Cooling Evolution of Hybrid Stars

H. Grigorian

Institut für Physik, Universität Rostock, D-18051 Rostock, Germany
E-mail: hovik.grigorian@uni-rostock.de
Department of Physics, Yerevan State University, 375025 Yerevan, Armenia

Abstract. The cooling of compact isolated objects for different values of the gravitational mass has been simulated for two alternative assumptions. One is that the interior of the star is purely hadronic and second that the star can have a rather large quark core. It has been shown that within a nonlocal chiral quark model the critical density for a phase transition to color superconducting quark matter under neutron star conditions can be low enough for these phases to occur in compact star configurations with masses below 1.3 $M_\odot$. For a realistic choice of parameters the equation of state (EoS) allows for 2SC quark matter with a large quark gap $\sim 100$ MeV for $u$ and $d$ quarks of two colors that coexists with normal quark matter within a mixed phase in the hybrid star interior. We argue that, if in the hadronic phase the neutron pairing gap in $3P_2$ channel is larger than few keV and the phases with unpaired quarks are allowed, the corresponding hybrid stars would cool too fast.

Even in the case of the essentially suppressed $3P_2$ neutron gap if free quarks occur for $M < 1.3 M_\odot$, as it follows from our EoS, one could not appropriately describe the neutron star cooling data existing by today.

It is suggested to discuss a "2SC+X" phase, as a possibility to have all quarks paired in two-flavor quark matter under neutron star constraints, where the X-gap is of the order of 10 keV - 1 MeV. Density independent gaps do not allow to fit the cooling data. Only the presence of an X-gap that decreases with increase of the density could allow to appropriately fit the data in a similar compact star mass interval to that following from a purely hadronic model.

1. INTRODUCTION

The "standard" scenario of neutron star cooling is based on the main process responsible for the cooling, which is the modified Urca process (MU) $nn \to npe\bar{\nu}$ calculated using the free one pion exchange between nucleons, see [3]. However, this scenario explains only the group of slow cooling data. To explain a group of rapid cooling data "standard" scenario was supplemented by one of the so called "exotic" processes either with pion condensate, or with kaon condensate, or with hyperons, or involving the direct Urca (DU) reactions, see [4, 5] and refs therein. All these processes may occur only for the density higher than a critical density, $(2 \div 6) n_0$, depending on the model, where $n_0$ is the nuclear saturation density. An other alternative to "exotic" processes is the DU process on quarks related to the

1 Supported by the Virtual Institute of the Helmholtz Association under grant No. VH-VI-041
phase transition to quark matter.

Recently, the cooling of neutron stars has been reinvestigated within a purely hadronic model [1], i.e., when one suppresses the possibility of quark cores in neutron star interiors. We have demonstrated that the neutron star cooling data available by today can be well explained within the "nuclear medium cooling" scenario, cf. [6, 7], i.e., if one includes medium effects into consideration. In the "standard plus exotics" scenario for hadronic models the in-medium effects have not been incorporated, see [8, 9, 10]. Recently [10] called this approach the "minimal cooling" paradigm. Some papers included an extra possibility of internal heating that results in a slowing down of the cooling of old pulsars, see [11] and Refs. therein.

The necessity to include in-medium effects into the neutron star cooling is based on the whole experience of condensed matter physics, see [12, 13, 14]. The relevance of in-medium effects for the neutron star cooling problem has been shown by [7, 12, 15, 16, 17] and the efficiency of the developed "nuclear medium cooling" scenario for the description of the neutron star cooling was demonstrated within the cooling code by [6] and then by [1].

Each scenario puts some constraints on dense matter equation of state (EoS). In particular the density dependencies of the asymmetry energy and the pairing gaps are the regulators of the heat production and transport. The former dependence is an important issue for the analysis of heavy ion collisions especially within the new CBM (compressed baryon matter) program to be realized at the future accelerator facility FAIR at GSI Darmstadt.

