THE ASTROPHYSICAL JOURNAL, 477:L99–L102, 1997 March 10

COOLING NEUTRON STARS WITH ACCRETED ENVELOPES

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Received 1996 November 8; accepted 1996 December 27

ABSTRACT

The relationships between the effective surface temperature $T_{\rm eff}$ and the internal temperature T_b of nonmagnetized neutron stars with and without accreted envelopes are calculated for $T_{\rm eff} > 5 \times 10^4$ K. We use updated equations of state and radiative opacities, and we improve considerably the electron conductive opacity. We examine various models of accreted layers (H, He, C, and O subshells produced by nuclear burning of accreted matter). The resulting $T_{\rm eff}$-T_b relationship is remarkably insensitive to the details of the models and depends mainly on the accreted mass ΔM. For $T_{\rm eff} > 10^5$ K, the accreted matter is generally more heat transparent. Even a small accreted mass ($\Delta M \gtrsim 10^{-13}\ M_\odot$) affects appreciably the cooling of a neutron star, leading to higher $T_{\rm eff}$ at the neutrino cooling stage and to lower $T_{\rm eff}$ at the subsequent photon stage. We illustrate this by simulating the standard cooling of neutron stars. The presence of accreted matter yields better agreement of our model cooling curves with the blackbody fits to the *ROSAT* spectral observations of cooling neutron stars, without invoking quark matter or superfluidity in the neutron star cores.

Subject headings: dense matter — pulsars: general — stars: neutron

1. INTRODUCTION

Recent *ROSAT* spectral observations of soft X-ray radiation from isolated pulsars (e.g., Ögelman 1995) yield valuable information on the effective surface temperatures $T_{\rm eff}$ of cooling neutron stars (NSs). A comparison of the measured $T_{\rm eff}$ with theoretical predictions provides an important tool to explore the physics of NSs and the fundamental properties of superdense matter in their interiors (e.g., Pethick 1992).

The cooling of a NS is affected strongly by the relationship between $T_{\rm eff}$ and the temperature T_b at the boundary of the inner, isothermal stellar region. This relationship has been studied thoroughly by Gudmundsson, Pethick, & Epstein (1983, hereafter GPE). Several authors (e.g., Van Riper 1991 and references therein) considered the influence of strong magnetic fields on this relationship.

One assumes traditionally that NS envelopes are composed of iron. In this Letter, we examine the nonmagnetized envelopes composed of light elements as well. The light elements can be provided by an accretion from a supernova remnant (e.g., Chevalier 1996 and references therein), from the interstellar medium (e.g., Nelson, Salpeter, & Wasserman 1993; Morley 1996), from a distant binary component, or by massive infalling bodies. Chemical composition affects the equation of state (EOS) and thermal conduction, and thus the thermal history of a NS.

We reconsider the iron envelopes also. We implement new, advanced EOS and thermal conductivity. This enables us to extend the results of previous studies to colder NSs, down to $T_{\rm eff} \sim 50\,000$ K. The details of the calculations will be published elsewhere (Potekhin, Chabrier, & Yakovlev 1997, hereafter PCY).

2. PHYSICAL INPUT

The temperature T in the outer, nonisothermal envelope of a NS is governed (GPE) by the thermal structure equation:

$$\frac{d\log T}{d\log P} = \frac{3}{16}\frac{PK}{g}\frac{T_{\rm eff}^4}{T^4}, \tag{1}$$

with the standard surface boundary condition at the optical depth $\tau = 2/3$. Here P is the pressure, g is the surface gravity, and $K = (1/K_{\rm rad} + 1/K_c)^{-1}$ is the opacity, composed of the radiative opacity $K_{\rm rad}$ and the electron conduction opacity K_c. Following GPE, we place the inner boundary of the nonisothermal envelope ($T = T_b$) at the density $\rho_b = 10^{10}$ g cm^{-3}. This envelope contains $\sim 10^{-7}$ of the NS mass. The actual nonisothermal layer is usually much thinner.

