Cooling of neutron stars with hyperonic admixtures

Adriana Raduta
IFIN-HH Bucharest

Collaborators: Armen Sedrakian (FIAS, Frankfurt),
Jia Jie Li (ITP, Frankfurt),
Fridolin Weber (San Diego Univ.)

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Neutrino and Photon Emission

- NS are born hot $T \approx 10^{11}$ K,
- cooling is realized via ν-emission from the whole body and by transport of heat towards the surface
  - i) thermal relaxation ($t \lesssim 10 - 100$ yrs); the crust and core are thermally decoupled; the surface temp. reflects the the crust's thermal state,
  - ii) ν-cooling ($t \lesssim 10^5$); the star is isothermal; the cooling is due to the core,
  - iii) γ-cooling ($t \gtrsim 10^5$); the cooling wave moves toward the surface
- global thermal balance

$$C(T_i)dT_i/dt = -L_\nu^{\rm inf}(T_i) - L_\gamma^{\rm inf}(T_s);\, T_i(t) = T(r,t)\exp\left[\Phi(r)\right],$$

- EoS determines the cooling: $\{n_i\}, i = B, L$ determine the fast cooling mechanisms, specific heat, superfluidify gaps

Neutrino emission from the core

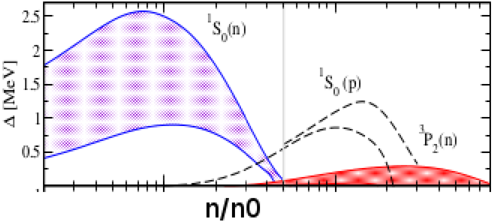
Mechanisms and emissivities (Q):

- bremsstrahlung: $B + B' \rightarrow B + B' + \nu_l + \tilde{\nu}_l$, $B = n, p$, $l = e, \mu, \tau$;
  $Q \propto T^8$ (slow),
- MURCA: $n + B \rightarrow p + B + l + \tilde{\nu}_l$;
  $Q \propto T^8$ (slow),
- DURCA: $\Lambda \rightarrow p + l + \tilde{\nu}_l$, $\Sigma \rightarrow n + l + \tilde{\nu}_l$, $\Sigma \rightarrow \Lambda + l + \tilde{\nu}_l$,
  $\Xi^- \rightarrow \Lambda + l + \tilde{\nu}_l$, $\Xi^- \rightarrow \Xi^0 + l + \tilde{\nu}_l$;
  $Q \propto T^6$ (fast),
- *in case of superfluidity* Cooper pair breaking formation (PBF):
  $BB \rightarrow B + B + \nu_l + \tilde{\nu}_l$;
  $Q \propto T^7$ (medium).

[Yakovlev, Kaminker, Gnedin & Haensel, Phys.Rep.354 (2001)]

Microphysics and thermal evolution

- Equation of State (EoS): composition (particle degrees of freedom, abundances), effective masses (emissivities, thermal properties), compactness (redshift)
- superfluidity (SF): $^1S_0$ if $0.1 \lesssim k_F \lesssim 1.2$ fm^{-1} (protons, hyperons),
  $^3P_2$ if $1.2 \lesssim k_F \lesssim 2(3?)$ fm^{-1} (neutrons)
  - significant dispersion of results because of interaction potentials and many body techniques,
    [Sedrakian & Clark (2018); Ding et al., PRC94 (2016)]



  - $\Delta(^3P_2) << \Delta(^1S_0)$
  - SF suppresses MURCA and DURCA; suppresses the specific heat

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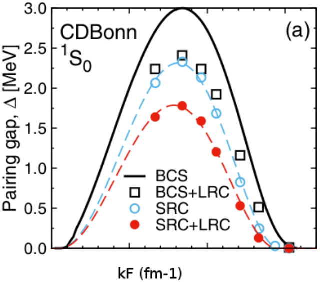

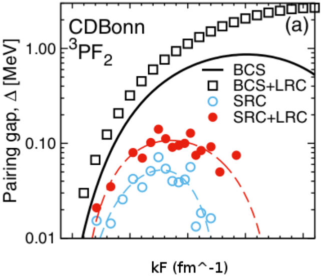

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  - SF suppresses MURCA and DURCA; suppresses the specific heat

