Constraints on the dense matter EoS from young and cold isolated NSs

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P-Pdot diagram for isolated neutron stars

- Magnetar-like emission
- XDINSs
- CCOs
- Rotation-powered
- ATNF Radio Pulsars

![P-Pdot diagram](image)

- Period derivative ($10^{-11}$ s/$s$)
- Spin Period (s)
- Surface dipolar B-field at pole ($10^{14}$ Gauss)
P-Pdot diagram for isolated neutron stars

Rotation-Powered Pulsars

Powered by rotational energy.
Typically emitting in radio.
Central Compact Objects

Powered by magnetic energy. Young, with bright SNRs. Typically emitting in the X-rays.

Rotation-Powered Pulsars

Powered by rotational energy. Typically emitting in radio.
P-Pdot diagram for isolated neutron stars

- Magnetar-like emission
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**X-rays Dim Isolated NSs**

Powered by magnetic energy. Old, almost pure blackbodies. Typically emitting in the X-rays.

**Central Compact Objects**

Powered by magnetic energy. Young, with bright SNRs. Typically emitting in the X-rays.

**Rotation-Powered Pulsars**

Powered by rotational energy. Typically emitting in radio.
Magnetars

Powered by magnetic energy. Characterized by outbursts and flares. Typically emitting in X-rays.

X-rays Dim Isolated NSs

Powered by magnetic energy. Old, almost pure blackbodies. Typically emitting in the X-rays.

Central Compact Objects

Powered by magnetic energy. Young, with bright SNRs. Typically emitting in the X-rays.

Rotation-Powered Pulsars

Powered by rotational energy. Typically emitting in radio.
Thermal luminosity versus age to test NS EoS

4 independent parameters: thermal luminosity, real age, period and period derivative

70 sources
(isolated, X-ray emitting NS)
(Observed with Chandra or XMM)

(Dehman et al. 2024 in prep)
To constrain EoS via cooling of isolated NSs we need to find extreme sources. Three very young and cold sources stand out from the rest of the group.
Three cold, young and isolated NSs

- PSR J0205+6440
  - Rotation-Powered Pulsar (P=0.06 s);
  - Chandra data;
  - Historical SN 1181 -> 839 yrs
  - D=2.0+/-0.3 kpc (Ranasinghe+2022)

- PSR B2334+61
  - RPP(P=0.49 s);
  - XMM-Newton data;
  - SNR G114.3+0.3 -> 7700 yrs, Yar-Uyaniker+2004);
  - D=2-3 kpc (McGowan+2006) or <700 pc, Ranasinghe+2022)

- CXOU J0852+4617
  - Central Compact Object;
  - Chandra data;
  - Associated to the SNR Vela Jr ->2.5-5 kyrs, Allen+2015;
  - D=0.5-1 kpc (Allen+2015);

How can we explain their being so young and yet so cold?
**Neutron star cooling**

\[ c_V(T) \frac{\partial (Te^\nu)}{\partial t} = \nabla \cdot (e^\nu \kappa \cdot \nabla (e^\nu T)) + e^{2\nu}(Q_j - Q_\nu) \]

**Ingredients:**

- Neutron star model: EoS + central pressure \( \rightarrow \) star structure & composition (fixed)
- Heat capacity \( C_V(\rho, T) \): main contribution by neutrons in the core
- **Thermal conductivity** \( \kappa(\rho, T, B) \) very large (star core rapidly isothermal), dominated by electrons, becomes **anisotropic** in presence of magnetic field
- Neutrino emissivity \( Q_\nu(\rho, T, B) \)
- Sources of internal heat \( Q_j \): nuclear reactions, **Ohmic dissipation**, accretion...
- Hydrostatic equilibrium models of envelope (i.e., liquid outermost 100 m), that due to its stronger gradients of density and temperature has much faster timescales than the interior
- Emission model (atmosphere, **blackbody**, condensed surface...)

[Potekhin et al. 2015, review]

[https://compose.obspm.fr/](https://compose.obspm.fr/)
Magnetic field evolution

- Neutron stars interior: complex multi-fluid system

- A solid crust is formed soon after birth; restricted nuclei mobility; conduction governed by electrons

- Core: full multi-fluid system

- Approximation: electrons MHD limit in the crust (eMHD)

\[
\frac{\partial \mathbf{B}}{\partial t} = - \nabla \times \left[ \frac{c^2}{4\pi \sigma_e} \nabla \times (e^\nu \mathbf{B}) + \frac{c}{4\pi en_e} \left[ \nabla \times (e^\nu \mathbf{B}) \right] \times \mathbf{B} \right]
\]

- Crustal-confined (perfect conductor at the crust-core interface).

