Could strange stars be in the color-flavor-locked phase: Tested by their thermal evolutions

Quan Cheng, Yun-Wei Yu and Xiao-Ping Zheng
Institute of Astrophysics, Central China Normal University, Wuhan 430079, China
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The thermal evolution of strange stars in both normal and color-flavor-locked (CFL) phases are investigated together with the evolutions of the stellar rotation and the r-mode instability. The heating effects due to the deconfinement transition of the stellar crust and the dissipation of the r-modes are considered. As a result, the cooling of the stars in the normal phase is found to be not very different from the standard one. In contrast, for the stars in the CFL phase, a big bump during the first hundred years and a steep decay (∼7% in ten years) at the ages of ∼10^{16} yrs are predicted in their thermal evolution curves. These unique features provide an effective observational test for determining whether or not the CFL phase is reached in strange stars. This thermal test method is independent of and complementary to the rotational test method, which is a direct consequence of the r-mode instability [see J. Madsen, Phys. Rev. Lett. 85, 10 (2000)].

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I. INTRODUCTION

Strange quark matter (SQM), made up of roughly equal numbers of up, down, and strange quarks, could be the absolute ground state of strong interaction [1–3], the most important astrophysical consequence of which is that compact stars could have a quark matter core (i.e., hybrid star) or even consist purely of SQM (i.e., strange star, SS; [4,5]). Furthermore, phenomenological and microscopic studies suggest that SQM at a sufficiently high density could undergo a phase transition into a color superconducting state, the typical cases of which are the two-flavor color superconductivity (2SC) and color-flavor-locked (CFL) phases [6,7]. In the following content, we adopt the abbreviations 2SSs and CSSs for the two types of SSs in the two different color superconducting phases, respectively, and NSSs for normal SSs.

Madsen [8] suggested that the SS models can be constrained by the most rapidly rotating pulsars in low mass X-ray binaries (LMXBs), because the rotation of compact stars should be suppressed by r-mode instability, which arises due to the action of the Coriolis force with positive feedback increasing gravitational radiation (GR) [9]. As a result, it is found that the CSS model could be not permitted by the LMXB data because of the too weak viscosities of CSSs, which cannot inhibit the r-modes effectively. In this paper we suggest something different from the rotational test to the models—a thermal test method, i.e., probing the interior of SSs by the temperature observations of compact stars. The most essential point of our work is to carefully investigate the influence of the r-mode instability on the thermal evolution of SSs. Therefore, our independent thermal test can be complementary to the direct rotational test.

The cooling behaviors of SSs have already been extensively investigated, ever since the emergence of the SS model. In the earliest works, it was accepted that the surface temperature of SSs should be significantly lower than traditional neutron stars at the same age due to the quark direct Urca (QDU) processes [11,14]. However, by considering that the electron fraction of SQM could be small or even vanish and thus the QDU processes could be switched off, Schaab et al. [15,16] proposed that the cooling of SSs dominated by the quark-modified Urca and quark bremsstrahlung processes could be slower than neutron stars with standard cooling. The possible existence of the color superconductivity makes the problem more complicated. It has been shown that the cooling of 2SSs is compatible with existing x-ray data but that CSSs cool down too rapidly, which completely disagrees with the observations [17].

Besides the stellar core consisting of SQM, SSs could also sustain a tiny nuclear crust with a maximum density below neutron drip (∼4 × 10^{11} g cm^{-3}) [4,18,19]. The mass of the crust as a function of the spin frequency \nu can be expressed as [20]

\[
M_\nu = M_\nu^0 \left(1 + 0.24\nu_3 + 0.16\nu_5\right),
\]

where \nu = \nu/10^3 Hz, and \nu_3 ∼ 10^{-3}M_\odot is the mass of the crust in the static case. With the spin down of a SS, the star shrinks and the density at the bottom of the crust exceeds neutron drip. As a result, the most inner part of the crust falls into the quark core and dissolves from baryons into quarks. During this process the released binding energy can heat the star. Therefore, Yuan and Zhang [21] proposed a so-called deconfinement (DC) heating mechanism, which can delay the cooling of SSs significantly. Especially for CSSs, the stellar thermal evolution could be completely determined by the DC heating [22]. As analyzed, the temporal dependence of the heating power should be determined by the spin-down history.

