COOLING OF SUPERFLUID NEUTRON STARS WITH MUONS

M. Bejger

N. Copernicus Astronomical Center
Bartycka 18, 00-716 Warsaw, Poland
e-mail: bejger@camk.edu.pl

D.G. Yakovlev

Ioffe Physical Technical Institute
Politekhnicheskaya 26, 194021 St. Petersburg, Russia
e-mail: yak@astro.ioffe.rssi.ru

and O.Y. Gnedin

Space Telescope Science Institute
3700 San Martin Drive, Baltimore, MD 21218, USA
e-mail: ognedin@stsci.edu

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We extend our modeling of cooling of superfluid Neutron Stars (NSs) by including the production of muons in the core, in addition to neutrons, protons, and electrons. The results are confronted with observations of middle-aged isolated NSs. Muons have little effect on the hydrostatic structure of NSs, on the slow cooling of low-mass NSs (RX J0822–43 and PSR 1055–52 in our model) and on the rapid cooling of massive NSs. They affect, however, the moderately fast cooling of medium-mass NSs (1E 1207–52, RX J0002+62, PSR 0656+14, Vela, and Geminga) and shift appreciably the mass range of these NSs to lower masses, which is important for correct interpretation of the observations. Moreover, the effects of muons can accurately be reproduced by a simple renormalization of NS models with no muons in the NS cores.

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1. Introduction

Rapid progress in detecting thermal emission from isolated Neutron Stars (NSs) with a new generation of orbital and ground-based observatories (*e.g.*, Refs. [1, 2]) stimulates active theoretical studies of cooling isolated NSs. It is well known that cooling history of NSs depends on physical properties of matter of supranuclear density in NS cores. These properties (composition of matter, Equation of State — EOS, critical temperatures of various superfluids, *etc.*) are largely unknown: they cannot be reproduced in laboratory or unambiguously calculated (because of the lack of exact manybody theory for describing the systems of particles interacting via strong forces). However, they may be constrained by comparing cooling calculations with observations of isolated NSs (*e.g.*, Ref. [3]).

We will focus on the theoretical interpretation of observations proposed recently in Refs. [4, 5] and [6] (hereafter KYG), and [7, 8]. The authors restricted themselves to model EOSs in the NS cores in which the presence of muons was neglected. In the present paper we show that the effect of muons on the cooling may be important.

For the observational basis, we take the same isolated middle-aged NSs as KYG, but exclude RX J1856-3754. The age of this intriguing radio-quiet NS has recently been revised [9]; the present value $t = 5 \times 10^5$ yrs is lower than the former one, 9×10^5 yrs, and the source has become less restrictive for cooling theories (*cf.* KYG and Ref. [7]). In addition, there are indications that the emission from the entire NS surface is obscured by the emission from a hot spot on the surface of the NS; if so the surface temperature is poorly determined from the present observations (*e.g.*, [2] and references therein).

The effective surface temperatures, T_s^∞, redshifted for a distant observer, and ages t of seven isolated NSs are taken from Table 3 of KYG and displayed in Figs. 2 and 3 below. The three youngest objects, RX J0822–43 [10], 1E 1207–52 [11], and RX J0002+62 [12], are radio-quiet NSs in supernova remnants.

The other objects, Vela (PSR 0833–45) [14], PSR 0656+14 [15], Geminga (PSR 0633+1748) [16], and PSR 1055–52 [17], are observed as radio pulsars. The adopted values of T_s^∞ are inferred from the observed spectra using various models of stellar emission described in KYG. Recently, the values of T_s^∞ for some of the sources have been revisited in Refs. [1,2,18–24]. Since the new data are basically in line with those used in KYG, we do not introduce the corresponding changes; they are insignificant for our analysis.

As shown in KYG, the observations can be explained using the models of NSs with the cores composed only of neutrons, protons, and electrons, and assuming the presence of nucleon superfluidity with the density dependent critical temperatures $T_c(\rho)$. Following KYG we consider superfluidities of three types produced by: (1) singlet-state pairing of protons in the NS core ($T_c = T_{cp}$); (2) singlet-state pairing of free neutrons in the inner crust ($T_c = T_{cns}$); and (3) triplet-state pairing of neutrons in the core ($T_c = T_{cnt}$). Owing to a large scatter of microscopic theoretical models of $T_c(\rho)$ (*e.g.* Ref. [25]), we treat $T_c(\rho)$ as free parameters.

