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# Cooling of a rotating strange star with a crust

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**Abstract.** As a strange star spins down, the nuclear matter in its crust contracts continuously into the quark core. The confined nuclear matter is dissolved into quark matter, liberating a lot of thermal energy. This process is called deconfinement heating. It is found that deconfinement heating dramatically changes the thermal evolution of a strange star. For a strange star with a strong surface magnetic field ($\sim 10^{12}$ Gauss), the star heats instead of cooling during the first 10 years. Therefore, contrary to the previous studies, we conclude that there is evidence for strange quark matter, if a heating period is observed for a very young pulsar. For a strange star with a weaker magnetic field, the surface temperature is higher than that of a neutron star in the photon cooling era. This could also signal the existence of strange quark matter.

**Key words:** dense matter – elementary particles – stars: interiors – stars: neutron

## 1. Introduction

The strange quark matter - made up of roughly equal numbers of up,down and strange quarks - may be more stable than atomic nuclei (Witten 1984). If true, this would have implications of fundamental importance for cosmology, compact objects, and laboratory physics (cf. Madsen & Haensel 1991, Glendenning 1990). If Witten's idea is correct, strange quark stars (strange stars) may exist (Haensel et al. 1986, Alcock et al. 1986). Theoretical and observational researches on strange stars might provide a scientific basis to test what is the true ground state of the hadron.

Much efforts are devoted to find observational differences between strange stars and neutron stars. There are some possibilities for distinguishing between these two kinds of compact objects. First, their mass-radius relationships are quite different. The neutron star mass decreases with radius, while the strange star mass increases in the same range (Alcock et al. 1986, Glendenning et al. 1995a,b). Unfortunately, strange stars have similar radii as neutron stars for masses near 1.4 $M_{\odot}$. Second, the Kepler period $P_{\rm K}$ of a strange star falls in the range of $0.55 \leq P_{\rm K}({\rm ms}) \leq 0.8$ (Glendenning & Weber 1992, Glendenning et al. 1995b), while that of a neutron star can hardly be less than 1 ms. Furthermore, young strange stars are not subject to the rotational-mode instability which slows rapidly rotating, hot neutron stars to rotation periods near 10 ms via gravitational wave emission (Madsen 1998, and references therein). Third, it has been pointed out recently that a strange star has a vibratory mode with an oscillation frequency of approximately 250 GHz, due to motion of the center of the expected crust relative to the center of the strange quark core. Radiation from currents generated in the crust at the mode frequency would be a strange star signature (Broderick et al. 1998). Finally, another clue is based on their different thermal evolution behaviors. Strange stars might cool more rapidly than neutron stars through the quark direct Urca process. As a consequence, it is generally accepted that the surface temperature of a strange star should be lower than that of a neutron star of the same age (Alcock & Olinto 1988, Pizzochero 1991, Page 1992, Schaab et al. 1996). However, within the uncertainties of the parameters, the electron fraction $Y_{\rm e}$ could be small or even vanish entirely, so the quark modified Urca process or the quark bremsstrahlung process dominates, strange stars cooling slowly than neutron stars with standard cooling (Schaab et al. 1997a,b).

Strange stars may be produced from ordinary neutron stars (Olinto 1987, Horvath & Benvenuto 1988, Dai et al. 1993, Gentile et al. 1993, Dai et al. 1995). After their formation, they rotate rapidly, possibly at the Kepler frequency. As a strange star spins down due to magnetic dipole radiation, its core density increases, which leads to a chemical heating process. This effect is significant at later times for weak magnetic fields (Reisenegger 1995, Cheng & Dai 1996). On the other hand, the nuclear matter in its crust falls into the quark core continuously and converts eventually into quark matter. During this exothermic reaction, the quark core is heated. This heating mechanism is called deconfinement heating. Haensel and Zdunik (1991) applied this heating source to accreting strange stars with crust. Recently, a fireball model was successfully put forward for explaining the observations of the unusual hard X-ray burster GRO J 1744-28. In this model, the fireball is triggered by the deconfinement heating of the accreted mass of a strange star with a weak dipolar magnetic field ($\leq 10^{11}$ G) (Cheng et al. 1998). The deconfine-

*Send offprint requests to*: Y.F. Yuan, Center for Astrophysics, University of Science and Technology of China, Hefei 230026, P.R. China ment heating is considered to determine the thermal evolution of an isolated rotating strange star with a crust.

