THERMAL EVOLUTION OF ISOLATED AND ACCRETING NEUTRON STARS... AND MORE

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INT workshop Astro-solids
April 18, 2018
Thermal evolution of isolated and accreting neutron stars
Cooling of isolated NSs

\[ t = 0: \ T \sim 10^9 - 10^{10} \text{ K.} \]

\[ t \lesssim 10^2 \text{ years} \]
- the core cools by \( \nu \)-emission,
- the crust by heat diffusion.
\[ \rightarrow \text{ crust properties.} \]

\[ t \lesssim 10^5 \text{ years} \]
- thermal balance between the core and the crust,
- cooling by \( \nu \)-emission;
\[ \rightarrow \text{ core properties.} \]

\[ t \gtrsim 10^5 \text{ years} \]
- cooling via emission of photons from the surface.
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\[ C(T_i) \frac{dT_i}{dt} = -L_\nu(T_i) - L_\gamma(T_s) + \underbrace{L_h}_0. \]

with \( T_i = T e^\phi \) and \( T_s(T_i) \) is given by a model for the heat blanketing envelope.
Observations of isolated NSs

Biases

- small objects: detection of NSs with $T \sim 10^5 - 10^7$ K within few kpc
- middle-aged NSs with extended supernova remnant.

Age and temperature determination

- age: uncertain unless the supernova as been observed in the past (cf. Crab pulsar): estimation from spin-down or modelling the expansion of the supernova.
- temperature: composition of the envelope unknown: H, He, ... Fe?

Observational data

X-ray telescopes eg. XMM-Newton, Chandra, Athena, ...

Heat equation

All observed NSs are in the core and photon dominated stages $\rightarrow$ dependence on core and envelope properties.

$$C(T_i) \frac{dT_i}{dt} = -L_\nu(T_i) - L_\gamma(T_S).$$
Neutrino emission

See eg. Table 1 of Potekhin et al. SSR (2015) - arXiv:1507.06186

Slow processes with $Q_{\nu} \propto T^8$

▶ modified Urca
\[ n + N \rightarrow p + N + l + \nu_l \]
with $N$ a spectator nucleon to ensure momentum conservation.

▶ NN-bremsstrahlung
\[ N + N \rightarrow N + N + \nu_l + \bar{\nu}_l \]

Fast process: direct Urca with $Q_{\nu} \propto T^6$
\[ n \rightarrow p + l + \bar{\nu}_l \]
with $l = e^-, \mu^-$. Momentum conservation imposes EOS-dependent density/mass threshold above which it operates.

Non-superfluid NSs

Two EOS, one allowing for DURCA.

▶ Hot (luminous) objects: low-mass NSs;
▶ Cold objects: high-mass NSs.
Thermal evolution of accreting NSs

Soft X-ray Transients

NSs in close binaries with a low-mass companion undergoing:

- repeated short periods of accretion;
- long quiescent phases.

Observations

Thermal equilibrium

Quasi-stationary state:

\[ C(T_i) \frac{dT_i}{dt} = -L_\infty(T_i) - L_\gamma(T_s) + L_h. \]

Heating

During the accretion phases, deep crustal heating.

\[ L_\infty = L_{\text{DCH}}(\langle \dot{M} \rangle) \]

with \( \langle \dot{M} \rangle \) estimated, averaged over periods of accretion and quiescence.

Ingredients

- Properties of the core: EOS and baryon superfluidity
- envelope models.

Figure showing a plot of \( \log_{10} L_\gamma \) vs. \( \log_{10} \dot{M} \) with data points and arrows indicating direction of change.

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Modelling

Thermal equilibrium

Quasi-stationary state:

\[ C(T_i) \frac{dT_i}{dt} = -L_\infty^{\nu}(T_i) - L_\infty^{\gamma}(T_s) + L_D^{\infty}(\langle \dot{M} \rangle). \]

Constraints

Low photon luminosity:

- very high \( \nu \) losses i.e. large \( L_{\nu} \);
- the most efficient \( \nu \)-process DURca is necessary: not all EoS allow for it.
- necessary to go beyond the minimal cooling model
Thermal evolution of isolated and accreting NSs

eg. Levenfish & Haensel (2007), Beznogov & Yakovlev (2015a,b)


- BHF EOS of Taranto et al. 2016 (AV18+Urbana) with a DURCA onset at $1.1M_\odot$
- two limiting models of envelope (non-accreted - blue and fully-accreted - red) from Potekhin et al. (2003)

Non superfluid matter

Consistent with the coolest SXT but not the middle-aged hot INS + problematic mass distribution (see also Beznogov & Yakovlev (2015a,b))
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Zhou et al. (2004): calculated with the same nucleon interaction as the EOS.

