Cooling of Neutron Stars

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Abstract. We introduce the theoretical basis for modeling the cooling evolution of compact stars starting from Boltzmann equations in curved space-time. We open a discussion on observational verification of different neutron star models by consistent statistics. Particular interest has the question of existence of quark matter deep inside of compact object, which has to have a specific influence on the cooling history of the star. Besides of consideration of several constraints and features of cooling evolution, which are susceptible of being critical for internal structure of hot compact stars we have introduced a method of extraction of the mass distribution of the neutron stars from temperature and age data. The resulting mass distribution has been compared with the one suggested by supernove simulations. This method can be considered as an additional checking tool for the consistency of theoretical modeling of neutron stars. We conclude that the cooling data allowed existence of neutron stars with quark cores even with one-flavor quark matter.

Acknowledgements

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References

1. H. Grigorian, Phys. Part. Nucl. **39** (2008) 1143
2. T. Klahn *et al.*, Phys. Lett. B **654**, 170 (2007)
3. J. M. Lattimer and M. Prakash, Astrophys. J. **550**, 426 (2001)
4. D. Blaschke, S. Fredriksson, H. Grigorian, A. M. Oztas and F. Sandin, Phys. Rev. D **72**, 065020 (2005)
5. D. Blaschke, H. Grigorian and D. N. Voskresensky, Astron. Astrophys. **424**, 979 (2004)
6. D. Page, U. Geppert and F. Weber, Nucl. Phys. A **777**, 497 (2006)
7. T. Takatsuka and R. Tamagaki, Prog. Theor. Phys. **112**, 37 (2004)
8. S. Popov, H. Grigorian and D. Blaschke, Phys. Rev. C **74**, 025803 (2006)
9. T. Schafer, Phys. Rev. D **62**, 094007 (2000)
10. H. Grigorian, Phys. Rev. C **74**, 025801 (2006)
11. M. Prakash, I. Bombaci, M. Prakash, P. J. Ellis, J. M. Lattimer and R. Knorren, Phys. Rept. **280**, 1 (1997)
12. D. Blaschke and H. Grigorian, Prog. Part. Nucl. Phys. **59**, 139 (2007)
13. Haensel, P., Potekhin, A.Y., Yakovlev, D.G. *Neutron Stars 1: Equation of State and Structure* (Springer, 2007) 619 p.
14. Weber F. *Pulsars as Astrophysical Laboratories for Nuclear and Particle Physics* (IoP Publishing, 1999) 682 p.
15. Shapiro S.L., Teukolsky S.A. *Black holes, white dwarfs, and neutron stars* (Wiley VCH, USA, 1983) 672 p.

COOLING OF NEUTRON STARS

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Helmholtz International Summer School

Dence matter in HIC and Astrophysics

Dubna 2008

COOLING OF HOT NEUTRON STARS LECTURE 1

- Schematic introduction of simulations
- **BOLTZMANN EQUATION IN CURVED SPACE – TIME**
- HEAT TRANSPORT AND NEUTRINO DIFFUSION
- HOT NEUTRON AND QUARK STAR EVOLUTION
- QUASI-EQUILIBRATE EVOLUTION OF COMPACT OBJECT
- Hot COMPACT STARS

PHASE DIAGRAM & COOLING SIMULATIONS

BOLTZMANN EQUATION IN CURVED SPACE - TIME

The Boltzmann equation for massless particles

Lindquist, R.W. 1966, Ann. Phys., 37, 478

$$p^\beta \left(\frac{\partial f}{\partial x^\beta} - \Gamma_{\beta\gamma}^\alpha p^\gamma \frac{\partial f}{\partial p^\alpha} \right) = \left(\frac{df}{d\tau} \right)_{coll} \quad (1)$$

- f is the invariant neutrino distribution function
- p^α is the neutrino 4-momentum
- $\Gamma_{\beta\gamma}^\alpha$ are the Christoffel symbols for the metric

$$ds^2 = -e^{2\phi} dt^2 + e^{2\Lambda} dr^2 + r^2 d\theta^2 + r^2 \sin^2 \theta d\Phi^2 \quad (2)$$

