The impact of heat blanketing envelopes on neutron stars cooling

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Abstract. The goal of this work is to investigate the effects of chemical composition of heat blanketing envelopes of neutron stars on their thermal states and thermal evolution. To this purpose, we employ newly constructed models of the envelopes composed of binary ion mixtures (H–He, He–C, C–Fe) varying the mass of lighter ions (H, He or C) in the envelope. The results are compared with those calculated using the standard “onion-like” envelope. For illustration, we apply these results to estimate the internal temperature of the Vela pulsar and to study cooling of neutron stars. We show that uncertainties in the chemical composition of the envelopes can lead up to $\sim 2.5$ times uncertainty of the internal temperature of the star which significantly complicates theoretical reconstruction of the internal structure of cooling neutron stars from observations of their thermal surface emission.

1. Introduction

An investigation of the properties of the matter of nuclear ($\rho_0 = 2.4 \times 10^{14}$ g cm$^{-3}$; see, e.g., [1]) and supranuclear densities is most important not only for astrophysics but for many other areas of physics. For example, such investigation is needed in nuclear physics, elementary particle physics and condensed matter physics. It is a challenging task for a lot of reasons and the study of neutron stars plays an important role in solving this problem because neutron stars are unique natural laboratories of superdense matter (see, e.g., [1, 2]). However, the properties of the superdense matter determine the internal structure of neutron stars which is not directly observable. Consequently, the ability to study the properties of the superdense matter is based on the ability to infer the internal structure of neutron stars from observations of their surface emission.

One of a few ways to do this is to construct theoretical models of thermal evolution of neutron stars and compare the theory with observational data (see, e.g., [2, 3]). However, here appears another problem. Such theories utilize the internal temperature of a neutron star ($T_b$) whereas from observations one can only extract its surface temperature ($T_s$). The $T_s - T_b$ relation is an important and still not fully resolved issue in the neutron star physics. It is determined by a thin but very significant heat blanketing envelope of the star (see, e.g., [4, 5]). And although the microphysics of these envelopes is more or less clear (unlike the microphysics of neutron star cores), their chemical composition is rather uncertain. This leads to uncertainties in $T_s - T_b$ relations and, in turn, in our understanding of the properties of the superdense matter in neutron star cores.
Thus, the main goal of our work is to investigate how the uncertainties of the chemical composition of heat blanketing envelopes affect the inference of the parameters of neutron stars from observations. To achieve this, we employ our recently developed models of heat blanketing envelopes composed of binary ion mixtures (H–He, He–C and C–Fe) [5]. We also use the “onion-like” model (layers of H, He, C and Fe) developed by Potekhin et al [4] as a reference for comparison with our models. That model (hereafter, the PCY97 model) is widely used in the astrophysical literature and has de-facto become a standard model of the heat blanketing envelope. Our objects of study are not too young ($t \gtrsim 100 \text{ yr}$) isolated cooling neutron stars. Such stars are thermally equilibrated and isothermal inside. The main temperature gradient still persists in the heat blanketing envelopes (see, e.g., [1, 2]), so that the $T_s - T_b$ relations are determined only by these envelopes.

In the following sections we briefly discuss formation scenarios of heat blanketing envelopes, thermal states of the Vela pulsar and neutron star cooling. More details on this topic are published elsewhere [6].

2. Formation scenarios

A few decades ago it was commonly thought that the outer envelopes and the atmospheres of neutron stars consist of heavy (iron-like) elements due to the formation of the envelopes in very hot and young neutron stars where all light elements had burnt into heavier ones in thermonuclear reactions. However, an analysis of the observed spectra has demonstrated that some neutron stars are better described by hydrogen atmosphere models (see, e.g., [7]) while some other stars are better described by carbon atmosphere models (see, e.g., [8]). This gives observational evidence that heat blanketing envelopes of neutron stars can consist not only of heavy elements but of light elements as well.

Possible formation scenarios include:

- The fallback of material on the neutron star surface after the supernova explosion;
- The accretion of hydrogen and/or helium from interstellar medium or from a binary companion (if the neutron star has passed the compact binary stage, e.g., [9]);
- Accreted hydrogen can burn into helium, then helium can burn into carbon and carbon into heavier elements (e.g., [10]).

All these processes contribute to the uncertainty of chemical composition of heat blanketing envelopes making it largely unknown.

