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The cooling neutron star in 3C 58

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Abstract. The upper limit on the effective surface temperature of the neutron star (NS) PSR J0205+6449 in the supernova remnant 3C 58 obtained recently by Slane et al. (2002) is analyzed using a modern theory of NS cooling (Kaminker et al. 2002). The observations can be explained by cooling of a superfluid NS with the core composed of neutrons, protons, and electrons, where direct Urca process is forbidden. However, combined with the data on the surface temperatures of other isolated NSs, it gives evidence (emphasized by Slane et al.) that direct Urca process is open in the inner cores of massive NSs. This evidence turns out to be less stringent than that provided by the well known observations of Vela and Geminga.

Key words. pulsars: individual: PSR J0205+6449 – stars: neutron – dense matter

1. Introduction

PSR J0205+6449, a pulsating X-ray source, was discovered by Murray et al. (2002) in the supernova remnant 3C 58, which is most likely associated with the historical supernova SN 1181. It is thus one of the youngest neutron stars (NSs) observed. Recently, using *Chandra* observations Slane et al. (2002) inferred an upper limit on the effective surface temperature (redshifted for a distant observer): $T_s^\infty < 1.08$ MK. They emphasized that this upper limit for a young NS is low, "suggesting the presence of some exotic cooling contribution in the interior". In other words, it provides evidence for the powerful direct Urca process (Lattimer et al. 1991) in the NS inner core, or for similar processes of enhanced neutrino emission in pion-condensed, kaon-condensed, or quark core, as reviewed, e.g., by Pethick (1992).

Here we analyze this intriguing possibility in more detail using recent results of the NS cooling theory (Kaminker et al. 2001; Yakovlev et al. 2001b; Kaminker et al. 2002, hereafter KYG; Yakovlev et al. 2002, hereafter YGKP) and taking into account the observational data on thermal emission of other isolated middle-aged NSs.

The observational basis is shown in Figs. 1 and 2. They display the upper limit of T_s^∞ for PSR J0205+6449 with the age of SN 1181, and the observational values of T_s^∞ for eight middle-aged isolated NSs, the same as in KYG and YGKP. They are: RX J0822–43, 1E 1207–52, and RX J0002+62 (radio-quiet NSs in supernova remnants); Vela, PSR 0656+14, Geminga, and PSR 1055–52 (observed as radiopulsars); and RX J1856–3754 (also a radio-quiet NS). We do not analyze the less likely possibility that the age of J0205+6449 is given by the pulsar dynamical age ≈5400 yr, measured by Murray et al. (2002); that case could be easier explained by the cooling theory. The values of T_s^∞ and t for other sources are the same as in KYG and YGKP, with the only exception of the age of RX J1856–3754, $t = 5 \times 10^5$ yr, as revised recently by Walter & Lattimer (2002). Note also a too slow spindown rate of 1E 1207–52 measured by Pavlov et al. (2002) which may cast doubts on the correct determination of the age of this NS.

2. Cooling theory

We confront the observational data with our simulations of NS cooling, using the recent cooling theory summarized in KYG and YGKP. For simplicity, we consider the models of NSs with the cores composed of neutrons, protons, and electrons (npe matter). We use the equation of state (EOS) in the NS core proposed by Prakash et al. (1988) (version I of the symmetry energy, with the compression modulus $K = 240$ MeV of the saturated nuclear matter; it is denoted as EOS A in KYG and YGKP).

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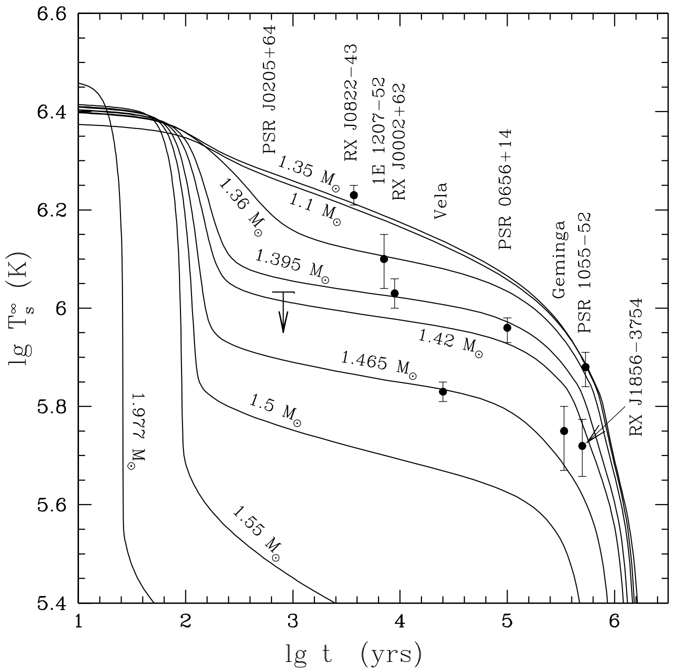

