X-ray radiation from cooling neutron stars and superfluid state of their cores

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Abstract

Cooling of neutron stars (NSs) with standard and enhanced neutrino energy losses is simulated taking into account the effect of nucleon superfluidity in the stellar cores on heat capacity and neutrino luminosity. The superfluidity affects X-ray emission from the surfaces of cooling NSs which gives a method to constrain the critical temperatures T_{cn} and T_{cp} of neutron and proton superfluids. The method is applied for interpretation of observations of PSR B0656+14 and the Geminga pulsar. The prospects of interpretation of future observations are outlined.

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1 Simulations of NS cooling

Observations of thermal radiation from the surfaces of cooling NSs can be used for obtaining important information on the parameters of NSs and on fundamental properties of superdense matter in their interiors. In particular, it is possible to impose restrictions on superfluid state of neutrons and protons in the stellar cores [1] by comparing observational data with theoretical cooling curves.

We simulated cooling of NSs with superfluid cores. We adopted a moderately stiff equation of state (EOS) [2] of dense matter composed of neutrons (n), protons (p) and electrons (e). We take into account the effects of nucleon superfluidity on heat capacity [3] and neutrino luminosity of the NS cores [4,5]. The neutrino luminosity can be either standard or enhanced by direct Urca process. We included also the neutrino emission due to creation of nucleon Cooper pairs [6,7,8] which is important [9] just after the superfluidity onset but which is commonly neglected in cooling theories. The critical temperatures T_{cn} and T_{cp} of neutron and proton superfluids are treated as free parameters constant throughout the NS core. Typical cooling curves are plotted in Fig. 1. The examples of standard cooling of the Geminga pulsar (age $t_0 = 3.4\times10^5$ yr) and enhanced cooling of PSR B0656+14 ($t_0 = 10^5$ yr) are presented in Figs. 2–5.

The first example refers to the standard cooling of a NS whose mass and radius are $M = 1.3M_\odot$ and $R = 11.71$ km. The neutrino energy losses are produced by the modified Urca reactions, nucleon-nucleon bremsstrahlung and Cooper pair creation. Figures 2 and 3 show the dependence of the effective surface (redshifted) temperature T_s on T_{cn} and T_{cp}. Geminga would be in the coolest state if T_{cn} and T_{cp} are high, i.e., the heat content is greatly reduced. If $5.0 \times 10^5 \lesssim T_s \lesssim 6.2 \times 10^5$ K, as derived from observations [10], then T_{cn} and T_{cp} lie in shaded areas in Fig. 3.

The second example refers to a NS with $M = 1.44\,M_\odot$, $R = 11.35$ km. It has a central kernel of mass $0.035\,M_\odot$, where the neutrino emission is greatly enhanced by the direct Urca process [11]. Since PSR B0656+14 is younger than

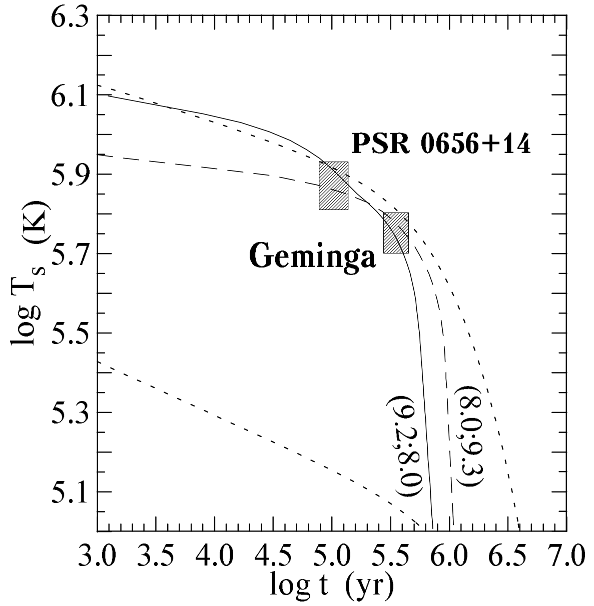

Figure 1: *Redshifted* surface temperature T_s vs NS age t. Dotted curves refer to nonsuperfluid nucleons in the NS core (upper curve — standard cooling, lower curve — enhanced cooling). Solid curve corresponds to the standard cooling and dashed curve to the enhanced cooling with superfluid nucleons; the figures in brackets are ($\log T_{cn}$, $\log T_{cp}$). Boxes show uncertainties in T_s (at 1σ level) and t (braking index n from 2.5 to 3.5) for PSR B0656+14 and Geminga (see text). Both pulsars can be interpreted within the same model (standard or enhanced).

