EVOLUTION OF THERMAL STRUCTURE AND RADIATION SPECTRUM OF COOLING NEUTRON STARS

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Abstract. Selfconsistent temperature profiles in the atmospheres and outer envelopes of neutron stars with and without H and He shells are determined using updated thermal conductivities, new OPAL radiative opacities and equation of state. The relationship between the internal and effective surface stellar temperatures is sensitive to chemical composition of surface layers. The evolution of spectra of thermal radiation from a cooling neutron star is strikingly different for stars with and without outer shells composed of light elements. This is important for interpretation of multiwavelength observations of neutron stars to determine, particularly, their surface chemical composition and properties of superdense interiors.

Introduction. Recent observations of the thermal emission from several isolated pulsars in X-rays with ROSAT (e.g., Ögelman 1995; Becker 1996), and probably in optical-EUV band with the HST (Pavlov et al. 1996a; Caraveo et al. 1996; Mignani et al. 1997), ESO NTT (Bignami et al. 1996) and EUVE (Edelstein et al. 1995, Halpern et al. 1996, Bignami et al. 1996) open a promising possibility to obtain a new important information on neutron stars (NSs).

Until now, a simple black-body spectrum has been commonly used to fit the spectral data. Last years significant progress has been achieved in constructing atmosphere models of isolated NSs (e.g., Pavlov et al. 1995; Rajagopal & Romani 1996; Zavlin et al. 1996a, b; Rajagopal et al. 1997). It has been shown that the atmosphere spectra differ from the blackbody ones and depend strongly on surface chemical composition and magnetic fields that is important for interpretation of observations (e.g., Pavlov et al. 1995, 1996a, b). The surface magnetic fields and chemical composition affect also thermal insulation of the outer envelopes and cooling of NSs (e.g., Shibanov & Yakovlev 1996; Potekhin et al. 1997).

Statement of the problem. We present the first selfconsistent calculation of temperature profiles through the NS atmosphere and outer envelope, and determine evolution of thermal radiation spectrum from a cooling NS in a wide spectral band. We consider the simplest case of low surface magnetic fields ($B < 10^{10}$ G) which affect neither atmospheric opacity nor equation of state. Since the chemical composition of the NS surface is unknown, we analyze various models. Iron surface is plausible from the supernova progenitor reasons. Light elements (H, He) can be provided, e.g., by accretion from interstellar medium, or from the supernova remnant at the postsupernova stage (e.g., Chevalier 1996), or from a distant binary component.

There are a few observational indications in favour of the light elements. First, if the optical radiation from the Geminga pulsar is of thermal origin and the spectral feature seen in this radiation is indeed the ion cyclotron line (Bignami et al. 1996) then the Geminga's surface contains light elements. Second, the spectral fit of the soft X-ray radiation from the Vela pulsar with the magnetic hydrogen atmosphere yields (Page et al. 1996) the distance and interstellar hydrogen column density in good agreement with other independent estimates (contrary to the blackbody fit). The fact that the continuum spectra from the magnetic iron atmosphere (Rajagopal et al. 1997) do not differ considerably from the blackbody ones is also in favour of the presence of H on the Vela's surface.

Thus, we consider the NSs envelopes with and without light (accreted) elements. Due to the strong gravitational stratification of accreted matter (Alcock & Illarionov 1980), the outermost layers consist of hydrogen. Light elements burn into heavier ones (He, C, O, Fe) in deeper layers. We use updated electron thermal conductivity, radiative opacity and equation of state, as described by Potekhin et al. (1997) and Zavlin et al. (1996a).