KYG considered cooling of NSs with rather strong pairing of protons and weak pairing of neutrons in the core, and with a strong pairing of neutrons in the crust. They found that cooling middle-aged NSs can be divided into three types.

- Type I NSs are low-mass NSs which show slow cooling with (modified or direct) Urca processes of neutrino emission strongly suppressed by proton superfluidity. The cooling curves, $T_s^\infty(t)$, are insensitive to NS mass, EOS in the core, and proton superfluidity (*i.e.*, to T_{cp}) as long as the latter is sufficiently strong. KYG interpreted RX J0822–43, and PSR 1055–52 as low-mass NSs.

- Type II NSs are medium-mass NSs which show moderately fast cooling regulated by direct Urca process partly reduced by proton superfluidity in the NS central kernels. The cooling curves are sensitive to NS mass, EOS, and especially the $T_{cp}(\rho)$ profiles in the NS kernel. If the EOS and $T_{cp}(\rho)$ are fixed, the effective surface temperature decreases smoothly with increasing M, and one can measure the mass ('weigh' medium-mass NSs) using the observed limits on $T_s^\infty(t)$. KYG treated 1E 1207–52, RX J0002+62, Vela, PSR 0656+14, and Geminga as medium-mass NSs.

- Type III NSs are massive NSs which show rapid cooling via direct Urca process in the NS kernels, almost unaffected by proton superfluidity. The surface temperatures of these NSs are low (a few times 10^5 K for $t \simeq 10^3$ yrs), being not too sensitive to the NS structure. No NS of such type has been observed so far.

2. Cooling models

We use the same cooling code as in KYG and modify the physics input in the NS core to include the effects of muons.

First, we have included muons in the EOS. We use a stiff EOS proposed in Ref. [26], the model I of the symmetry energy of nucleon matter with the compression modulus of saturated nuclear matter $K = 240$ MeV. The *same model of nucleon–nucleon interaction* was adopted by KYG (EOS A in their notations) who, however, artificially suppressed the presence of muons. Now we include the muons and obtain EOS Aμ. We will compare the results obtained with EOSs A and Aμ.

For EOS Aμ, the muons appear at $\rho \geq \rho_\mu = 2.55 \times 10^{14}$ g cm^{-3} (when the electron chemical potential exceeds the muon rest energy). Their fraction is lower than 10% everywhere in the NS core. Their appearance slightly softens the EOS, slightly increases the fraction of protons and decreases the fraction of electrons. These changes weakly affect the NS internal structure, reducing the maximum NS mass by 1.4%. The masses M, central densities ρ_c, and radii R of two NS configurations for EOSs A and Aμ are given in Table I. The first configuration corresponds to a maximum-mass NS. The second corresponds to the onset of powerful direct Urca neutrino emission [27] in the NS kernel ($\rho_\mathrm{c} = \rho_\mathrm{D}$, $M = M_\mathrm{D}$).

TABLE I

NS models employing EOSs A and Aμ (without and with muons).

Model	Main parameters	EOS A	EOS Aμ
Maximum mass model	$M_\mathrm{max}/M_\odot$	1.977	1.950
	$\rho_\mathrm{cmax}/10^{14}$ g cm^{-3}	25.75	26.55
	R, km	10.754	10.602
Direct Urca threshold model	$M_\mathrm{D}/M_\odot$	1.358	1.249
	$\rho_\mathrm{D}/10^{14}$ g cm^{-3}	7.851	7.423
	R, km	12.98	12.952

Another modification of the cooling code consists of incorporating the heat capacity of muons. It is straightforward (*e.g.*, Ref. [28]) and has no noticeable effect on the NS cooling.