SPF*: BHF approximation for the SP potential.

When $T \leq T_c$, formation of Cooper pairs $\rightarrow$ superfluidity.

DURCA threshold
Superfluidity (SPF)

- Zhou et al. (2004): calculated with the same nucleon interaction as the EOS.
- SPF *: BHF approximation for the SP potential.

When $T \leq T_c$, formation of Cooper pairs $\rightarrow$ superfluidity.

- exponentially suppresses of all reactions involving the SPF baryons;
- broadens the onset of the DURCA threshold.
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When $T \leq T_c$, formation of Cooper pairs $\rightarrow$ superfluidity.

- exponentially suppresses of all reactions involving the SPF baryons;
- broadens the onset of the DURCA threshold.
- initiates a new neutrino processes: "PBF" (pair breaking and formation processes): $B \rightarrow B + \nu + \bar{\nu}$; $Q_{\nu} \propto T^7$ very strongly reduced for $^1S_0$ pairing by in-medium effects, $\Rightarrow$ only operating for $^3P_2$ neutron pairing.

Cooling curves (similar trends for SXTs)
Thermal evolution of isolated and accreting NSs


- BHF EOS of Taranto et al. 2016 (AV18+Urbana) with a DURCA onset at $1.1M_\odot$
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SPF gaps consistent with the EOS

- smooth mass distribution
- but too strong SPF reduction of the DURCA process and PBF processes.
Thermal evolution of isolated and accreting NSs

- BHF EOS of Taranto et al. 2016 with a DURCA onset at $1.1M_{\odot}$
- SPF gaps calculated with the same nucleon interaction
- two limiting models of envelope (non-accreted - blue and fully-accreted - red)

Consistency with the data

- middle aged INSs and hot SXTs = low-mass NSs where proton SPF suppresses slow $\nu$-processes and no neutron SPF hence no PBF process.
- cold SXTs = massive NSs with fully operating DURCA process: protons and neutrons not superfluid at the center of massive stars
- smooth mass distribution: protons and neutrons SPF at the center of medium-mass NSs.

see also Beznogov & Yakovlev (2015a,b), Han & Steiner PRC (2017)
Conclusions

- joint modeling of INSs and SXTs required;
- modeling of SXTs indicates that the DURCA is required: go beyond the minimal cooling model + constrain on the EOS;
- some general trends on baryon SPF can be derived;
- more observations of INSs and SXTs;
- determination of the mass of some of these NSs.
- consistent calculations of the EOS and the SPF gaps.
...and more: (hyper)nuclei and neutron stars
Hyperonic equations of state

Hyperons ($Y$)

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Structure

Density

Equation of state

$P (\text{MeV} \text{ fm}^{-3})$

$\rho (\text{MeV} \text{ fm}^{-3})$

$\rho_0 \simeq 3 \times 10^{14} \text{ g cm}^{-3}$
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$M - R$ plot

Equation of state

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$M - R$ plot

Observational constraint:

- each EoS has a maximum mass $M_{\text{max}}$;
- $M_{\text{max}}$ reduced when $Y$ are included;
- consistency with the observations: $M_{\text{max}} \geq M_{\text{obs}}^{\text{max}}$;
- Largest masses observed: PSR J1614-2230 & PSR J0348+0432
  
  \[ M_{\text{obs}}^{\text{max}} \approx 2 \, M_{\odot}. \]
- Hyperon puzzle: Can hyperons be present in NSs and yet $M_{\text{max}} \geq 2 \, M_{\odot}$?
Experimentally calibrated hyperonic EoS

Experimental properties of hypernuclei

Gal et al., RMP (2016)

- $\sim 40$ $\Lambda$-hypernuclei
  + measurement of binding energy
- only one unambiguous $\Lambda\Lambda$-hypernuclei:
  measurement of the bond energy:
  \[ \Delta B_{\Lambda\Lambda}(^6\text{He}) = 0.67 \pm 0.17 \text{ MeV}. \]
- few $\Xi$-hypernuclei
  but no measurement of binding energy
- no $\Sigma$-hypernuclei
  repulsive $\Sigma$-nucleon interaction?