In [21] and [22], as usual, the spin down of SSs is considered to be due only to the magnetic dipole radiation (MDR).

\[1\] In the CFL case, both the neutrino emission and the quark thermal capacity are blocked off, whereas the cooling due to the photon emission from the stellar surface is still effective. Therefore, an extremely large temporal derivative of temperature can be obtained by dividing the photon luminosity by the tiny heat capacity, which leads to the rapid cooling. See the grey band in the right panel of Fig. [3].

*Electronic address: yuyw@phy.ccnu.edu.cn
However, as aforementioned, the spin of young compact stars could also be limited by r-mode instabilities. In other words, if the r-mode amplitude is large enough, the early spin down of SSs could be dominated by GR rather than MDR [23]. This could significantly influence the process of the release of the crust-binding energy. On the other hand, as an extra heating effect, the shear viscous dissipation of r-modes can also deposit energy into the thermal state of the stars [24–26]. The main purpose of this paper is to test the CSS model by investigating its thermal evolutions with the above-mentioned heating effects.

In the next section we briefly introduce the thermal evolution equation of SSs, where both DC heating and the heating due to viscous dissipation of r-modes (RM heating hereafter) are involved. The spin evolution of SSs involving both MDR and GR brakings is described in Sec. [31] which is essential to solve the thermal evolution equation. The calculated results and some discussions are provided in Secs. [32] and [33] respectively.

II. THERMAL EVOLUTION EQUATION

For simplicity, in this paper, the temperature in the interior (the core) of a SS is assumed to distribute nearly uniformly, and the gradient from the interior temperature to the surface temperature is considered to be mainly caused by the thin crust. Following [27], the relationship between the surface temperature $T_s$ and the interior temperature $T$ can be expressed by $T_s = 3.08 \times 10^6 \frac{1}{T} \frac{1}{g_{s,14}^{1/4} \rho_{0}}$, where $T_9 = T/10^9$ K and $g_{s,14}$ is the proper surface gravity of the star in units of $10^{14}$ cm s$^{-2}$. As a result, the luminosity of the surface photon emission of the star can be calculated to $L_\gamma = 4\pi R^2 \sigma T_s^4$, where $R$ is the stellar radius and $\sigma$ is the Stefan-Boltzmann constant. Of course, as usually considered, neutrino emission could play a much more important role in the cooling of a young NSS.

Denoting the neutrino luminosity by $L_\nu$ and the powers of the DC and RM heatings by $H_{DC}$ and $H_{RM}$, the thermal evolution of a SS can be solved from

$$C \frac{dT}{dt} = -L_\gamma - L_\nu + H_{DH} + H_{RM},$$

where $C$ is the thermal capacity of the star. The expressions of $C$ and $L_\nu$ for normal SQM are taken the same as those in [22] and [25], which were originally calculated by Iwamoto [28]. In the presence of color superconductivity, the thermal capacity and neutrino emissions contributed by the paired quarks are significantly suppressed by some exponential factors, which can be found in [17].