The possibility of deconfinement heating of an isolated strange star is considered in Sect. 2. The description of strange matter is presented in Sect. 3. the cooling curves of strange stars with deconfinement heating and their comparison with those with chemical heating are given in Sect. 4. The conclusion and discussions are summarized in Sect. 5.

## 2. Deconfinement heating

A strange star can be divided roughly into two distinct phases, the inner quark core and the solid nuclear crust. Between these two parts, there is a strong outward electric field ($\sim 10^{17}$ V cm$^{-1}$). It is sufficiently strong to stabilize the gap between the crust and the quark matter surface, preventing conversion of ordinary atomic matter into strange matter. Obviously, free neutrons, being neutral, do not feel the Coulomb barrier and cannot exist in the quark core. Consequently, as pointed out by Alcock et al. (1986), the density at the base of the nuclear crust is strictly limited by the neutron drip. Based on the above assumption and using the simplest form of the bag model equation of state for strange matter (bag constant $B^{1/4}$ =145 MeV), Glendenning and Weber (1992) calculated in general relativity the mass of the nuclear solid crust of a rotating strange star. The crust mass $M_{\rm c}$ is about $10^{-5}\ M_{\odot}$ for a typical non-rotating strange star with a total mass $M = 1.5\ M_{\odot}$. When the angular velocity of the crust $\Omega$ changes from the Kepler angular velocity, $\Omega_{\rm K}$, to zero, the mass of the crust $\Delta M_{\rm c}$ is reduced by about $1.8 \times 10^{-5}\ M_{\odot}$ (see Fig. 1). The Glendenning and Weber's result is fitted by the analytic expression

$$M_{\rm c}(\Omega) - M(0) \ = \ 10^{-5}{\rm M}_{\odot}\ [0.238 \left(\frac{\Omega}{\Omega_{\rm K}}\right) + 0.389 \left(\frac{\Omega}{\Omega_{\rm K}}\right)^2 + 1.15 \left(\frac{\Omega}{\Omega_{\rm K}}\right)^3 ]\ , \quad (1)$$

where $P_{\rm K} = 2\pi/\Omega_K$=0.78 ms (Glendenning et al. 1995b). The general relativistic value of $\Omega_{\rm K}$ is about 0.61–0.71 times that of the newtonian Kepler frequency (Weber & Glendenning 1992, Friedman et al. 1989, Haensel & Zdunik 1989).

In the following, we derive an almost similar result to Glendenning and Weber's in a simple and heuristic, but not strict way. For simplicity, we use newtonian dynamics and postulate that the crust is always in hydrostatic equilibrium and in uniform rotation. A change in the stellar rotation rate results in a change in the baryon density $n_{\rm drip}$ at the base of the crust which is approximately written as

$$\frac{\Delta n_{\rm drip}}{n_{\rm drip}} \approx -\frac{\Omega \Delta\Omega}{G\rho_{\rm c}}\ , \quad (2)$$

for $\Omega^2 \ll G\rho_{\rm c}$, where $\rho_{\rm c}$ is the central density of the strange stars, $G$ is the gravity constant and the symbol $\Delta$ denotes the Lagrangian variation (Reisenegger 1995). Because the density at the base stays at the neutron drip density $\rho_{\rm drip}$ ($\rho_{\rm drip} = 4.3 \times 10^{11}$ g cm$^{-3}$), all the nuclear matter in the crust whose density is between $\rho_{\rm drip} + \Delta\rho_{\rm drip}$ and $\rho_{\rm drip}$ falls into the quark core:

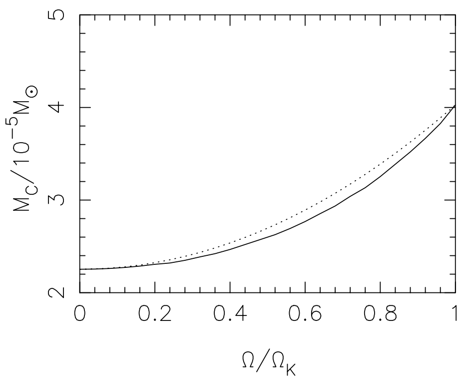


**Fig. 1.** Nuclear matter crust mass as a function of rotational frequency $\Omega$ (in units of the Kepler frequency) for $M$=1.5 $M_{\odot}$ strange star (solid line) (Glendenning & Weber 1992). The parabolical line according to Eq. 4 ($\Delta M_{\rm c} = 1.8\ 10^{-5}\ M_{\odot}$) is also plotted for comparison. The bag constant is $B^{1/4} = 145$ MeV

