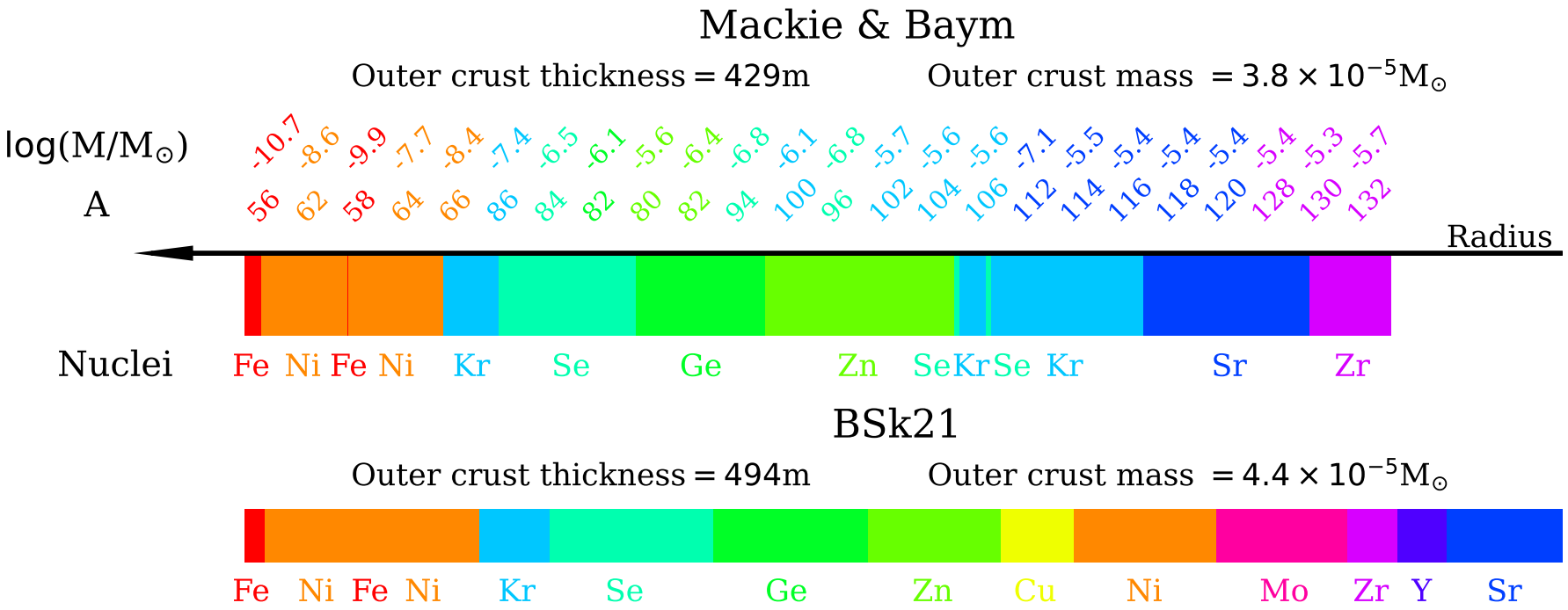
[Makie & Baym 1977]

Adjuted to AME2016 [Huang et al. 2017]