- Potential boundary conditions (i.e. no current, \(\nabla \times \mathbf{B} = 0\)) - better force-free magnetosphere.

[Please note that the equation provided is a simplified representation of the full eMHD equations, which are more complex and involve additional terms for the fluid dynamics of the plasma.]

[Ohmic dissipative term: the magnetic resistivity is very sensitive to temperature evolution and electron density.

Hall drift term: It naturally creates magnetic discontinuity, and transfers energy between different scales.]

[Pons et al. 2019, review]
Cooling model: neutrino vs photon cooling stages

Neutrino cooling dominates during the first 10-100 kyr: the star cools from inside.

Photon cooling dominates when the star is cold enough, so that neutrino production is much less efficient, and heat is mostly transferred to the surface and radiated.

Isolated neutron stars are X-ray bright because they are born hot, visible as thermal emitters.

For magnetars at least, need for extra heating.
### Neutrinos Reactions

#### Core

<table>
<thead>
<tr>
<th>Process</th>
<th>$Q_\nu$ [erg cm(^{-3}) s(^{-1})]</th>
<th>Onset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modified Urca (n-branch)</td>
<td>$8 \times 10^{21} \mathcal{R}_n^{MU} n_p^{1/3} T_9^8$</td>
<td>$Y_p^c = 0.01$</td>
</tr>
<tr>
<td>$nn \rightarrow pnev_\nu, pne \rightarrow nnv_\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modified Urca (p-branch)</td>
<td>$8 \times 10^{21} \mathcal{R}_p^{MU} n_p^{1/3} T_9^8$</td>
<td></td>
</tr>
<tr>
<td>$np \rightarrow ppev_\nu, ppe \rightarrow npv_\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N-N bremsstrahlung</td>
<td>$7 \times 10^{19} \mathcal{R}_n^{nn} n_n^{1/3} T_9^8$</td>
<td></td>
</tr>
<tr>
<td>$nn \rightarrow nnv_\nu$</td>
<td>$1 \times 10^{20} \mathcal{R}_p^{np} n_p^{1/3} T_9^8$</td>
<td></td>
</tr>
<tr>
<td>$np \rightarrow npv_\nu$</td>
<td>$7 \times 10^{19} \mathcal{R}_p^{pp} n_p^{1/3} T_9^8$</td>
<td></td>
</tr>
<tr>
<td>e-p Bremsstrahlung</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$ep \rightarrow epv_\nu$</td>
<td>$2 \times 10^{17} n_p^{-2/3} T_9^8$</td>
<td></td>
</tr>
<tr>
<td>Direct Urca</td>
<td>$4 \times 10^{27} \mathcal{R}_U^{DU} n_e^{1/3} T_9^6$</td>
<td>$Y_p^c = 0.11$</td>
</tr>
<tr>
<td>$n \rightarrow pev_\nu, pe \rightarrow n_\nu\nu$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$n \rightarrow p\mu^- \bar{\nu}<em>\mu, p\mu^- \rightarrow n</em>\nu\mu$</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Crust

<table>
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<th>Process</th>
<th>$Q_\nu$ [erg cm(^{-3}) s(^{-1})]</th>
<th>Onset</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pair annihilation</td>
<td>$9 \times 10^{20} F_{pair}(n_e, n_{e^+})$</td>
<td></td>
</tr>
<tr>
<td>$ee^+ \rightarrow \nu\bar{\nu}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Plasmon decay</td>
<td>$1 \times 10^{20} I_{pl}(T, y_e)$</td>
<td></td>
</tr>
<tr>
<td>$\Gamma \rightarrow \nu + \bar{\nu}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$e$-nucleus Bremsstrahlung</td>
<td>$3 \times 10^{12} L_{eN} Z \rho_0 n_e T_9^6$</td>
<td></td>
</tr>
<tr>
<td>$N - N$ Bremsstrahlung</td>
<td>$7 \times 10^{19} R_{NN} f_v n_n^{1/3} T_9^8$</td>
<td></td>
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</table>