The BE in the comoving basis

$$p^b \left(e_b^\beta \frac{\partial f}{\partial x^\beta} - \Gamma_{bc}^a p^c \frac{\partial f}{\partial p^a} \right) = \left(\frac{df}{d\tau} \right)_{coll} \quad (3)$$

The non-zero Ricci coefficients are

$$\begin{aligned} \Gamma_{00}^1 = \Gamma_{01}^0 = e^{-\phi} e^{-\Lambda} \left(\frac{\partial(\gamma e^\phi)}{\partial r} + \frac{\partial(\gamma v e^\Lambda)}{\partial t} \right), \quad \Gamma_{11}^0 = \Gamma_{10}^1 = e^{-\phi} e^{-\Lambda} \left(\frac{\partial(\gamma e^\Lambda)}{\partial t} + \frac{\partial(\gamma v e^\phi)}{\partial r} \right), \\ \Gamma_{20}^2 = \Gamma_{22}^0 = \Gamma_{30}^3 = \Gamma_{33}^0 = -v \Gamma_{22}^1 = v \Gamma_{21}^2 = -v \Gamma_{33}^1 = v \Gamma_{31}^3 = \frac{\gamma v e^{-\Lambda}}{r}, \quad \Gamma_{33}^2 = -\Gamma_{32}^3 = -\frac{\cot \theta}{r}. \end{aligned} \quad (4)$$

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HEAT TRANSPORT AND NEUTRINO DIFFUSION

The neutrino 4-momentum is

$$p^a = (\omega, \omega\mu, \omega(1-\mu^2)^{1/2} \cos \Phi, \omega(1-\mu^2)^{1/2} \sin \Phi)$$

- μ is the cosine of the angle between the neutrino momentum and the radial direction
- ω is the neutrino energy in a comoving frame

The BE in the spherically symmetric case

$$\begin{aligned} \omega(e_0^t + \mu e_1^t) \frac{\partial f}{\partial t} + \omega(e_0^r + \mu e_1^r) \frac{\partial f}{\partial r} - \omega^2(\mu \Gamma_{00}^1 + \mu^2 \Gamma_{10}^1 + (1-\mu^2) \Gamma_{20}^2) \frac{\partial f}{\partial \omega} \\ - \omega(1-\mu^2)(\Gamma_{00}^1 + \Gamma_{22}^1 + \mu \Gamma_{10}^1 - \mu \Gamma_{20}^2) \frac{\partial f}{\partial \mu} = \left(\frac{df}{d\tau} \right)_{coll}. \end{aligned} \quad (5)$$

Applying the operator to equation (5) and defining the i^{th} moment

Thorne, K. S. 1981, MNRAS 194, 439

$$\frac{1}{2} \int_{-1}^{+1} d\mu \mu^i, \quad i = 0, 1, 2, \dots, \quad M_i = \frac{1}{2} \int_{-1}^{+1} d\mu \mu^i f, \quad Q_i = \frac{1}{2} \int_{-1}^{+1} d\mu \mu^i \left(\frac{df}{d\tau} \right)_{coll}.$$

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HEAT TRANSPORT AND NEUTRINO DIFFUSION

Let us introduce N_ν , F_ν , and S_N are the number density, number flux and number source term, respectively, while J_ν , H_ν , P_ν , and S_E are the neutrino energy density, energy flux, pressure, and the energy source term:

$$N_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_0 \omega^2, \quad F_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_1 \omega^2, \quad S_N = \int_0^\infty \frac{d\omega}{2\pi^2} Q_0 \omega \quad (6)$$

$$J_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_0 \omega^3, \quad H_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_1 \omega^3, \quad P_\nu = \int_0^\infty \frac{d\omega}{2\pi^2} M_2 \omega^3, \quad S_E = \int_0^\infty \frac{d\omega}{2\pi^2} Q_0 \omega^2. \quad (7)$$