NS thermal evolution

- thermal evolution depends on mass, EoS, SF properties

- it additionally depends on composition of the envelope (correlated with the age), exotica, heat sources (accretion, magnetic field, rotation)

  [Page et al., ApJS 155 (2004); Yakovlev & Pethick, Ann. Rev. Astron. Astrophys. (2004); Page, Geppert & Weber, NPA 777 (2006)]

- pioneering work on cooling on NS with hyperons

  [Haensel & Gnedin, A&A290, 290 (1994); Schaab, Balberg & Schaffner-Bielich, ApJ504, L99 (1998); Tsuruta et al., ApJ691, 621 (2009)]

  Conclusion: as soon as they nucleate, hyperons lead to fast cooling even if hyperonic SF is accounted for

Cooling of hyper-nuclear stars: recent contributions

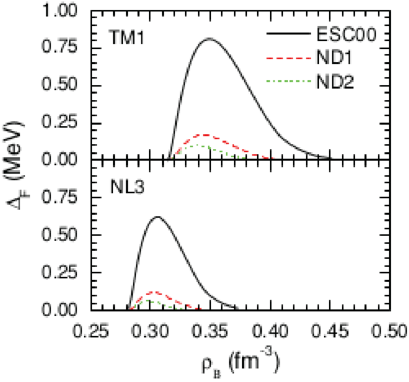
- Raduta, Sedrakian & Weber, MNRAS 475, 4347 (2018)
  isolated NS; Fe-envelope; several EoS (DDME2, GM1A, SWL); Λ and Ξ SF
- Negreiros, Tolos, Centelles, Ramos & Dexheimer, ApJ 863, 104 (2018)
  isolated NS; Fe-envelope; FSU2H; no Y-SF
- Grigorian, Voskresensky & Maslov, arXiv:1808.01819
  isolated NS; composition of the envelope depends on age; MKVORHϕ; in-medium MURCA

Conclusion: massive stars with hyperonic admixture in agreement with thermal observations; significant dependence on SF gaps

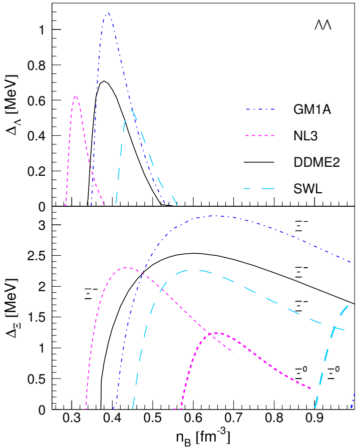
cooling agents not the same!!!

Hyperonic pairing

$$\text{BCS equation}: \quad \Delta(k) = -\frac{1}{4\pi^2}\int dk' k'^2 \frac{V(k,k')\Delta(k')}{\sqrt{[e(k')-\mu(k)]^2+\Delta^2(k')}},$$

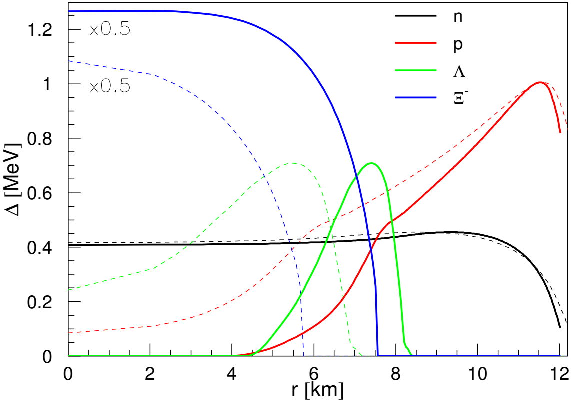


Wang & Shen, Phys. Rev. C81 (2010)



Raduta, Sedrakian, Weber, MNRAS (2018)

