The Cooling Neutron Star in 3C 58

D. G. Yakovlev¹, A. D. Kaminker¹, P. Haensel², and O. Y. Gnedin³

¹ Ioffe Physical Technical Institute, Politeknicheskaya 26, 194021 St. Petersburg, Russia
² N. Copernicus Astronomical Center, Bartycka 18, 00-716 Warsaw, Poland
³ Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA

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Abstract. The upper limit of 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 observational limit 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 the evidence 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 Slane et al. (2002) inferred, from Chandra observations, an upper limit of its effective surface temperature (redshifted for a distant observer): $T_s^\infty < 1.08$ MK. As emphasized by the authors, this upper limit is low, for a young NS, “suggesting the presence of some exotic cooling contribution in the interior” (Slane et al. 2002). In other words, it gives evidence that the powerful direct Urca process (Lattimer et al. 1991) is open in the NS inner core, or 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 a recent version 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 observational data on thermal emission of other isolated middle-aged NSs.

The observational basis is shown in Fig. 1. It displays the upper limit of $T_s^\infty$ for PSR J0205+6449 with the age of SN 1181, and the observational values of $T_s^\infty$ 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 a less likely possibility that the age of J0205+6449 is correctly determined by the pulsar dynamical age $\approx 5400$ yr measured by Murray et al. (2002); this case would be simpler for the cooling theory. The values of $T_s^\infty$ and ages $t$ for other sources are the same as in KYG and YGKP; the only exception is that we take the age $t = 5 \times 10^{53}$ yr of RX J1856–3754 as revised recently by Walter & Lattimer (2002). Note 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 a recent version of the cooling theory summarized in KYG and YGKP. For simplicity, we consider the models of NSs with the cores composed of neutrons, protons, and electrons. 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). The maximum NS mass, for this EOS, is $M_{\text{max}} = 1.977 M_\odot$ (with the central density $\rho_{\text{max}}^c = 2.575 \times 10^{15}$ g cm$^{-3}$). The adopted EOS opens direct Urca process in the NSs with masses $M > M_D = 1.358 M_\odot$ and central densities higher than $\rho_D = 7.851 \times 10^{14}$ g cm$^{-3}$.
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 will be characterized by the density dependent critical temperatures $T_{cp}(\rho)$ and $T_{cnt}(\rho)$ (Fig. 2). 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 $T_c(\rho)$ 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 $2 \times 10^9 \text{ K}$ and $1.5 \times 10^{10} \text{ K}$, respectively. Our phenomenological superfluid models are consistent with current microscopic models of nucleon superfluidity in NS cores (e.g., Lombardo & Schulze 2001).

3. Theory and observations

Figure 1 compares the observational data with theoretical cooling curves, $T_s^{\infty}(t)$. Adopting model 1p of proton superfluidity and model 2nt of neutron superfluidity we obtain a family of the cooling curves (solid lines) 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, $M \lesssim M_I$, 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, $M_I \lesssim M \lesssim M_{II}$, undergo moderately fast cooling via direct Urca process partly reduced by proton superfluidity; their cooling is very sensitive to NS mass, EOS, and $T_{cp}(\rho)$ model. (III) Massive NSs, $M \gtrsim M_{II}$, show fast cooling via direct Urca process in the NS centers almost nonreduced by proton superfluidity. At $t \sim 10^5 \text{ yr}$, for our NS models, we have $M_I \sim 1.36 \text{ M}_\odot$ and $M_{II} \sim 1.52 \text{ M}_\odot$.

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. 1 by dotted lines. As long as a NS is hot and its internal temperature is larger than the maximum of $T_{cnt}(\rho)$, the neutron superfluidity is absent and the star cools as described above (along a solid line). However, the appearance of a moderately strong neutron superfluidity induces powerful neutrino emission due to Cooper pairing of neutrons, which leads to a really fast cooling. In low-mass NSs ($M \lesssim M_D$), where direct Urca process is forbidden, this fast cooling has nothing to do with direct Urca process. As seen from Fig. 1, one can easily explain the upper limit of $T_s^{\infty}$ for PSR J0205 by cooling of such a star. Moreover, by changing the maximum of $T_{cn}(\rho)$, one can explain all relatively cold sources in Fig. 1 (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 may seem that the current observa-
tional 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 the same EOS and superfluid properties of their cores (e.g., model 2nt, solid lines in Fig. 1) and the presence of direct Urca process in massive NSs. If this is true, the two sources, RX J0822, and PSR 1055, hottest for their ages, 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 $T_{\infty}$ 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) impose stronger arguments in favor of direct Urca process, than the newly reported data on PSR J0205. Let us remind that our interpretation enables one to measure 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 could be lower than the masses of Vela and Geminga.

4. Conclusions

We have proposed the theoretical interpretation of the upper limit of $T_{\infty}$ of PSR J0205+6449 reported recently by Slane et al. (2002). Although our interpretation is based on 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 come to qualitatively similar conclusions choosing other EOSs and density profiles of superfluid critical temperatures of nucleons in NS interiors. Let us emphasize that the current observational data are explained by cooling of NSs with the cores composed of neutrons, protons and electrons (n, p, and e), without invoking any concept of exotic matter. Nucleon superfluidity in the NS cores is a widely accepted phenomenon. Remember that pairing of nucleons in atomic nuclei is an experimental fact. 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 $T_{\infty}$, 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 the evidence for open direct Urca process, although less stringent than the evidence provided by the data on the Vela and Geminga pulsars.

Future observations of PSR J0205+6449 would be extremely important. If the temperature $T_{\infty}$ or the upper limit appear to be lower than 0.8 MK, it would mean (in the frame of our interpretation) that PSR J0205+6449 is really the coldest observed NS. It will impose then the most stringent 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 a type has been observed so far). The values of $T_{\infty}$ below 0.15 MK (the lowest $T_{\infty}$ given by the maximum-mass model) for PSR J0205+6449 could not be explained by the proposed theory.

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