- integrating over the neutrino energy
- utilizing the continuity equation
- assumption of a quasi-static evolution

The neutrino transport equation Burrows, A., & Lattimer, J. M. 1986, ApJ, 307, 178

$$\frac{\partial(N_\nu/n_B)}{\partial t} + \frac{\partial(e^{\phi} 4\pi r^2 F_\nu)}{\partial a} = e^{\phi} \frac{S_N}{n_B}$$

$$\frac{\partial(J_\nu/n_B)}{\partial t} + P_\nu \frac{\partial(1/n_B)}{\partial t} + e^{-\phi} \frac{\partial(e^{2\phi} 4\pi r^2 H_\nu)}{\partial a} = e^{\phi} \frac{S_E}{n_B}$$

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HEAT TRANSPORT AND NEUTRINO DIFFUSION

The distribution function in the diffusion approximation:

$$f(\omega, \mu) = f_0(\omega) + \mu f_1(\omega), \quad f_0 = [1 + e^{(\frac{\omega - \mu_\nu}{kT})}]^{-1} \quad (8)$$

- f_0 is the distribution function at equilibrium ($T = T_{mat}$, $\mu_\nu = \mu_\nu^{eq}$)
- ω and μ_ν are the neutrino energy and chemical potential

The moments M_i of f are

$$M_0 = f_0, \quad M_1 = \frac{1}{3}f_1, \quad M_2 = \frac{1}{3}f_0, \quad \text{and} \quad M_3 = \frac{1}{5}f_1. \quad (9)$$

The equation (??) is now

$$e^{-\Lambda} \left(\frac{\partial f_0}{\partial r} - \omega \frac{\partial \phi}{\partial r} \frac{\partial f_0}{\partial \omega} \right) = 3 \frac{Q_1}{\omega}. \quad (10)$$

The collision term Q_1 can be represented as

$$\left(\frac{df}{dt} \right)_{coll} = \omega \left(j_a(1-f) - \frac{f}{\lambda_a} + j_s(1-f) - \frac{f}{\lambda_s} \right) \quad (11)$$

- j_a is the emissivity
- λ_a is the absorptivity
- j_s and λ_s are the scattering contributions

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HEAT TRANSPORT AND NEUTRINO DIFFUSION

The explicit form of the diffusion coefficient D

$$D(\omega) = \left(j + \frac{1}{\lambda_a} + \kappa_1^s \right)^{-1}. \quad (12)$$

Using the relation ($\eta_\nu = \mu_\nu/T$ is the neutrino **degeneracy parameter**)

$$\frac{\partial f_0}{\partial r} = - \left(T \frac{\partial \eta_\nu}{\partial r} + \frac{\omega}{T} \frac{\partial T}{\partial r} \right) \frac{\partial f_0}{\partial \omega}, \quad (13)$$

we obtain

$$f_1 = -D(\omega) e^{-\Lambda} \left[T \frac{\partial \eta}{\partial r} + \frac{\omega}{T e^\phi} \frac{\partial (T e^\phi)}{\partial r} \right] \left(- \frac{\partial f_0}{\partial \omega} \right). \quad (14)$$

Now the energy-integrated lepton and energy fluxes are

$$\begin{aligned} F_\nu &= - \frac{e^{-\Lambda} e^{-\phi} T^2}{6\pi^2} \left[D_3 \frac{\partial (T e^\phi)}{\partial r} + (T e^\phi) D_2 \frac{\partial \eta}{\partial r} \right] \\ H_\nu &= - \frac{e^{-\Lambda} e^{-\phi} T^3}{6\pi^2} \left[D_4 \frac{\partial (T e^\phi)}{\partial r} + (T e^\phi) D_3 \frac{\partial \eta}{\partial r} \right]. \end{aligned} \quad (15)$$

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HEAT TRANSPORT AND NEUTRINO DIFFUSION