The density dependence of the asymmetry energy also determines the proton fraction in neutron star matter and thus governs the onset of the very efficient direct Urca (DU) process. The DU process, once occurring, would lead to a very fast cooling of neutron stars. Within the "standard + DU" scenario the transition from slow cooling to the rapid cooling occurs namely due to the switching on the DU process. Thus the stars with \( M < M_{\text{DU}}^{\text{crit}} \) cool down slowly whereas the stars with the mass only slightly above \( M_{\text{DU}}^{\text{crit}} \) cool down very fast. Since it is doubtful that many neutron stars belonging to an intermediate cooling group have very similar masses, from our point of view such a scenario seems unrealistic, cf. [1, 18]. The modern EoS of the Urbana-Argonne group [19] allows for the DU process only for very high density \( n > 5n_0 \) (where \( n_0 \) is the saturation nuclear density) that relates to the neutron star masses \( M \geq M_{\text{DU}}^{\text{crit}} \approx 2 M_\odot \). Thus, using mentioned Urbana-Argonne based EoS and the "standard +DU" scenario one should assume that the majority of experimentally measured cooling points relates to very massive neutron stars that seems us still more unrealistic.

The assumption about the mass distribution can be developed into a more quantitative test of cooling scenarios when these are combined with population synthesis models. The latter allow to obtain Log N – Log S distributions for nearby coolers which can be tested with data from the ROSAT catalogue [20]. Analysis [20] has supported ideas put forward in [1].

At high star masses the central baryon density exceeds rather large values \( n > 5n_0 \). At these densities exotic states of matter as, e.g., hyperonic matter or quark matter perhaps are permitted. Ref. [21] argued that the presence of the
quark matter in massive compact star cores is a most reliable hypothesis.

The possibility of the existence of neutron stars with large quark matter cores is also not excluded [2, 22, 23, 24]. In the quark matter the DU process yielding the rapid cooling may arise on interacting but unpaired quarks [25].

In this review we want to sketch a scenario for the cooling of hybrid stars.

2. STRUCTURE OF HYBRID NEUTRON STARS

In describing the hadronic part of the hybrid star, as in [1], we exploit a modification of the Urbana-Argonne V18 + δv + U1X* model of the EoS given in [19], which is based on the most recent models for the nucleon-nucleon interaction with the inclusion of a parameterized three-body force and relativistic boost corrections. Actually we continue to adopt an analytic parameterization of this model by Heiselberg and Hjorth-Jensen [26], hereafter HHJ.

The HHJ EoS fits the symmetry energy to the original Argonne V18 + δv + U1X* model in the mentioned density interval yielding the threshold density for the DU process \( n_{c}^{DU} \approx 5.19 n_0 \) (\( M_{c}^{DU} \approx 1.839 M_\odot \)).

We employ the EoS of a nonlocal chiral quark model developed in [27] for the case of neutron star constraints with a 2-flavor color superconductivity (2SC) phase. It has been shown in that work that the Gaussian formfactor ansatz leads to an early onset of the deconfinement transition and such a model is therefore suitable to discuss hybrid stars with large quark matter cores [28].

The quark-quark interaction in the color anti-triplet channel is attractive driving the pairing with a large zero-temperature pairing gap \( \Delta \sim 100 \text{ MeV} \) for the quark chemical potential \( \mu_q \sim (300 \div 500) \text{ MeV} \), cf. [29, 30], for a review see [13] and references therein. The attraction comes either from the one-gluon exchange, or from a non-perturbative 4-point interaction motivated by instantons [31], or from non-perturbative gluon propagators [32].

There may also exist a color-flavor locked (CFL) phase [33] for not too large values of the dynamical strange quark mass or large values of the baryon chemical potential [34]. In this phase the all quarks are paired. However, the 2SC phase occurs at lower baryon densities than the CFL phase, see [35, 36]. For applications to compact stars the omission of the strange quark flavor is justified by the fact that chemical potentials in central parts of the stars do barely reach the threshold value at which the mass gap for strange quarks breaks down and they appear in the system [37].

Following Refs [38] we omit the possibility of the hadron-quark mixed phase and found a tiny density jump on the phase boundary from \( n_{c}^{\text{hadr}} \approx 0.44 \text{ fm}^{-3} \) to \( n_{c}^{\text{quark}} \approx 0.46 \text{ fm}^{-3} \).

In Fig. 1 we present the mass-radius relation for hybrid stars with HHJ EoS vs. Gaussian nonlocal chiral quark separable model (SM) EoS. Configurations for SM model, given by the solid line, are stable, whereas without color super conductivity (“HHJ-SM without 2SC”) no stable hybrid star configuration is possible. In the case “HHJ-SM with 2SC” the maximum neutron star mass proves to be 1.793 \( M_\odot \).
FIGURE 1. Mass - radius relations for compact star configurations with different EoS: purely hadronic star with HHJ EoS (dashed line), stable hybrid stars with HHJ - Gaussian nonlocal chiral quark separable model (SM) with 2SC phase (solid line) and with HHJ - SM, without 2SC phase (dash-dotted line). Data for two sources are also indicated, see [39, 40].

