The unpairing effect in magnetars: cooling and rotational dynamics

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Magnetars - strongly magnetized compact stars :

- Can they be fundamentally different from NS on microscopic level ?
- New phases, new features ?
- Can we predict the observation manifestations of this novelty ?

Observations:

- Flares, quakes and (anti)-glitches (observed!)
- Sufrace B-fields $\sim 10^{15}$ G (inferred!)
- Gravitational wave from mountains (expected!)

Conjectures:

- The interior field can be by factors 10-100 larger than the surface B-fields
- For $B \sim 10^{16} - 10^{17}$ G the EM energy becomes of the order of the nuclear scale
- My focus here is: ———–-UNPAIRING EFFECT of B-FIELD —————

Pairing patterns in nuclear matter

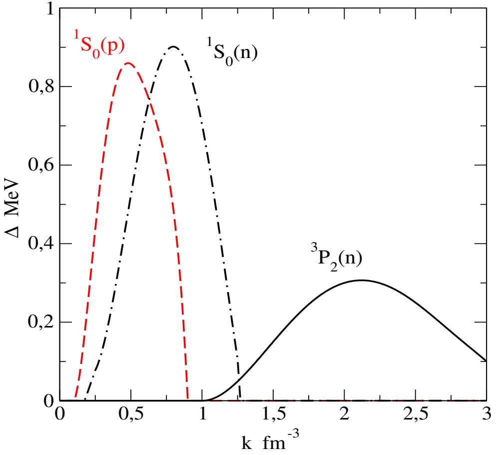


Figure : Neutrons $^1S_0$ (low density) and $^3P_2$ pairings (high density) Protons $^1S_0$ (always low density)

Basics of "unpairing effect"

- Coherence length of Cooper pairs

$$\xi_p \simeq \frac{\hbar^2 k_F}{\pi m^* \Delta} \gg \text{interparticle distance}$$

- Larmor radius:

$$R_L = \frac{c p_\perp}{eH}, \quad \text{for} \quad H \to \infty \quad R_L \to 0.$$

- Un-pairing sets in at a critical field H_{c2} when

$$R_L < \xi \quad \to \quad H_{c2} = \frac{\Phi_0}{2\pi\xi^2} \sim 10^{16}\,\mathrm{G}, \quad \Phi_0 = \frac{\pi\hbar c}{e}$$

- Because $H_{c2}(r) = H_{c2}(\rho)$:

for $H \leq \times 10^{15}$ fully s-conducting
for $H \geq 2 \times 10^{16}$ completely non-s-conducting
for $10^{15} \leq H \leq 2 \times 10^{16}$ partially s-conducting

EOS and composition

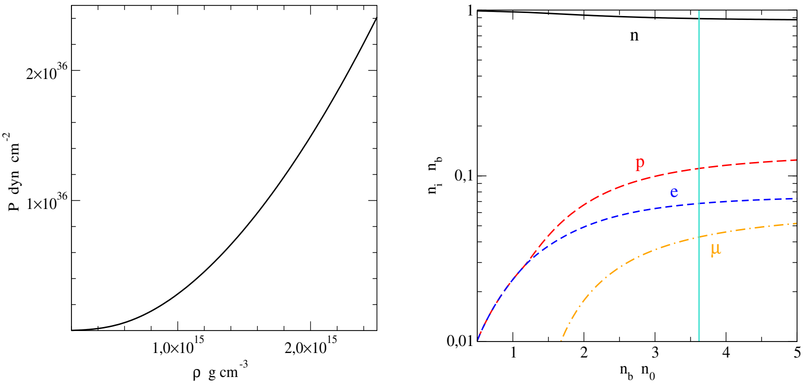


Figure : Left panel: Density-functional EOS of nuclear matter with producing $2M_\odot$ (Colucci and Sedrakian, 2013, 2014) Right panel: The abundances for n-p-e-μ matter. Vertical line is the Urca threshold

Ginzburg-Landau theory of neutron-proton mixture

Neutron ϕ and proton ψ condensate coupled to electromagnetism:

$$F[\phi,\psi] \quad = \quad F_n[\phi] + \alpha\tau|\psi|^2 + \frac{b}{2}|\psi|^4 + b'|\psi|^2|\phi|^2 + \frac{1}{4m_p}\left|\left(-i\hbar\boldsymbol{\nabla} - \frac{2e}{c}\boldsymbol{A}\right)\psi\right|^2 + \frac{B^2}{8\pi},$$

$$\delta F[\phi,\psi]/\delta\psi = 0, \quad \rightarrow \quad \frac{1}{4m_p}\left(-i\hbar\boldsymbol{\nabla} - \frac{2e}{c}\boldsymbol{A}\right)^2\psi + \alpha\tau\psi + b|\psi|^2\psi + b'|\phi|^2\psi = 0.$$