Catalyzed outer crust EoS → original crust



Simple nuclear model II



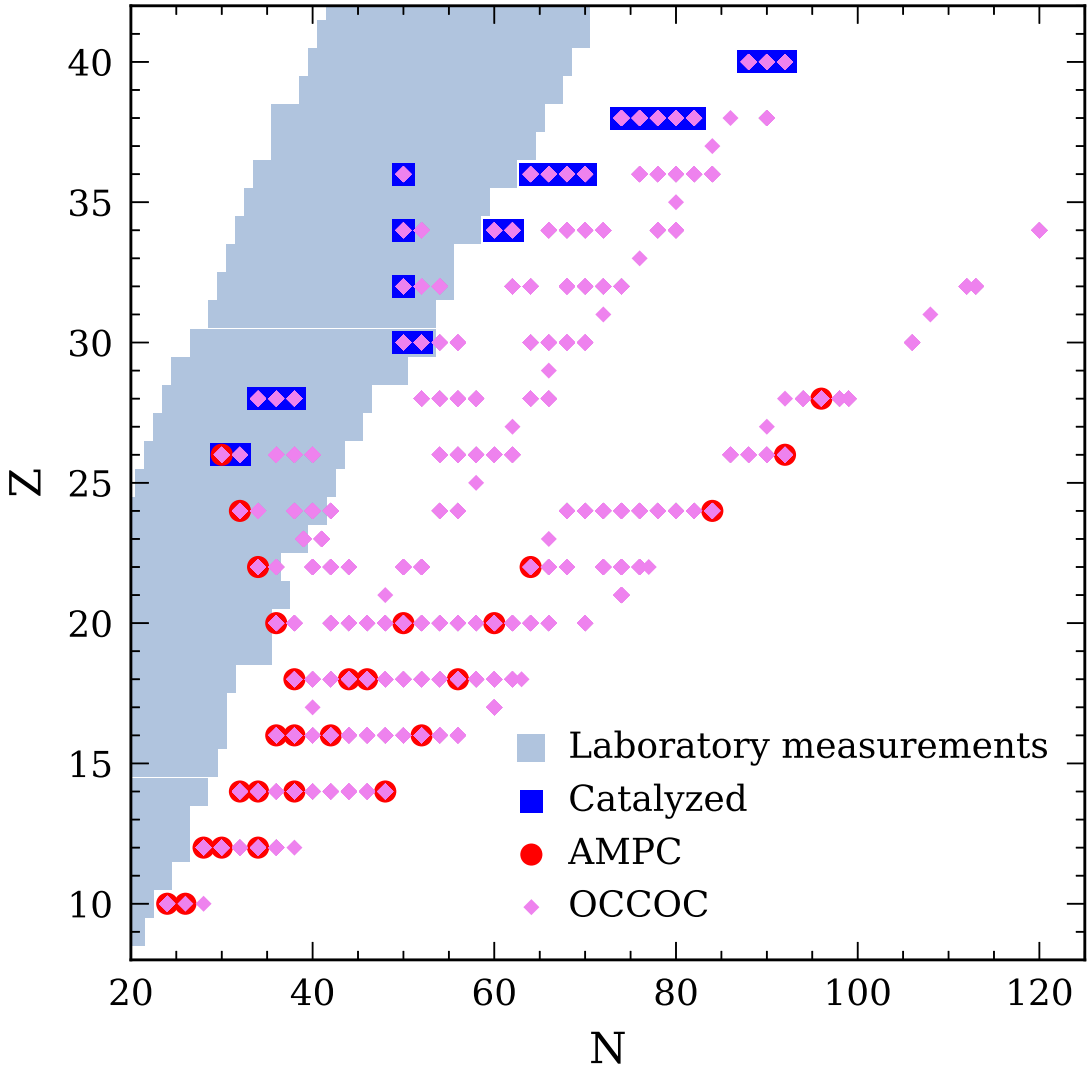
Simple nuclear model III

Accreted Material Part (AMPC)

- ^{56}Fe ashes
- Local equilibrium
- Slowly invading the partially accreted crust

Compressed Original Outer Crust (OCCOC)

- Evaluate each shell of the original outer crust under compression
- Like calculating 24 local equilibrium AMPC
- Large number of nuclei
- Large number of heat sources



Heat Sources and properties of the OCCOC I

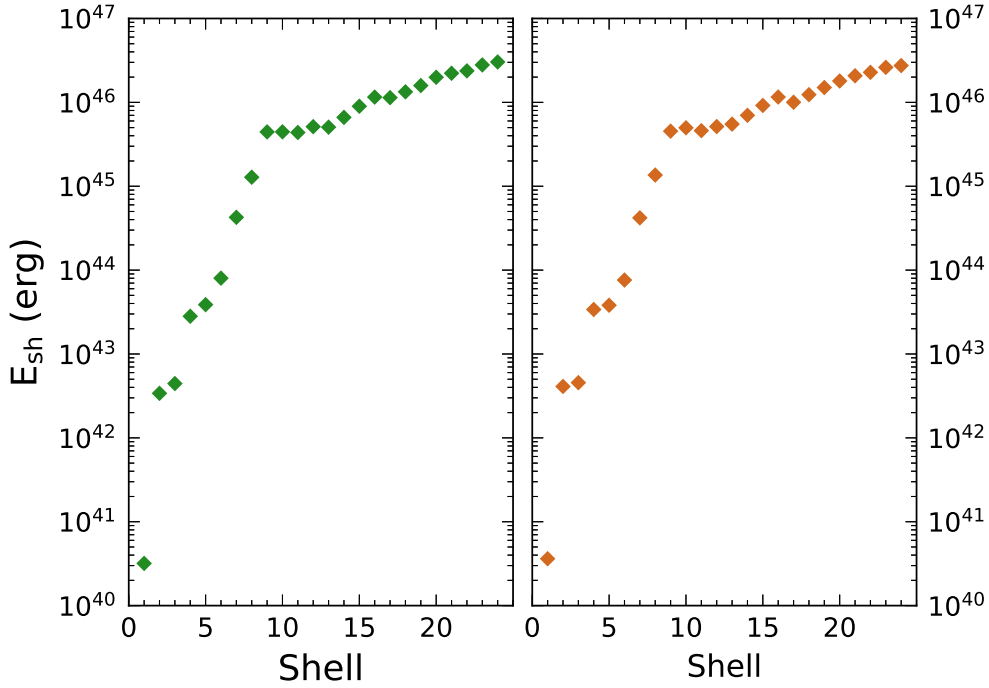
After an increase of pressure $\sim 10^{32}$ dyn/cm^2, Partially Accreted Crust $\rightarrow$ FAC

Heat sources in the OCCOC

- Largest E/A in shallowest shells BUT largest total energy in deepest shells.