The power of the DC heating is obviously determined by the transition rate of the nuclear matter at the bottom of the crust. Equation (1) further indicates that the transition rate depends on the variation rate of the spin frequency. Therefore, by denoting the heat release per dissolved neutron by $g_{\nu}$, the power of the DC heating can be estimated by [22]

$$H_{DC} = -g_\nu \frac{1}{m_\nu} \frac{dM_c}{d\Omega} \frac{d\Omega}{dt},$$

where $m_\nu$ and $\Omega$ are the mass of baryon and spin angular velocity of the star, respectively. In the conventional MDR model, the temporal derivation of the angular velocity can be calculated by $d\Omega/dt = -\Omega/\tau_m$, where the magnetic braking timescale reads $\tau_m = 1.69 \times 10^9 \frac{B_{12}^{-2} (\Omega/\sqrt{\mu B})}{\mu_s} \ s$, $B_{12}$ is the magnetic field intensity in units of $10^{12}$ G, and $\sqrt{\mu B}$ represents the order of the Keplerian rotation limit with $G$ being the gravitational constant and $\rho$ the mean stellar density. However, by considering the arising of r-mode instability, which can lead to the loss of stellar angular momentum via GR, the spin-down history of SSs needs to be re-investigated more carefully.

It is natural to consider that a great amount of the stellar rotational energy can be transferred into r-modes. Subsequently, the energy carried by the r-modes can be further dissipated by both bulk and shear viscosities. To be specific, the part of the r-mode energy dissipated by the bulk viscosity escapes from the star via neutrino emission, whereas the part corresponding to the shear viscosity can be deposited into internal energy, which could be of great importance for the stellar thermal evolution. Following [23] and [25], the power of such RM heating can be written as

$$H_{RM} = \frac{2E}{\tau_{sv}} = \frac{\alpha^2\bar{J}MR^2\Omega^2}{\tau_{sv}},$$

where $E = \frac{4\alpha^2\bar{J}MR^2\Omega^2}{3}$ is the canonical energy of the r-modes with $\bar{J} = 1.635 \times 10^{-2}$ for $n = 1$ polytrope, $\alpha$ the amplitude of the r-modes, and $M$ the stellar mass. For normal SQM, the shear viscous time scale is $\tau_{sv} = 5.41 \times 10^9 \frac{\bar{a}_{0,14}^{5/3}}{\rho_{0,5}} s$, where $\alpha_{c,0.1} = \alpha/0.1$ is the strong coupling [29]. In presence of color superconductivity, a fraction or all of the quarks are paired and thus the shear viscosity contributed by these paired quarks should be suppressed by a factor of $\exp(3/3k_B T)$, where $\Delta$ is the pairing gap. In such a case, the shear viscosity due to electron-electron scattering becomes more important for the r-mode damping. The corresponding time scale can be expressed as $\tau_{sv}^C = 2.95 \times 10^9 (\mu_e/\mu_q)^{-4/3} T_q^{5/2} s$, where $\mu_e$ and $\mu_q$ are the chemical potentials of electrons and quarks, respectively. On the other hand, as pointed out by [8], an extra viscosity due to the rubbing between the solid nuclear crust and the electron atmosphere of the quark core could lead to a more effective dissipation of the r-mode energy, which determines a time scale of $\tau_{sa} = 1.42 \times 10^9 (\nu/1 \ kHz)^{-1/2} T_q^3 s$.  

III. SPIN DOWN OF SS

As mentioned above, the GR due to r-mode instability could play an important role in the spin down of a SS. Following the phenomenological model developed by Owen et al. [23] and Ho and Lai [30], the spin down of the star affected by both MDR and GR brakings can be solved from

$$\frac{d\Omega}{dt} = -\frac{\Omega}{\tau_m} - \frac{2Q\alpha^2\Omega}{\tau_v},$$

where $Q = 0.094$ is a constant determined by the stellar structure. The viscous time scale here, $\tau_v$, includes the effects of
both bulk and shear viscosities, which can be calculated by
\[ \tau_v = \left( \frac{1}{\tau_g} + \frac{1}{\tau_m} \right)^{-1}. \]
For normal SQM, the bulk viscous time scale reads \( \tau_{v,b} = 0.886(\Omega/\sqrt{G\rho})^{-2}T_9^{-2}m_{s,100}^{-4} \) s, where \( m_{s,100} \) is the mass of strange quark in units of 100 MeV [8, 29]. In presence of color superconductivity, this time scale should also be prolonged by a factor of exp(2\( \Delta/ \kappa_0 T \)). In order to solve Eq. (5), we must simultaneously determine the evolution of the r-mode amplitude by
\[ \frac{d\alpha}{dt} = \alpha \left( \frac{1}{\tau_g} - \frac{1}{\tau_v} \right) + \frac{1}{2\tau_m}, \] (6)
where the GR time scale reads \( \tau_g = 3.26(\Omega/\sqrt{G\rho})^{-6} \) s for \( n = 1 \) polytrope.

