A&A 379, L5–L8 (2001)
DOI: 10.1051/0004-6361:20011329

Astronomy & Astrophysics

Letter to the Editor

$^1S_0$ neutron pairing vs. observations of cooling neutron stars

D. G. Yakovlev[1], A. D. Kaminker[1], and O. Y. Gnedin[2]

[1] Ioffe Physical Technical Institute, Politekhnicheskaya 26, 194021 St. Petersburg, Russia
[2] Institute of Astronomy, Madingley Road, Cambridge CB3 0HA, UK
e-mail: kam@astro.ioffe.rssi.ru; ognedin@ast.cam.ac.uk

Received 13 August 2001 / Accepted 24 September 2001

Abstract. As shown recently by Kaminker et al. (2001), current observations of thermal emission of isolated middle-aged neutron stars (NSs) can be explained by cooling of NSs of different masses with the cores composed of neutrons, protons and electrons, assuming rather strong superfluidity (SF) of protons, weak triplet-state SF of neutrons and neglecting singlet-state SF of neutrons. We show that this explanation remains correct in the presence of singlet-state SF of neutrons in the NS crust and outermost core but under stringent constraints on the density profile of the SF critical temperature $T_{\rm cns}(\rho)$. In order to explain observations of (young and hot) RX J0822–43 and (old and warm) PSR 1055–52 and RX J1856–3754 as cooling not too massive NSs, the maximum $T_{\rm cns}^{\rm max}$ should be rather high ($\gtrsim 5 \times 10^9$ K) and the decrease of $T_{\rm cns}(\rho)$ outside the maximum should be sharp. These results place important constraints on the models of nucleon SF in dense matter.

Key words. stars: neutron – dense matter

1. Introduction

Cooling of NSs depends on the poorly known properties of matter in NS interiors. Combined with the best observational data, the cooling theory can be used to explore the properties of this matter, in particular, critical temperatures $T_{\rm c}$ of SF of neutrons (n) and protons (p) (supplementing very model-dependent microscopic calculations, e.g., Lombardo & Schulze 2001). SF of nucleons reduces the emissivity of neutrino reactions and affects the nucleon heat capacity (e.g., Yakovlev et al. 1999). Moreover, SF initiates a specific neutrino emission associated with Cooper pairing of nucleons (Flowers et al. 1976). In this way nucleon SF becomes a strong regulator of NS cooling.

Recently Kaminker et al. (2001, hereafter Paper I) proposed the interpretation of observations of thermal emission from eight isolated middle-aged NSs (Fig. 1) using simple models of cooling NSs with superfluid cores (composed of neutrons, protons and electrons). Accordingly, one can consider three types of nucleon SFs with density dependent $T_{\rm c}(\rho)$: singlet-state ($^1S_0$) neutron SF in the NS inner crust and the outermost core ($T_{\rm c} = T_{\rm cns}$); triplet-state ($^3P_2$) neutron SF in the core ($T_{\rm cnt}$); and $^1S_0$ proton SF in the core ($T_{\rm cp}$). For simplicity, in Paper I $^1S_0$ neutron SF was neglected. The main reason was that, being mainly located in a thin crust, this SF seemed unimportant for middle-aged NSs. In Paper I the observations were explained with the models of cooling NSs of different masses assuming rather strong proton SF and weak $^3P_2$ neutron SF. The models require neither exotic composition of NS core nor additional NS reheating.

We extend the results of Paper I by including $^1S_0$ neutron superfluidity and show that, contrary to our expectation, this superfluidity is important.

Send offprint requests to: D. G. Yakovlev,
e-mail: yak@astro.ioffe.rssi.ru

2. Cooling models with $^1S_0$ neutron pairing

We simulate NS cooling with our fully relativistic nonisothermal cooling code (e.g., Gnedin et al. 2001). The physics input is mostly the same as in Paper I. In particular, we adopt a moderately stiff equation of state (EOS) of matter in the NS core proposed by Prakash et al. (1988) (their model I with the compression modulus of saturated nuclear matter $K = 240$ MeV). The outer heat blanketing NS envelope is assumed to be composed of iron, but the atmosphere may be made of hydrogen. The maximum mass of our NS models is 1.977 $M_\odot$ (central density $\rho_{\rm c,\,max} = 2.575 \times 10^{15}$ g cm^{-3}). For the given EOS, a powerful direct Urca process of neutrino emission (Lattimer et al. 1991) is forbidden if $M < M_{\rm D} = 1.358\ M_\odot$ ($\rho_{\rm c} < 7.851 \times 10^{14}$ g cm^{-3}). In this case, a NS undergoes a *slow* cooling mainly via modified Urca process. A NS with $M > M_{\rm D}$ possesses a central kernel, where direct Urca process is open, initiating *fast* cooling.