$$\Delta M_{\rm c} \approx \frac{3\gamma P_{\rm drip} R \Omega \Delta\Omega}{(G\rho_{\rm c})^2}\ , \quad (3)$$

where $\gamma = 4/3$ is the adiabatic index at the neutron drip, $P_{\rm drip} = 7.8 \times 10^{29}$ dynes cm$^{-2}$ is the pressure at the neutron drip (Baym et al. 1971) and $R$ is the radius of the star. We find that the relationship between $M_{\rm c}(\Omega)$ and $\Omega$ according to the Eq. (2) is written as

$$M_{\rm c}(\Omega) = M_{\rm c}(0) + \Delta M_{\rm c} \left(\frac{\Omega}{\Omega_{\rm K}}\right)^2\ , \quad (4)$$

where

$$\Delta M_{\rm c} \ = \ \frac{3\gamma P_{\rm drip}\Omega_{\rm K}^2 R}{2(G\rho_{\rm c})^2} = \ 2.4\ 10^{-5} M_{\odot} \left(\frac{R}{10^6\ {\rm cm}}\right)^{-2} \left(\frac{\rho_{\rm c}}{7.6\ 10^{14}\ {\rm g\ cm}^{-3}}\right)^{-2} \left(\frac{M}{1.5\ M_{\odot}}\right)\ . \quad (5)$$

The dotted line in Fig. 1 is the parabolical line according to Eq. 4 for comparison ($\Delta M_{\rm c} = 1.8\ 10^{-5}\ M_{\odot}$) (see Fig. 1). Our result is consistent with the result of Glendenning and Weber (1992) when extrapolated to $\Omega \to \Omega_{\rm K}$, therefore, it is a good approximation.

The surplus matter in the crust falls into the quark core in the form of neutrons which are absorbed by the quark bag in an exothermic reaction, i.e., $n \to u + 2d, d + u \to u + s$, with a heat release per absorbed neutron $q_{\rm n}$, which is treated as a free parameter (Haensel & Zdunik 1991). During this process, the energy produced per baryon in the core is given by,

$$\frac{dE}{dt} = -q_n \frac{1}{M} \frac{dM_{\rm c}}{d\Omega} \frac{d\Omega}{dt}\ . \quad (6)$$

When $\Omega/\Omega_{\rm K} \geq 0.1$, Eq. 1 is used to calculate $dM_{\rm c}/d\Omega$, otherwise, Eq. 4 is applied. We find that if only Eq. 4 is used, this does not affect the final results significantly.

## 3. Properties of strange matter

We use the MIT bag model to describe strange matter (Farhi & Jaffe 1984). In this model, the properties of strange matter are completely determined by three parameters: the bag constant $B$, the mass of the strange quark $m_{\rm s}$ and the coupling constant of the strong interaction $\alpha_{\rm c}$, respectively. Besides, there is still a non-physical parameter, the renormalization point $\rho_{\rm R}$. There are some electrons in the core to maintain the charge neutrality. The electron fraction depends on $m_{\rm s}$, $\alpha_{\rm c}$ and the baryon density in the core. Unfortunately, the electron fraction depends on the chosen renormalization point $\rho_{\rm R}$. There are two renormalization points which are frequently chosen. One is the renormalization on shell ($\rho_{\rm R} = m_{\rm s}$) (Duncan et al. 1983, Schaab et al. 1997a,b). The other is the renormalization $\rho_{\rm R} = M_{\rm N}/3 = 313$ MeV (Farhi & Jaffe 1984). The difference between these two choices is that $Y_{\rm e} = 0$ above a certain density in the first case. It is pointed out by Duncan et al. (1983) that the neutrino emissivity of strange matter depends strongly on its electron fraction. If $Y_{\rm e} = 0$, the quark direct and modified Urca processes are forbidden, and the quark bremsstrahlung neutrino pair emission dominates (Schaab et al. 1997a,b). Our calculations are carried out in both schemes.

## 4. Cooling curves of strange stars with deconfinement heating

In our calculations, we take $M = 1.5\ M_{\odot}$, $B^{1/4} = 145$ MeV, so the corresponding central density of strange stars is $\rho_{\rm c} \simeq 7.6\ 10^{14}$ g cm$^{-3}$. We assume that the spin decrease of the star is due to the magnetic dipole radiation and take as the initial period $P_{\rm i} = P_{\rm K} = 0.78\ ms$. The magnetic tilt angle is $45°$. With regard to the relationship between the interior temperature $T$ and the surface temperature $T_{\rm s}$, we use the isothermal core approximation which assumes that the internal temperature $T$ is constant within the stellar core with $\rho_{\rm c} \geq \rho_{\rm b} = 10^{10}$ g cm$^{-3}$ (Glen & Sutherland 1980). Hence, we apply the result of Gudmundsson et al. (1983), or a recent version, the result of Potekhin et al. (1997). Given the surface magnetic field strength $B_{\rm surf}$, $\alpha_{\rm c}$ and $m_{\rm s}$, the cooling curve of strange stars with deconfinement heating can be calculated.