The coefficients D_2 , D_3 , and D_4 are defined through ($x = \omega/T$)

$$D_n = \int_0^\infty dx x^n D(\omega) f_0(\omega) (1 - f_0(\omega)) ,$$

The explicit expression for the absorption mean free path

$$\frac{1}{\lambda_a} = \frac{G_F^2}{\pi^2} \int_0^\infty dE_e E_e^2 [1 - f_{eq}(E_e)] \int_{-1}^{+1} d\cos\theta \frac{(\cos\theta - 1)}{1 - e^{-z}} [AR_1 + R_2 + BR_3] \quad (16)$$

$$R_s^{out} = 4G_F^2 \frac{(\cos\theta - 1)}{1 - e^{-z}} [AR_1 + R_2 + BR_3] \quad (17)$$

The polarization functions

$$R_1 = (\mathcal{V}^2 + \mathcal{A}^2) [\text{Im } \Pi_L^R(q_0, q) + \text{Im } \Pi_T^R(q_0, q)] \quad (18)$$

$$R_2 = (\mathcal{V}^2 + \mathcal{A}^2) \text{Im } \Pi_T^R(q_0, q) - \mathcal{A}^2 \text{Im } \Pi_A^R(q_0, q) \quad R_3 = 2\mathcal{V}\mathcal{A} \text{Im } \Pi_{VA}^R(q_0, q) . \quad (19)$$

- $\mathcal{V} = Cg_V$ and $\mathcal{A} = Cg_A$ for the absorption, C is the Cabibbo factor

- $\mathcal{V} = g_V/2$ and $\mathcal{A} = g_A/2$ for the scattering

To include all six neutrino types, one can redefine the diffusion coefficients

$$D_2 = D_2^{\nu_e} + D_2^{\bar{\nu}_e} , \quad D_3 = D_3^{\nu_e} - D_3^{\bar{\nu}_e} , \quad D_4 = D_4^{\nu_e} + D_4^{\bar{\nu}_e} + 4D_4^{\nu_\mu} . \quad (20)$$

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HOT NEUTRON AND QUARK STAR EVOLUTION

Using the equation for the electron fraction and the matter energy equation

$$\frac{\partial Y_e}{\partial t} = -e^\phi \frac{S_N}{n_B}, \quad Y_L = \frac{N_\nu}{n_B} + Y_e \quad (21)$$

$$\frac{d(E/n_B)}{dt} + P \frac{d(V/n_B)}{dt} = -e^\phi \frac{S_N}{n_B} \quad (22)$$

$$Te^\phi \frac{\partial s}{\partial t} + \mu_\nu e^\phi \frac{\partial Y_L}{\partial t} + \frac{\partial(e^{2\phi} 4\pi r^2 \mathbf{H}_\nu)}{\partial a} = 0 \quad (23)$$

we obtain

$$\frac{\partial N_\nu/n_B}{\partial t} + \frac{\partial Y_e}{\partial t} + \frac{\partial(e^\phi 4\pi r^2 F_\nu)}{\partial a} = 0 \quad (24)$$

$$\frac{\partial Y_L}{\partial t} + \frac{\partial(e^\phi 4\pi r^2 \mathbf{F}_\nu)}{\partial a} = 0 \quad (25)$$

$$(26)$$

$$F_\nu = -\frac{e^{-\Lambda} e^{-\phi} T^2}{6\pi^2} \left[\mathbf{D}_3 \frac{\partial(Te^\phi)}{\partial r} + (Te^\phi) \mathbf{D}_2 \frac{\partial \eta}{\partial r} \right] \\ H_\nu = -\frac{e^{-\Lambda} e^{-\phi} T^3}{6\pi^2} \left[\mathbf{D}_4 \frac{\partial(Te^\phi)}{\partial r} + (Te^\phi) \mathbf{D}_3 \frac{\partial \eta}{\partial r} \right] . \quad (27)$$