3. Thermal states of the Vela pulsar

Let us consider the Vela pulsar as an example and analyze its thermal states using the available observational data. Vela is a middle-aged pulsar, its characteristic age is $t \approx 11 \text{ kyr}$. Therefore, its thermal relaxation has occurred long ago and its redshifted internal temperature $\tilde{T}$ is constant throughout the star (excluding the heat blanketing envelope). The redshifted effective surface temperature of the Vela pulsar was estimated by Pavlov et al [11] to be $T_s^\infty = 0.68 \pm 0.03 \text{ MK}$ (at 68% confidence level for a magnetic hydrogen atmosphere model and “canonical” model of a neutron star with the mass $M = 1.4 \text{ M}_\odot$ and radius $R = 10 \text{ km}$). Specifically, we use the value $T_s^\infty = 0.68 \text{ MK}$, which corresponds to $T_s = T_s^\infty/\sqrt{1-x_g} = 0.89 \text{ MK}$, with $x_g = 2GM/(Rc^2)$. Then we employ $T_s - T_b$ relations from [4, 5] to calculate $T_b$ and the redshifted internal temperature $\tilde{T} = T_b/\sqrt{1-x_g}$. Although Vela possesses a magnetic field $B \sim 3 \times 10^{12} \text{ G}$, this field has no strong influence on the $T_s - T_b$ relations [12].

The results are presented on Fig. 1 which shows the inferred internal Vela’s temperature $\tilde{T}$ calculated with different envelope models. For a fixed envelope model, $\tilde{T}$ is plotted as a function of $\Delta M$, an accumulated mass of light elements in the envelope. In particular, for the H–He
envelope (the dotted curve) $\Delta M = \Delta M_H$ is the accumulated mass of hydrogen; for the He–C envelope (the dashed curve) $\Delta M = \Delta M_{He}$ is the mass of helium; for the C–Fe envelope (the dot-dashed curve) $\Delta M = \Delta M_C$ is the mass of carbon and, finally, for the PCY97 envelope model (the solid gray curve) $\Delta M$ is the mass of light elements (H+He+C).

It is important to note that the chemical composition of any envelope has some natural limitations due to thermonuclear and pycnonuclear reactions and electron captures [4, 5]. At high temperatures and/or densities hydrogen transforms into helium, then helium into carbon, etc. Such temperatures and densities are accessible in the heat blanketing envelopes thus limiting their chemical compositions. The consequences are two-fold. First, different envelopes may have different densities at the bottom ($\rho_b = 10^8$ g cm$^{-3}$ for the H–He envelope and $\rho_b = 10^{10}$ g cm$^{-3}$ for the other envelopes). Second, maximum possible value of $\Delta M$ is also different for different envelopes.

As seen from Fig. 1 the uncertainties in the chemical composition of the envelope can cause up to $\sim 2.5$ times variation in the internal temperature for a fixed observable surface temperature. The largest variation of the internal temperature occurs in the PCY97 model because it takes into account a wider range of elements than any binary envelope model. Another notice is the anomalous behavior of the H–He curve (explained in [5]). For all other curves $\tilde{T}$ decreases when $\Delta M$ increases because light elements increase heat transparency (as detailed in [5]).

As Vela is at the neutrino cooling stage (e.g., [2]) the main factor which determines its thermal evolution is the neutrino cooling function $\ell(T) = L^{\nu}_C(T)/C(T)$, where $L^{\nu}_C$ is the neutrino luminosity of the star and $C$ is its heat capacity (see, e.g., [13]). The neutrino cooling function is a fundamental parameter of superdense matter in a neutron star core, and it is determined by the internal temperature. A convenient unit of $\ell$ is $\ell_{SC}$ which is the so-called “standard neutrino candle” (a non-superfluid star which cools via neutrinos generated in the modified Urca process). Using the fit expression for the neutrino cooling function from [14], which is independent of the equation of state (EOS) of nucleon matter in the stellar core, we can calculate the quantity $f_\ell = \ell(\tilde{T})/\ell_{SC}(\tilde{T})$, the neutrino cooling function of Vela expressed in terms of standard candles.
We have demonstrated that a factor of $\sim 2.5$ uncertainty in the internal temperature translates into a factor of $\sim 200$ uncertainty in $f_\ell$ (see [6] for details). This greatly complicates an investigation of the properties of the superdense matter and emphasizes once more the importance of chemical composition of heat blanketing envelopes.