It is generally believed that r-mode instability would finally arrive at a saturation state due to some nonlinear effects. Lindblom et al. [31, 32] suggested that the nonlinear saturation may be determined by dissipation of energy in the production of shock waves. Moreover, the decay of the amplitude of the order unity is due to leaking of energy into other fluid modes, leading to a differential rotation configuration [33]. Afterwards, the coupling between r-modes and other modes was analyzed [34, 35]. On the other hand, the role of differential rotation in the evolution of r-modes was also studied thoroughly [36, 37]. All these works obtained a credible conclusion that the maximal saturation amplitude of r-modes may not be larger than the small value of \( 10^{-3} \).

During the saturation state, Eqs. (5) and (6) would be replaced by
\[ \frac{d\Omega}{dt} = \frac{\Omega}{\tau_m 1 - \kappa Q} - \frac{2\Omega}{\tau_g (1 - \kappa Q)}, \] (7)
and
\[ \frac{d\alpha}{dt} = 0, \] (8)
respectively, where \( \kappa = \alpha_{\text{sat}}^2 \). As a rough estimation, the upper limit of the r-mode energy can be connected to the stellar rotational energy by \( E_{\text{max}} \approx \kappa Q E_{\text{rot}} \).

In Fig. 1 we plot the spin-down behaviors of both NSSs and CSSs. By considering that only a small fraction of quarks in the 2SC phase are paired, the evolution behavior of a 2SS is qualitatively similar to a NSS (see [22]). So in this paper the case of 2SSs will not be discussed specifically. As previously found in [25], the spin velocity of SSs at the very first time would decrease exponentially due to the exponential increase of the r-modes. After the r-modes enter into the saturation state with a constant amplitude, the spin evolution dominated by the GR braking can be determined by \( \Omega \approx -\Omega/\tau_g \approx -\Omega^7 \), which gives \( \Omega \approx r^{-1/6} \). This analytical estimation could be pretty valid for CSSs, which is similar to the case of neutron stars [23, 24], but not so good for NSSs for \( t > 100 \) yrs due to a self-decrease of the saturation amplitude (Instead, \( \Omega \propto r^{-1/14} \) approximately). After some time, the braking due to MDR would become comparable to and eventually exceed the GR braking, which leads to \( \Omega \propto r^{-1/2} \). In Fig. 1 two values of the saturation of \( \kappa = 10^{-6} \) and \( 10^{-8} \) are considered for a comparison. Obviously, by pushing the saturation to smaller values, the influence of the r-modes becomes weaker. Then, the spin evolution returns to the traditional one due to only MDR and all issues discussed in this paper return to the case considered in [22]. So in the following calculations we only took the value \( \kappa = 10^{-6} \) into account. The other model parameters are taken as follows. The initial values of the r-mode amplitude, angular velocity, and interior temperature are \( \alpha_0 = 10^{-10}, \Omega_0 = \frac{2}{5} \sqrt{G\rho}, \) and \( T_0 = 10^{10} \) K, respectively. The parameters for SSs are \( M = 1.4M_\odot \), and \( R = 10 \) km, and for the SQM are \( \alpha_c = 0.2, \Delta = 100 \) MeV, \( m_e = 100 \) MeV, \( q_0 \sim 20 \) MeV, and \( Y_e \sim 10^{-5} \).
FIG. 2: The temporal dependences of the powers of the DC (solid) and RM (dashed) heatings for NSSs (left panel) and CSSs (right panel). The magnetic fields are the same as in Fig. 1.