The equilibrium value of the condensate $\psi(\alpha\tau + b|\psi|^2 + b'|\phi|^2) = 0$, the two possible (normal-superconducting) equilibrium solutions

$$\psi = 0, \quad T > T_c, \qquad |\psi|^2 = -\frac{1}{b}(\alpha\tau + b'|\phi|^2), \quad T \le T_c.$$

The variation of the GL functional with respect to the electromagnetic vector potential $\delta F[\phi,\psi]/\delta\boldsymbol{A} = 0$ gives

$$\frac{c}{4\pi}\boldsymbol{\nabla}\times\boldsymbol{\nabla}\times\boldsymbol{A} = -\frac{i\hbar e}{m}\left(\psi^*\boldsymbol{\nabla}\psi - \psi\boldsymbol{\nabla}\psi^*\right) - \frac{4e^2}{mc}|\psi|^2(\boldsymbol{A}_{\rm em} + 2\boldsymbol{A}_{\rm ent}) = \boldsymbol{j}$$

The new aspect is the entrainment current $\propto \boldsymbol{A}_{\rm ent} \propto \boldsymbol{\nabla}\phi$.

For $H \to H_{c2}$ we have $\psi \to 0$ is small, therefore, linearize

$$\boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{A} = 0 + O(|\psi|^2).$$

$$\boldsymbol{\nabla} \times \boldsymbol{A}_{\text{ent}} = 0,$$

except at the singular points where the neutron vortices are located. Therefore,

$$\boldsymbol{A} \to \boldsymbol{A}_{\text{em}}$$

Consider the geometry

$$B \parallel z, \quad \boldsymbol{A}_{\text{em}} = Bx \parallel y, \quad \psi = \psi(x).$$

The GL equation becomes

$$\boxed{-\psi'' + \frac{4\pi^2}{\Phi_0^2} B^2 x^2 \psi = -\frac{4m_p}{\hbar^2}\left(\alpha\tau + b'|\phi|^2\right)\psi + O(|\psi|^2).}$$

Solution in analogy to the harmonic oscillator:

$$-\frac{4m_p}{\hbar^2}\left(\alpha\tau + b'|\phi|^2\right) = \left(n + \frac{1}{2}\right)\frac{4\pi B}{\Phi_0}.$$

We are interested in the strongest field for which solutions with $\psi \neq 0$ are still possible, then case $n = 0$ corresponds $B = H_{c2}$.

$$H_{c2} = \frac{\Phi_0}{2\pi}\left[-\frac{4m_p}{\hbar^2}\left(\alpha\tau + b'|\phi|^2\right)\right] = \frac{\Phi_0}{2\pi\xi_p^2}\left[1 + \frac{|b'||\phi|^2}{\alpha|\tau|}\right], \quad (m_p|\alpha\tau|)^{1/2} = \frac{\hbar}{2\xi_p}.$$

The correction comes from Cooper-pair $\rightarrow$ Cooper pair scattering (from Alford, Good, Reddy, 2005)

$$\frac{b'|\phi|^2}{\alpha\tau} = \frac{n_n}{n_p}\frac{|b'|}{|b|}, \qquad \frac{n_n}{n_p}\frac{|b'|}{|b|} = \frac{27\pi^2}{8}G_{np}\frac{n_n^2}{\mu_p^2\mu_n^2}\frac{\Delta_p^2}{m_p k_{F_p}}.$$

n_b/n_0	k_{Fp}	Δ_p	m_p^*/m_p	ξ_p	δ_L	κ	H_{c2}
0.140	0.12	0.02	0.93	76.1	929.2	12.2	0.06
0.300	0.20	0.24	0.89	11.9	425.0	35.6	2.73
0.700	0.36	0.76	0.81	7.8	161.1	20.6	6.25
0.900	0.44	0.85	0.78	8.7	119.5	13.7	4.75
1.300	0.58	0.81	0.74	13.0	75.2	5.8	2.01
1.700	0.74	0.62	0.70	22.8	51.2	2.2	0.64
1.900	0.81	0.45	0.68	35.0	44.3	1.3	0.27
2.100	0.88	0.16	0.67	106.4	39.2	0.4	0.03