Fig. 1. Observational limits on surface temperatures of nine NSs compared with cooling curves of NSs with several masses. The curves are calculated adopting proton superfluidity **1p** and neutron superfluidity **2nt** in the NS cores.

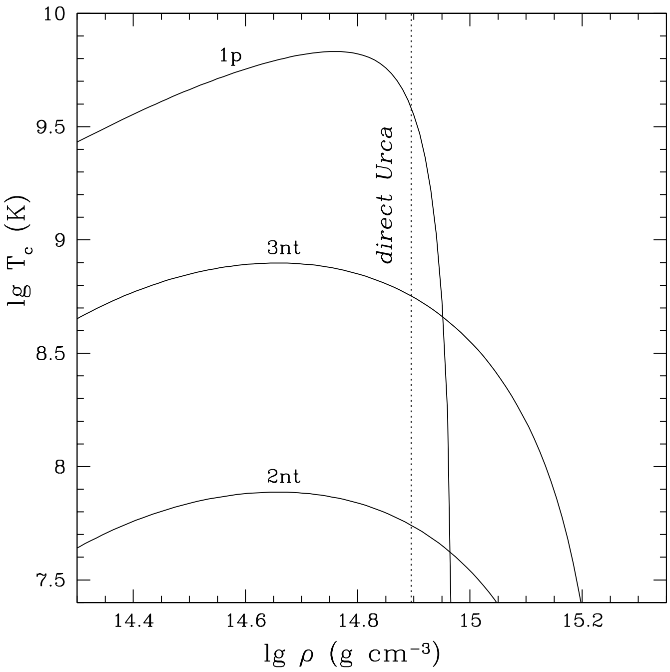

Fig. 3. Density dependence of the critical temperatures of superfluidity of protons (model **1p**) and neutrons (models **2nt** and **3nt**) in a NS core. Vertical dotted line shows direct Urca threshold, $\rho = \rho_{\rm D}$.

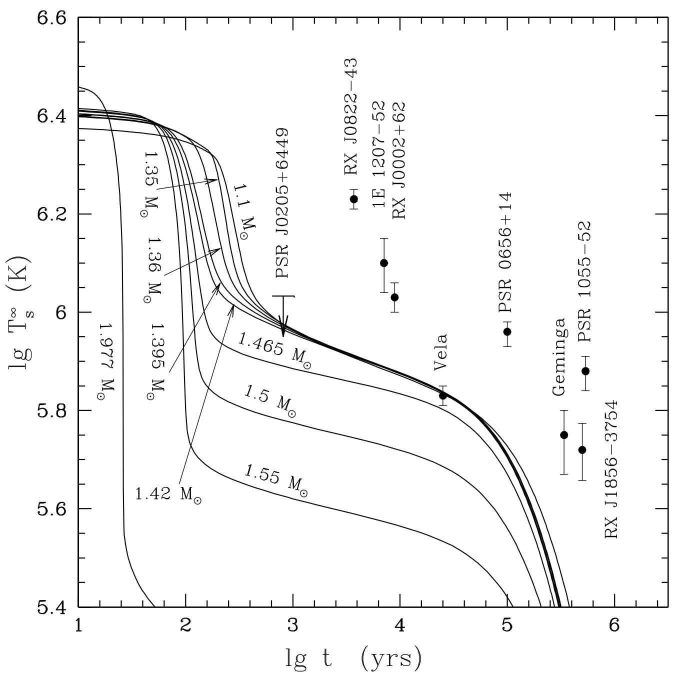

Fig. 2. Same as in Fig. 1 but for model **3nt** of neutron superfluidity instead of **2nt**.

