Thermal evolution of rotating strange star in color superconductivity phase

Zheng Xiaoping* Zhou Xia, Yu Yunwei
The Institute of Astrophysics, Huazhong Normal University, Wuhan 430079, China.

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ABSTRACT

Under the combination effect of the recommencement heating due to spin-down of strange stars and the heat perseveration due to weak conduct heat of the crust, the Cooper pair breaking and formation (PBF) in color superconductivity quark matter arises. We investigated the cooling of the strange stars with a crust in color superconductivity phase including both deconfinement heating and PBF process. We find that deconfinement heating can delay the thermal evolution of strange stars and the PBF process suppresses the early temperature rise of the stars. The cooling strange stars behave within the brightness constraint of young compact objects when the color superconductivity gap is small enough.

Key words: stars: neutron–stars: evolution – dense matter– pulsars: general

1 INTRODUCTION

In 1990’s, a breakthrough came with ROSAT for measuring thermal radiation directly from the surface of pulsars. ROSAT offered the first confirmed detections for such surface thermal radiation from at least three pulsars. Recently radio pulsars and isolated neutron stars (NSs) have been extensively with the new powerful x-ray observatories Chandra and XMM-Newton. The pulsars of possible measuring surface temperature have considerable numbers (Trimper, 2005; Tsuruta, 2006) At the same time, more careful and detailed theoretical investigation of various input microphysics has been in progress. Understanding the data and constraining the composition of NS interior matter are hoped. Standard, enhanced and minimal scenarios are usually proposed as cooling NS theories. These models emphatically show stellar mass dependence of cooling NS behaviors. However, large theoretical uncertainties in the supernuclear density regime may be in trouble. Strange quark matter stars (strange stars, SSs) may exist in accordance with high density physics. Phenomenological and microscopic studies have confirmed that quark matter at a sufficiently high density, as in compact stars, undergoes a phase transition into a color superconducting state, which are typical cases of the 2-flavor color superconductivity (2SC) and color-flavor locked (CFL) phases (Shovkovy, 2004; Alford, 2004). Theoretical approaches also concur that the superconducting order parameter, which determines the gap \( \Delta \) in the quark spectrum, lies between 1 and 100 MeV for baryon densities existing in the interiors of compact stars. Of course, a color superconducting phase could occurs in SSs, and its effect on the cooling of the stars is a significant issue. Blaschke, Klähn & Voskresensky (2000) show that the stars in CFL phase (CSS hereafter) cool down too rapidly, which disagrees with the data. In those calculations an important factor, as described below, is ignored.

An SS, both in normal phase and in color superconducting phase, can sustain a tiny nuclear crust with a maximum density below neutron drip \( (\sim 10^{11}\text{g cm}^{-3}) \) and mass typically \( M_c \leq 10^{-5}\text{M}_\odot \) due to the existence of a strong electric field on the quark surface (Alcock, Farhi & Olinto, 1986; Usov, 2004; Zheng & Yu, 2006). The spin-down of the star makes the matter at the bottom of the crust compress. As soon as the density exceeds neutron drip, the surplus matter in the crust falls into the quark core in the form of neutrons. Consequently, the engulfed neutrons dissolve into quarks, and the released energy during this process leads to a so-called deconfinement heating (DH) (Yuan & Zhang, 1999; Yu & Zheng, 2006).

DH extremely changes the cooling behavior of CSSs. It delays the cooling of the stars especially for CSSs so the CSSs could be observed until \( 10^5 \sim 10^7 \) year old, not ruled out by the x-ray data. For CSSs with crust, however, a hundreds-of-years rise of temperature (Yu & Zheng, 2006) may be a matter of debate after the birth of the stars in the absence of data for support. As known, the temperature gradient from surface to core in compact stars could be or even more than two orders of magnitude. Weak conducting crust makes the deconfinement heat settle inside quark matter core. Thus the core temperature may reach \( 10^{10} \sim 10^{11}\text{K} \), just be in the vicinity of paring of quarks. The superconducting pair breaking and formation (PBF) is important. The initial estimates in Ref (Yu & Zheng, 2006)

* Email: zhxp@phy.ccnu.edu.cn
did not take properly into account the neutrino emissivity from this processes.