Finally, we have modified the emissivities of neutrino reactions in the NS cores (as described in Ref. [29]). The main effect of muons is to *lower the threshold density* ρ_D *of onset of direct Urca process* (Table I). The lowering is associated with the changes of the fractions of neutrons, protons, and electrons in muonic matter which relaxes the onset condition. At $\rho < \rho_\mathrm{D}$, modified Urca process is basically the leading one. At $\rho > \rho_\mu$, two new branches of this process appear, the neutron and proton branches, where the muons participate instead of the electrons. However, these new branches have little effect on the cooling because their emissivity is comparable to the emissivity of the ordinary modified Urca process. The ordinary direct Urca process operates at $\rho > \rho_\mathrm{D}$. At still higher density $\rho > \rho_{\mathrm{D}\mu}$ ($\rho_{\mathrm{D}\mu} = 9.257 \times 10^{14}$ g cm^{-3}, for EOS Aμ) another direct Urca process is open, where the muons participate instead of the electrons. We have included it into the code but, again, it has little effect on the cooling because its emissivity is comparable to the emissivity of the ordinary direct Urca process.

Now we describe our models of superfluidity in NSs. As in KYG, we assume that the triplet-state pairing of neutrons in the NS cores is weak (maximum $T_{\rm cnt} < 10^8$ K) and can be ignored. Otherwise, a strong neutrino emission due to Cooper pairing of neutrons would accelerate the cooling and hamper the interpretation of observations of older NSs. The singlet-state pairing of neutrons in the crust controls the neutrino luminosity of low-mass NSs and has no direct relation to the presence of muons in the NS core. While exploring the effects of muons we ignore this pairing (see also Sect. 3).

Thus, we focus on the proton superfluidity in the core. We parameterize the dependence of $T_{\rm cp}$ on the proton Fermi wavenumber $k = (3\pi^2 n_p)^{1/3}$ (n_p being the proton number density) by the same expression as Eq. (1) in KYG and consider two models of superfluidity, 1p and 2p, employed by KYG. The corresponding $T_{\rm cp}(\rho)$ profiles are plotted in Fig. 1. The maximum of $T_{\rm cp}(\rho)$ is about the same ($\sim 7 \times 10^9$ K) for all models, but superfluidity 2p extends to a higher densities than 1p. Since we use the *same model of nucleon interaction* for EOSs A and Aμ, we have the *same dependence of* $T_{\rm cp}$ *on* k (but different dependences of $T_{\rm cp}$ on ρ because the proton fractions

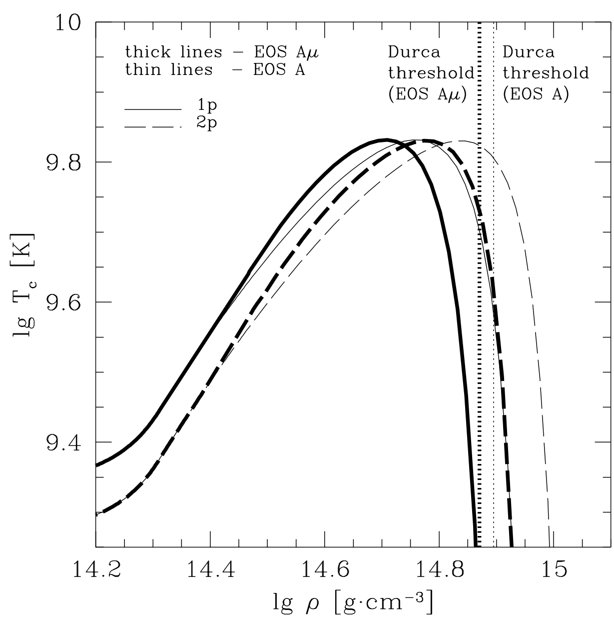

Fig. 1. Density dependence of the critical temperature of proton superfluidity for models 1p and 2p, and for EOS Aμ (with muons, thick lines) and EOS A (without muons, thin lines). Vertical dotted lines indicate the direct Urca (Durca) threshold.

are different for EOSs A and Aμ). The curves in Fig. 1 are typical of the microscopic calculations (*e.g.*, Ref. [25]). As discussed above, the muons shift both the direct Urca threshold and the $T_{\rm cp}(\rho)$ profile to lower values of ρ. The latter shift, due to the increase in the proton fraction, is bigger. For instance, $T_{\rm cp}(\rho)$ for model 1p of proton superfluidity vanishes below the direct Urca threshold in the muonic matter, but persists above the direct Urca threshold in the matter without muons.