Some part of the NS envelope can be unstable convectively (Zavlin et al. 1996; Rajagopal & Romani 1996). The temperature gradient over the convective zone is smaller than that given by equation (1). We have included this effect but found that it modifies the $T_{\rm eff}$-T_b relationship by less than 0.1%.

We assume that an accreted envelope may consist of subshells of different chemical composition (H, He, C, O). For the outer layers, composed of H and He, we use the Saumon-Chabrier EOS (Saumon, Chabrier, & Van Horn 1995). For the low-density nonaccreted (Fe) material, we employ the OPAL EOS (Rogers, Swenson, & Iglesias 1996). At high density, where the ions are fully ionized, we calculate P as the sum of ideal gas ion and electron pressures plus the Coulomb correction of ions (Hansen & Vieillefosse 1975; DeWitt, Slattery, & Chabrier 1996). The C and O subshells always lie in the full-ionization domain. For iron, there is a gap between the densities covered by the OPAL data and the domain of full ionization. In this case, we use an interpolation procedure described in PCY.

The radiative opacities are taken from the OPAL opacity library. They are improved over those used in the previous studies of NS envelopes. Radiative conduction operates in the very surface layers, while at a greater depth, the heat is carried by electrons.

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The electron conductive opacities are evaluated at any electron degeneracy with the numerical code (Potekhin & Yakovlev 1996) for the electron transport coefficients along magnetic fields. We use the regime of zero magnetic field and introduce some improvements. First, in the solidified part of the envelope, we use a new expression for the electron thermal conductivity (Baiko & Yakovlev 1995). Second, in liquid matter, the electron conduction due to the electron-ion (*ei*) scattering is complemented by the conduction due to the electron-electron (*ee*) scattering (recalculated and fitted in PCY). Third, we derive and use the advanced electron thermal conductivity due to the *ei* scattering. The scattering is described with the non-Born Coulomb cross sections and with the ion structure factors evaluated for a responsive electron background with the local field correction (Chabrier 1990). These structure factors are more accurate than those used previously (e.g., Itoh et al. 1983). In partially ionized matter, K_c was calculated (PCY) using the mean ion approximation with effective ion charge consistent with the adopted EOS.

3. RESULTS

For an accretion of H-He, the outermost layers consist of pure H, owing to the strong gravitational stratification (Alcock & Illarionov 1980), whereas He sinks into deeper layers. While sinking within the NS, freshly accreted matter burns into heavier elements. The details of the burning are uncertain, and we have analyzed several cases. First we take typical burning temperatures and densities from Ergma (1986) and Schramm, Langanke, & Koonin (1992). We considered other models also, shifting the interfaces and replacing the elements according to the results of Iben (1974), Miralda-Escudé, Haensel, & Paczyński (1990), and Blaes et al. (1992) (see PCY for details). We also constructed a toy-model envelope with all accreted material replaced by He.

The $T_{\rm eff}$-T_b relationship proved to be remarkably robust to all modifications, and it depends actually on the accreted mass ΔM and surface gravity g only. Introducing $g_{14} = g/(10^{14}$ cm s$^{-2})$, $Q = (T_{\rm eff}/10^6\ {\rm K})^4/g_{14}$, and $T_{b9} = T_b/(10^9$ K), the relationship is fitted as

$$Q = (aQ_{\rm Fe} + Q_{\rm a})/(a + 1)\,. \qquad (2)$$

Here $Q_{\rm Fe} = (7\zeta)^{2.25} + (\zeta/3)^{1.25}$ corresponds to a purely iron envelope, $Q_a = (18.1T_{b9})^{2.42}$ corresponds to a purely accreted envelope, $\zeta = T_{b9} - 0.001(7T_{b9}\sqrt{g_{14}})^{1/2}$, and $a = [1.2 + 0.0099(g_{14}^2\Delta M/M)^{-0.38}]T_{b9}^{5/3}$. For $4.7 \le \log T_{\rm eff} \le 6.5$ and $0.4 \le g_{14} \le 6$, and for all possible values of ΔM, the maximum fit error is below 6%, and the typical error is about 3%; the fit accuracy of $Q_{\rm Fe}$ is a factor of 1.5 better.