Additionally, within the “HHJ-SM with 2SC” phase we will allow for the possibility of a weak pairing channel for all the quarks which were unpaired, with typical gaps $\Delta_X \sim 10$ keV $\div 1$ MeV, as in the case of the CSL pairing channel, see [41, 42]. Since we don’t know yet the exact pairing pattern for this case, we call this hypothetical phase “2SC+X”. In such a way all the quarks get paired, some strongly in the 2SC channel and some weakly in the X channel.

3. COOLING

We compute the neutron star thermal evolution adopting our fully general relativistic evolutionary code. This code was originally constructed for the description of hybrid stars by [24]. The main cooling regulators are the thermal conductivity, the heat capacity and the emissivity. In order to better compare our results with results of other groups we try to be as close as possible to their inputs for the quantities which we did not calculate ourselves. Then we add inevitable changes, improving EoS.

The density $n \sim 0.5 \div 0.7 \, n_0$ is the boundary of the neutron star interior and the inner crust. The latter is constructed of a pasta phase discussed by [43], see also recent works of [44, 45].

Further on we need the relation between the crust and the surface temperature for neutron star. The sharp change of the temperature occurs in the envelope.
3.1. Cooling Evolution of Hadronic Stars

Here we will shortly summarize the results on hadronic cooling.

In framework of ”minimal cooling” scenario the pair breaking and formation (PBF) processes may allow to cover an ”intermediate cooling” group of data (even if one artificially suppressed medium effects)\cite{6}. These processes are very efficient for large pairing gaps, for temperatures being not much less than the value of the gap.

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{fig2}
\caption{Neutron and proton pairing gaps according to model I (thick solid, dashed and dotted lines) and according to model II (thin lines), see text. The $1S_0$ neutron gap is the same in both models, taken from \cite{46}.}
\end{figure}

Gaps that we have adopted in the framework of the ”nuclear medium cooling” scenario, see \cite{1}, are presented in Fig. 2. Thick dashed lines show proton gaps which were used in the work of \cite{9} performed in the framework of the “standard plus exotics” scenario. We will call the choice of the “3nt” model from \cite{9} the model I. Thin lines show $1S_0$ proton and $3P_2$ neutron gaps from \cite{48}, for the model AV18 by \cite{49} (we call it the model II). Recently \cite{47} has argued for a strong suppression of the $3P_2$ neutron gaps, down to values $\sim 10$ keV, as the consequence of the medium-induced spin-orbit interaction.

These findings motivated \cite{1} to suppress values of $3P_2$ gaps shown in Fig. 2 by an extra factor $f(3P_2,n) = 0.1$. Further possible suppression of the $3P_2$ gap is almost not reflected on the behavior of the cooling curves.

Contrary to expectations of \cite{47} a more recent work of \cite{50} argued that the $3P_2$ neutron pairing gap should be dramatically enhanced, as the consequence of the strong softening of the pion propagator. According to their estimate, the $3P_2$ neutron pairing gap is as large as $1 \div 10$ MeV in a broad region of densities, see Fig. 1 of their work. Thus results of calculations of \cite{47} and \cite{50}, which both had the same aim to include medium effects in the evaluation of the $3P_2$ neutron gaps, are in a deep discrepancy with each other.

- Including superfluid gaps we see, in agreement with recent microscopic findings

\end{document}
FIGURE 3. Fig. 21 of [1]. Gaps are from Fig. 2 for model II. The original $3P_2$ neutron pairing gap is additionally suppressed by a factor $f(3P_2, n) = 0.1$. The $T_s - T_{in}$ relation is given by “our fit” curve of Fig. 4 in [1]. For more details see [1].

3.2. Cooling Evolution of Hybrid Stars with 2SC Quark Matter Core

For the calculation of the cooling of the quark core in the hybrid star we use the model [24]. We incorporate the most efficient processes: the quark direct Urca (QDU) processes on unpaired quarks, the quark modified Urca (QMU), the quark bremsstrahlung (QB), the electron bremsstrahlung (EB), and the massive gluon-
photon decay (see [22]). Following [52] we include the emissivity of the quark pair formation and breaking (QPFB) processes. The specific heat incorporates the quark contribution, the electron contribution and the massless and massive gluon-photon contributions. The heat conductivity contains quark, electron and gluon terms.