As present in (Schaab, Voskresensky, Sedrakian, Weber, & Weigell, 1997, Prashanth & Madappa, 2001), in superfluid neutron stars, the superfluid PBF processes accelerate mildly both the standard and the nonstandard cooling scenario. Former works mentioned that just below the critical temperature $T_c$, the neutrino pair emissivity from the PBF processes of superconduction neutron pairs greatly exceeds that from the so-called modified Urca processes in neutron star interiors (Yakovlev, Kaminker, & Levenfish, 1999; Gusakov, Kaminker, Yakovlev, & Gnedin, 2004). Similarly, in CSSs, the PBF process also dominates the cooling when $T$ falls below $T_c$. But, differing from superfluid neutron stars, the dominating PBF process occurs at the earliest ages due to much large the paring gap in quark matter than normal nuclear matter. The PBF process may cancel out the early temperature rise of CSSs. The purpose of this paper is to investigate this possibility.

The star is cooler and PBF process is suppressed if a CSS is bare. Inversely, a wrapped CSS with nuclear crust has a hot core. The temperature could be in the vicinity of pairing temperature. Our analysis shows the PBF process can’t change the cooling behavior of bare CSSs but probably improves the early cooling curves of CSSs and significantly suppresses the stellar temperature for given parameters.

The rest of our paper is arranged as follows: We recall neutrino emissivity and specific heat in color superconductivity, and DH mechanism in Sect.2 and 3 respectively. The cooling curves and the corresponding explanations are presented in Sect.4. Section 5 contains our conclusion and discussions.

\section{Neutrino Emissivities and Specific Heat in Color Superconductivity Phase}

The most efficient cooling process in unpaired quark matter is the quark direct Urca(QDU) process $d \rightarrow u \bar{e} \overline{\nu}$ and $u \rightarrow d \bar{e} \overline{\nu}$, given by Iwamoto(1982)

$$\epsilon^{(D)} \approx 8.8 \times 10^{-26} \epsilon_c \frac{\rho_b}{\rho_0} T_c^{1.1} \text{erg cm}^{-3} \text{sec}^{-1}.$$ (1)

where $\epsilon_c$ is the strong coupling constant, $\rho_0$ is the baryon density and $\rho_b = 0.17 m^{-3}$ is the nuclear saturation density, $Y_e = \epsilon_c / \rho_0$ is the electron fraction and $T_c$ is the temperature in units of 10$^9$K. When the QDU process being switched off due to a small electron fraction, the dominating contribution to the emissivities is the quark modified Urca(QMU) $dq \rightarrow u \nu \bar{e} \overline{\nu}$ and quark bremsstrahlung(QB) processes, estimated as $\epsilon^{(M)}$

$$\epsilon^{(M)} \approx 2.83 \times 10^{-12} \epsilon_c^2 \frac{\rho_b}{\rho_0} T_c^8 \text{erg cm}^{-3} \text{sec}^{-1},$$ (2)

$$\epsilon^{(QB)} \approx 2.98 \times 10^{-19} \frac{\rho_b}{\rho_0} T_c^8 \text{erg cm}^{-3} \text{sec}^{-1}.$$ (3)

Because of the pairing in CFL color superconducting phase, the emissivity of QDU process is suppressed by a factor of $\exp(-\Delta / T)$ and the emissivity of QMU and QB processes are suppressed by a factor $\exp(-2\Delta / T)$ for $T < T_c$. So, in our calculation below, we use the equation (1) with a factor of $\exp(\Delta / T)$ and equation (2) and equation (3) with a factor of $\exp(-2\Delta / T)$.