3. Results and discussion

The results of the cooling calculations are illustrated in Figs. 2 and 3, which also show the observational data.

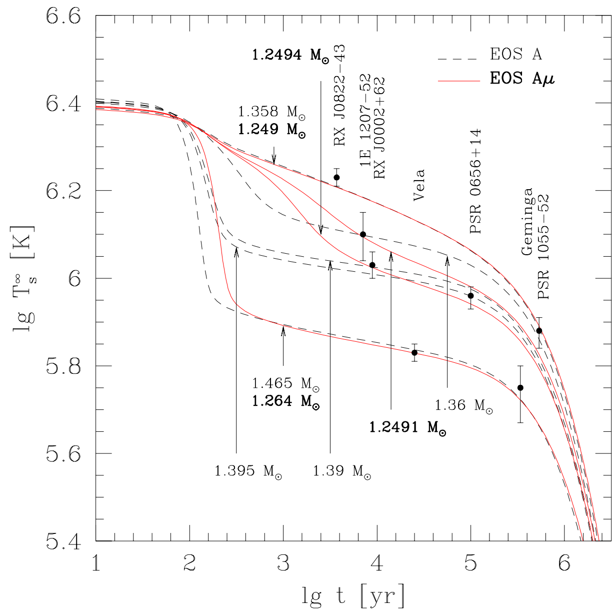

Fig. 2. Observational limits on surface temperatures of seven NSs compared with cooling curves for NSs of several masses, adopting 1p proton superfluidity and either EOS Aμ (with muons, solid lines) or EOS A (without muons, dashed lines). If two masses are given, an upper value corresponds to EOS A and a lower (boldface) value to EOS Aμ.

According to our models, the cooling curves of low-mass NSs with and without muons are almost indistinguishable. The neutron superfluidity in the crust can affect the cooling of these stars in exactly the same way as discussed in Ref. [5] and KYG for the NSs without muons. The calculations also show that muons have almost no effect on rapid cooling of massive NSs.

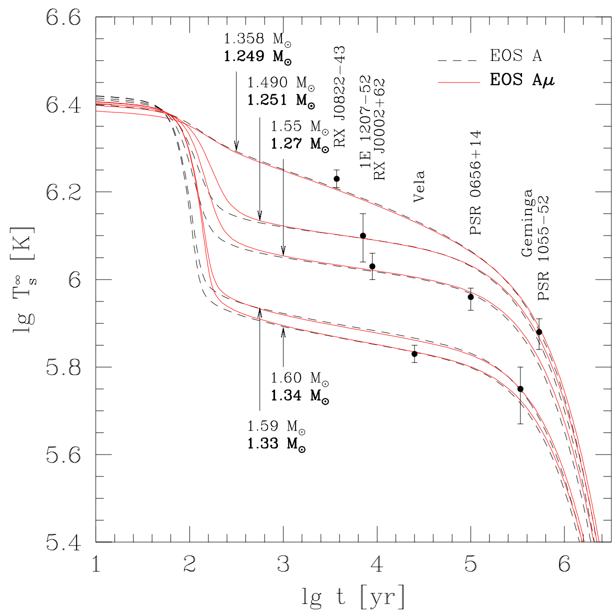

Fig. 3. Same as Fig. 2, but for proton superfluidity model 2*p*.

However the effect of muons on moderately fast cooling of medium-mass NSs is substantial. Figure 2 corresponds to model 1*p* of proton superfluidity. Without muons, the $T_{\rm cp}(\rho)$ profile extends above the direct Urca threshold (Fig. 1). Accordingly, we have a representative class of medium-mass NSs (dashed curves). By varying the mass M from 1.36 $M_\odot$ to 1.465 $M_\odot$ we can explain the observations of the five sources (1E 1207–52, RX J0002+62, Vela, PSR 0656+14, and Geminga) by the cooling of medium-mass NSs, and thus 'weigh' these NSs (Ref. [4], KYG). In the presence of muons, the proton critical temperature $T_{\rm cp}(\rho)$ drops to zero below the direct Urca threshold, $\rho_{\rm D}$ (Fig. 1), *i.e.*, the proton superfluidity disappears in the centers of NSs with masses somewhat lower than the threshold mass $M_{\rm D}$. The transition from slow to fast cooling occurs in a very narrow mass range, from 1.249 $M_\odot$ to 1.264 $M_\odot$, so we have no representative class of medium-mass NSs. The proposed interpretation of the five sources as medium-mass NSs containing muons becomes unlikely (just as in the absence of superfluidity, see KYG).