Geminga, its cooling (Figs. 4 and 5) is controlled by the neutrino emission. The valley of low T_s at low $T_{cn} \approx T_{cp}$ is produced by the combined action of the direct Urca process and Cooper pair creation. If $6.4 \times 10^5 \lesssim T_s \lesssim 8.3 \times 10^5$ K, as given by observations [12], then the allowed superfluidity strips are quite different from those for Geminga in Fig. 3.

The temperatures T_{cn} and T_{cp} obtained are rather uncertain but consistent with those predicted by microscopic theories of nucleon superfluidity (see [1,9], for references). These preliminary results can be greatly improved in the future using new observations and selfconsistent simulations. The latter require a representative set of EOSs (from soft to stiff) supplied with density-dependent T_{cn} and T_{cp} derived from *the same microscopic models* (one can generally expect higher T_c for softer EOS). This would link superfluidity and EOS and impose constraints on EOS and NS masses (higher masses are favorable for enhanced cooling).

The cooling is also strongly affected by chemical composition [13] and magnetic field [14] on the NS surface. The latter parameters influence the spectra of NS radiation [15] and thus the values of T_s deduced from observations [16]. All these factors should be taken into account for interpretation of observations; they can be constrained from observed spectra and light curves of NS thermal emission [17].

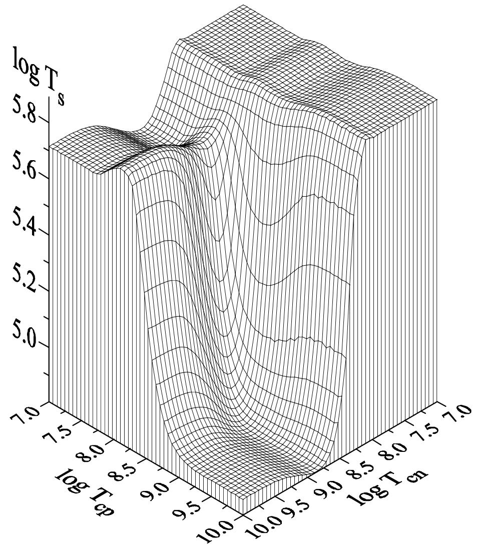

Figure 2: Effective surface temperature T_s vs T_{cn} and T_{cp} for the standard cooling at Geminga's age $t = t_0$.

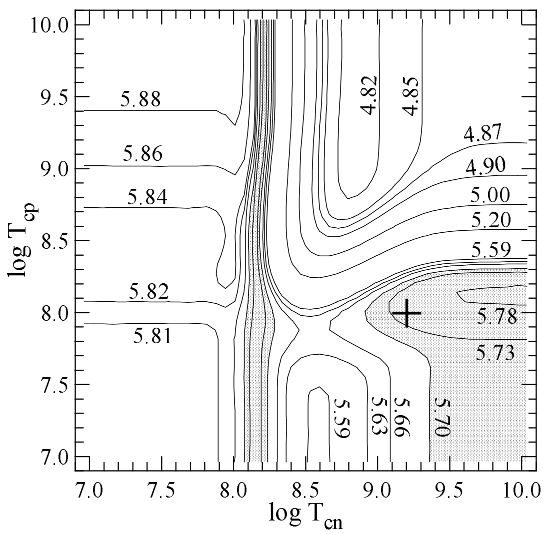

Figure 3: Projections $\log T_s$=const (figures near the curves) on ($\log T_{cn}$, $\log T_{cp}$) – plane for the standard cooling of Geminga (Fig. 2). Shaded strip shows 1σ confidence region; cross corresponds to the solid curve in Fig. 1.

2 Observations, current status and prospects

Nearly 40 isolated NSs have been detected in X-rays by the *ROSAT* and *ASCA* observatories including radio pulsars [18] and candidates to radio-silent isolated NSs [19].