As $T$ falls below $T_c$, the PBF process dominates the cooling in quark matter. The neutrino emissivity from the PBF process in quark matter can be expressed as (Prashanth & Madappa, 2001)

$$\epsilon^{(PBF)}_0 \approx 1.4 \times 10^{20} N_e F_{\nu_\alpha} \frac{\rho_b}{\rho_0} (\frac{\rho_b}{\rho_0})^2 \frac{1}{3} T_c^7 \text{erg cm}^{-3} \text{sec}^{-1}. \quad (4)$$

$$\epsilon^{(PBF)}_m = \epsilon^{(PBF)}_0 \left[1 - \frac{m^2}{4p_F^2} + \frac{1}{2} \frac{c_A}{c_e} \left(2 + \frac{m^2}{12p_F^2}\right) \right] \quad (5)$$

where $N_\nu$ is the number of neutrino flavor, $\theta_\alpha = \frac{c^2}{\rho_0} \left[1 + \frac{1}{2} \left(\frac{c_A}{c_e}\right)^2\right]$, where $c_e$ and $c_A$ are flavor dependent vector and axial-vector coupling constants respectively and we use the date in table 1 of Prashanth & Madappa(2001). The correction factor, $F = \frac{f(y)}{y^2} \int_0^\infty dx \left(\frac{y}{\sqrt{x^2 - y^2}} \frac{1}{x + 1}\right)^2$.

In order to compute the cooling curves of the stars, we need to give the specific heat of the electrons and quarks (Iwamoto, 1982):

$$c_e \approx 2.5 \times 10^{20} \frac{\rho_b}{\rho_0} \frac{1}{3} T_c^7 \text{erg cm}^{-3} \text{K}^{-1} \quad (6)$$

$$c_q \approx 0.6 \times 10^{20} \frac{\rho_b}{\rho_0} \frac{1}{3} T_c^7 \text{erg cm}^{-3} \text{K}^{-1} \quad (7)$$

But in color superconductivity phase, the quark specific heat is changed exponentially (Blaschke, Klähn & Voskresensky, 2000)

$$c_q = 3.2 c_q(T_c) \left[2.5 - 1.7 \left(\frac{T_c}{T}\right) + 3.6 \left(\frac{T_c}{T}\right)^2 \right] \exp\left(-\frac{\Delta}{k_B T}\right) \quad (8)$$

where $T_c$ is related to $\Delta$ as $\Delta = 1.76 T_c$. The quarks contribution to the specific heat is suppressed by color-superconduction while the temperature decreases, the specific heat becomes dominated by the electrons. Compare with the total mass of the stars, the mass of the crust is very small ($M_c \ll 10^{-5} M_\odot$). So we can neglect the curstral contribution to neutrino emissivity and specific heat (Lattimer, Van Riper, Prakash & Prakash, 1994).

\section{Deconfinement Heating in Strange Stars with Crust}

The Deconfinement heating is affected by the surplus number of neutrons in the crust falling into the quark core with a strongly exothermic process and the mass of the crust is changed. The total heat released per unit time as a function of $T$ is:

$$H_{dec}(t) = -\frac{1}{m_b} \frac{dM_c}{dt} \nu,$$ (9)

where $q_n$, the heat release per absorbed neutron, is expected to be in the range $q_n \sim 10 - 40 \text{MeV}$ its specific value depending on the assumed SQM model, and $m_b$ is the mass of baryon. Assuming the spin-down is induced by the magnetic dipole radiation, the evolution of the rotation frequency $\nu$ is given by (Yu & Zheng, 2006)

$$\nu = -\frac{8\pi^2}{3 I c^2} I^2 \nu^3 \sin^2 \theta,$$ (10)

where $I$ is the stellar moment of inertia, $\mu = \frac{2}{3} B R^3$ is the magnetic dipole moment and $\theta$ is the inclination angle between magnetic and rotational axes. The mass of the crust
$M_c$ can be approximated by a quadratic function of rotation frequency $\nu$. As discussed in (Zdunik, 2001; Yu & Zheng, 2006), the mass of the crust reads

$$M_c = M_c^0 (1 + 0.24 \nu^2 + 0.16 \nu^4)$$ (11)

where $\nu = \nu/10^3$Hz and $M_c^0 \leq 10^{-5}M_\odot$ is the mass of the crust in the static case.