The maximum NS mass for this EOS is $M_{\rm max} = 1.977\ M_\odot$ (with the central density $\rho_{\rm c}^{\rm max} = 2.575 \times 10^{15}$ g cm^{-3}). The adopted EOS opens direct Urca process in the NSs with masses $M > M_{\rm D} = 1.358\ M_\odot$ and central densities above $\rho_{\rm D} = 7.851 \times 10^{14}$ g cm^{-3}.

In our simulations, we take into account superfluidity of nucleons in the NS interiors. Superfluidity suppresses many neutrino emission processes (e.g., direct and modified Urca processes, nucleon-nucleon bremsstrahlung) but opens a specific powerful mechanism of neutrino emission due to the Cooper pairing of nucleons (proposed by Flowers et al. 1976; see, e.g., Yakovlev et al. 2001a for details), and also affects the heat capacity of matter. We include the singlet-state pairing of protons and the triplet-state pairing of neutrons in the NS cores but, for simplicity, we neglect the singlet-state pairing of neutrons in the NS crusts. The core superfluids are characterized by the density-dependent critical temperatures $T_{\rm cp}(\rho)$ and $T_{\rm cnt}(\rho)$ (Fig. 3). We use one model of strong proton superfluidity (model **1p** described, e.g., in KYG), and two models of triplet-state neutron superfluidity (model **2nt** of weak superfluidity and model **3nt** of moderately strong superfluidity). The critical temperatures $T_{\rm c}(\rho)$ are parameterized by Eq. (1) in KYG. The parameters of model **1p** are given in KYG; the parameters of models **2nt** and **3nt** are the same as for model **1nt** in KYG, but the parameter T_0 is now equal to 2×10^9 K and 1.5×10^{10} K, respectively. Our phenomenological superfluid models are consistent with the current microscopic models of nucleon superfluidity in NS cores (e.g., Lombardo & Schulze 2001).

3. Theory and observations

Figures 1 and 2 compare the observational data with theoretical cooling curves, $T_{\rm s}^\infty(t)$.

Adopting model **1p** of proton superfluidity and model **2nt** of neutron superfluidity we obtain (Fig. 1) a family of cooling curves for NSs with different masses M. Actually, superfluidity **2nt** is rather weak and has almost no effect on NS cooling. The properties of such cooling models are discussed in KYG and YGKP. One can distinguish NSs of three types:
(I) Low-mass NSs, $M \lesssim M_{\rm I}$, are very slowly cooling NSs where modified or direct Urca processes are strongly suppressed by proton superfluidity; their cooling curves are almost independent of NS mass and EOS.
(II) Medium-mass NSs, $M_{\rm I} \lesssim M \lesssim M_{\rm II}$, undergo moderately fast cooling via direct Urca process partly reduced by proton superfluidity; their cooling is very sensitive to NS mass, EOS, and $T_{\rm cp}(\rho)$ model.
(III) Massive NSs, $M \gtrsim M_{\rm II}$, show fast cooling via direct Urca process in the NS centers almost unaffected by proton superfluidity. At $t \sim 10^5$ yr, for our NS models, we have $M_{\rm I} \sim 1.36\ M_\odot$ and $M_{\rm II} \sim 1.52\ M_\odot$. These values are easily varied by choosing other EOSs and proton superfluid models (KGY, YGKP).

The situation would be drastically different if we adopted neutron superfluidity **3nt** instead of **2nt**. We would get a number of cooling curves plotted in Fig. 2. As long as a NS is hot and its internal temperature is larger than the maximum of $T_{\rm cnt}(\rho)$, the neutron superfluidity is absent and the star cools as shown in Fig. 1. However, the appearance of a moderately strong neutron superfluidity induces powerful neutrino emission due to the Cooper pairing of neutrons, which leads to a very fast cooling. In low-mass NSs ($M \leq M_{\rm D}$), where direct Urca process is forbidden, this fast cooling has nothing to do with direct Urca process. As seen from Fig. 2, one can easily explain the upper limit of $T_{\rm s}^\infty$ for PSR J0205 by cooling of such a star. Moreover, by changing the maximum of $T_{\rm cn}(\rho)$, one can explain all relatively cool sources in Figs. 1 and 2 (including the coldest ones such as Vela and Geminga) by cooling of low-mass NSs with their own models of neutron superfluidity in the NS cores. In this way, it seems that the current observational data do not require direct Urca process (or similar processes in pion or kaon condensed matter, or in quark matter).