The calculations are based on the hadronic cooling scenario presented in Fig. 3 and we add the contribution of the quark core. For the Gaussian form-factor the quark core occurs already for $M > 1.214 M_{\odot}$ according to the model [27], see Fig. 1. Most of the relevant neutron star configurations (see Fig. 3) are then affected by the presence of the quark core.

First we check the possibility of the 2SC+ normal quark phases Fig. 4. The variation of the gaps for the strong pairing of quarks within the 2SC phase and the gluon-photon mass in the interval $\Delta, m_{g,\gamma} \sim 20 \div 200$ MeV only slightly affects the results. The main cooling process is the QDU process on normal quarks. We see that the presence of normal quarks entails too fast cooling. The data could be explained only if all the masses lie in a very narrow interval $(1.21 < M/M_{\odot} < 1.22$ in our case). In case of the other two crust models the resulting picture is similar.

The existence of only a very narrow mass interval in which the data can be fitted seems us unrealistic as by itself as from the point of view of the observation of the neutron stars in binary systems with different masses, e.g., $M_{B1913+16} \approx 1.4408 \pm 0.0003 M_{\odot}$ and $M_{J0737-3039B} \approx 1.250 \pm 0.005 M_{\odot}$, cf. [53]. Thus the data can’t be satisfactorily explained.

We first check the case $\Delta_X$ to be constant. For the $\Delta_X \approx 1$ MeV cooling is too slow [2]. It is true for all three crust models. Thus the gaps for formerly unpaired quarks should be still smaller in order to obtain a satisfactory description of the cooling data.
For the $\Delta_X = 30$ keV the cooling data can be fitted but have a very fragile dependence on the gravitational mass of the configuration. Namely, we see that all data points, except the Vela, CTA 1 and Geminga, correspond to hybrid stars with masses in the narrow interval $M = 1.21 \div 1.22 \, M_\odot$.

Therefore we would like to explore whether a density-dependent X-gap could allow a description of the cooling data within a larger interval of compact star masses.

We employ the ansatz: X-gap as a decreasing function of the chemical potential

$$\Delta_X(\mu) = \Delta_c \exp[-\alpha(\mu - \mu_c)/\mu_c], \quad (1)$$

where the parameters are chosen such that at the critical quark chemical potential $\mu_c = 330$ MeV for the onset of the deconfinement phase transition the X-gap has its maximal value of $\Delta_c = 1.0$ MeV and at the highest attainable chemical potential $\mu_{\text{max}} = 507$ MeV, i.e. in the center of the maximum mass hybrid star configuration it falls to a value of the order of 10 keV. We choose the value $\alpha = 10$ for which $\Delta_X(\mu_{\text{max}}) = 4.6$ keV. In Fig. 5 we show the resulting cooling curves for the gap model II with gap anzatz (1) which we consider as the most realistic one.

We observe that the mass interval for compact stars which obey the cooling data constraint ranges now from $M = 1.32 \, M_\odot$ for slow coolers up to $M = 1.75 \, M_\odot$ for fast coolers such as Vela, cf. with that we have found with the purely hadronic model [1] with different parameter choices. Note that according to a recently suggested independent test of cooling models [20] by comparing results of a corresponding population synthesis model with the Log N - Log S distribution of nearby isolated X-ray sources the cooling model I did not pass the test. Thereby it would be interesting to see whether our quark model within the gap ansatz II could pass the Log N - Log S test.

FIGURE 5. Cooling curves for hybrid star configurations with Gaussian quark matter core in the 2SC phase with a density dependent pairing gap according to Eq. (1) for model II.
4. CONCLUSION

- Within a nonlocal, chiral quark model the critical densities for a phase transition to color superconducting quark matter can be low enough for these phases to occur in compact star configurations with masses below $1.3 M_\odot$.
- For the choice of the Gaussian form-factor the 2SC quark matter phase arises at $M \approx 1.21 M_\odot$.
- Without a residual pairing the 2SC quark matter phase could describe the cooling data only if compact stars had masses in a very narrow band around the critical mass for which the quark core can occur.
- Under assumption that formally unpaired quarks can be paired with small gaps $\Delta_X < 1$ MeV (2SC+X pairing), which values we varied in wide limits, only for density dependent gaps the cooling data can be appropriately fitted.