The evolution of the surface temperature is shown in Fig. 2 for $B = 10^{12}$ G (curve a), $10^{11}$ G (curve b), $10^{10}$ G (curve c), $10^{9}$ G (curve d), $10^{8}$ G (curve e), and in the absence of deconfinement heating (solid line). In this figure, $\alpha_{\rm c}$ is taken to be 0.1, $m_s$ is taken to 200 MeV, $q_{\rm n}$ is taken to be 20 MeV and $\rho_{\rm R}$ is taken to be 313 MeV. With these parameters, the quark direct Urca process dominates. It is evident that the deconfinement heating increases the surface temperature dramatically. For strange stars with weak magnetic fields ($B_{\rm surf} \leq 10^{10}$ G), their surface temperatures are high, even at the photon cooling era.

Fig. 3 presents the results for $B_{\rm surf} = 10^{9}$ G, $\alpha_{\rm c} = 0.1$, $m_{\rm s} = 200$ MeV, $\rho_{\rm R}$=313 MeV, and $q_{\rm n} = 10$ MeV (dotted-dashed line), or $q_{\rm n} = 40$ MeV (dotted line), or without deconfinement heating but with chemical heating (dashed line) (Cheng & Dai 1996). One can see from this figure that chemical heating is unimportant comparing with deconfinement heating and there is a rather weak dependence of results on the value of $q_{\rm n}$ (Haensel & Zdunik 1991).

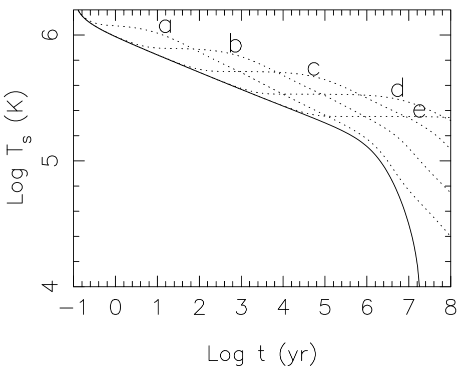


**Fig. 2.** Evolution of the surface temperature of strange stars with $\alpha_{\rm c} = 0.1$, $m_{\rm s} = 200$ MeV, $\rho_{\rm R}$=313 MeV, and $q_{\rm n} = 20$ MeV for $B_{\rm surf} = 10^{12}$ G (curve a),$10^{11}$ G (curve b),$10^{10}$ G (curve c), $10^{9}$ G (curve d),$10^{8}$ G (curve e), and no heating (solid line). The initial rotation frequency is taken to be $\Omega_{\rm K}$ and the initial magnetic tilt angle is taken to be $45°$

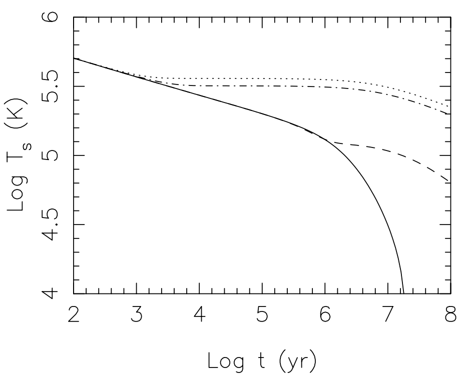


**Fig. 3.** Evolution of the surface temperature of strange stars with $\alpha_{\rm c} = 0.1$, $m_{\rm s} = 200$ MeV, $\rho_{\rm R}$=313 MeV for $B_{\rm surf} = 10^{9}$ G and $q_{\rm n} = 40$ MeV (dotted line) or $q_{\rm n} = 10$ MeV (dotted-dashed line) or without deconfinement heating but with chemical heating (dashed line)