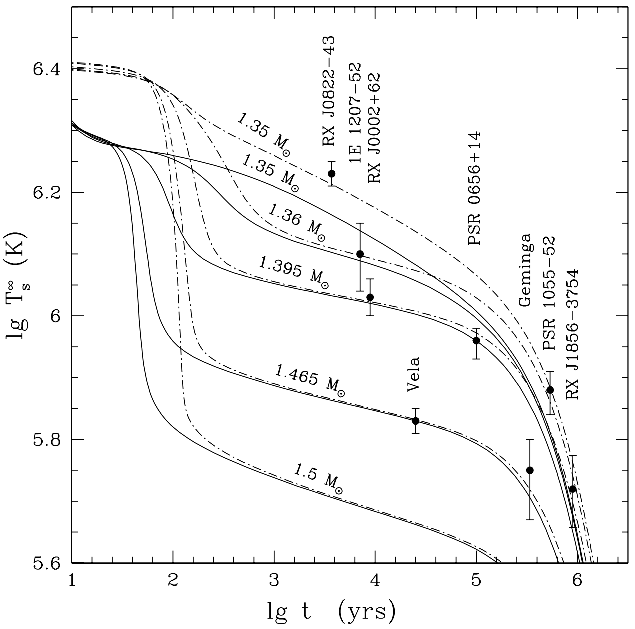

Fig. 1. Observational limits on surface temperatures of eight NSs compared with cooling curves for NS models with masses from 1.35 to 1.5 $M_\odot$. Dot-and-dash curves are obtained including proton SF in the NS core shown in Fig. 2. Solid curves include, in addition, model 1 of $^1S_0$ neutron SF from Fig. 2.

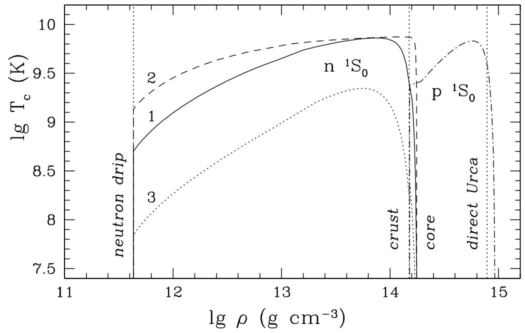

Fig. 2. Density dependence of the critical temperatures for one model of the proton SF (dots-and-dashes) and three models 1, 2 and 3 of $^1S_0$ neutron SF (Table 1) used in cooling simulations (Figs. 1 and 3). Vertical dotted lines indicate neutron drip, core-crust interface, and the direct Urca threshold.

We will confront theoretical cooling curves with the same observational data as in Paper I; the only exclusion is RX J1856–3754, for which new data have become available. Figure 1 shows the limits on the effective surface temperature, T_s^∞, as measured by a distant observer, versus stellar age t for eight NSs. The youngest three are radio-quiet NSs in supernova remnants; the oldest is also a radio-quiet NS; the others are observed as radio pulsars. The values of T_s^∞ are taken from the following sources: RX J0822–43 – Zavlin et al. (1999), 1E 1207–52 – Zavlin et al. (1998), RX J0002+62 – Zavlin & Pavlov (1999), PSR 0833–45 (Vela) – Pavlov et al. (2001), PSR 0656+14 – Possenti et al. (1996), PSR 0630+178 (Geminga) – Halpern & Wang (1997), PSR 1055–52 – Ögelman (1995), and RX J1856–3754 – Pons et al. (2001). As in Paper I the values of T_s^∞ for the four youngest NSs are inferred from the observations using hydrogen atmosphere models while for other SNs (but RX J1856) they are inferred using the blackbody model. For RX J1856, we take $T_s^\infty = 0.52 \pm 0.07$ MK, as inferred using the analytic fit with the Si-ash atmosphere model, and $t = 9\times10^5$ K (Pons et al. 2001). We assume that wide errorbar of T_s^∞ given by this model is in line with current poor understanding of thermal emission from RX J1856 (also see Burwitz et al. 2001). It is also possible (Pons et al. 2001; Burwitz et al. 2001) that the source has a colder surface (0.25 MK) with a hot spot. This case would be easier for our interpretation (see below) than the case we adopt.