Figure 1 shows log $(T_b/T_{\rm eff})$ as a function of $T_{\rm eff}$ for various ΔM at $g_{14} = 2.43$ (e.g., for a NS with radius $R = 10$ km and mass $M = 1.4\ M_\odot$).

For a nonaccreted envelope ($\Delta M = 0$), our results are in good agreement with the GPE power-law fit, within its validity range ($T_{\rm eff} \gtrsim 10^{5.5}$ K). For colder NSs, the electron conduction domain extends into the nondegenerate region, and the curve bends. Other curves demonstrate the effect of accretion. Even a thin mantle of H or He with mass $\Delta M = 10^{-16}M$, which extends only to $\rho \sim 10^3$ g cm^{-3}, is significant.

The consequence of these results on the NS cooling is illustrated in Figure 2. We have used the fully relativistic cooling code of Gnedin & Yakovlev (1993) and adopted the moderately stiff EOS of Prakash, Ainsworth, & Lattimer (1988) in a NS core. The core is assumed to consist of neutrons, protons, and electrons (no exotic cooling agents such as quarks, etc.). We have used the NS model with $M = 1.3\ M_\odot$. The central density $\rho_c = 1.12 \times 10^{15}$ g cm^{-3} is insufficient to switch on powerful neutrino cooling because of the direct Urca process (Lattimer et al. 1991). Our star cools via the "standard" neutrino energy losses (mainly via the modified Urca process) that are included in a way described by Levenfish & Yakovlev (1996). In order to illustrate the effect of accretion,

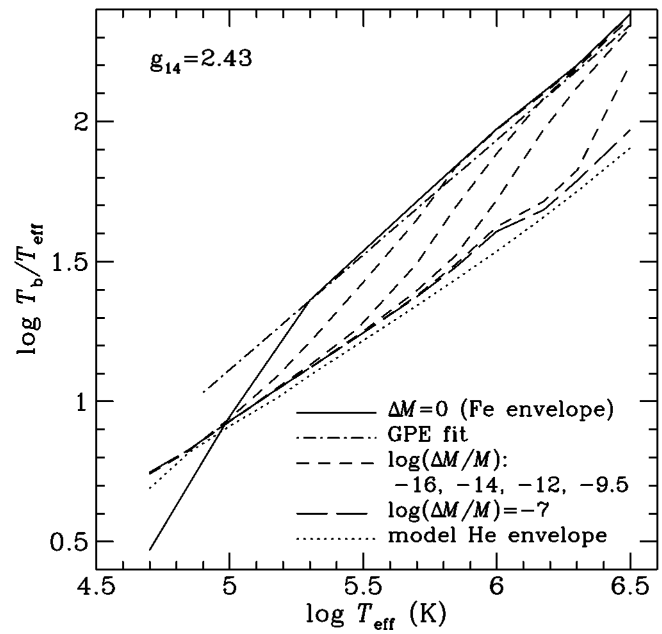

FIG. 1.—Temperature increase through a nonaccreted (Fe; *solid line*) NS envelope, and partially (*short-dashed lines*) and fully (*long-dashed line*) accreted NS envelopes.

