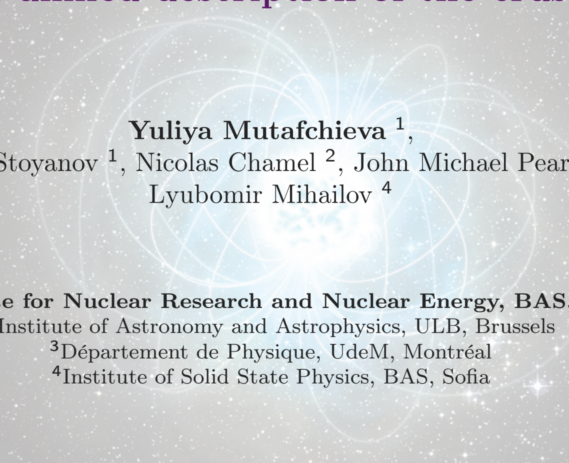
Magnetic field influence on magnetar crusts – a unified description of the crust



Yuliya Mutafchieva [1],
Zhivko Stoyanov [1], Nicolas Chamel [2], John Michael Pearson [3],
Lyubomir Mihailov [4]

[1]**Institute for Nuclear Research and Nuclear Energy, BAS, Sofia**
[2]Institute of Astronomy and Astrophysics, ULB, Brussels
[3]Département de Physique, UdeM, Montréal
[4]Institute of Solid State Physics, BAS, Sofia

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Magnetars

Magnetars:

- 29 sources classified as magnetars*: 15 SGRs (11 confirmed, 4 candidates), and 14 AXPs (12 confirmed, 2 candidate)
- observed surface magnetic fields up to $\sim 10^{15}$ G*
    - radio pulsars: typical surface magnetic fields of order 10^{12} G
- internal magnetic fields as high as 10^{18} G (according to numerical simulations)

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*McGill Magnetar Catalog [Olausen & Kaspi (2014) ApJS 212, 6]

Neutron star structure

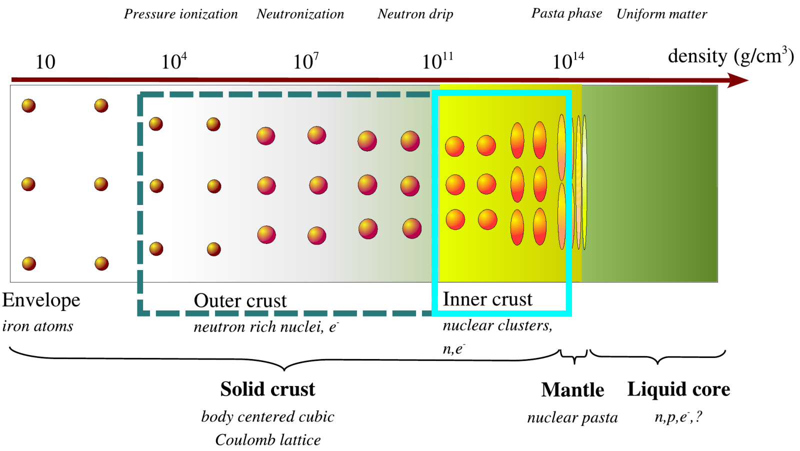


Figure from: *P. Haensel, A.Y. Potekhin, and D.G. Yakovlev, (2007) Neutron Stars 1: Equation of state and structure*

Outer crust model

Cold nonaccreting NS

We determine the equilibrium properties by minimising the Gibbs energy per nucleon, assuming:

- Matter: in ground state, at zero temperature, in a uniform magnetic field
- Atoms: fully ionized; in body-centred-cubic lattice
- Electrons: relativistic Fermi gas
- In each layer (pressure P): only a single species of nuclei ${}^{A}_{Z}X$
- Masses: 2016 Atomic Mass Evaluation (AME) data[⋆], complemented with the microscopic atomic mass model HFB-24

NC, et al. (2012) Phys Rev C, 86, 055804

[⋆] supplemented by recent measurements of copper isotopes [Welker A. et al., 2017, Phys. Rev. Lett., 119, 192502]