Comparing OCCOC to ...

- Sources of the OCCOC are temporary and in AMPC permanent.
- Sink FA outer crust and OCCOC over neutron drip $\sim 7.5 \times 10^{45}$ erg
- Accreted material outer crust $\rightarrow 2.2 \times 10^{46}$ erg
  OCCOC $\rightarrow 1.3 \times 10^{46}$ erg (⚠ inner crust)
- Sink the OCCOC completely $\sim 4.3 \times 10^{47}$ erg



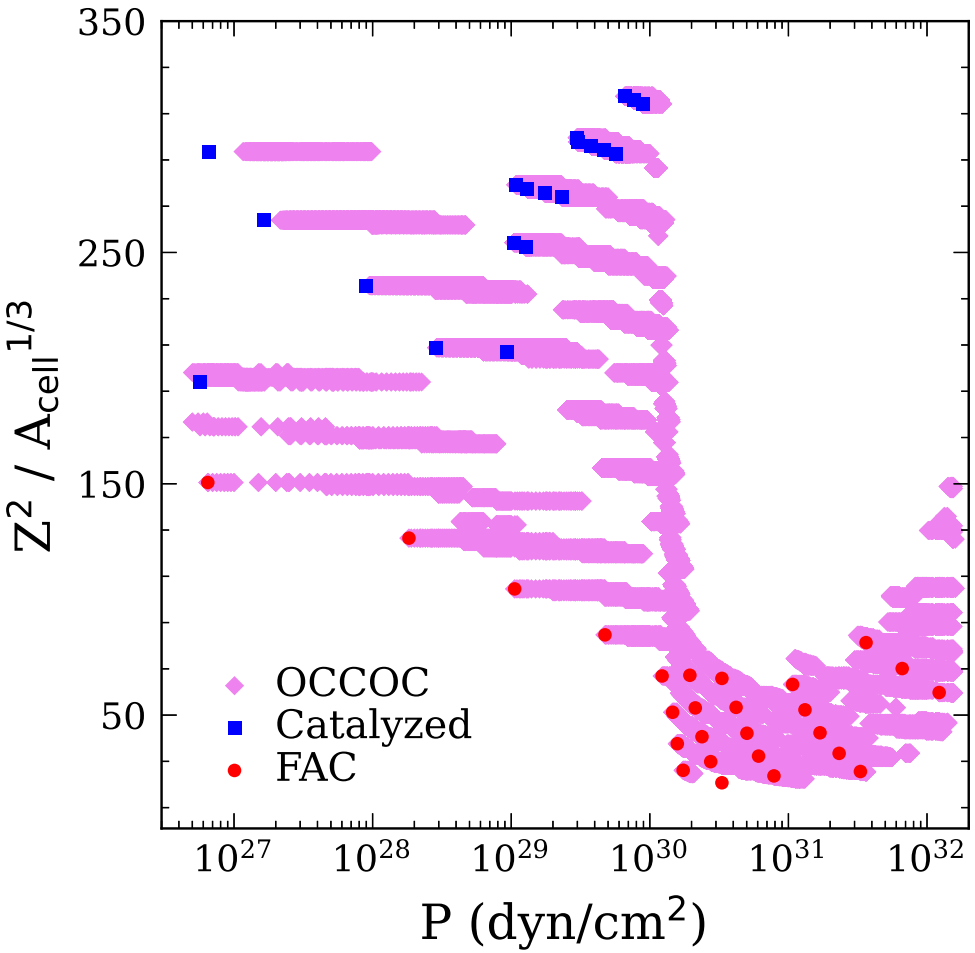
Crust properties of the OCCOC

Quantities $\propto Z^2/A_{\rm cell}^{1/3}$

- melting temperature: $T_m^{\rm FAC} < T_m^{\rm OCCOC}$
- shear modulus: $\sigma^{\rm FAC} < \sigma^{\rm OCCOC}$

Composition dependent quantities tha influence cooling and transport equations

- thermal conductivity,
- heat capacity.



Conclusion and open questions

Conclusions

- We computed the catalog of heat sources appearing in an originally catalyzed outer crust under compression.
- Heat sources of the compressed outer crust are not negligible compared to that of the accreted material part for low levels of accretion.
- Properties of the compressed crust are different from that of a catalyzed crust, and of the fully accreted crust.

Open discussion

- Neutron drip anomaly pushes for:
  - reevaluation of shells neutrons left
  - reevaluation of shells neutrons go to
- density inversion, source of swapping and gravitational release

LS, J. L. Zdunik, P. Haensel and M. Fortin, 2022, A&A, 662, A63