4. Neutron star cooling

Now let us consider the cooling of isolated neutron stars using a simple example. Specifically, we study the thermal evolution of the star with the mass $M = 1.4 \, M_\odot$ and BSk21 EOS [15]. Such star has the radius $R = 12.60 \, \text{km}$. For illustration, we assume $f_\ell = 1$ (the standard neutrino candle) and focus on the effects of the envelopes. After fixing $f_\ell$ and an envelope model but varying $\Delta M$, we obtain a sequence of cooling curves $T_\infty^s(t)$ [redshifted effective surface temperatures versus stellar age]. These curves are almost universal, i.e. independent of the EOS in the core and of the mass $M$ [16].

Some examples of our calculations are presented in Fig. 2. The thick curves correspond to the envelopes composed of pure elements (He, C, Fe) and the fully accreted PCY97 envelope (the solid gray curve). The dark-gray area is filled with the cooling curves for the C–Fe envelopes with different $\Delta M$; the medium-gray area is filled with the cooling curves for the He–C envelopes, and the light-gray area with the cooling curves for the PCY97 envelopes (if they are not covered by binary envelopes). The H–He envelopes are excluded for a better visual representation of the figure. We have also added the observational data on isolated neutron stars (see [14] and references therein). Neutron star labels are as follows: (1) PSR J1119–6127; (2) RX J0822–4300 (in Pup A); (3) PSR J1357–6429; (4) PSR B0833–45 (Vela); (5) PSR B1706–44; (6) PSR J0538+2817; (7) PSR B2334+61; (8) PSR B0656+14; (9) PSR B0633+1748 (Geminga); (10) PSR B1055–52; (11) RX J1856.4–3754; (12) PSR J2043+2740; (13) RX J0720.4–3125; (14) PSR J1741–2054; (15) XMMU J1732–3445; (16) Cas A neutron star; (17) PSR J0357+3205 (Morla); (18) PSR B0531+21 (Crab); (19) PSR J0205+6449 (in 3C 58).

As seen from Fig. 2, variations in the chemical composition of the heat blanketing envelopes significantly affect the cooling curves. A star with an iron envelope, being a standard neutrino candle ($f_\ell = 1$; the dot-dashed curve), cannot explain many observational sources. Taking into account different chemical compositions of the envelope, we can explain more sources but not all of them. To explain the remaining sources one needs to consider deviations from the standard neutrino candle. Warm sources require $f_\ell < 1$ ($f_\ell \sim 0.01$ for XMMU J1732–3445; see, e.g., [14]), while cold sources require $f_\ell > 1$ ($f_\ell \sim 10^2 − 10^4$ for the Vela pulsar depending on the exact composition of the envelope [6]). Furthermore, Fig. 2 implies that observations of all isolated neutron stars at the photon cooling stage (i.e., with the age $t \gtrsim 100 \, \text{kyr}$; see, e.g., [2]) are compatible with $f_\ell \lesssim 1$.

5. Conclusions

We have analyzed the effects of uncertainties in the chemical composition of the heat blanketing envelopes on thermal states and cooling of neutron stars. We have briefly outlined possible formation scenarios of the envelopes with different compositions (Sec. 2). Then, taking the Vela pulsar as an example, we have demonstrated that the uncertainties in the chemical composition of the envelopes can translate up to $\sim 2.5$ times uncertainties in the internal stellar temperature for a fixed observable surface temperature and up to $\sim 200$ times uncertainties in the neutrino cooling function which is the most important parameter of superdense matter in neutron star cores (Sec. 3). Finally, we have presented some examples of cooling curves for a neutron star with $f_\ell = 1$ (standard neutrino candle) and different heat blanketing envelopes (Sec. 4). The effects of the envelopes are clearly seen from Fig. 2. To sum up, all these results demonstrate that a proper analysis of the chemical composition of neutron star heat blanketing envelopes is essential in the order to reliably infer the properties of superdense matter in the neutron star cores.
Needless to say, our consideration is not complete. More work is required to resolve this problem. For example, one can consider multicomponent (> 2) ion mixtures either diffusively equilibrated or not. The evolution of initially not diffusively equilibrated envelopes can be also modeled. Moreover, it will be useful to improve the existing models of diffusive nuclear burning in the envelopes [10] and take into account the effects of magnetic fields. Evidently, any additional reliable information on the formation history and evolution of the envelopes would be most welcome. However, all these problems are far beyond the scope of the present paper.

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