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QUASI-EQUILIBRATE EVOLUTION OF COMPACT OBJECT

The structure equations are

$$\frac{\partial r}{\partial a} = \frac{1}{4\pi r^2 n_B e^\Lambda}, \quad \frac{\partial m}{\partial a} = \frac{\rho}{n_B e^\Lambda} \quad (28)$$

$$\frac{\partial \phi}{\partial a} = \frac{e^\Lambda}{4\pi r^4 n_B} (m + 4\pi r^3 P), \quad (29)$$

$$\frac{\partial P}{\partial a} = -(\rho + P) \frac{e^\Lambda}{4\pi r^4 n_B} (m + 4\pi r^3 P) \quad (30)$$

with the boundary conditions

$$\begin{aligned} r(a=0) &= 0; \quad m(a=0) = 0, \\ \phi(a=a_s) &= \frac{1}{2} \log \left[1 - \frac{2m(a=a_s)}{r(a=a_s)} \right]; \quad P(a=a_s) = P_s \end{aligned} \quad (31)$$

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COOLING EVOLUTION WITHOUT NEUTRINO TRAPPING

- The flux energy per unit time $l(r)$ through a spherical slice at distance r from the center is:

$$l(r) = -4\pi r^2 k(r) \frac{\partial(T(r)e^\Phi)}{\partial r} e^{-\Phi} \sqrt{1 - \frac{2M}{r}}.$$

The factor $e^{-\Phi} \sqrt{1 - \frac{2M}{r}}$ corresponds to the relativistic correction of the time scale and the unit of thickness.

- The equations for energy balance and thermal energy transport are:

$$\frac{\partial}{\partial N_B} (l e^{2\Phi}) = -\frac{1}{n} (\epsilon_\nu e^{2\Phi} + \mathbf{c} \mathbf{v} \frac{\partial}{\partial t} (T e^\Phi))$$

$$\frac{\partial}{\partial N_B} (T e^\Phi) = -\frac{1}{k} \frac{l e^\Phi}{16\pi^2 r^4 n}$$

where $n = n(r)$ is the baryon number density, $N_B = N_B(r)$ is the total baryon number in the sphere with radius r and

$$\frac{\partial N_B}{\partial r} = 4\pi r^2 n \left(1 - \frac{2M}{r} \right)^{-1/2}$$

D. Blaschke, H. Grigorian and D. N. Voskresensky, *Astronomy and Astrophysics* **368**, 561 (2001).

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STELLAR MATTER UNDER COMPACT STAR CONDITIONS

The stellar matter including the quark core of compact stars consists of neutrons protons, up, down quarks, electrons and neutrinos in beta equilibrium and with the charge neutrality condition.

- β -equilibrium $n \longleftrightarrow p + e^- + \bar{\nu}_e$ —in nuclear matter
 $d \longleftrightarrow u + e^- + \bar{\nu}_e$ —in quark matter

$$\mu_n = \mu_p + \mu_e + \mu_{\nu_e}$$

$$\mu_d = \mu_u + \mu_e + \mu_{\nu_e}$$

where μ_e, μ_{ν_e} are the electrons and the neutrino chemical potentials.

- Charge neutrality $n_p - n_e = 0$: —in nuclear matter
 $\frac{2}{3}n_u - \frac{1}{3}n_d - n_e = 0$ —in quark matter

The contribution from the leptons should be added to the thermodynamical potential Ω_q :

$$\Omega(\phi, \Delta; \mu_q, \mu_e, T) = \Omega_q(\phi, \Delta; \mu_q, \mu_e, T) + \Omega_e(\mu_e, T) + \Omega_{\nu_e}(\mu_{\nu_e}, T)$$

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CONFIGURATION OF COMPACT STARS WITHOUT SHELL CONDENSATE AND TEMPERATURE EFFECT

The star configuration could be defined from the **Tolman-Oppenheimer-Volkoff equations**

$$\frac{dP}{dr} = -\frac{[\epsilon(r) + P(r)][m(r) + 4\pi r^3 P(r)]}{r[r - 2m(r)]}$$

$$m = 4\pi \int_0^r r^2 \epsilon(r) dr$$

The equations are solved for the set of central densities $n_q(0)$ for which the stars are stable. The total mass $M = m(r)$ of the star is defined on the radius r so that $P(r) = 0$.