4 COOLING SIMULATIONS AND DISCUSSIONS

Considering the energy equation of the star, the cooling equation can be written as:

$$C_V \frac{dT}{dt} = -L_\nu - L_\gamma + H,$$ (12)

where $C_V$ is the total specific heat, the term $H$ indicates the heating energy per unit time, in our work $H = H_{dec}$. $L_\nu$ is the total neutrino luminosity and $L_\gamma$ is the surface photon luminosity given by

$$L_\gamma = 4\pi R^2 \sigma T_\gamma^4,$$ (13)

where $\sigma$ is the Stefan-Boltzmann constant and $T_\gamma$ is the surface temperature.

The thermal evolution of bare strange stars is investigated by (Blaschke, Klahn & Voskresensky, 2000). They showed that the bare strange stars are very cool objects. To simulate the cooling behavior of CSSs with a nuclear crust, we first would like to go into the PBF effect in particular. MDU and QB processes. The existence of the crust of the CSSs brings two effects: heat perseveration due to the crust as a cover and deconfinement heating due to the spin down of the stars. The deconfinement heating causes the CSSs to be very hot objects has been investigated (Yu & Zheng, 2006). The heat perseveration deposits a vast amount of the latent heat inside the stars, thus the temperature probably rises the level in the vicinity of paring quarks at early cooling stage of some CSSs. We can foresee that the combination effect will significantly change the cooling behavior of CSSs.

We now address the problem of cooling curves of CSSs with a crust. The surface temperature of the stars is related to internal temperature by a coefficient determined by the scattering processes occurring in the crust. We apply an formula which is demonstrated by (Gudmundsson, Pethick & Epstein 1983). It reads

$$T_s = 3.08 \times 10^6 g_{s,14}^{1/4} T_b^{0.5495},$$ (14)

where $g_{s,14}$ is the proper surface gravity of the star in units of $10^{14}$cm s$^{-2}$. In principle, magnetic fields may change the expression of Eq(14). However, Potekhin, Yakovlev and Prakash (2001) have present that the effect is negligible if the field strength is lower than $10^{13}$G. So Eq(14) is a good approximation for our case.

We consider a model of canonical strange star of $1.4M_\odot$ at a constant density in our work, which is a very good approximation for strange stars of mass $M \leq 1.4M_\odot$. We choose $q_{0} = 20$MeV, the initial temperature $T_0 = 10^9$K, initial period $P_0 = 0.78$ms, and the magnetic tilt angle $\theta = 45^\circ$. We also considered the gravitational red-shift and then the effective surface temperature detected by a distant observer is $T_s^\infty = T_s \sqrt{1 - R_s/R}$, where $R_s$ is the gravitational stellar radius.

We first plot the cooling curves in Fig.1 showing the cooling behaviors of strange stars with crust mass $10^{-5}$ and $10^{-4}M_\odot$ and gaps from 0.1Mev to 100Mev in various magnetic fields. The observation data are taken from (Page, Latimer, Prakash & Steiner, 2004), which are shown in order to give the reader to feel the position of the data in the logarithm $T_s^\infty - t$ plane. As displayed, the x-ray data can’t rule out the existence of CSSs for a wide range of parameters. It is quit different point from the suggestion in (Blaschke, Klahn & Voskresensky, 2000).

Figure 2 are depicted to illustrate the brightness constraint on models, suggested by (Grigorian, 2005). In our results, the curves for larger gaps (panels a and b) may show the slight contradiction with the fact that we don’t see any of very hot compact objects with field about $10^{11} \sim 10^{12}$G because the core temperature is still much lower than the gaps. For the gap of 1Mev (panel c), the PBF process significantly reduces the temperature rise at early periods. The cooling curves are improved at ages $10^{3} \sim 10^{4}$ years not to be contrary to the brightness constraint. For smaller gap (panel d), the QDU and QB processes as well as the PBF process become somewhat important and hence the cooling curves lies below the brightness constraint. In accordance with our results, we can see that the deconfinement heating delays the cooling of CSSs but the PBF effect partially cancel out the heating at early ages. The cooling curves later are governed by the equilibrium between photon and heating ($L_\gamma = H_{dec}$).

5 CONCLUSIONS

We have studied the cooling behaviors of rotating CSSs including the PBF process in the core of the stars and the deconfinement heating effect due to spin down of the stars. The deconfinement heating greatly delays the cooling of color conduction stars. The x-ray data, thus, don’t rule out the existence of color superconduction stars for a wide range of parameters. The PBF effect suppresses the temperature rise of the stars at early ages for the smaller gaps so that very hot compact stars, which we have never seen, would be avoided.