Figure 3 is the same as Fig. 2 but for model 2*p* of proton superfluidity. This superfluidity extends above $\rho_{\rm D}$ with and without muons (Fig. 1). Therefore, we have representative classes of medium-mass NSs and we can weigh our five medium-mass sources in both cases. Without muons, as in KYG, we obtain the masses from 1.49 $M_\odot$ to 1.60 $M_\odot$. With muons, we obtain significantly lower (and narrower) mass range for the same sources, from 1.27 $M_\odot$ to 1.34 $M_\odot$.

The inferred mass range changes in the presence of muons because they lower the threshold density $\rho_{\rm D}$ of direct Urca process and shift the decreasing slope of the $T_{\rm cp}(\rho)$ profile to an even lower density (Fig. 1). Accordingly, direct Urca process becomes stronger at lower ρ and this accelerates the cooling of lower-mass NSs. Therefore, the mass range of medium-mass NSs shifts to lower M.

4. Conclusions

We have simulated the cooling of superfluid NSs with and without muons. The inclusion of muons does not violate the main results of Refs. [4–8] on the existence of three types of cooling superfluid NSs. As in KYG, we can interpret RX J0822–43, and PSR 1055–52, as low-mass NSs, and 1E 1207–52, RX J0002+62, Vela, PSR 0656+14, and Geminga, as medium-mass NSs. This interpretation requires strong singlet-state proton pairing and weak triplet-state neutron pairing in the NS cores.

Muons do not change the hydrostatic structure of NSs. The muon heat capacity and direct/modified Urca processes involving muons have almost no effect on NS cooling. The cooling curves of low-mass and high-mass NSs are insensitive to the presence of muons.

However, muons *do affect* the cooling of medium-mass NSs and the associated 'weighing' of observed NSs proposed in Ref. [4] and KYG. For the same nucleon–nucleon interaction model and the superfluid properties of NS cores, we obtain noticeably lower masses of NSs with muons than without muons (Fig. 3). Therefore, one should take muons into account for a correct interpretation of observations.

It is remarkable that muons *affect the cooling by their mere existence, as passive particles.* We could switch off all neutrino reactions and heat capacity associated with muons (*i.e.*, retain the 'old' physics input in the NS core) but employ the fractions of neutrons, protons and electrons in the EOS modified by the presence of muons. The cooling curves obtained in this numerical experiment would almost coincide with the exact ones. This means that *the effects of muons can be accurately incorporated by renormalizing the NS models containing no muons at all.* In other words, any model of a cooling NS with muons is equivalent to a certain model of a cooling NS without muons. Clearly, the muons will have similar effects in the presence of hyperons in supranuclear matter. This circumstance may be helpful in constructing the codes to simulate cooling of NSs containing hyperons.

The existence of three types of cooling NSs is effectively regulated by two factors. The first is the onset of the powerful direct Urca process of neutrino emission at densities $\rho > \rho_{\rm D}$; the second is the strong proton superfluidity extending at $\rho > \rho_{\rm D}$. The latter suppresses the direct and modified Urca processes at or just above the critical density $\rho_{\rm D}$ but opens them at higher ρ. In this way the superfluidity smears out the sharp transition between the slow and rapid cooling regimes and creates a representative class of medium-mass NSs, favorable for the interpretation of observations. These conditions may be also realized in NS cores containing hyperons, pion or kaon condensates, or quark matter. We will analyze different models of NS cores in future publications.

The data on RX J0002+62 are now questionable because the extraction of the thermal surface radiation from the observed spectrum is most complicated (G.G. Pavlov, private communication). A new useful constraint is provided by recent observations of PSR J0205+6449 (P. Slane, D.J. Helfand, S.S. Murray, *Astrophys. J. Lett.* **571**, L45, 2002), a pulsar in 3C 58, with $t = 820$ yr and $T_{\rm s}^{\infty} < 1.1$ MK).

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