NS with hyperons by DDME2: pairing gaps

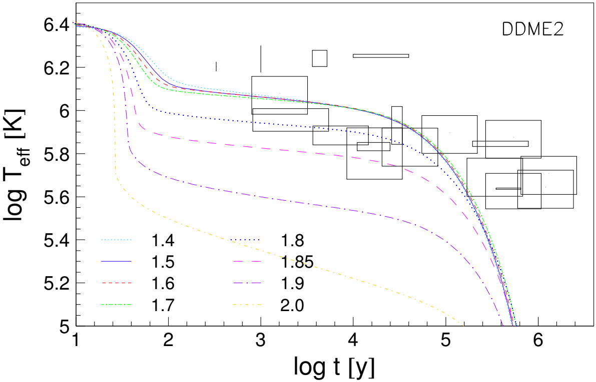


DDME2 of Fortin et al., PRC94
solid: $2M_\odot$; dashed: $1.8M_\odot$

the core of massive NS is strippec
of p-SF

p$^1S_0$: Chen et al., NPA555 (1993)
n$^3P_2$: gap b of Page et al., ApJSS155 (2004)
Λ SF from BCS using ESC00 [Rijken, NPA691; Filikhin & Gal, NPA707]
Ξ^- SF from BCS using ESC08c [Rijken et al. (2013); Garcilazo et al., PRC94]

NS with hyperons by DDME2: cooling curves



$n \to p + l + \tilde{\nu}$ forbidden

$\Sigma^- \to n + l + \tilde{\nu}$ forbidden

$\Xi^- \to \Lambda + l + \tilde{\nu}$ suppressed

$\Lambda \to p + l + \tilde{\nu}$ suppr./active

$\Sigma^- \to \Lambda + l + \tilde{\nu}$ suppr./active

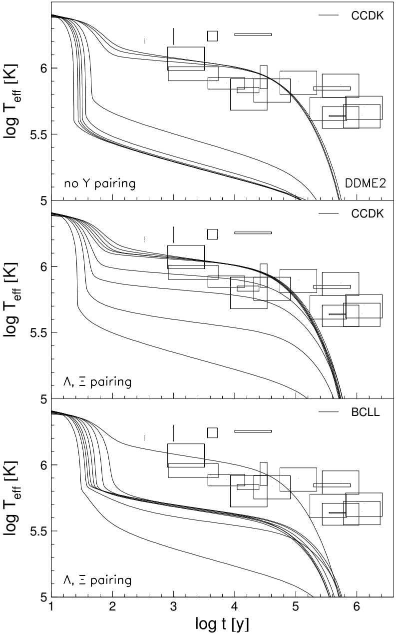
agreement for $M \lesssim 1.85 M_\odot$

$M_\Lambda = 1.39 M_\odot$; $M_{\Xi^-} = 1.54 M_\odot$; $M_{\Sigma^-} = 1.60 M_\odot$

[Raduta, Sedrakian & Weber, MNRAS 475, 4347 (2018)]

data:Beznogov and Yakovlev, MNRAS447 (2014)

Cooling curves: DDME



M=1.3, 1.4, 1.5, 1.6, 1.7, 1.8, 1.85, 1.9, $2M_\odot$
data: `Beznogov & Yakovlev, MNRAS (2015)`

p(CCDK), no Y-SF: $M > 1.55 M_\odot$ too cold

p(CCDK), Y-SF: OK up to $1.85 M_\odot$

p(BCLL), Y-SF: $M \gtrsim 1.4 M_\odot$ too cold

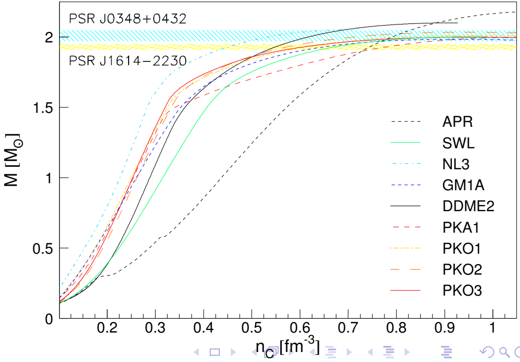
Raduta, Sedrakian & Weber, MNRAS 475, 4347 (2018)