Outer crust model

Cold nonaccreting NS

$$g = \frac{\mathcal{E}+P}{n}$$

g – Gibbs free energy per nucleon
$\mathcal{E}$ – average energy density
P – total pressure
n – average nucleon number density

$$\mathcal{E} = n_N M'(Z,A) + \mathcal{E}_e + \mathcal{E}_L$$

$n_{\boldsymbol{N}} = n/A$ – number density of nuclei
$M'(Z,A)$ – mass of nuclei
$\mathcal{E}_{\boldsymbol{e}}$ – electron energy density
$\mathcal{E}_{\boldsymbol{L}}$ – lattice energy density

$$P = P_e + P_L$$

$P_{\boldsymbol{e}}$ – electron pressure
$P_{\boldsymbol{L}}$ – lattice pressure

$$\mathcal{E}_L(n_e), n_e(B_\star, \mu_e)$$

$n_{\boldsymbol{e}}$ – electron number density
$B_\star$ – magnetic field strength

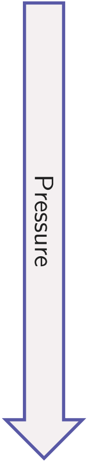
$$B_\star = B/B_{\rm crit}, \qquad B_{\rm crit} = \frac{m_{\boldsymbol{e}}^2 c^3}{e\hbar} \simeq 4.4 \times 10^{13}\ \mathrm{G}$$

The Gibbs free energy can be expressed as:

$$g = \frac{M'(A,Z)}{A} + \frac{Z}{A}\left(\mu_e - m_e c^2 + \frac{4}{3}\frac{\mathcal{E}_L}{n_e}\right)$$

Equilibrium composition

Outer crust results (AME2016⋆, HFB-24)



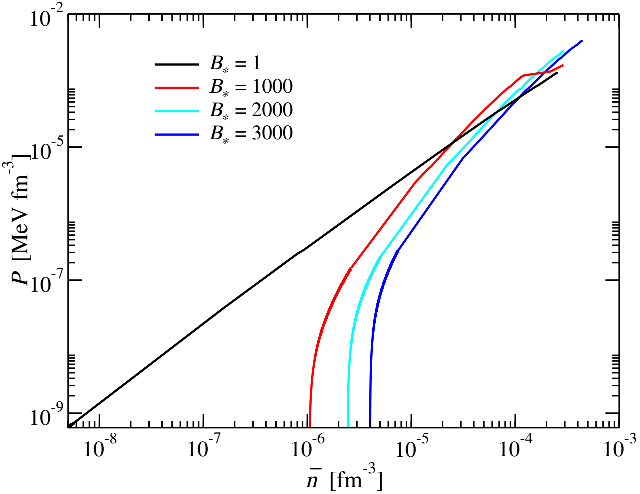
$B_\star = 1$	$B_\star = 1000$	$B_\star = 2000$	$B_\star = 3000$
$^{56}\mathbf{Fe}$	$^{56}\mathbf{Fe}$	$^{56}\mathbf{Fe}$	$^{56}\mathbf{Fe}$
$^{62}\mathbf{Ni}$	$^{62}\mathbf{Ni}$	$^{62}\mathbf{Ni}$	$^{62}\mathbf{Ni}$
$^{58}\mathbf{Fe}$	—	—	—
$^{64}\mathbf{Ni}$	$^{64}\mathbf{Ni}$	—	—
$^{66}\mathbf{Ni}$	—	—	—
—	$^{88}\mathbf{Sr}$	$^{88}\mathbf{Sr}$	$^{88}\mathbf{Sr}$
$^{86}\mathbf{Kr}$	$^{86}\mathbf{Kr}$	$^{86}\mathbf{Kr}$	$^{86}\mathbf{Kr}$
$^{84}\mathbf{Se}$	$^{84}\mathbf{Se}$	$^{84}\mathbf{Se}$	$^{84}\mathbf{Se}$
$^{82}\mathbf{Ge}$	$^{82}\mathbf{Ge}$	$^{82}\mathbf{Ge}$	$^{82}\mathbf{Ge}$
—	—	$^{132}\mathbf{Sn}$	$^{132}\mathbf{Sn}$
$^{80}\mathbf{Zn}$	$^{80}\mathbf{Zn}$	$^{80}\mathbf{Zn}$	—
—	—	$^{128}\mathrm{Pd}$	$^{128}\mathrm{Pd}$
—	—	$^{126}\mathrm{Ru}$	$^{126}\mathrm{Ru}$
$^{78}\mathrm{Ni}$	$^{78}\mathrm{Ni}$	—	—
$^{80}\mathrm{Ni}$	$^{80}\mathrm{Ni}$	—	—
$^{124}\mathrm{Mo}$	$^{124}\mathrm{Mo}$	$^{124}\mathrm{Mo}$	$^{124}\mathrm{Mo}$
$^{122}\mathrm{Zr}$	$^{122}\mathrm{Zr}$	$^{122}\mathrm{Zr}$	$^{122}\mathrm{Zr}$
$^{121}\mathrm{Y}$	$^{121}\mathrm{Y}$	—	—
—	—	$^{124}\mathrm{Zr}$	$^{124}\mathrm{Zr}$
$^{120}\mathrm{Sr}$	$^{120}\mathrm{Sr}$	$^{120}\mathrm{Sr}$	$^{120}\mathrm{Sr}$
$^{122}\mathrm{Sr}$	$^{122}\mathrm{Sr}$	$^{122}\mathrm{Sr}$	$^{122}\mathrm{Sr}$
$^{124}\mathrm{Sr}$	$^{124}\mathrm{Sr}$	$^{124}\mathrm{Sr}$	$^{124}\mathrm{Sr}$