The integral parameters M and R feel the existence of the diquark condensation: the EoS becomes softer. Also are sensitive on temperature variations. Both are decreasing the values of the M_{max} and R_{max} of the core approximately 10% from their values of the $T = 0$ and $\Delta = 0$ cases.

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PNS EVOLUTION WITH NEUTRINO TRAPPING

D. N. Aguilera, D. Blaschke, H. Grigorian, arXiv:astro-ph/0212237

- Mass defect $\Delta M \sim 0.05 \div 0.4 M_{\odot} \Rightarrow 10^{53} \div 10^{54} \text{ erg}$
- Effect due to Un-Trapping of (Anti-)Neutrinos
- Explosion possible: Phase transition 1st Order
- GRB with time delay $\Rightarrow$ Cannon Ball Model

MASS DEFECT - ESTIMATION OF ENERGY

- During the cooling evolution the star must lose an amount of energy: the energy release will have an equivalent in a mass defect. We estimated this from the diquark condensation as about $0.1 M_{\odot}$. It corresponds to the estimated energy $(\Delta/\mu)^2 \simeq 10^{52} \text{ erg}$ of the diquark condensate, see Ref. [*].

*D. K. Hong, S. D. Hsu and F. Sannino, Phys. Lett. B516,362 (2001).

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COOLING OF HYBRID NEUTRON STARS

LECTURE 2

- ◉ Configurations of Hybrid stars
- ◉ Cooling processes in QM
- ◉ Crust, SC Gaps and ...
- ◉ Time Evolution of Surface Temperature
- ◉ Constraints from Observations
- ◉ Summary & Discussion

PHASE TRANSITION: NUCLEAR MATTER $\longrightarrow$ QUARK MATTER

- Walecka model (p,n,e)+(σ,ω) $\longrightarrow$ Bag model (u,d,e)
- Maxwell construction: $P^{Had} = P^{Quark}$ $\mu_B^{Had} = \mu_B^{Quark}$

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STABILITY OF HADRONIC AND HYBRID STARS

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HYBRID CONFIGURATIONS

- Critical masses for phase transition
 $M_c = 1.2 M_\odot$ HHJ - INCQM (Gaussian) with 2SC
 $M_c = 1.82 M_\odot$ - without 2SC

H. Grigorian, D. Blaschke, D.N. Aguilera. Phys.Rev.C 69 (2004) 065802

COOLING MECHANISM

Neutrino processes in quark matter: Emissivities

- ➔ Quark direct Urca (QDU) the most efficient processes

$$\epsilon_\nu^{\text{QDU}} \simeq 9.4 \times 10^{26} \alpha_s u Y_e^{1/3} \zeta_{\text{QDU}} T_9^6 \text{ erg cm}^{-3} \text{ s}^{-1},$$

Compression $u = n/n_0 \simeq 2$, strong coupling $\alpha_s \approx 1$

- ➔ Quark Modified Urca (QMU) and Quark Bremsstrahlung (QB)

$$\epsilon_\nu^{\text{QMU}} \sim \epsilon_\nu^{\text{QB}} \simeq 9.0 \times 10^{19} \zeta_{\text{QMU}} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1}.$$

- ➔ Suppression due to the pairing (2CS, CFL, X)

$$\text{QDU} : \zeta_{\text{QDU}} \sim \exp(-\Delta_q/T)$$

$$\text{QMU and QB} : \zeta_{\text{QMU}} \sim \exp(-2\Delta_q/T) \text{ for } T < T_{\text{crit},q} \simeq 0.4 \Delta_q$$