Neutron Star EoS with hyperons:

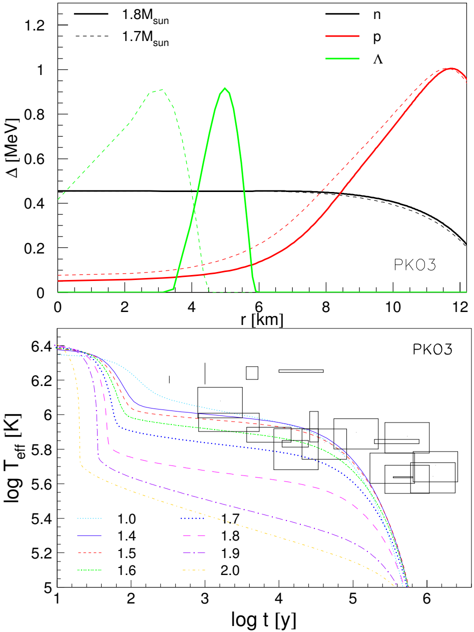
Model	Ref.	K (MeV)	L (MeV)	n_{DU} (fm^{-3})	M_{DU} ($M_\odot$)	n_Λ (fm^{-3})	M_Λ ($M_\odot$)	Y_2	n_{Y_2} (fm^{-3})	M_{Y_2} ($M_\odot$)
NL3	[1]	271.6	118.9	0.21	0.85	0.28	1.47	Ξ^-	0.33	1.73
GM1A	[2]	300.7	94.4	0.28	1.10	0.35	1.49	Ξ^-	0.41	1.67
DDME2	**[1]**	**250.9**	**51.2**	-	-	**0.34**	**1.39**	Ξ^-	**0.37**	**1.54**
SWL	[3]	260.0	55.0	0.90	2.00	0.41	1.5	Ξ^-	0.45	1.65
PKA1	[4]	230.0	103.5	0.25	0.98	0.32	1.44	Σ^-	0.39	1.57
PKO1	[4]	250.3	97.7	0.25	1.01	0.33	1.53	Ξ^-	0.53	1.87
PKO3	**[4]**	**262.4**	**83.0**	**0.28**	**1.22**	**0.33**	**1.55**	Σ^-	**0.45**	**1.81**

[1] Fortin et al., Phys. Rev. C 94 (2016);
[2] Gusakov, Haensel & Kantor, MNRAS 429 (2014);
[3] Spinella, Ph.D. Thesis, SDSU (2017);

[4] Li, Long & Sedrakian, EPJA54 (2018).



Cooling of NS with hyperons

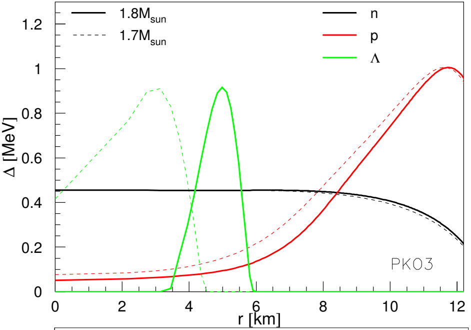


N-DURCA active in $M \geq 1.22 M_\odot$, partially suppressed by n^3P_2 and p^1S_0

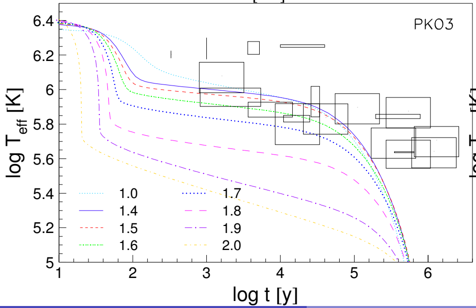
(Λ, p) active in $M \geq 1.56 M_\odot$
protons and Λ in the core $M > 1.7 M_\odot$ are normal