⋆AME 2016 supplemented with copper measurements

Equation of state

Outer crust results (AME2016*, HFB-24)

The pressure as a function of the baryon number density for different B_*



$n_s \simeq 2.50 \times 10^{-10} B_\star^{6/5}\,\mathrm{fm}^{-3}$ – surface density; for $B_\star = 3000 \rightarrow n_s \simeq 3.27 \times 10^{-6}\,\mathrm{fm}^{-3}$

Inner crust model

Cold nonaccreting NS

Extended Thomas-Fermi+Strutinsky Integral (ETFSI) approach with the *same* functional as in the outer crust (BSk24) is used:

- **semiclassical expansion in powers of** $\hbar^2$: the energy becomes a functional of $n_n(r)$ and $n_p(r)$ and their gradients only
- **proton shell effects** are added perturbatively (neutron shell effects are much smaller and therefore neglected)

In order to further speed-up the calculations, the neutron-saturated clusters are supposed to be spherical (no pastas) and $n_n(r)$, $n_p(r)$ are parametrized.

Pearson, et al. (2018) Mon.Not.R.Astron.Soc. 481, 2994.
Pearson,Chamel,Goriely,Ducoin (2012) Phys.Rev.C 85, 065803.

Inner crust model

Cold nonaccreting NS

Determining the equilibrium properties by minimising the Gibbs free energy per nucleon at fixed pressure is numerically more delicate in the inner crust $\Longrightarrow$ minimising at fixed baryon number density

- for densities $\rho_{ND} \gtrsim 4 \times 10^{11}$ g cm^{-3}
- assuming a perfect crystal of nuclei embedded in a sea of electrons and unbound neutrons
- the nuclear clusters - unaffected by the presence of the magnetic field

Magnetic field influence: on the electron gas, using routines developed by *A. Y. Potekhin, G. Chabrier (2013) Astron. Astrophys. 550, A43*

Equilibrium composition

Inner crust results (BSk24)

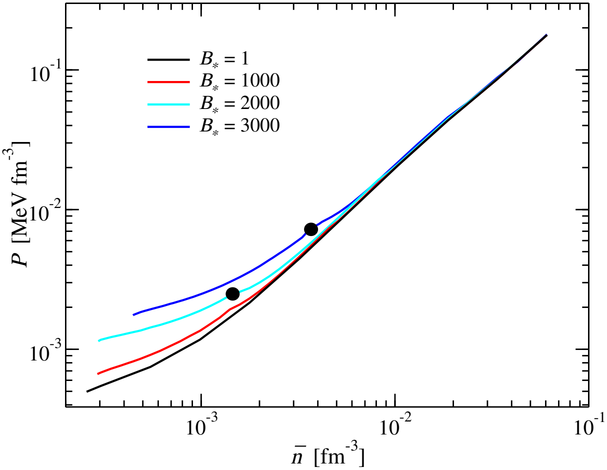
$\bar{n}$ [fm^{-3}]	$B_\star = 1$		$B_\star = 1000$		$B_\star = 2000$		$B_\star = 3000$	
	Z	N	Z	N	Z	N	Z	N
5.474×10^{-4}	40	182	41	174	40	185	49	141
9.864×10^{-4}	40	285	40	290	39	328	41	222
1.777×10^{-3}	40	413	40	409	41	421	40	381
3.203×10^{-3}	40	553	40	547	40	497	40	636
5.772×10^{-3}	40	697	40	687	40	679	40	651
1.040×10^{-2}	40	821	40	824	40	789	40	760
1.874×10^{-2}	40	934	40	954	40	988	40	1024
3.378×10^{-2}	40	1061	40	1067	40	1101	40	1045
6.087×10^{-2}	40	1185	40	1185	40	1196	40	1194

