NEUTRINO EMISSION FROM NEUTRON STARS *

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The main mechanisms of neutrino emission from the matter of supranuclear density in superfluid cores of neutron stars are reviewed, with the emphasis on the cores composed of nucleons. The effects of neutrino emission on the thermal evolution of neutron stars are described. The prospects of exploring the fundamental (but still poorly known) properties of supranuclear matter by comparing simulations of neutron star thermal evolution with observations are outlined.

1. Introduction

Neutron stars are the most compact stellar objects in the Universe. Their typical masses are $M \sim 1.4\,M_\odot$ (where $M_\odot$ is the solar mass), while their radii are only ~ 10 km. Their mean mass density reaches a few ρ_0 ($\rho_0 \approx 2.8 \times 10^{14}$ g cm^{-3} is the standard nuclear matter density); their central density can exceed $10\,\rho_0$. Accordingly, neutron stars can be regarded as unique astrophysical laboratories of supranuclear matter.

It is currently thought (e.g., Ref. [1]) that a neutron star consists of a thin crust (of mass $\lesssim 10^{-2} M_\odot$) and a core (where the mass density $\rho \gtrsim \rho_0/2$). The crustal matter contains atomic nuclei, electrons, and (at $\rho \gtrsim 4 \times 10^{11}$ g cm^{-3}) free neutrons. The core can be subdivided into the outer ($\rho \lesssim 2\rho_0$) and inner parts. The outer core consists of neutrons (n), with an admixture of protons (p), electrons (e), and muons (all constituents being strongly degenerate). The composition of the inner core is unknown. It may be the same as in the outer core but may also contain hyperons, pion or kaon condensates, quark matter, or a mixture of different phases.

*Supported by grants 05-02-16245 and 03-07-90200 of the Russian Foundation for Basic Research and by grant 1115.2003.2 of the Russian Leading Science School Program.
†Partially supported by the INTAS grant YSF 03-55-2397 and by the Russian Science Support Foundation

Table 1. Main processes of neutrino emission in nucleon matter

Process	Reactions		L_ν, erg s^{-1}	Comment
Direct Urca	$n \to pe\bar{\nu}$	$pe \to n\nu$	$\sim 10^{44-46} T_9^6 \mathcal{R}$	fast
Modified Urca	$nN \to pNe\bar{\nu}$	$pNe \to nN\nu$	$\sim 10^{39-40} T_9^8 \mathcal{R}$	slow
Bremsstrahlung	$NN \to NN\nu\bar{\nu}$		$\sim 10^{37-39} T_9^8 \mathcal{R}$	very slow
Cooper pairing	$\widetilde{N}\widetilde{N} \to \nu\bar{\nu}$		$\lesssim 10^{40-42} T_9^8$	moderate

Nucleons, hyperons, and quarks can be in superfluid state. Microscopic theories of dense matter are model dependent. The fundamental problem of the equation of state (EOS) and composition of the matter in neutron star cores is still unsolved.

Here, we briefly review neutrino processes in neutron stars with nucleon cores and their effect on neutron star cooling (see, e.g., Refs. [2,3,4,5,6] for more details).

2. Neutrino Emission Processes

Neutron stars are born hot in supernova explosions, with the internal temperature $T \sim 10^{11}$ K, producing a powerful neutrino outburst. In one minute after the birth a star becomes transparent for neutrinos. We discuss the following neutrino-transparent stage when the neutrino emission is much weaker than at the supernova stage but still important for neutron star cooling.

We outline the neutrino emission from stellar cores which is usually more powerful than from crusts. The main neutrino reactions in nucleon cores are listed in Table 1. It is important to know the neutrino emissivities Q (erg cm^{-3} s^{-1}) for these reactions and the associated neutrino luminosities L_ν (erg s^{-1}), which are the emissivities integrated over the star volume.

The most powerful is the direct Urca process [7]. In the matter composed of n, p, and e, this is the beta decay of a neutron and subsequent electron capture by a proton (Table 1). The process occurs if the proton fraction is sufficiently high (to satisfy momentum conservation). This happens only for some EOSs in the inner cores of massive stars, where the density exceeds a certain density threshold $\rho_{\rm D}$.

In addition, there are slower neutrino processes (Table 1), which operate in the outer and inner cores. They are two modified Urca processes (for N=n or p) and three bremsstrahlung processes (nn, pp and np). The modified Urca processes differ from the direct Urca by an additional nucleon-spectator N (which simplifies momentum conservation). In the presence of muons there are additional Urca processes, with muons instead of electrons.