However, the main point is that NSs may have different masses, surface magnetic fields, etc., but they *must have* the same EOS and superfluid properties of their cores. Thus, all the sources should be explained by one set of models of $T_{\rm cn}(\rho)$ and $T_{\rm cp}(\rho)$. A natural explanation (KYG, YGKP) is to assume a weak neutron superfluidity in the NS cores (e.g., model **2nt**, Fig. 1) and the presence of direct Urca process in massive NSs. If this is true, the two hottest sources for their ages, RX J0822 and PSR 1055, can be treated as low-mass NSs of type I, while 1E 1207, RX J002, Vela, PSR 0656, Geminga, and RX J1856 can be treated as medium-mass NSs of type II. This interpretation would be impossible without introducing the direct Urca process. Notice that the revised age of RX J1856 (Walter & Lattimer 2002) changes its status from a type I NS (e.g., KYG) to a type II NS. If PSR J0205 has the surface temperature just below the inferred upper limit, it belongs to the family of type II NSs and requires direct Urca process in its core. The appropriate cooling curve (e.g., the $M = 1.42\ M_\odot$ curve in Fig. 1) would lie *above* the cooling curves for Vela and Geminga which means that Vela and Geminga would be *colder* for their ages than PSR J0205. In other words, the well-known observational data on Vela and Geminga (e.g., Pavlov et al. 2001; Halpern & Wang 1997) provide stronger arguments in favor of direct Urca process than the newly reported data on PSR J0205. Let us recall that our interpretation enables one to measure the masses of type II NSs for a fixed EOS and superfluid properties of NS interiors (see KYG and YGKP). In the above scenario (Fig. 1), the mass of PSR J0205 would be lower than the masses of Vela and Geminga.

4. Conclusions

We propose a theoretical interpretation of the upper limit on $T_{\rm s}^\infty$ of PSR J0205+6449 reported recently by Slane et al. (2002). Although our interpretation is based on the specific NS models with given EOS and superfluid properties of NS interiors, it is, in fact, quite generic. As discussed in KYG and YGKP, we could arrive to qualitatively similar conclusions by choosing other EOSs and density profiles of the superfluid critical temperatures. Let us emphasize that the current observational data are explained by cooling of NSs with the cores composed of neutrons, protons, and electrons, without invoking any exotic matter. Nucleon superfluidity in NS cores is a widely accepted phenomenon; pairing of nucleons in atomic nuclei is proved experimentally. On the contrary, exotic phases of matter (pion and kaon condensates, quark matter) remain undetected. It is therefore comfortable to find that the npe matter with superfluid nucleons, which can be treated as a *minimal model* of NS cores, is sufficient to explain the present observations of cooling NSs.

Our main conclusion is that the detected upper limit of $T_{\rm s}^\infty$, by itself, does not indicate that direct Urca process or similar processes of strong neutrino emission operate in the NS core. Combined with the observational data for other isolated middle-aged NSs, it gives some evidence for the direct Urca process, although less stringent than the evidence provided by the Vela and Geminga pulsars.

Future observations of PSR J0205+6449 would be extremely important. If the temperature $T_{\rm s}^\infty$ appears to be lower than 0.8 MK, it would mean (in the frame of our interpretation) that PSR J0205+6449 is indeed the coldest observed NS. It would then provide the strongest argument that direct Urca process is open in the NS cores. Were the detected temperature or the upper limit be around 0.3 MK, this would be a strong indication that PSR J0205+6449 is a rapidly cooling massive NS of type III (no NS of such type has been observed so far). The values of $T_{\rm s}^\infty$ below 0.15 MK (the lowest $T_{\rm s}^\infty$ given by the maximum-mass model) for PSR J0205+6449 could not be explained by the proposed theory.

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