$\bar{n}$ – mean baryon number density

Equation of state

Inner crust results (BSk24)

The pressure as a function of the baryon number density



YM, et al. (2019) Phys Rev C, 99, 055805

Equilibrium properties - matching

Outer and inner crust results

Inner-crust (outer-crust) properties at the neutron-drip point

$B_\star$	$\bar{n}_{\rm drip}$ (fm^{-3})	Z	N	$e_{\rm drip}$ (MeV)	$P_{\rm drip}$ (MeV fm^{-3})
1000	2.91×10^{-4}	41 (38)	96 (86)	-2.17 (-2.25)	6.65×10^{-4} (6.56×10^{-4})
2000	2.95×10^{-4}	41 (38)	95 (86)	-3.82 (-3.90)	1.14×10^{-3} (1.15×10^{-3})
3000	4.45×10^{-4}	49 (38)	113 (86)	-3.85 (-3.92)	1.75×10^{-3} (1.74×10^{-3})

$\bar{n}_{drip}$ — drip-point density; $e_{\rm drip}$ — drip-point energy; $P_{\rm drip}$ — drip-point pressure

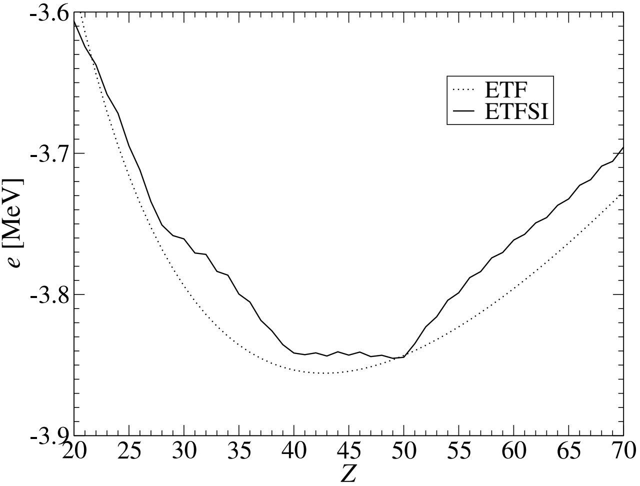
- the neutron-drip composition and the equation of state obtained for various magnetic-field strengths are compatible with those obtained using our outer crust code
- there is not a perfect matching since the outer and inner regions of the crust are described using different models

YM, et al. (2019) Phys Rev C, 99, 055805

Equilibrium properties

Inner crust results (BSk24)

The energy per nucleon at the neutron-drip point for $B_\star = 3000$



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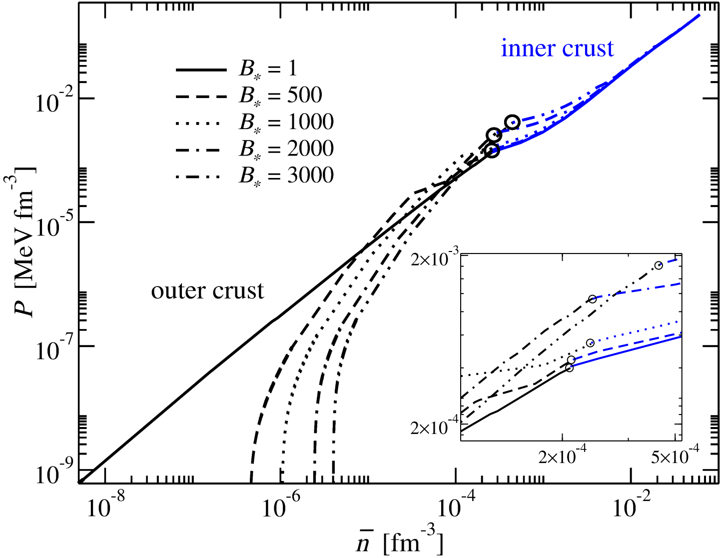
Equation of state - matching

Outer and inner crust results

The pressure as a function of the baryon number density



Conclusions and outlook

- Strong magnetic fields have significant influence on the outermost regions - EOS, composition
- Inner-crust EOS is weakly altered if the magnetic field lies below a few times 10^{16} G

But more work needs to be done...

Inner crust:

- neutron spin-polarization
- free protons region
- “pasta” phases
- ...

Core

→ Unified equation of state of the whole magnetar

Thank you for your attention

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