Neutrino reactions are greatly affected by nucleon superfluidity. When the temperature T drops much below the critical temperature T_c for a given nucleon species, the energy gap in the nucleon energy spectrum greatly (exponentially) suppresses all reactions involving such nucleons (e.g., Ref. [3]).

Also, superfluidity initiates a specific neutrino process owing to *Cooper pairing of nucleons* [8] (annihilation of Bogoliubov quasi-nucleons $\widetilde{N}$ into neutrino pairs, Table 1). This process is forbidden in nonsuperfluid matter. With decreasing T, it becomes allowed at $T = T_c$, produces the maximum emissivity at $T \sim 0.8\,T_c$, and is exponentially suppressed at $T \ll T_c$. For realistic density profiles $T_c(\rho)$ at T much below the maximum value of $T_c(\rho)$, the neutrino luminosity due to this process behaves as $L_\nu^{\rm CP} \propto T^8$ and may exceed the luminosity provided by the modified Urca process in a nonsuperfluid star by up to two orders of magnitude [5,9].

Order-of-magnitude estimates of neutrino luminosities for the cited processes are given in Table 1, where $T_9 = T/10^9$ K and $\mathcal{R}$ describes the reduction of the luminosity by superfluidity (with $\mathcal{R} = 1$ and $L_\nu^{\rm CP} = 0$ in a nonsuperfluid star).

3. Neutrino emission and cooling neutron stars

Because the neutrino emission depends on the internal structure of neutron stars and affects their cooling, it allows one to explore the internal structure by comparing the cooling theory with observations. Here we follow Ref. [10].

Observations of isolated neutron stars, whose thermal surface radiation has been detected or constrained, are summarized in Fig. 1 (the data are the same as in Refs. [9,10]). We present the stellar ages t and effective surface temperatures T_s^∞ inferred from observations; '∞' means the quantity redshifted to the reference frame of a distant observer. Arrows show the upper limits on T_s^∞ (in cases no thermal radiation has been detected).

The cooling theory gives *cooling curves*, $T_{\rm s}^\infty(t)$ (e.g., Fig. 1). In $t \lesssim 100$ years the stellar interiors become thermally relaxed. At $t \lesssim 10^5$ years, a star cools mainly via neutrino emission; at $t \gtrsim 10^5$ years it cools via thermal surface emission of photons.

Figure 1 shows the *basic cooling curve*. It is calculated for a star with a non-superfluid nucleon core which cools slowly via the modified Urca process. This curve is almost independent of the EOS and neutron star mass. It cannot explain the observations – some sources are hotter and some colder than predicted by the curve.

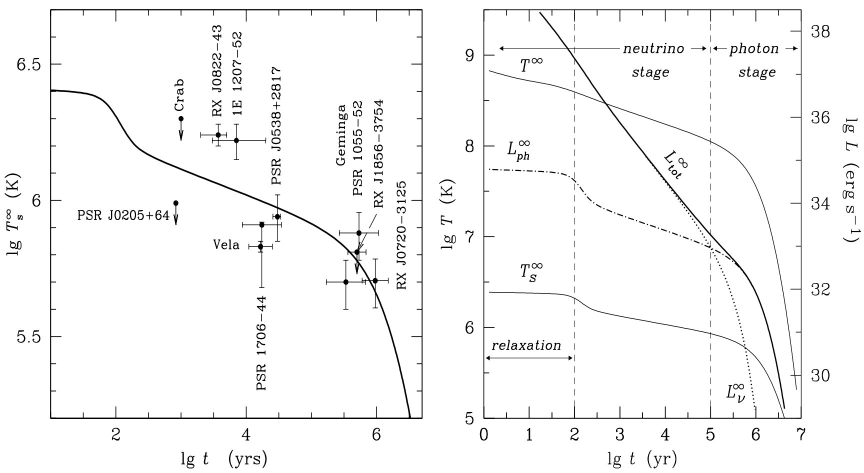

Figure 1. *Left:* Observational limits of surface temperatures for several isolated neutron stars compared with the basic theoretical cooling curve. *Right:* Internal and surface temperatures; neutrino, photon and total luminosities (redshifted for a distant observer) for the basic cooling model.