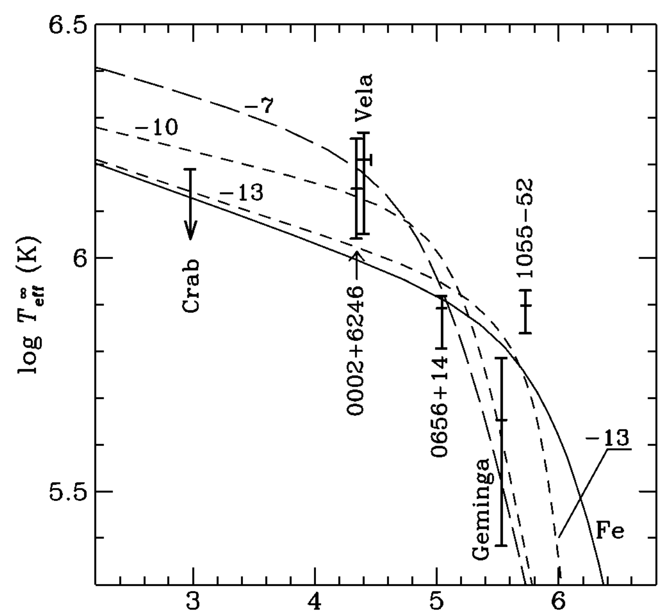

FIG. 2.—Standard cooling of a NS with a nonaccreted envelope, and partially and fully accreted envelopes, compared with observations of thermal radiation from six pulsars (Table 1). The numbers along the curves give log $\Delta M/M$.

TABLE 1

AGES AND SURFACE TEMPERATURES OF ISOLATED PULSARS

Pulsar Name	t (kyr)	$T_{\rm eff}$ (10^6 K)
PSR 0531+21 Crab	0.942[a]	<1.55 (3 σ)[b]
RXJ 0002+6246	≈24[c]	1.1–1.8[c]
3U 0833−45 Vela	22–29[d]	(1.3–1.9),[e] ≈1.3[f]
PSR 0656+14	110[g]	$(0.78^{+0.05}_{-0.14})$[h]
1E 0630+178 Geminga	320[g]	$(0.45^{+0.14}_{-0.15})$[i]
PSR 1055−52	540[g]	$(0.79^{+0.06}_{-0.10})$[h]

[a] Time elapsed since the supernova event.
[b] Becker & Aschenbach 1995.
[c] Hailey & Craig 1995.
[d] Lyne et al. 1996.
[e] Cumulative error bar of three fits (Ögelman et al. 1993).
[f] Two-component fit (Ögelman 1995).
[g] Characteristic age (Ögelman 1995).
[h] Greiveldinger et al. 1996.
[i] Blackbody + power-law fit (Halpern & Ruderman 1993).

we use a simplified NS model, neglecting the nucleon superfluidity in the core and internal reheating.

Figure 2 presents the cooling curves—effective temperatures $T^\infty_{\rm eff}$, as measured by a distant observer, versus NS age t. We assume that the accreted material is accumulated during the first 10^2 yr (e.g., at the post-supernova stage). The fraction of accreted mass $\Delta M/M$ varies from 0 to $\sim 10^{-7}$. A further increase of ΔM does not affect the cooling.

The change of slopes of the cooling curves at $t = 10^5$–10^6 yr reflects a transition from the neutrino to the photon cooling stage. Initially, T_b is ruled by the neutrino emission, independent of the thermal insulation of the NS envelope. Since the accreted envelopes of NSs that are not too cold are more heat transparent (Fig. 1), $T_{\rm eff}$ is noticeably higher than for a nonaccreted NS. At the photon stage, the NS cools mainly via the surface emission, and the transparency of the accreted envelope accelerates the cooling.

For comparison, we plot the $T_{\rm eff}$ (with 1 σ confidence intervals) of those pulsars, from which the soft X-ray radiation has been registered by *ROSAT*, and the 3 σ upper limit for the Crab pulsar. For Geminga, PSR 1055−52, and PSR 0656+14, we plot the values of $T_{\rm eff}$ obtained for the *soft* components of the two- and three-component X-ray spectra models (these components are associated with the thermal NS emission). For Vela, we extend downward the confidence interval obtained by Ögelman, Finley, & Zimmermann (1993), according to the more recent spectral fit of Ögelman (1995), which gives a more plausible NS radius than the previous fit.