Results for the critical field

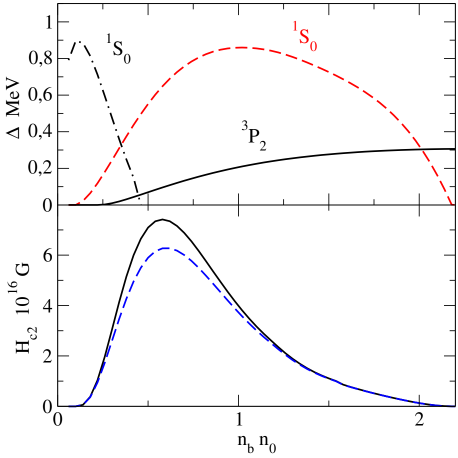
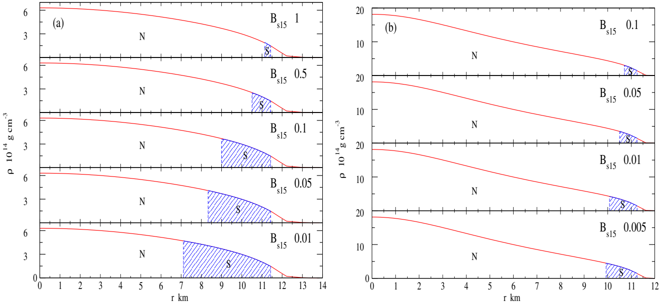


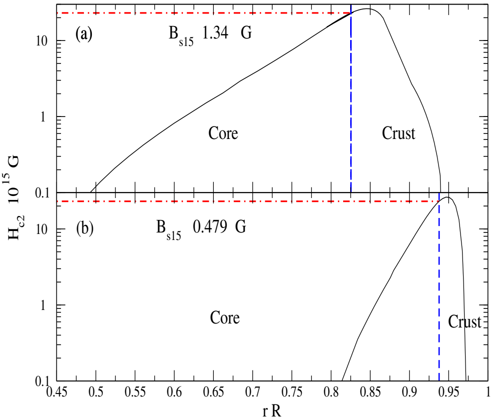
Figure : This H_{c2} takes into account the coupling the background neutron fluid in the framework of Ginzburg-Landau theory which gives 20% correction.

Region occupied by the superconducting core



Left panel: $1.4 M_{\odot}$ star internal structure with proton superconductor (shaded) core; right panel: the same for maximum mass star.

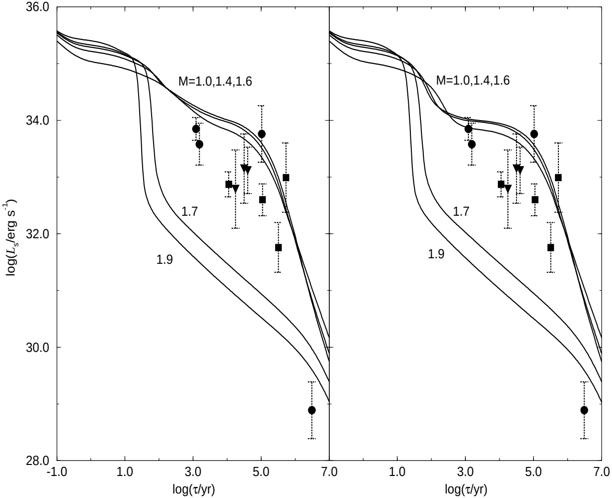
Critical field profile



Dependence of H_{c2} on internal radius for (a) 1.4 $M_{\odot}$, $R = 13.85$ km star and (b) maximum-mass $2.67 M_{\odot}$, $R = 11.99$ km star. The crust core interface (vertical dashed line) is located at 11.43 km for the first star and at 11.25 km for the second. The maximal value of Hc2 in each model is attained at the crust-core interface. and is indicated by the horizontal dash-dotted line; the values of the corresponding surface fields are shown in the plot

II. Cooling processes

General picture



Cooling curves displaying three regions of distinct cooling: (a) initial non-isothermal core regime; (b) the isothermal neutrino cooling regime; (c) the photon cooling regime.