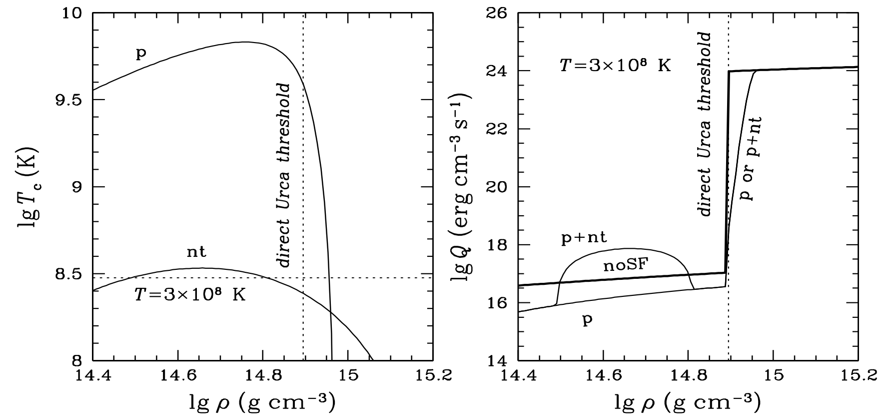

Figure 2. *Left:* Illustrative models of critical temperatures for singlet-state proton (p) and triplet-state neutron (nt) pairing in a neutron star core. *Right:* Neutrino emissivity in the same core at $T = 3 \times 10^8$ K for non-superfluid matter (thick line; noSF) and either for proton pairing (p) or for proton and neutron pairing (p+nt). The vertical dotted line shows the direct Urca threshold.

At the next step let us take into account the effects of enhanced neutrino emission in massive neutron stars (Fig. 2). We adopt a moderately stiff EOS of dense nucleon matter from Ref. [11] (the same modification as in Ref. [4]).

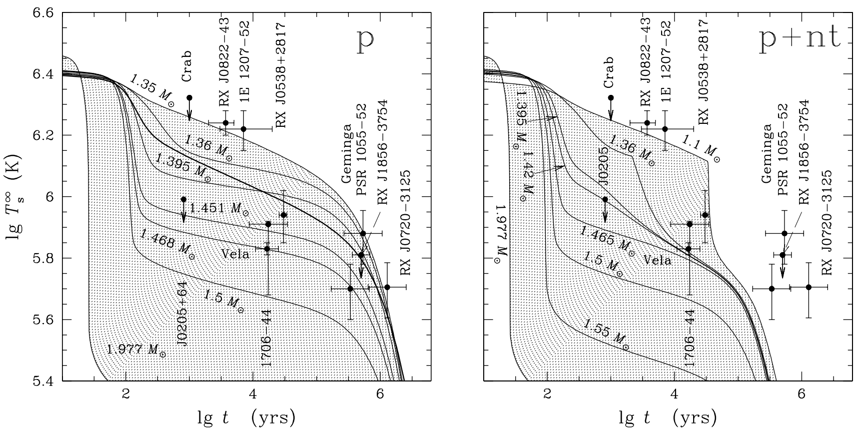

Figure 3. *Left:* Cooling of neutron stars of several masses (indicated near the curves) with proton superfluidity p from Fig. 2 in the cores. *Right:* Same as in the left panel but adding the effect of neutron superfluidity nt.

It opens the direct Urca process at $\rho > \rho_{\rm D} = 7.851 \times 10^{14}$ g cm^{-3}, i.e., at $M > M_{\rm D} = 1.358\,M_\odot$ (M being the gravitational mass) and gives the maximum neutron-star mass $M_{\rm max} = 1.977\,M_\odot$. In non-superfluid matter the direct Urca process switches on sharply at $\rho > \rho_{\rm D}$. If M exceeds $M_{\rm D}$ only by 0.1%, the neutrino luminosity owing to the direct Urca process is already so strong that $T_s^\infty(t)$ falls much below the T_s^∞ for coldest observed stars in Fig. 1 (close to the lowest curves in Fig. 3). Therefore, we have either the basic curve for $M \leq M_{\rm D}$ or much lower curves for more massive stars; these curves are inconsistent with the data.

However, protons and neutrons in neutron star cores can be in superfluid state. As a rule, protons undergo singlet-state pairing, whereas neutrons undergo triplet-state pairing (e.g., Ref.[12]) with density dependent critical temperatures $T_{\rm cp}(\rho)$ and $T_{\rm cnt}(\rho)$ which are very sensitive to theoretical models. Figure 2 shows some phenomenological $T_{\rm cnt}(\rho)$ and $T_{\rm cp}(\rho)$ curves [4] and their effect on the neutrino emissivity.