We will not rely on any particular (very model dependent) microscopic calculation of SF critical temperature $T_c(\rho)$. Instead, following Paper I, we parameterize T_c as

$$T_c = T_0 \, \frac{k^2}{k^2+k_1^2} \, \frac{(k-k_2)^2}{(k-k_2)^2+k_3^2} \,, \tag{1}$$

for $k < k_2$, and $T_c = 0$ for $k \geq k_2$. Here, $k = k_{FN}$ is the nucleon (N = n or p) Fermi wavenumber (measured in fm^{-1}). The parameters T_0, k_1, k_2, k_3 of our SF models are given in Table 1.

As in Paper I we adopt a typical proton SF (Fig. 2). We also assume that $^3P_2$ neutron SF in the NS core is weak (maximum $T_{cnt}^{max} < 10^8$ K) and does not affect cooling (see Paper I for details). Neglecting $^1S_0$ neutron SF, we obtain the dot-and-dashed cooling curves displayed in Fig. 1 for several values of M. The upper curve is calculated for M = 1.35 $M_\odot$ but it is actually the same for all M from 1.1 $M_\odot$ to M_D. The dot-and-dashed curves in Fig. 1 are slightly different from analogous curves in Paper I since now we use a denser grid of mass zones in the cooling code. In agreement with Paper I we see that tuning M we can explain the observations of all eight sources.

Now let us include $^1S_0$ neutron SF. Figure 2 shows the three models we consider. Models 1 (solid line) and 2 (dashes) correspond to about the same, rather strong SF (with maximum $T_{cns} \approx 7\times10^9$ K). The main difference is that $T_{cns}(\rho)$ in model 2 has flatter maximum and sharper fall in the maximum wings. Model 3 (dots) describes much weaker SF, with maximum $T_{cns} \approx 2.4\times10^9$ K and a narrower density profile.

The solid lines in Fig. 1 show cooling curves calculated under the same assumptions as the dot-and-dashed lines but including $^1S_0$ neutron SF (model 1). As expected, the presence of this SF shortens the initial thermal relaxation stage from 100 yrs to 30–50 yrs (Gnedin et al. 2001) but does not affect strongly the cooling of middle-aged NSs with open direct Urca process ($M > M_D$). Thus, $^1S_0$ neutron SF does not change the results of Paper I for $M > M_D$ and the proposed interpretation of observations of five sources, 1E 1207–52, RX J0002+62, Vela, PSR 0656+14, and Geminga.

Table 1. Parameters of ^{1}S$_0$ SF models in Eq. (1).

SF	$T_0/10^9$ K	k_1, fm^{-1}	k_2, fm^{-1}	k_3, fm^{-1}
p	20.29	1.117	1.241	0.1473
1n	10.2	0.6	1.45	0.1
2n	7.9	0.3	1.45	0.01
3n	1800	21	1.45	0.4125

However, this SF drastically affects the cooling of low-mass ($M \leq M_{\rm D}$) NSs. Its main effects are to lower $T_{\rm s}^\infty$ at $t \lesssim 3 \times 10^5$ yrs by an additional neutrino emission associated with the ^{1}S$_0$ Cooper pairing of neutrons and to lower $T_{\rm s}^\infty$ further at $t \gtrsim 3 \times 10^5$ yrs by reducing heat capacity of neutrons in the crust. The importance of the Cooper emission can be explained as follows. The neutrino emission from the core of a middle-aged NS is strongly reduced by SF suppression of the majority of neutrino reactions ($T \ll T_{\rm cp}$). The neutrino emission due to ^{1}S$_0$ neutron pairing is also greatly suppressed in the bulk of the inner NS crust, where $T \ll T_{\rm cns}$, but remains active in two thin layers, where $T_{\rm cns}(\rho)$ is closer to the internal temperature T: near the neutron drip point and in the outermost part of the core. Consider, for instance, the outermost core. Since the emission layer is thin, the emissivity can be written as $Q^{\rm CP} = Q_0 T^7 F(T/T_{\rm cns})$, where Q_0 may be regarded as constant (easily obtained from Eq. (79) in Yakovlev et al. 1999) and $F(\tau)$ is a known function. If we approximate the dependence of $T_{\rm cns}$ on radial coordinate r in our thin layer by a linear function $T_{\rm cns}(r) = T + A(r - r_0)$ and integrate over this layer, we obtain the Cooper–pairing (non-redshifted) neutrino luminosity:

$$L^{\rm CP} = 4\zeta\pi r_0^2 Q_0 T^7 h, \quad \zeta = \int_0^1 {\rm d}\tau \, \frac{F(\tau)}{\tau^2} = 6.63, \qquad (2)$$

where $h = T/A$ is the characteristic width of the layer (variation scale of $T_{\rm cns}(r)$ at $r \approx r_0$). Adopting a typical value $r_0 = 12$ km and the neutron number density $n_{\rm n} = 0.1$ fm^{-3}, we have $L^{\rm CP} \approx 8.9 \times 10^{38}\, T_9^7\, (h/100 \text{ m})$ erg s^{-1}, where $T_9 \equiv T/10^9$ K. For a typical scale $h \sim 100$ m, the luminosity $L^{\rm CP}$ is comparable to the standard (modified Urca) luminosity of the entire non-superfluid NS core! It may easily outweight the SF suppression of the neutrino luminosity in other reactions. In Paper I we analyzed analogous effect with regard to ^{3}P$_2$ neutron SF in the core and showed that such SF, if available, strongly accelerates cooling (even for $M > M_{\rm D}$) and complicates interpretation of observations. Here we demonstrate that a similar but less pronounced effect is produced by ^{1}S$_0$ neutron SF at $M < M_{\rm D}$.

According to Fig. 1, the ^{1}S$_0$ neutron SF complicates interpretation (Paper I) of observations of the youngest and hot source RX J0822–43 and of two oldest and warm sources, PSR 1055–52 and RX J1856–3754 by the NS models with $M < M_{\rm D}$. The less stringent complication for RX J1856–3754 is evidently associated with too wide errorbar of $T_{\rm s}^\infty$. Let us focus (Fig. 3) on cooling of low-mass NS models with regard to interpretation of these three sources. For certainty, we again exploit the 1.35 $M_\odot$ model although nearly the same is true for any M from 1.1 $M_\odot$ to $M_{\rm D}$. To save the proposed interpretation we must rise the upper cooling curve in Fig. 1.

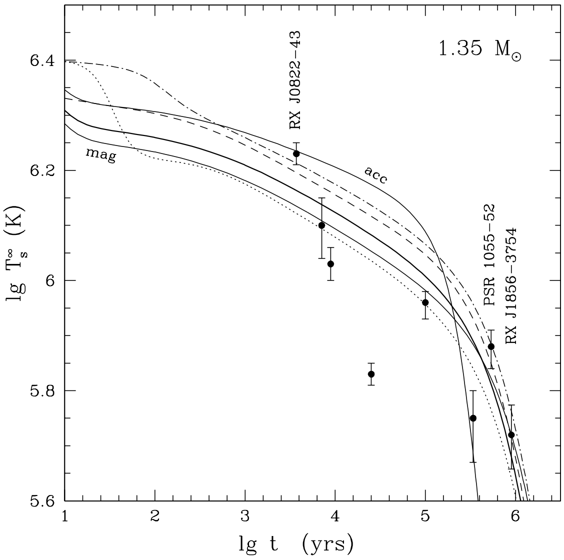

Fig. 3. Cooling curves of the 1.35 $M_\odot$ NS model vs observations of RX J0822–43, PSR 1055–52 and RX J1856–3754. Dot-and-dashed curve: proton SF in the NS core. Solid, dashed and dotted curves include, in addition, models 1, 2 and 3 of ^{1}S$_0$ neutron SF (Fig. 2), respectively. Full solid line is the same as in Fig. 1. Thin solid curve *acc* is calculated assuming the presence of $10^{-10}\, M_\odot$ of hydrogen on the NS surface. Thin solid curve *mag* is obtained assuming the dipole surface magnetic field (10^{12} G at the magnetic pole).