Pair-breaking processes

The condensates support processes

$$[NN] \to [NN] + \nu + \bar{\nu}, \quad [NN] \ldots$$

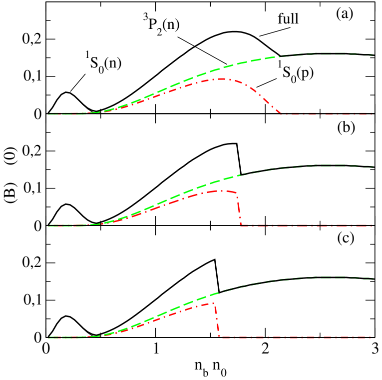


Figure : Red protons, green neutrons, black - total emissivity of pair-breaking processes

Urca process

In the strong B-field the Urca constraint is kinematically lifted

… forbidden if … < 11%, but allowed in … B − fields

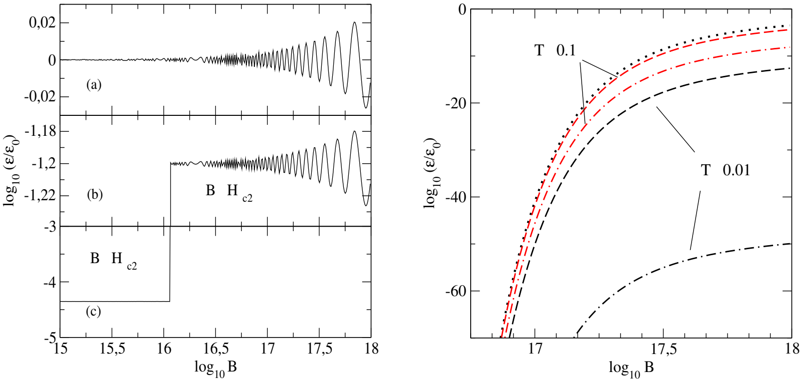


Figure : Left panel: allowed regime; Right panel: forbidden regime.

III. Rotational dynamics

Low-field pulsars

$$\textit{electrons} + \underbrace{\textit{proton} - \textit{flux} - \textit{tubes} + \textit{neutron} - \textit{vorticity}}_{\textit{strongly coupled}}$$

Scattering is electromagnetic Core is slowly responding to glitches producing part of post-glitch relaxation (Sedrakian et al, ApJ, vol. 447, pp. 305 and 324).

High-field pulsars

$$\underbrace{\textit{electrons} + \textit{proton} - \textit{plasma}}_{\textit{strongly coupled}} + \textit{neutron} - \textit{vorticity}$$

Strong force is at work (Sedrakian, Phys. Rev. D 58, 021301(R)).

Scattering of proton quasiparticles in the continuum off the cores of neutron vortices strongly temperature dependent

Dynamical coupling times

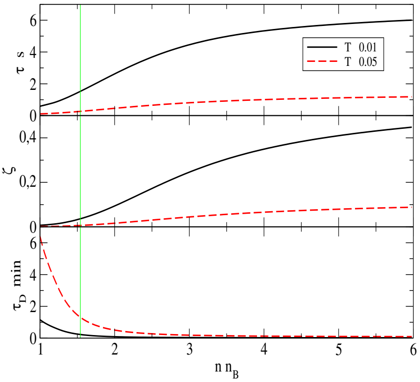
If protons are normal they couple to the neutron quasiparticles in the cores of neutron vortices via the strong force:

$$\tau^{-1} = 13.81 \times n_V \left(\frac{\mu_n}{\mu_p}\right)^2 \frac{T}{\varepsilon^0_{1/2}} \times e^{-\frac{\varepsilon^0_{1/2}}{T}} \frac{\hbar}{m_p^* \xi_n^2} \frac{d\sigma}{d\Omega}$$

Microscopic times-scales are of order of sec.

$$\eta = \frac{m_p^* n_p}{\tau_v n_V},$$

Drag-to-lift ratio and dynamical coupling time x



$$\zeta = \frac{\eta}{\rho_n \omega_0} = \frac{1}{2\Omega\tau_v}\frac{n_p}{n_n}, \qquad \tau_D = \frac{1}{2\Omega}\left(\zeta + \varsigma \quad\right).$$

Summary

Magnetars are non-superconducting! *...at least partially*

Urca process in largely un-suppressed

Magnetar cores are coupled to the star on short time-scales

Publications in collab. Monika Sinha (IIT, Jodpur)
Phys. Rev. C 91, 035805 (2015); (arXiv:1502.02979)
El. Part. and Atom. Nuclei Lett., in press (arXiv:1403.2829)

Thank you for your attention!