#### Core and crust

- **Cooper Pair Breaking and Formation (CPBF)**
  - $\tilde{B}\tilde{B} \rightarrow \nu\bar{\nu}$
  - $1 \times 10^{21} n_N^{1/3} F_{AB} T_9^7$

- **Electron Synchrotron**
  - $e^B \rightarrow e\nu\bar{\nu}$
  - $9 \times 10^{14} S_{AB,BC} B_{13}^2 T_9^5$
Magneto-thermal simulations for NS cooling

Different cooling curves playing with these parameters

- **B-field poloidal strength:** \((1, 3, 5, 7, 10, 20, 50, 70) \times 10^{12} \) G (No toroidal field)
- **Mass:** \((1.4, 1.6, 1.8)\) solar mass
- **EoS:** (SLy4, BSK24, GM1A (+SLy4))

Nucleonic EoS
- Nucleonic EoS (high proton fraction)

Nucleonic & Hyperonic EoS

81 possible cooling histories for each NS!
Cooling curves for different EoSs

SLy4
(Nucleonic EoS)

BSK24
(Nucleonic EoS)

GM1A
(Nucleonic + Hyperonic EoS)
Cooling curves for different EoSs

SLy4
(Nucleonic EoS)

BSK24
(Nucleonic EoS)

GM1A
(Nucleonic + Hyperonic EoS)
Cooling curves for different EoSs and B-fields

- $M = 1.8 M_\odot$
- $M = 1.6 M_\odot$
- $M = 1.4 M_\odot$

Thermal luminosity, $L_{\text{th}}$ (erg s$^{-1}$)

Magnetic field, $B_p$ (Gauss)

Cooling curves for different EoSs and B-fields
Comparison with observed luminosities

A single suitable EoS should explain all NSs.

First direct measurement of enhanced cooling.
Comparison with observed period and derivatives

- Rotation-powered pulsars
- Central compact objects
- ATNF radio pulsars

Period derivative, $\dot{P}$ (s s$^{-1}$)

Magnetic field, $B_p$ (Gauss)

Spin period, $P$ (s)
Machine learning approach
Conclusion

● Neutron stars are unique laboratories to constrain dense matter equation of state

● They require an inter-disciplinary approach, in this case spanning from observations, numerical simulations, nuclear astrophysics and machine learning analysis.

● We found that three known neutron stars cannot be explained by «minimal» cooling scenarios, and required the presence of a fast cooling mechanism active at early ages.

● Recent studies involving meta-modelling of a large sample of EoS (Margueron et al. 2018) points out that only 25% percent of the commonly used EoS do activate fast cooling at least for certain high masses.
Backup slides
Why did we exclude PSR B0656+14?
Considering all possible factors
On age and distance estimates

1) We consider only sources where the real age is known, typically from studies of their associated Supernova Remnant (SNR).

1) We consider only sources with solid measurements of the distances, either from kinematic studies of the SNR, HI measurements or proper motion.

- A more general picture will be presented in Dehman+2024 (in prep.)
Data analysis

70 sources
Sample of all the known X-rays emitting isolated NSs.

Source selection

Data reduction

Spectral analysis

A simple spectral modeling
Using Xspec, we described the spectra using blackbody, atmospheric emission, power-law or a combo of these components;

XMM-Newton and Chandra archival data
We only used data from these sensitive X-rays observatories.

Thermal flux estimation
We then calculated the flux emitted by the thermal component (if present)
Spectral emission from these sources

- PSR J0205+6440 emission is dominated by a power-law component due to the nebula contribution; it however has a small (but significant) thermal contribution (see also Slane+2004).
- PSR B2334+61 and CXOU J0852-4617 emission is purely thermal.

**Models used:** bbodyrad, nsa (thermal), powerlaw (non-thermal)
A hidden contribution from the whole NS surface?

- What if interstellar absorption was covering an additional thermal contribution from the whole surface?
- We calculated an upper limit to the additional thermal luminosity we might have missed coming from the whole NS surface;
A Machine Learning approach

- We consider the two pulsars and run our simulations in a 4D-space including $P$, $P_{\text{dot}}$, $L_{\text{th}}$, and $t$. 
A ML approach: Results II

- **SLy4** is not supported by any of the sources ($P < 0.05$)... 
- ...independently of adding the age information 
- **$B_p$** and **$M$** are estimated 
- Promising for applying the method in larger samples 
- The method can be applied to other studies