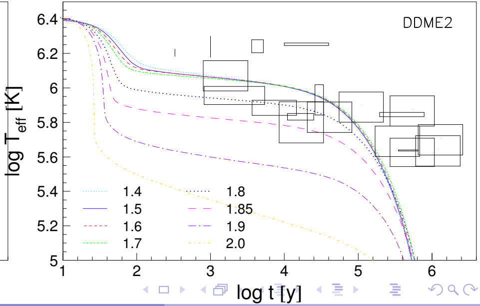
(Ξ^-, Λ) active in $M \geq 1.89 M_\odot$

Cooling of NS with hyperons

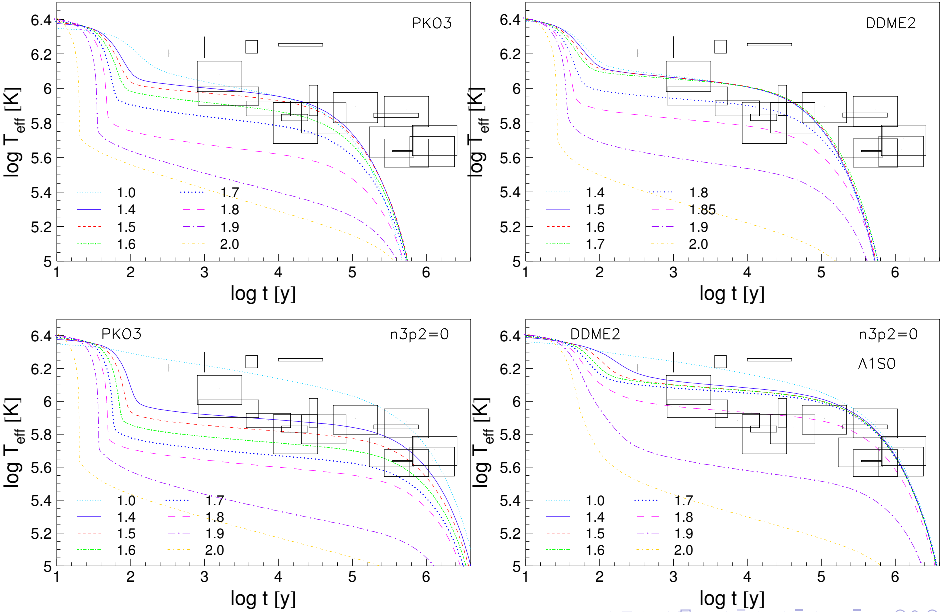


- EoS-dependence manifests in the fast cooling regime
- oldest stars' thermal states are difficult to describe
- broad selection of pairing gaps in different channels
  - p $^1S_0$ regulates $\Lambda \to p + l + \tilde{\nu}_l$
  - n $^3P_2$ controls the late ν- and γ-stages





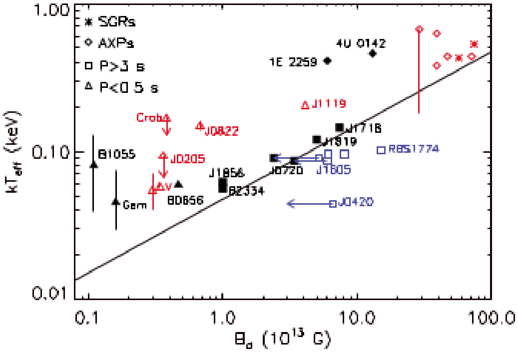
n $^3P_2$ pairing



Conclusions

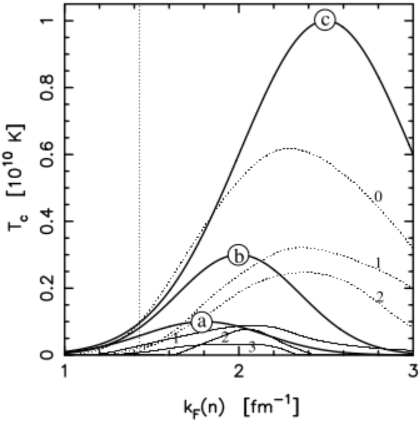
- a large set of RMF EoS with hyperons, including HF EoS
- SF in different nucleonic and hyperonic channels
- thermal states of intermediate-mass hyper-NS are compatible with data (middle-age objects)
- oldest NS thermal states are very sensitive to n $^3P_2$ SF-gap
- non-vanishing n $^3P_2$ SF-gap requires heat sources in order to make old NS comply with data [Haensel & Gnedin, AA290, 458 (1994)]