FIG. 3: The evolutions of the surface temperature of NSSs (left panel) and CSSs (right panel) with both DC and RM heating effects. The magnetic fields are the same as in Fig. 1. The light grey bands present the case without heating.

IV. RESULTS

The temporal dependences of the heating powers are numerically calculated and presented in Fig. 2. As shown, the RM heating could play a dominate role in the thermal evolution of SSs during their middle ages, i.e., from $\sim 100$ yrs to $\sim 10^{10}$ yrs. By contrast, the DC heating exceeds the RM heating for $t \lesssim 100$ yrs or $t \gtrsim 10^{10}$ yrs. The stronger the dipole magnetic field, the weaker the RM heating. For NSSs with $B = 10^{12}$ G, the RM heating becomes always subordinate to the DC heating. On one hand, following the analytical spin-down history of CSSs, the temporal evolution of the DC heating can be approximated to $H_{\text{DC}} \propto \Omega \dot{\Omega} \propto t^{2/3}$ in the GR braking stage and $H_{\text{DC}} \propto \Omega \dot{\Omega} \propto t^{-2}$ in the MDR braking stage, while for the RM heating $H_{\text{RM}} \propto \Omega^2/\tau_{\text{sf}} \propto t^{-5/12}T^{-1}$ and $\propto t^{-5/4}T^{-1}$ in the GR and MDR braking stages, respectively. On the other hand, for NSSs, we can get $H_{\text{DC}} \propto t^{-8/7}$ and following $H_{\text{DC}} \propto t^{-2}$, while $H_{\text{RM}} \propto \Omega^2/\tau_{\text{sf}} \propto t^{1/3}T^{-5/3}$.

The RM heating is eventually switched off due to the end of the r-mode instability. As a result, we plot the thermal evolution curves of both NSSs and CSSs in Fig. 3 where the standard cooling of SSs without heating is shown by the light grey bands. As seen, the change in the thermal history of SSs arising from heating effects could be remarkable, as previously claimed by [22].

For CSSs, as analyzed by Yu and Zheng [22], the main thermal evolution can be directly determined by the equilibrium equation $L_e = H$, since both $L_e$ and $C$ vanish due to the color superconductivity. Therefore, their thermal history during the equilibrium can be divided into RM and DC heating stages. In the first stage, $T^2 \propto t^{-5/12}T^{-1}$ (GR braking) and $T^2 \propto t^{-5/4}T^{-1}$ (MDR braking) gives $T \propto t^{-5/36}$ and $T \propto t^{-5/12}$, respectively. The realistic one could fall between these two extremes. In the second stage, the DC heating and MDR braking gives $T \propto t^{-1/2}$. Here, the most interesting thing could be the sharp transition between these two stages. As clearly shown in the
FIG. 4: The evolution of NSSs (left panel) and CSSs (right panel) for $\sigma_{\rm cut} = 10^{-3}$. The shaded areas are r-mode unstable regions. The labels for the open cycles represent the value of log($t$/yrs). The magnetic fields are the same as in Fig. 1.