So the present day cooling data could be still explained by hybrid stars, however, when assuming a complex pairing pattern, where quarks are partly strongly paired within the 2SC channel, and partly weakly paired with gaps $\Delta_X < 1$ MeV, being rapidly decreasing with the increase of the density.

It remains to be investigated which microscopic pairing pattern could fulfill the constraints obtained in this work. Another indirect check of the model could be the Log N - Log S test.

ACKNOWLEDGMENTS

The research has been supported by the Virtual Institute of the Helmholtz Association under grant No. VH-VI-041 and by the DAAD partnership programme between the Universities of Yerevan and Rostock. In particular I acknowledge D. Blaschke for his active collaboration and support. The results reported in these Proceedings are obtained in collaboration with my colleagues D. Blaschke, D.N. Voskresensky and D.N. Aguilera. I thank the organizers of Spa HLPR2004 meeting.

REFERENCES

1. D. Blaschke, H. Grigorian, and D.N. Voskresensky, Cooling of Neutron Stars. Hadronic Model, Astron. Astrophys., 424, 979 (2004).
2. H. Grigorian, D. Blaschke, and D. Voskresensky, arXiv:astro-ph/0411619 (2004).
3. B. Friman, and O. V. Maxwell, Astrophys. J, 232, 541 (1979)
4. S. Tsuruta, Phys. Rep., 56, 237 (1979)
5. S. Shapiro, and S. A. Teukolsky,1983, Black Holes, White Dwarfs, and Neutron Stars: The Physics of Compact Objects (Wiley, New York), chapter 11
6. Ch. Schaab, D. Voskresensky, A.D. Sedrakian, F. Weber, and M. K. Weigel, Astron. Astrophys., 321, 591 (1997)
7. D. N. Voskresensky, in: "Physics of Neutron Star Interiors", Lecture Notes in Physics, (Eds.) D. Blaschke, N.K. Glendenning, A. Sedrakian, Springer, Heidelberg (2001), p. 467-502.
8. S. Tsuruta, M. A. Teter, T. Takatsuka, T. Tatsumi, and R. Tamagaki, Astrophys. J, 571, L143 (2002)
9. D. G. Yakovlev, O. Y. Gnedin, A. D. Kaminker, K. P. Levenfish, and A. Y. Potekhin, *Adv. Space Res.*, **33**, 523 (2004)

10. Page, D., Lattimer, J.M., Prakash, M., Steiner, A.W. [arXiv: astro-ph/0403657]

11. S. Tsuruta, 2004, in: *Proceedings of IAU Symposium “Young Neutron Stars, and their Environments”*, F. Camilo, B.M. Gaensler (Eds.), **218**

12. A. B. Migdal, E. E. Saperstein, M. A. Troitsky, and D. N. Voskresensky, *Phys. Rep.*, **192**, 179 (1990)

13. R. Rapp, J. Wambach, *Nucl. Phys.*, A, **573**, 626 (1994)

14. Yu. B. Ivanov, J. Knoll, H. van Hees, and D. N. Voskresensky, *Phys. Atom. Nucl.*, **64**, 652 (2001)

15. D. N. Voskresensky, and A. V. Senatorov, *JETP Lett.*, **40**, 1212 (1984)

16. D. N. Voskresensky, and A. V. Senatorov, *JETP*, **63**, 885 (1986)

17. D.N. Voskresensky, and A.V. Senatorov, 1987, *Sov. J. Nucl. Phys.*, A, **45**, 411; A. V. Senatorov, and D. N. Voskresensky, *Phys. Lett.*, B **184**, 119 (1987)