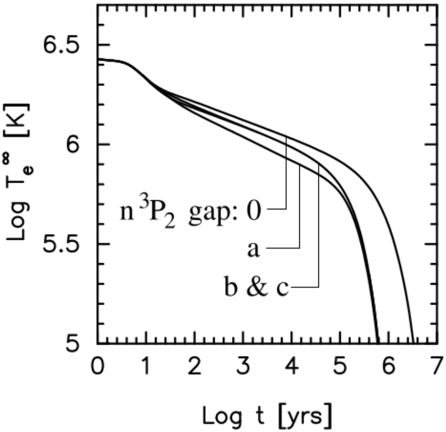
Magnetic field effect on T_{eff}



Heating by resistive effects
Pons et al., PRL 98, 071101 (2007)

Neutron $^3P_2$ gap - effect on cooling

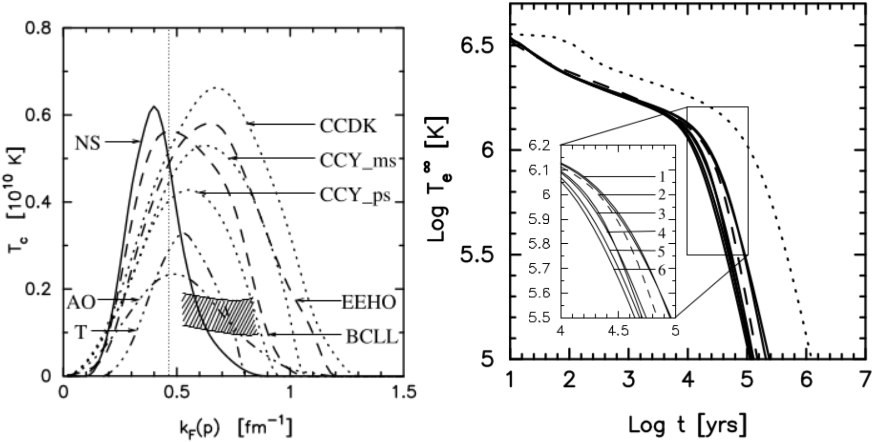




$1.4 M_\odot$, APR

[Page et al., ApJS 155, 623 (2004)]

Proton $^1S_0$ gap - effect on cooling



$1.1M_\odot$, APR

1=NS, 2=T, 3=AO, 4=BCLL, 5=CCY_ms, 6=CCDK

[Page et al., ApJS 155, 623 (2004)]

Magnetic field

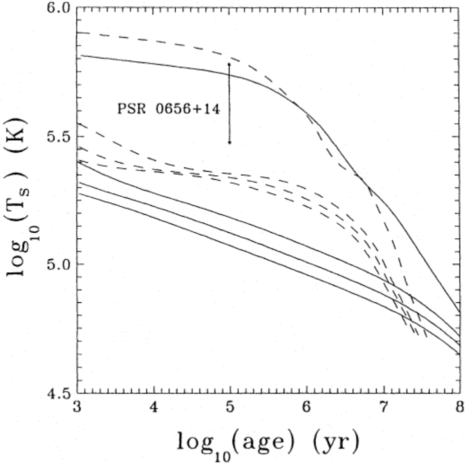


Fig. 2. Cooling curves in the presence of nucleon superfluidity, with $T_{c,n} = T_{c,p} = 10^9$ K. Solid curves: no magnetic field. Dashed curves: $B = 3 \times 10^{12}$ G. The curves correspond to a set of neutron star models with $M/M_\odot$ = 1.3, 1.4, 1.5, 1.7, lower temperature corresponding to higher mass

[Haensel & Gnedin, AA290, 458 (1994)]