right panel of Fig. 3 an extremely steep decay of the stellar temperature appears in the thermal evolution curves of CSSs at the age of $\sim 10^{-6}$ yrs. The range of the temperature during this transition is $\sim 3 \times 10^5$ K–$3 \times 10^6$ K. Such a time and temperature region in the $T - t$ panel is just consistent with the most observational data [38]. On the other hand, such a steep decay indicates that the stellar temperature can be found to decrease, most rapidly, by about seven percent in ten years, as shown in the insert in the right panel of Fig. 3. Another interesting feature in the thermal evolution curves of CSSs is the big bump appearing during the first hundred years, where the equilibrium between the heating and cooling effects has not been built ($H_{\rm DC} \gg L_{\nu}$). Because of the appearance of the r-modes, the deconfinement transition of the stellar crust can take place much earlier and more quickly than the case with only MDR braking, which means that most binding energy of the crust could be released within the first hundred years. Therefore, the bumps obtained here are nearly independent of the strength of the magnetic fields, whereas in [22] such a bump only exists in the high magnetic field case. It should be pointed out that, due to the thermal relaxation of the stellar crust which is not considered in our calculations, the variation of the interior temperature of SSs at early ages actually cannot be immediately reflected by the surface emission. However, because the crust of SSs is only tiny, which is just the outer part of the crust of traditional neutron stars, the relaxation time scale of SSs could only be on the order of several years (e.g., see Figs. 2 and 3 in [16]). Therefore, an infant CSS at the age of several tens to a hundred years is still expected to have a high temperature of $\sim 10^7$ K (emitting at $\sim 1$ keV).

For NSSs, their thermal histories are not very different from the standard one, except for very late ages. In principle, the histories of NSSs could be divided into four stages, which are determined by $CT = H - L_{\nu}$, $CT = L_{\nu}$, $CT = L_{\gamma}$, and $CT = H_{\rm DC}$ (MDR braking), respectively. Of course, for a specific NSS with a fixed magnetic field, there may only be two or three stages. In the first stage, the heating powers and the neutrino luminosity could be comparable to each other, so an analytical calculation is infeasible. For the following three stages, we can easily get $T \propto t^{-1/4}$, $T \propto \exp(-t)$, and $T \propto t^{1/2}$, respectively, for $C \propto T$ and $L_{\nu} \propto T^6$ (QDU). Different from CSSs, it is not easy to produce an early temperature bump by NSSs because of their very intense neutrino emission during the first hundred years.

Finally, for an integrated impression of the thermospin evolution of SSs, we plot the evolution curves of SSs in the $T - \nu$ panel in Fig. 4, where the r-mode instability windows are also presented. Some qualitative descriptions for such figures are provided in [22]. Here we emphasize that (i) for NSSs, after their birth at the region with high $\nu$ and $T$ where the r-mode is stable, their thermospin evolution is basically determined by the boundary of the r-mode instability window and that (ii) for CSSs, they can stay at the bottom of the r-mode instability window for tens of thousands of years.

V. SUMMARY AND DISCUSSIONS

The SS hypothesis and the specific state of the SQM in SSs are some of the most fascinating mysteries in both physics and astronomy. In this paper, we investigated the thermal evolution of SSs by considering both the deconfinement transition of the stellar crust and the r-mode instability of the fluid core. The results show the following: (i) The cooling of NSSs with heating effects is only somewhat different from the well-known standard one. Therefore, there seems still no significant discrepancy between the NSS model and the temperature observations of pulsars. (ii) For CSSs, there are two interesting features found in their thermal histories. One is the big temperature bump during the first hundred years and the other is the steep decay of the temperature at the ages of $\sim 10^4$–$10^6$
The serious problem of the CSS model is that, to our knowledge, neither the early bump nor the steep decay (∼7% in ten years) has been reported from observations, though they should be easily detected if they indeed exist. Let us recall the constraint on the CSS model given by Madsen [8], who claimed that the CSS model is not permitted by the most rapid pulsars because these pulsars locate deep at the r-mode instability window of CSSs. Therefore, we conclude that both the rotational and thermal tests on the SS models, which are independent of each other, suggest that the CSS model is disfavored by both the rotation and temperature observations of compact stars. As an alternative consideration discussed in [8], the following two possibilities are worthy of attention: (i) The CFL phase is not reached at densities relevant in pulsars, but the SQM could still be stable because the NSS model is not ruled out. (ii) The CFL phase appears in a hybrid star, in which only the stellar core consists of quark matter. Similar to the traditional neutron stars, hybrid stars could pass the tests by both the spin and temperature observations of pulsars.

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