Considering poorly understanding properties of color superconductivity of strange quark matter, we use a simple parameterized model for color superconductivity to produce the cooling curves in a wide range of gap parameters ($0.1 \sim 100$Mev). Although we have been referring to CFL superconduction phase in this paper, our approach and result is generally suitable for other possible superconduction phase, such as spin-one color conductivity et al. The smaller gap curves are in favor of the brightness constraint suggestion, as such a favor is likely to constrain the existence of what phase in strange stars further.

Finally, we must point out that the stars may cool down too slow at old ages over $10^6$ years for the existence of not only photon emission but also the heating effect. The cooling curves should be reproved in future if the decrease of the magnetic moment for spin-down of the stars, both field decay and dipole alignment, is involving.
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REFERENCES
Alcock C., Farhi E. & Olinto A. 1986, ApJ, 310, 261.
Alford. M. 2004, J. Phys. G, 30, 441
Blaschke, D., & Klähn, T., & Voskresensky, D.N. 2000, ApJ, 533, 406.
Grigorian. H. 2005, [arXiv:astro-ph/0507052]
Gudmundsson, E. H., Pethick, C. J., & Epstein, R. I. 1983, Geophysica, 141, 1.
Iwamoto, N. 1982, Ann. Phys., 141, 1.
Lattimer, J.M., Van Riper, K. A., Prakash, M. & Prakash, M. 1994, ApJ, 425, 802.
Page, D., Lattimer, J. M., Prakash, M. & Steiner, A.W. 2004, ApJS, 155.
Potekhin, A. Y., Yakovlev, D. G., Prakash. 2001, A & A, 374, 213.
Prashanth, & Madappa, 2001, Phys.Lett. B, 516, 345.
Schaab, C., Voskresensky, C., Sedrakian, A.D., F. Weber, F. & Weigell, M.K., 1997, A&A, 321, 591.
Shovkovy, I. A. 2004, Lectures delivered at the IARD 2004 conference, Saas Fee, Switzerland, June 12-19, and at the Helmholtz International Summer School and Workshop on Hot points in Astrophysics and Cosmology, JINR, Dubna, Russia, Aug. 2-13, [arXiv:nucl-th/0410091]
S. L. Shapiro, S. A. Teukolsky, Black Holes, White Dwarfs, and Neutron Stars, The physics of Compact Objects (Wiley, New York, 1983).
Trümper J E, 2005, in ASI proceedings of The Electromagnetic Spectrum of Neutron Stars, Marmaris Turkey, Japan; in press in the proceedings of this symposium (OMEG05), November 8-11 2005, University of Tokyo, Tokyo, Japan; in press in the proceedings of this symposium, eds. Kubono, et al. (AIP), 2006, astro-ph/060213
Yu Yunwei & Zheng Xiaoping, acceptance for publication in A & A, [arXiv:astro-ph/0411023]
Yuan, Y. F. & Zhang, J. L. 1999, A&A, 344, 371.
Zdunik, J.L., Haensel, P. & Gourgoulhon, E. 2001, A&A, 372, 535.
Zheng, X. P. & Yu, Y. W. 2006, A&A, 445, 627.

Figure 1. Cooling curves for difference gap (panels: a 100MeV, b 10MeV, c 1MeV, d 0.1MeV). The magnetic fields $10^{11} G \sim 10^{13} G$. The solid curves is for the result of $M_{\odot} = 10^{-5} M_{\odot}$, the dot curves is for the result of $M_{\odot} = 10^{-6} M_{\odot}$ The dot-dashed curve is for the result in color superconductivity phase without deconfinement heating.

Figure 2. Cooling curves with PBF effect (dot curves) and without PBF effect (solid curves) and the brightness constraint (panels: a 100MeV, b 10MeV, c 1MeV, d 0.1MeV). The crust mass takes $M_{\odot} = 10^{-5} M_{\odot}$ The shaded region represents the brightness constraint (Grigorian, 2005).