We plot the values of $T_{\rm eff}$ derived by fitting the Planck spectrum to the measured X-ray spectrum. Alternatively, one often infers $T_{\rm eff}$ from the apparent luminosity over the whole observed spectral range. In the latter case, however, the inferred $T_{\rm eff}$ depends strongly on the assumed NS distance (usually poorly known) and model-dependent radius.

The blackbody fits do not take into account the influence of the magnetized atmosphere. The fits for PSR 0656+14 (Anderson et al. 1993), Geminga (Meyer, Pavlov, & Mészáros 1994), and Vela (Page, Zavlin, & Shibanov 1996), which employ the models of magnetized atmospheres, have resulted in a few times lower $T_{\rm eff}$ than the blackbody fits. Our justification for using the blackbody fits here is that the existing models of magnetized atmospheres do not take proper account of absorption by neutral atoms. The appropriate opacities are still under investigation (Potekhin & Pavlov 1997 and references therein).

The magnetic fields affect the thermal insulation of NS envelopes also. However, it has been shown (e.g., Shibanov & Yakovlev 1996) that the dipole magnetic fields $\lesssim 10^{13}$ G affect the cooling much more weakly than predicted by the studies of simplified magnetic field geometries (e.g., Van Riper 1991).

As seen from Figure 2, the presence of accreted matter provides a simple explanation of cooling of RXJ 0002+6246, Vela, and Geminga by the standard neutrino emission without invoking superfluidity of NS matter (cf. Page 1994; Levenfish & Yakovlev 1996). Note that the accretion rate of Vela estimated by Morley (1996), multiplied by its age, yields log $\Delta M/M_\odot \approx -9.5$, just matching the center of the error bar in Figure 2. For PSR 0656+14, the scenarios with and without the accretion are equally consistent with the blackbody fits, especially if its braking index is assumed to be less than 3 (as happens for all four pulsars with known braking indices; see Lyne et al. 1996), i.e., its true age is somewhat higher than the characteristic age. PSR 1055−52 is rather old and warm, which probably suggests the presence of reheating.

4. CONCLUSIONS

We have obtained a new and simple relationship (eq. [2]) between surface and internal temperatures of NSs with and without accreted envelopes. We have used new state-of-the-art calculations of EOS and opacities of NS envelopes. The obtained relationship is insensitive to the details of the models of the envelopes but depends on the accreted mass. We have shown that the presence of accreted material strongly affects the thermal structure and history of NSs.

For illustration, we have used the standard cooling model of NSs and the blackbody fits to the observed spectra. The presence of accreted envelopes yields better agreement of the cooling curves with these fits. Using our model, we need neither superfluidity nor exotic matter in the neutron star cores to obtain such agreement. It would be interesting to extend the present study, using different EOSs in the NS interiors and the effects of superfluidity, in an attempt to explain the observational data in the frame of the standard cooling. This work is under way.

More sophisticated cooling models and atmospheric spectral fits can also gain from the inclusion of accreted envelopes (e.g., Page 1997). Recent observations of the Geminga pulsar suggest a possible H or He cyclotron feature in its spectrum (Bignami et al. 1996), which may be direct observational evidence of the presence of light elements in the pulsar atmosphere. Morley (1996) argues that pulsars do accrete matter. This accretion should be taken into account in the cooling theories.

We are grateful to Dany Page, Einar Gudmundsson, and Yura Shibanov for fruitful discussions, to George Pavlov for useful remarks, and to Forrest Rogers for providing the OPAL data. This work was supported in part by the RBRF grant 96-02-16870a, INTAS grant 94-3834, and DFG-RBRF grant 96-02-00177G. A. Y. P. gratefully acknowledges the hospitality of the theoretical astrophysics group of the Ecole Normale Supérieure de Lyon and of the NORDITA staff.

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