The input parameters for studying the thermal structure of NS envelopes are the surface gravity g, the effective temperature $T_{\rm eff}$ and the mass ΔM of accreted H/He matter. The density-temperature range of study is $-5 \leq \log \rho$ [g cm^{-3}] ≤ 10 and $4.4 \leq \log T$ [K] ≤ 9 at $4.7 \leq \log T_{\rm eff}$ [K] ≤ 6.5. We solve the atmosphere-model equations in the NS atmosphere (Zavlin et al. 1996a) and the thermal structure equations in the outer NS envelope (Potekhin et al. 1997) up to density $\rho_b = 10^{10}$ g cm^{-3}, at which the NS interior is isothermal ($T = T_b$). The obtained relationships $T_{\rm eff}$–T_b are then used in cooling simulations of NSs as described by Potekhin et al. (1997). We adopted a moderately stiff equation of state of Prakash et al. (1988) in

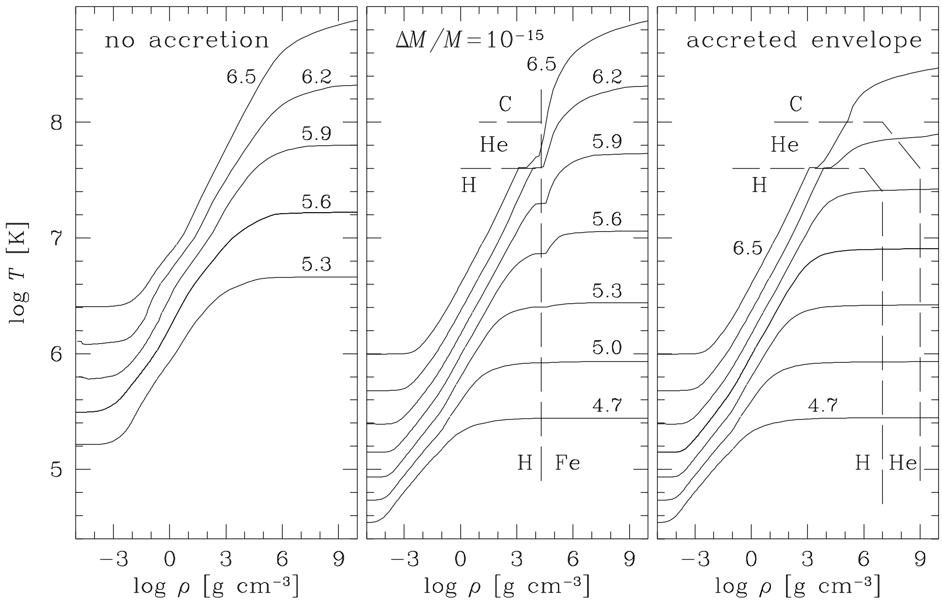

Figure 1. Temperature profiles in NSs with different accreted envelopes (from left to right): $\Delta M/M = 0$ (purely iron envelope), 10^{-15} and $\geq 10^{-7}$ (fully accreted envelope). The curves are labeled by the values of $\log(T_{\rm eff}/10^6$ K). Dashes separate regions of different chemical composition produced by nuclear burning.

the NS core and examined two NS models with nonsuperfluid cores. The first model corresponds to $M = 1.30\,M_\odot$, $R = 11.72$ km ($g_{14} = g/(10^{14}$ cm s$^{-2}) = 1.55$). The central density $\rho_c = 1.12 \times 10^{15}$ g cm^{-3} is insufficient to switch on the rapid neutrino cooling (direct Urca process). This is a typical example of the *standard* NS cooling (the neutrino luminosity is mainly produced by the modified Urca processes). The second model corresponds to $M = 1.44\,M_\odot$, $R = 11.35$ km ($g_{14} = 1.88$). The central density $\rho_c = 1.37 \times 10^{15}$ g cm^{-3} is high enough to allow for the direct Urca process to operate (Lattimer et al. 1991) in a small central kernel, and we have an example of *rapid* cooling. As a result, we obtain the cooling curves, $T_{\rm eff}$ and $T_{\rm surf}$ vs. age t ($T_{\rm surf}$ is the real temperature of the outermost atmospheric layers), and appropriate radiation spectra along these curves.