The obvious solution is to take ^{1}S$_0$ neutron SF with steeper slopes of $T_{\rm cns}(\rho)$ near the crust–core interface and the neutron drip point. This decreases the characteristic scale h and the "harmful" luminosity $L^{\rm CP}$. For example, taking model 2 of ^{1}S$_0$ neutron SF instead of model 1 (Fig. 2) we obtain the dashed cooling curve (Fig. 3) which is closer to the dot-and-dashed curve than the thick solid curve. (Another example: shifting $T_{\rm cns}(\rho)$ for model 2 into the crust would additionally rise the cooling curves.) Note that the cooling curves are insensitive to the details of the $T_{\rm cns}(\rho)$ profiles near the maximum of $T_{\rm cns}(\rho)$ as long as $T_{\rm cns}^{\rm max} \gtrsim 5 \times 10^9$ K, but they are very sensitive to the decreasing slopes of $T_{\rm cns}(\rho)$. A similar effect was reported in Paper I with regard to the $T_{\rm cp}(\rho)$ profiles. Taking smoother and lower $T_{\rm cns}(\rho)$, model 3, we obtain a NS that is much colder than required by observations (dotted line in Fig. 3). Therefore, ^{1}S$_0$ neutron SF with $T_{\rm cns}^{\rm max} < 5 \times 10^9$ K and/or with smoothly decreasing slopes of the $T_{\rm cns}(\rho)$ profile near the crust-core interface and neutron drip point *violates* the proposed interpretation.

Let us stress that the observations of these three sources can be fit even with our initial model 1 of ^{1}S$_0$ neutron SF. The high surface temperature of RX J0822–43 can be explained assuming the presence of low–mass surface envelope of light elements. This effect is modeled using the results of Potekhin et al. (1997). Light elements increase the electron thermal conductivity of NS surface layers and raise T_s^∞ at a neutrino cooling stage, $t \lesssim 3 \times 10^5$ yrs (curve *acc* in Fig. 3). In order to explain the observations of PSR 1055–52 and RX J1856–3754, we can assume again model 1 SF, iron surface and the dipole surface magnetic field ($\sim 10^{12}$ G at the magnetic pole; line *mag*). Such a field makes the NS surface layers overall less heat-transparent (Potekhin & Yakovlev 2001), rising T_s^∞ at $t \gtrsim 3 \times 10^5$ yrs. Note that the dipole field $\gtrsim 10^{13}$ G has the opposite effect, similar to that produced by the surface envelope of light elements. Thus, we can additionally vary cooling curves by assuming the presence of light elements and/or the magnetic field on the NS surface. However, these variations are less pronounced than those produced by nucleon SF. For instance, we cannot reconcile the cooling curves with observations of PSR 1055–52 assuming model 3 of neutron SF with any surface magnetic field.

3. Summary

Extending the results of Paper I, we have shown that observations of thermal emission from eight isolated NSs are consistent with a simple model of cooling superfluid NSs of different masses. As in Paper I, the cooling model implies rather strong proton SF and weak $^3P_2$ neutron SF in the NS core. In addition, we have included the effects of $^1S_0$ neutron SF in the crust and found that it does not affect noticeably interpretation of 1E 1207–52, RX J0002+62, Vela, PSR 0656+14, and Geminga as NSs with masses $M > M_D$. However, this SF is crucial for interpretation of RX J0822–43, PSR 1055–52, and RX J1856–3754 (hotter for their ages) as NSs with $M < M_D$.

The interpretation requires the density profiles of $T_{cns}(\rho)$ with rather flat and not too low maximum ($\gtrsim 5 \times 10^9$ K) and steep decrease of $T_{cns}(\rho)$ in the wings. These requirements constrain the models of nn interaction in dense matter. We have compared the $^1S_0$ SF gaps $\Delta(k_{Fn}) = T_{cns}/0.57$ for our models 1–3 with the results of numerous microscopic calculations, shown in Fig. 7 in Lombardo & Schulze (2001). The gaps for models 1 and 3 are typical for microscopic theories in which medium effects reduce $^1S_0$ pairing not too strongly. The gap for model 2 is less ordinary (has too sharp decreasing slope at large k_{Fn}).