Among the radio pulsars, *the middle-age pulsars* ($t \approx 10^5 - 10^6$ yr) are most promising for observing the thermal emission. Non-thermal X-rays from a NS magnetosphere and surrounding compact synchrotron (plerion) nebula powered by the pulsar are not too strong as for young Crab-like or Vela-like pulsars. The NS surfaces are still hot enough to contribute into the total X-ray flux. X-ray thermal emission has been observed from at least 3 middle-age nearby pulsars, B0656+14, B1055-52 and Geminga [18]. These pulsars are bright point-like X-ray sources. New data can be easily obtained with a moderate spatial resolution provided by the SODAT ($\sim 1 - 2'$) and JET-X ($\sim 20''$) telescopes on board of the *SXG* observatory with reasonable exposure of about 10-20 ks. Deeper spectral and timing observations would be useful to resolve better the soft thermal X-ray component emitted from the NS surfaces, harder thermal component produced by the hot polar caps, and non-thermal magnetospheric emission dominated in hard X-rays [12]. This would diminish uncertainties of the surface temperature, clarify its distribution over the NS surface and constrain the mass-radius relation using new, high-quality energy-resolved light curves. A discovery of photoionization jumps [15] and/or of electron cyclotron lines [10] in the spectra of magnetized NSs would give directly the surface magnetic field and chemical composition. Large effective area of the *SXG* LEPC detector are favorable for deeper observations of 3 more distant (1-2 kpc), less bright, middle-age pulsars B0538+28, B0355+54, B0114+58 (detected without reliable spectral and timing information) and of 8 other similar objects (not too strict upper limits of count rates were obtained in *ROSAT* short-pointed or serendipitous observations [18]). This would enlarge the family of middle-age pulsars studied in X-rays.

The surfaces of old ($t \gtrsim 10^6$ yr) radio pulsars are too cold to be visible in X-rays. However, thermal X-ray emission from hot polar spots on their surfaces seems to be visible on the non-thermal magnetospheric background, at least for 2 ordinary pulsars B1929+10, B0950+08 [20] and 1 millisecond pulsar J0437-4715 [16,17]. Detection of spectra and light curves would constrain the mass-radius relation of NSs and, hence, EOS in their cores. It is possible since the light curves are affected by gravitational bending of photon trajectories near the NSs [21]. The spectra and light curves can also give information on the surface structure and magnetic field. In total, 4 old ordinary and 7 millisecond pulsars were detected in X-rays [18]. The maximum of the hot-spot emission (0.2-0.7 keV) lies in the SODAT and JET-X energy bands. Further observations of old pulsars with these instruments are required to resolve the contributions from the thermal hot-spot and non-thermal magnetospheric emissions, to get new constraints on (poorly known) hot-spot sizes and temperature distributions, mechanisms of magnetospheric radiation, NS parameters and to clarify the energy balance of rotation-powered radio pulsars.

Recently a new class of radio-silent NSs has been discovered. They are point-like X-ray objects associated mainly with supernova remnants (SNRs) [19]. The latter association and X-ray properties of the objects, the lack of optical counterparts, accretion disks and other phenomena related to the accreting binary systems indicate that they are likely to be isolated NSs not seen as radio pulsars. In addition, there are two point-like X-ray objects not associated with SNRs [22-24]. They can be either old NSs, or dead radio pulsars, emitting X-rays due to accretion from interstellar matter, or middle-age cooling NSs.

Some of the objects in SNRs show sine-like pulsations with periods 5-12 s and almost steady spin-down $\dot{P} \sim 10^{-11}$–10^{-12} s/s [25]. Their spectra are well fitted by a combination of power-law and black-body (BB) with high temperature $T_{BB} \sim 0.1 - 0.7$ keV and spectral index $\approx$ 2–4. The SNR ages are $\sim 10^3 - 3 \times 10^4$ yr. If confirmed, these objects may be young ($t \lesssim 3 \times 10^4$ yr) and hot isolated NSs promising for cooling studies. In contrast to the Crab-like and Vela-like pulsars, they might be not deemed by the mag-