Thermal structure of NSs. In Fig. 1 we show the temperature profiles in the envelope of a NS with $M = 1.4 M_\odot$, $R = 10$ km, $g_{14} = 2.43$ and different accreted shells at several $T_{\rm eff}$. Heat is mainly carried by radiation in the outermost atmospheric layers and by electrons in the deeper layers. Possible convection is also included. It is shown to occur and change the temperature profiles near the atmosphere bottom. It affects hard tails of the radiation spectra but has no effect on the $T_{\rm eff}$–T_b relationship (e.g., Zavlin et al. 1996b; Potekhin et al. 1997). One can observe two isothermal regions,

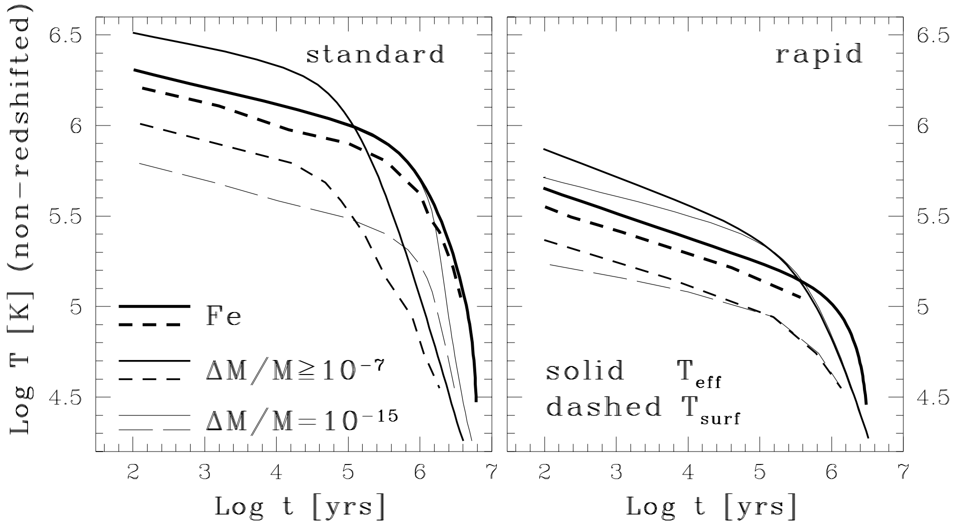

Figure 2. Standard and rapid cooling of NSs with different accreted envelopes.

$T = T_{\rm surf}$ and $T = T_b$. The first one corresponds to the outermost atmospheric layers fully transparent for those photons which make the main contribution into the luminosity. The second region is related to the isothermal interiors with very high electron conduction. Radiative and electron thermal conductivities are smaller for heavier elements. Hence, the accreted envelope is more heat-transparent than the iron one, and leads to cooler interiors at the same $T_{\rm eff}$. Even a thin accreted mantle $\Delta M/M = 10^{-15}$, which extends only to $\rho \sim 10^4$ g cm^{-3}, affects considerably the temperature profiles. The larger ΔM, the stronger is the effect. At $\Delta M/M = 10^{-7}$ the accreted matter fills the entire nonisothermal envelope ($\rho < \rho_b$), and further increase of ΔM does not change thermal structure of a NS. The temperature $T_{\rm surf}$ is determined by the dependence of the radiative opacity on radiation frequency ν. The iron opacity appears to be, on average, less frequency dependent, and the atmosphere structure becomes closer to the grey atmosphere, where $T_{\rm surf}$ is a few tens % lower than $T_{\rm eff}$. On the other hand, the hydrogen opacity behaves mainly as ν^{-3} which yields lower $T_{\rm surf}$ at the same $T_{\rm eff}$ (Zavlin et al. 1996a). With decreasing ΔM in a cold NS, the internal temperature T_b becomes independent of ΔM at $\Delta M/M \leq 10^{-17}$, while $T_{\rm surf}$ remains sensitive to the presence of accreted matter down to $\Delta M/M \sim 10^{-21}$ (due to a very thin atmosphere, $\rho \leq 1$ g cm^{-3}).