Note, that our results depend crucially on the choice of $T_{cp}(\rho)$ at $\rho \sim \rho_D$. By taking $T_{cp}(\rho)$ shown in Fig. 2, we obtain the NS masses in the range from 1.1 $M_\odot$ to 1.47 $M_\odot$, in a good agreement with the well-known masses of radio pulsars in binary systems (Thorsett & Chakrabarty 1999). Adopting another $T_{cp}(\rho)$ profile with smoother decrease of T_{cp} at high density, we would obtain higher masses for the same sources. The inferred mass range is also affected by the choice of EOS in the NS core (Paper I). However, all these features do not affect our conclusions on the properties of $^1S_0$ neutron SF needed for the NS models with $M < M_D$.

One can see that the cooling of NSs with $M < M_D$ is sensitive to the density profile of free neutrons near the crust bottom and neutron drip point. We have used only one model of free-neutron distribution in the crust, assuming atomic nuclei to be spherical. It would be interesting to consider the models with non-spherical nuclei at the crust bottom (e.g., Pethick & Ravenhall 1995) and take into account SF of nucleons confined in atomic nuclei.

Let us stress that inferring T_s^∞ from observational data is the most complicated problem (as discussed partly in Yakovlev et al. 1999). It would be important to improve the limits on T_s^∞ and the NS ages in the future high–quality observations; they may change considerably. Our interpretation is most sensitive to the data on RX J0822–43, and especially on PSR 1055–52, and RX J1856–3754. These sources seem to be excellent for testing the cooling theories.

Acknowledgements. We are grateful to the referee, G. G. Pavlov, for useful suggestions, as well as to K. Levenfish and A. Potekhin for critical remarks. The work was supported partly by RFBR (grant No. 99-02-18099).

References

Burwitz, V., Zavlin, V. E., Neuhäuser, R., et al. 2001, A&A, accepted [astro-ph/0109374]

Gnedin, O. Y., Yakovlev, D. G., & Potekhin, A. Y. 2001, MNRAS, 324, 725

Flowers, E. G., Ruderman, M., & Sutherland, P. G. 1976, ApJ, 205, 541

Halpern, J. P., & Wang F. Y.-H. 1997, ApJ, 477, 905

Kaminker, A. D., Haensel, P., & Yakovlev, D. G. 2001, A&A, 373, L17, Paper I

Lattimer, J. M., Pethick, C. J., Prakash, M., & Haensel, P. 1991, Phys. Rev. Lett., 66, 2701

Lombardo, U., & Schulze, H.-J. 2001, in Physics of Neutron Star Interiors, ed. D. Blaschke, N. Glendenning, & A. Sedrakian (Springer, Berlin), 31

Ögelman, H. 1995, in Lives of Neutron Stars, ed. M. A. Alpar, Ü. Kiziloğlu, & J. van Paradjis (Kluwer, Dordrecht), NATO ASI Ser., 101

Pavlov, G. G., Zavlin, V. E., Sanwal, D., Burwitz, V., & Garmire, G. P. 2001, ApJ, 552, L129

Pethick, C. J., & Ravenhall, D. G. 1995, Ann. Rev. Nucl. Particle Sci., 45, 429

Pons, J., Walter, F., Lattimer, J., Prakash, M., Neuhäuser, R., & An, P. 2001, ApJ, submitted [astro-ph/0107404]

Possenti, A., Mereghetti, S., & Colpi, M. 1996, A&A, 313, 565

Potekhin, A. Y., Chabrier, G., & Yakovlev, D. G. 1997, A&A, 323, 415

Potekhin, A. Y., & Yakovlev, G. G. 2001, A&A, 374, 213

Prakash, M., Ainsworth, T. L., & Lattimer, J. M. 1988, Phys. Rev. Lett., 61, 2518

Thorsett, S. E., & Chakrabarty, D. 1999, ApJ, 512, 288

Yakovlev, D. G., Levenfish, K. P., & Shibanov, Yu. A. 1999, Physics–Uspekhi, 42, 737 [astro-ph/9906456]

Zavlin, V. E., Pavlov, G. G., & Trümper, J. 1998, A&A, 331, 821

Zavlin, V. E., & Pavlov, G. G. 1999, private communication

Zavlin, V. E., Trümper, J., & Pavlov, G. G. 1999, ApJ, 525, 959