Usual approach to hyperons

Adjust the couplings for the $\Lambda$ to reproduce:

- the $\Lambda$-potential in symm. NM $U^N_{\Lambda}(n_0)$
- the $\Lambda$-potential in pure $\Lambda$ matter $U^\Lambda_{\Lambda}(n_0)$ or $U^\Lambda_{\Lambda}(n_0/5)$

Fortin, Avancini, Providência, Vidaña, PRC 95 (2017)

RMF models (TM1, TM2$\omega\rho$, NL3, NL3$\omega\rho$, DDME2) + modeling of hypernuclei

Experimentally calibrated potentials

- $U^N_{\Lambda}(n_0) \in [-36, -30]$ MeV
  usually (-30, -28) MeV
- $U^\Lambda_{\Lambda}(n_0) \in [-14, -9]$ MeV
- or $U^\Lambda_{\Lambda}(n_0/5) \in [-6, -5]$ MeV
  usually (-5, -1) MeV

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Define two limiting hyperonic NS EOS:

- ’minimal hyperonic model’: only \( \Lambda \) included, calibrated to hypernuclear data.
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- ’maximal hyperonic model’: \( \Sigma \) and \( \Xi \) included in addition
  - with \( U^N_{\Xi}(n_0, 2/3n_0) = -14 \text{ MeV} \)
  - suggested by experiments
  - \( U^N_{\Sigma}(n_0) = 0, 30 \text{ MeV} \)
  - without \( \sigma^* \) and \( \phi \)-mesons.
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$\rightarrow \Delta M_{\max} \simeq 0.2 M_{\odot}$.

$\rightarrow$ consistency with $2 M_{\odot}$ for DDME2 and DD2 (Fortin+ arXiv:1711.09427 + finite-$T$)

$\rightarrow$ if SU(6) symmetry broken?
  $\Delta M_{\max} \sim 0.4 M_{\odot}$ . . .
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\[ \text{if SU(6) symmetry broken?} \]
\[ \Delta M_{\text{max}} \approx 0.4 M_\odot \ldots \]

How to reduce \( \Delta M_{\text{max}} \)?

- experimental constraints on the \( \Xi \) and \( \Sigma \) hyperons
- astrophysical constraints?

Hyperons in NSs NOT ruled out by the observations of 2 \( M_\odot \) PSRs.
Approximate formula for the radius and crust thickness


- All you need is . . . : the core EOS down to a chosen density \( n_b \) with \( \mu(n_b) = \mu_b \).
- Obtain the \( M(R_{\text{core}}) \) relation solving the TOV equations.
- Obtain \( M(R) \) with
  \[
  R = R_{\text{core}} \left/ \left( 1 - \left( \frac{\mu_b^2}{\mu_0^2} - 1 \right) \left( \frac{R_{\text{core}} c^2}{2GM} - 1 \right) \right) \right. \]

2 unknowns

- \( \mu_0 = 930.4 \, \text{MeV} \) - minimum energy per nucleon of a bcc lattice of \( ^{56}\text{Fe} \).
- \( \mu_b \) at the core-crust transition? For \( L \in [30, 120] \, \text{MeV}, \; n_b \in [0.06, 0.10] \, \text{fm}^{-3} \) (Ducoin+ PRC 2011)
  - \( \mu_b = (P + \rho)/n \) at \( n_0/2 = 0.08 \, \text{fm}^{-3} \)

Results

- \( \Delta R \lesssim 0.2\% \) for \( M > 1 \, M_\odot \)
- \( \Delta l^{\text{cr}} \lesssim 1\% \) for \( M > 1 \, M_\odot \)

+ Formulas for NSs with an accreted crust.

TOV solution for the unified EoS, for the core EOS
Approximate \( M(R) \)
Mirror nuclei and NS radii

Yang & Piekarewicz PRC (2018)

\[ R_{\text{mirr}}(Z, N) = R_p(N, Z) - R_p(Z, N) \]

- inspired by Brown PRL (2017) for Skyrme models
- 14 RMF models
- \( R_{\text{mirr}}(^{50}\text{Ni-Ti}) \): correlated with the radius of low-mass stars.

Fortin, Providência, Pais, in prep.

- 9 out of 14 RMF models
- Unified EOSs
- Approximate approach

EOS construction


- outer crust from BPS
- core down to the core-crust transition density from RPA
- in between polytrope with \( \Gamma = 4/3 \).

More correlations studied employing \( \sim 50 \) EOS. Stay tuned!

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- modeling of SXTs indicates that the DURCA is required: go beyond the minimal cooling model + constrain on the EOS;
- some general trends on baryon SPF can be derived;
- more observations of INSs and SXTs;
- determination of the mass of some of these NSs.
- consistent calculations of the EOS and the SPF gaps.

- Fortin et al. PRC 94 (2017): hyperonic RMF EoSs consistent by the existence of $2M_\odot$ NSs.
- More experimental constraints for hyperons necessary to reduce the $\Delta M_{\text{max}}$.
- Be careful when gluing an EoS for the core to one for the crust!
- Use unified EoS:
  - Fortin et al. PRC 94 (2016): 48 unified nucleonic and hyperonic EoSs as supplemental material + confrontation with nuclear constraints.
- Fortin, Providência, Pais, in prep.: extensive study of correlations between properties of nuclei and of neutron stars.