- ➔ PBF $e + e \rightarrow e + e + \nu + \bar{\nu}$

$$\epsilon_\nu^{ee} = 2.8 \times 10^{12} Y_e^{1/3} u^{1/3} T_9^8 \text{ erg cm}^{-3} \text{ s}^{-1},$$

becomes important for $\Delta_q/T \gg 1$

D. Blaschke, H. Grigorian, D.N. Voskresensky, Astron. & Astrophys. 368 (2001) 561

DIRECT URCA IN HADRON MATTER

• DU critical densities

$n_c = 2.7 n_0$ non linear Walecka (NLW)

$n_c = 5.0 n_0$ Heiselberg, Hjorth-Jensen

HHJ; [Heiselberg, H., Hjorth-Jensen, M. 1999, \[arXiv:astro-ph/9904214\]](#)

• DU critical masses

$M_c = 1.25 M_\odot$ - NLW

$M_c = 1.84 M_\odot$ - HHJ

DU CONSTRAINT

$n \rightarrow p + e + \bar{\nu}_e$ implies $p_n \leq p_p + p_e$, charge neutrality results in

$$x_{DU}(x_e) \geq \frac{1}{1 + (1 + x_e^{1/3})^3}$$

➔ no muons: $x_{DU} = 11.1\%$

➔ relativistic limit ($n_e = n_\mu$): $x_{DU} = 14.8\%$

$$x_e = n_e / (n_e + n_\mu)$$

HS WITH DIFFERENT STRUCTURE

SC PAIRING GAPS

CRUST MODEL

$$\Delta M_L(t) = e^{-t/\tau} \Delta M_L(0)$$

D. Page, J. M. Lattimer, M. Prakash, and A. W. Steiner, *Astrophys. J. Supp.* **155**, 623 (2004).

D. G. Yakovlev, K. P. Levenfish, A. Y. Potekhin, O. Y. Gnedin, and G. Chabrier, *Astron. Astrophys.* **417**, 169 (2004).

SURFACE TEMPERATURE & AGE DATA

$$\frac{dU}{dt} = \sum_i C_i \frac{dT}{dt} = -\varepsilon_\gamma - \sum_j \varepsilon_\nu^j$$

Data taken from:
Yakovlev et al.,
A & A **389** (2002) L24;

Medium Cooling Scenario:
D. Blaschke, H. Grigorian
and D. N. Voskresensky,
A&A **424** (2004) 979.

Fast Coolers

COOLING OF LIGHT STARS MODELS

Brightness constraint for cooling models of young neutron stars

- (i) *All objects with temperatures exceeding $T = 4 \times 10^6$ K are potentially observable.* The probability of finding an object increases with its luminosity because of the increase of the visibility volume and reduction of the absorption of x-rays by the interstellar medium.
- (ii) *The distribution of young objects is a steplike function of temperature for higher temperatures.*
- (iii) *The uncertainty of the BC border is of the same order as the error bars of the measured temperatures at the corresponding age.*

H. Grigorian, Phys. Rev. **Q74:025801,2006**

SOME ANOMALIES

The most of pathologies of hadronic stars are descendible

- with AV18 gaps, π -condensate, MMU ($3P_2$ - is **NOT** suppressed)

- with Gaps from Yakovlev et al. 2003

WHY DU IS A PROBLEM?

TEMPERATURE IN THE STAR INTERIOR

OGS

COOLING OF HS WITH SINGLE FLAVOR QM

Hybrid stars with d-quark drip

D. Blaschke, F.S., T. Klähn, in preparation

Mass Distribution of NS

EXTRACTED MASS DISTRIBUTION

SUMMARY

- Cooling of NSs is one of testing schemes for High density matter EoS
- Mass distribution of NS is extracted from the cooling model
- Cooling data allowed existence of HS even with one flavor QM
- DU can be considered as a problem

OPEN QUESTIONS & DISCUSSION

- ◉ Do Hybrid NSs an alternative or the solution of problems of compact stars?
- ◉ Do for all constraints exist a valid HNS model?
- ◉ Can magnetic field and surface heating modify the main conclusions on cooling of NS?
- ◉ Is the mass distribution of NSs an observable?