Cooling. Fig. 2 shows the effects of accreted envelope on the standard and rapid cooling curves. $T_{\rm eff}$ determines the total radiative energy flux, while $T_{\rm surf}$ determines the Rayleigh–Jeans (optical) part of flux $F_\nu \propto \nu T_{\rm surf}$ $(R/D)^2$, where D is the distance to NS. At the neutrino cooling stage ($t \leq (10^4$–$10^5)$ yrs), when a NS cools mainly via the internal neutrino

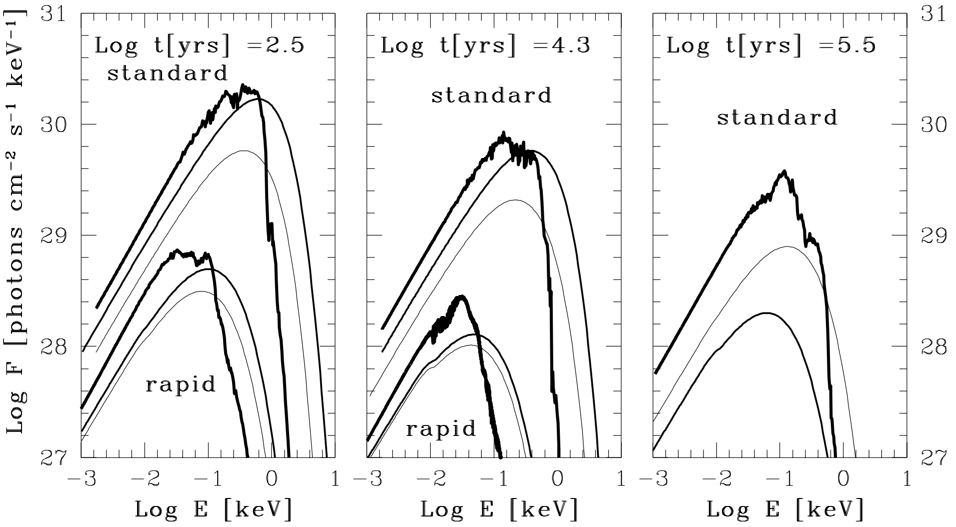

Figure 3. Spectra of thermal emission (nonredshifted) from surfaces of NSs of different ages shown in Fig. 2. Different line thickness corresponds to different masses of accreted envelopes in accordance with Fig. 2.

energy losses, the accreted envelope increases $T_{\rm eff}$. The larger $\Delta M/M$, the higher the NS photon luminosity. The behavior of $T_{\rm surf}$ is different and varies nonmonotonically with $\Delta M/M$ – a thin accreted shell can cool the surface even better than a thick one. This is explained by the atmospheric effects described above. At the photon cooling stage ($t \geq 10^5 - 10^6$ yrs), when the star cools mainly via the surface photon emission, the accreted envelope accelerates the cooling (decreases $T_{\rm eff}$). The dependence of $T_{\rm surf}$ on $\Delta M/M$ becomes generally monotonic. The older and cooler the star, the thinner is the outer, thermally insulating shell, and the smaller is ΔM which affects the cooling.

Spectral evolution. Spectral evolution of thermal emission from the standard and rapidly cooling NSs is shown in Fig. 3. Radiation from a NS with the iron envelope reveals prominent spectral features in soft X-rays associated with the iron absorption lines and photoionization jumps. The features vary in time. No strong features are seen in the spectra of the NSs covered with accreted matter: atmospheric H is almost fully ionized for the relatively hot NSs displayed. The X-ray parts of spectra of NSs with the accreted mantle are generally harder. This is because the light mantle is more transparent for hard photons and we see deeper and hotter stellar layers in X-rays. For NSs of the same age the difference ($T_{\rm eff}^{\rm acc} - T_{\rm eff}^{\rm Fe}$) is positive at the neutrino cooling stage and enhances the hardness effect. The difference becomes negative for older NSs and suppresses the effect. On the other hand, the NSs with iron surface are brighter in optics since their surfaces are hotter. At other equal conditions (age, mass, radius, distance, interstellar absorption) the difference of optical fluxes from NSs with and without H envelopes can reach $\sim 0.5^m$. Even at the level of $20 - 26^m$, typical for NSs, this difference is quite measurable with the sensitivity of modern telescopes (HST, ESO NTT, etc.). The models of NSs with Fe and H surfaces might equally well fit the observational data in some spectral band, e.g., in soft X-rays (see Pavlov et al. 1996b). Then multiwavelength observations from optics through EUV to X-rays together with other independent measurements of distance, interstellar absorption, stellar age, would help to discriminate which material the faces of NSs are made of and what are the properties of superdense NS interiors.

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