First we assume strong proton superfluidity p alone. It extends to densities $\rho > \rho_{\rm D}$ and suppresses the modified Urca process in low-mass stars ($M < M_{\rm D}$). The neutrino luminosity of these stars becomes lower (Fig. 2), being determined by a weaker mechanism (*nn* bremsstrahlung, unaffected by proton superfluidity). This *rises* the cooling curves of low-mass stars and allows one to explain the observations of stars hottest for their age, such as RX J0822–43, 1E 1207–52, PSR B1055–52 (left panel of Fig. 3).

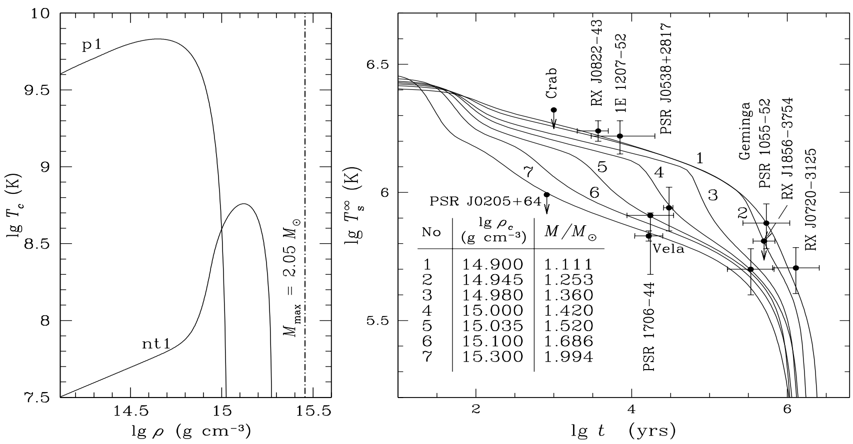

Figure 4. *Left:* Model density dependence for critical temperatures of protons (p1) and neutrons (nt1) in a nucleon stellar core for the EOS which forbids the direct Urca process. *Right:* Cooling of neutron stars of several masses (indicated in the inset) with pairing p1 and nt1 for the same EOS.

Thus, we may treat these sources as low-mass neutron stars.

Proton pairing p suppresses even the direct Urca process at $\rho \sim \rho_{\rm D}$. At higher ρ pairing gradually dies out, opening the direct Urca process. The gradual opening broadens the direct Urca threshold (Fig. 2) and ensures the gradual decrease of cooling curves with increasing M. In this way we may attribute masses to observed neutron stars [13], as shown in the left panel of Fig. 3, and explain all the data. For instance, we obtain $M \approx 1.47\,M_\odot$ for the Vela pulsar. However, this *weighing* of neutron stars is sensitive [14] to the EOS of dense matter, to the direct Urca threshold, and to superfluidity model $T_{\rm cp}(\rho)$. Even strong pairing p dies out in the centers of massive stars ($M \sim M_{\rm max}$), where direct Urca process is allowed. Thus, massive stars cool very rapidly, as if they are non-superfluid, and become very cold.

Now let us include also neutron pairing nt with the peak of $T_{\rm cnt}(\rho)$ as low as $\sim 4 \times 10^8$ K at $\rho \sim 4 \times 10^{14}$ g cm^{-3}. This pairing is mild and insignificant, according to nuclear physics standards, but crucial for the cooling. It appears in a cooling star when the internal temperature falls below the peak value. It creates then a powerful neutrino emission owing to Cooper pairing of neutrons in outer stellar cores, especially efficient in low-mass stars. The emission accelerates the cooling (the right panel of Fig. 3) and violates the interpretation of the observations of such sources as PSR B1055–52. Thus, this mild neutron superfluidity contradicts the observations.

The opposite example is given in Fig. 4. Let us consider neutron stars with nucleon cores and employ the EOS [15] which forbids the direct Urca process in all stars with $M \leq M_{\max} = 2.05\, M_{\odot}$. Furthermore, let us adopt the model of strong proton pairing p1 and mild neutron pairing nt1 (the left panel of Fig. 4). Pairing p1 is similar to pairing p in Fig. 2; it suppresses the modified Urca process in low-mass stars. The peak of $T_{\rm cnt}(\rho)$ for pairing nt1 is as low as for pairing nt but shifted to higher densities. Accordingly, pairing nt1 is inefficient in low-mass stars and does not affect their cooling. However, the enhanced neutrino emission owing to this pairing operates in massive stars and accelerates their cooling. Then the cooling of stars with different masses enables us to explain the data (the right panel of Fig. 4), but only under stringent constraints on the $T_{\rm cnt}(\rho)$ profile [9]. Note that a discovery of a neutron star slightly colder than those observed now would ruin this interpretation.