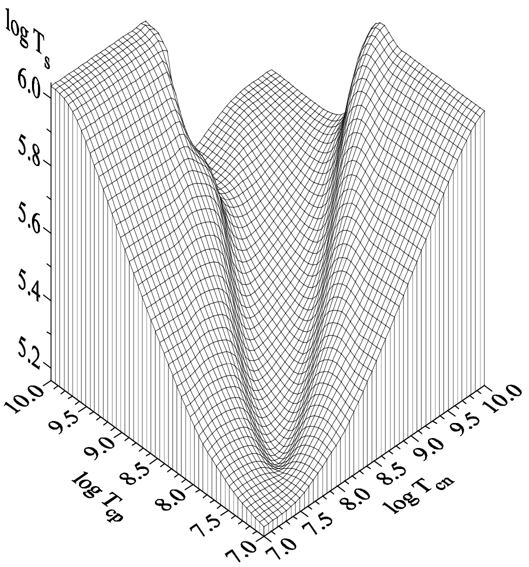

Figure 4: Same as in Fig. 2 but for enhanced cooling of PSR B0656+14.

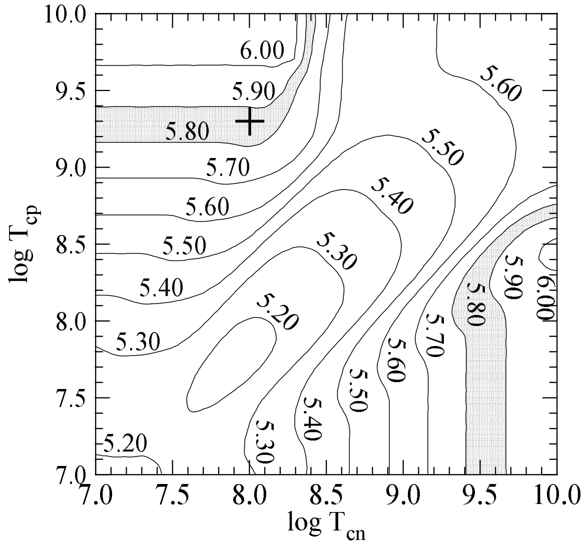

Figure 5: Same as in Fig. 3 but for enhanced cooling of PSR B0656+14; cross corresponds to the dashed curve in Fig. 1.

netospheric emission. Among nearly 15 detected objects [25, 26], periodic pulsations have been detected in 8 cases. No reliable spectral information has been obtained for about half of them. Pulsating objects (e.g., [25] and references therein) are usually interpreted either as anomalous X-ray pulsars, due to their low luminosities ($10^{34} - 10^{35}$ erg/s) and soft spectra, or as "magnetars" (NSs with huge magnetic fields $B = 10^{14}$–10^{16} G). Until recently it has been difficult to explain these luminosities by thermal emission of cooling NSs of ages $10^3 - 10^4$ yr. However, it has been shown [27] that the young magnetized ($B \gtrsim 10^{14}$ G) cooling NSs covered by light-element envelopes can be hotter and brighter than ordinary NSs. Huge magnetic fields can explain rapid spin-down, slow rotation and absence of radio-pulsar emission. Thus, these objects might be cooling "magnetars", NSs with unusual properties, similar to soft gamma-ray repeaters but emitting only in soft X-rays. Note, that superhigh field B shifts the ion cyclotron lines into the 1–10 keV region. Their discovery with SODAT or JET-X, e.g., for 1E 1841-045 in Kes 73 [25], would confirm or reject the magnetar hypothesis. The luminosities of the resolved non-pulsating (pulse fraction $P_f \lesssim 13 - 45\%$) point sources [26] ($10^{32} - 10^{33}$ erg/s) and their BB-temperatures (0.1–0.3 keV) are generally lower than in pulsating ones. It is possible that they are older and cooler magnetars. The same could be concluded on slowly pulsating (5.89 s, $P_f = 12\%$) isolated NS candidate RXJ0720.4-3125 [24] and its non-pulsating twin RXJ1856.5-3754 ($P_f \lesssim 15\%$) [22, 23].

We indicated several observational problems to be solved with the future X-ray missions, such as *AXAF*, *XMM*, *ASTRO E*, *SXG*. Combined with theoretical results, they present a promising tool to study physics and astrophysics of NSs.

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