18. E. E. Kolomeitsev, and D. Voskresensky, [arXiv:nucl-th/0410063](http://arxiv.org/abs/nucl-th/0410063) (2004)

19. A. Akmal, V.R. Pandharipande, and D.G. Ravenhall, *Phys. Rev.* C **58**, 1804 (1998)

20. S. Popov, H. Grigorian, R. Turolla, and D. Blaschke, *arXiv:astro-ph/0411618* (2004)

21. M. Baldo, G. F. Burgio, and H. J. Schulze, [arXiv:astro-ph/0312446](http://arxiv.org/abs/astro-ph/0312446) (2003)

22. D. Blaschke, T. Klähn, and D.N. Voskresensky, *Astrophys. J.* **533**, 406 (2000).

23. D. Page, M. Prakash, J.M. Lattimer, and A. Steiner, *Phys. Rev. Lett.* **85**, 2048 (2000).

24. D. Blaschke, H. Grigorian, and D.N. Voskresensky, *Astron. Astrophys.*, **368**, 561 (2001).

25. N. Iwamoto, *Phys. Rev. Lett.* **44**, 1637 (1980)

26. H. Heiselberg, and M. Hjorth-Jensen, *Astrophys. J.* **525**, L45 (1999).

27. D. Blaschke, S. Fredriksson, H. Grigorian, and A. Öztas, *Nucl. Phys.*, A, **736**, 203 (2004).

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

29. M. Alford, K. Rajagopal, and F. Wilczek, *Phys. Lett.*, B **422**, 247 (1998).

30. D. Blaschke, and C.D. Roberts, *Nucl. Phys.*, A **642**, 197 (1998); J.C.R. Bloch, C.D. Roberts, and S.M. Schmidt, *Phys. Rev.*, C **60**, 65208 (1999).

31. M. Alford, K. Rajagopal, and F. Wilczek, *Phys. Lett.*, B **357**, 443 (1999); T. Schäfer, and F. Wilczek, *Phys. Rev.* D **62**, 094007 (2000).

32. D. Blaschke, and C.D. Roberts, *Nucl. Phys.*, A **642**, 197 (1998); J.C.R. Bloch, C.D. Roberts, and S.M. Schmidt, *Phys. Rev.*, C **60**, 65208 (1999).

33. M. Alford, K. Rajagopal, and F. Wilczek, *Nucl. Phys.*, B **357**, 443 (1999); T. Schäfer, and F. Wilczek, *Phys. Rev. Lett.*, **82**, 3956 (1999).

34. M. Alford, J. Berges, and K. Rajagopal, *Nucl. Phys.*, B **558**, 219 (1999).

35. A.W. Steiner, S. Reddy, and M. Prakash, *Phys. Rev.*, D **66**, 094007 (2002).

36. F. Neumann, M. Buballa, and M. Oertel, *Nucl. Phys.*, A714, 481 (2003).

37. C. Gocke, D. Blaschke, A. Khalatyan, and H. Grigorian, *arXiv:hep-ph/0104183* (2002)

38. D.N. Voskresensky, M. Yasuhira, and T. Tatsumi, Phys. Lett. B **541**, 93 (2002); *Nucl. Phys.*, A **723**, 291 (2002).

39. M. Prakash, J.M. Lattimer, A.W. Steiner, and D. Page, *Nucl. Phys.*, A **715**, 835 (2003).

40. T. Schäfer, *Phys. Rev.*, D **62**, 094007 (2000).

41. Ainsworth, T., Wambach, J., and Pines, D., *Phys. Rev. Lett.*, **92**, 173 (1989).

42. J. Cottam, F. Paerels, and M. Mendez, *Nature*, **420**, 51 (2002).

43. A. Schmitt, Q. Wang, and D. H. Rischke, *Phys. Rev.*, D **66**, 114010 (2002).

44. A. Schwenk, B. Friman, *Phys. Rev. Lett.*, **92**, 082501 (2004).

45. T. Takatsuka, and R. Tamagaki *Prog. Theor. Phys.* **112**, pp. 37-72 (2004).

46. T. Maruyama, et al., *arXiv:nucl-th/0402002*, (2004)

47. T. Tatsumi, T. Maruyama, D. N. Voskresensky, T. Tanigawa, S. Chiba, *arXiv:nucl-th/0502040* (2005)

48. T. Maruyama, et al., *arXiv:nucl-th/0402002*, (2004)

49. T. Maruyama, et al., *arXiv:nucl-th/0502040* (2005)

50. V. A. Khodel, J. W. Clark, M. Takano, and M. V. Zverev, *Phys. Rev. Lett.* **93**, 151101 (2004)

51. H. Grigorian, and D. N. Voskresensky, [arXiv:astro-ph/0501675](http://arxiv.org/abs/astro-ph/0501675) (2005)

52. P. Jaikumar, and M. Prakash, *Phys. Lett.*, B **516**, 345 (2001).

53. I.H. Stairs, *Science* **304**, 547 (2004).