4. Conclusions

We have outlined the main neutrino emission mechanisms in nucleon cores of neutron stars. We have shown than these mechanisms are greatly affected by the EOS and by superfluid properties of dense matter. We have demonstrated that the neutrino emission strongly regulates the cooling of isolated neutron stars. Current observations of cooling neutron stars can be explained by different theoretical models of dense matter. Nevertheless the theory rules out some theoretical models (e.g., the model in the right panel of Fig. 3).

Neutron star cooling can also be regulated by the surface magnetic fields and by the presence of light (accreted) elements on stellar surfaces (see, e.g., Refs. [4,6,10]). The fields and accreted elements affect the thermal conductivity of surface layers. They may increase the surface temperature $T_s^\infty(t)$ of middle-aged stars and decrease $T_s^\infty(t)$ for $t \gtrsim 10^5$ yrs. In addition, the neutrino emission and cooling can be modified [6] by the presence of different forms of matter (hyperons, pion or kaon condensates, deconfined quarks) in neutron stars (and in strange quark stars). Also, the cooling can be affected by some reheating mechanisms, for instance, by the viscous dissipation of rotational energy or Ohmic decay of magnetic field. All in all, current observations of cooling neutron stars can be explained by drastically different physical models of dense matter.

New observations of neutron stars are required for a better understanding of their internal structure. Observations of cooling neutron stars should be analyzed together with other observational data. The data should be combined with new theoretical results, particularly, with new studies of nucleon superfluidity and neutrino emission properties. This would allow one to obtain more stringent constraints on neutron star structure.

Acknowledgments

DY is grateful to the organizers of CSSP-2005 and to the RFBR (travel grant 05-02-26668z) for financial support which allowed him to participate in CSSP-2005.

References

1. P. Haensel, In: *Final Stages of Stellar Evolution*, C. Motch and J.-M. Hameury (eds.), EAS Publications Series: EDP Sciences, 249 (2003).
2. C.J. Pethick, *Rev. Mod. Phys.* **64**, 1133 (1992).
3. D.G. Yakovlev, A.D. Kaminker, O.Y. Gnedin, and P. Haensel, *Phys. Rep.* **354**, 1 (2001).
4. D.G. Yakovlev and C.J. Pethick, *Ann. Rev. Astron. Astrophys.* **42**, 169 (2004).
5. D. Page, J.M. Lattimer, M. Prakash, and A.W. Steiner , *Astroph. J. Suppl.* **155**, 623 (2004).
6. D. Page, U. Geppert, and F. Weber, *Nucl. Phys. A*, accepted (2005) [astro-ph/0508056].
7. J.M. Lattimer, C.J. Pethick, M. Prakash, and P. Haensel, *Phys. Rev. Lett.* **66**, 2701 (1991).
8. E.G. Flowers, M. Ruderman, and P.G. Sutherland, *Astrophys. J.* **205**, 541 (1976).
9. M.E. Gusakov, A.D. Kaminker, D.G. Yakovlev, and O.Y. Gnedin, *Astron. Astrophys.* **423**, 1063 (2004).
10. D.G. Yakovlev, O.Y. Gnedin, M.E. Gusakov, A.D. Kaminker, K.P. Levenfish, and A.Y. Potekhin, *Nucl. Phys.* **A 752**, 590c (2005).
11. M. Prakash, T.L. Ainsworth, and J.M. Lattimer, *Phys. Rev. Lett.* **61**, 2518 (1988).
12. U. Lombardo and H.-J. Schulze, In: *Physics of Neutron Star Interiors*, D. Blaschke, N.K. Glendenning, and A. Sedrakian (eds.), Springer: Berlin, 30 (2001).
13. A.D. Kaminker, P. Haensel, and D.G. Yakovlev, *Astron. Astrophys.* **373**, L17 (2001).
14. A.D. Kaminker, D.G. Yakovlev, and O.Y. Gnedin, *Astron. Astrophys.* **383**, 1076 (2002).
15. F. Douchin and P. Haensel, *Astron. Astrophys.* **380**, 151 (2001).