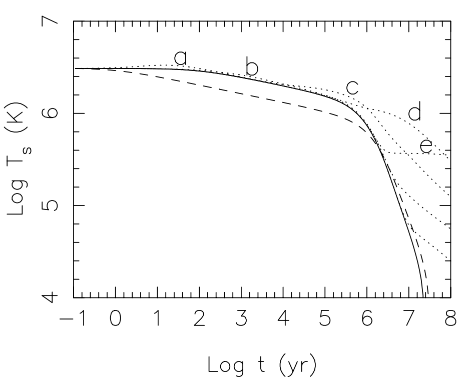


**Fig. 4.** Evolution of the surface temperature of strange stars with $\alpha_{\rm c} = 0.15$, $m_{\rm s} = 150$ MeV, $\rho_{\rm R} = m_{\rm s}$ and $q_{\rm n} = 20$ MeV for the same cases as in Fig. 1 and the cooling curve of standard neutron stars (dashed line)

In Fig. 4, we show the surface temperature evolution corresponding to Fig. 1 for $\alpha_{\rm c} = 0.15, m_s = 150$ MeV and $\rho_{\rm R} = m_{\rm s}$. $Y_e = 0$ in this case, so the quark bremsstrahlung process dom-

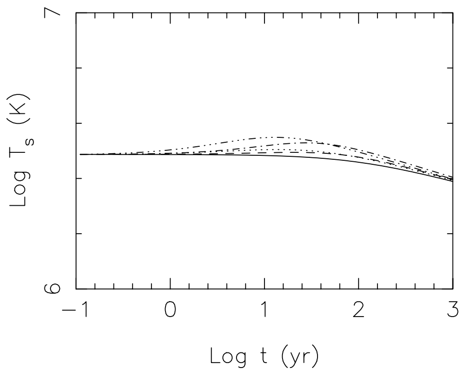


**Fig. 5.** Evolution of the surface temperature of strange stars with $\alpha_c = 0.15$, $m_s = 150$MeV, $\rho_R = m_s$, $B_{surf} = 10^{12}$ G for $\Omega = \Omega_K, q_n = 40$ MeV (dot-dashed line), $\Omega = \Omega_K, q_n = 10$ MeV (dashed line), $\Omega = \Omega_K/2, q_n = 40$ MeV (dot-dot-dot-dashed line), $\Omega = \Omega_K/2, q_n = 10$ MeV (dotted line), during an early time. The initial magnetic tilt angle is taken to be $45^0$

inates (Iwamoto 1982). As a comparison, the dashed line in this figure indicates the cooling curve of standard neutron stars through the modified Urca process. For strange stars with a weak magnetic field, their surface temperatures are still higher than these of neutron stars at the photon cooling era as Fig. 2 shows, because the neutrino processes are unimportant at this stage. One can see from Fig. 4 case(a) that there is a region of increase of $T_s$ during the first ten years. Similar results are also shown in Fig. 5 for different parameters. The reason is that the stronger the magnetic field is, the faster the rotational frequency slows down due to the magnetic dipole radiation, hence most of the nuclear matter in the crust falls into the quark core during an earlier and shorter time, which causes heating instead of cooling. Since the other heating mechanisms in neutron stars such as crust cracking heating (Cheng et al. 1992) or chemical heating (Reisenegger 1995) have their counterparts in strange stars, these differences might be unique. Furthermore, there are some mechanisms which result in fast cooling of the compact objects, such as the effect of the interior magnetic field on the modified Urca process (Yuan & Zhang 1998) or the influence of a hydrodynamic flow in the stellar core on the neutrino emissivity (Urpin & Shalybkov 1996). If they exist, the deconfinement heating is more important because it is not affected by these effects.

## 5. Conclusion and discussions

The deconfinement heating of a rotating strange star with a crust dramatically changes its thermal evolution. When this heating source becomes important depends on the strength of the magnetic field of the star. The stronger its surface magnetic field is, the earlier the additional heat is released. Because this kind of heating mechanism is unique to strange stars, it might signal the existence of strange quark matter. For strange stars with weak magnetic fields, their surface temperature are still higher than those of neutron stars at the later times. For instance, if the $T_s$ of an old pulsar ($t \sim 10^7$ yr) with $B = 10^8$ G is higher than $10^5$ K, or even more, it might be a strange star (see Fig. 4), especially when the effect of the interior magnetic field or the hydrodynamic motions in the stellar core is significant.

It has been pointed out in the previous discussions that thinner crusts of strange star would lead to temperature drops at even earlier times and thus to an earlier onset of the photon-cooling era. In this case a prompt drop of the pulsar temperature within the first 30 yr after its formation, could offer a good signature of a strange star (Pizzochero 1991, Schaab 1997a,b). However, in our opinion, for strange stars with the same strong magnetic field as most neutron stars have ($\sim 10^{12}$ G), there is a deconfinement heating period for the first 30 years (Case a in Fig. 3), which might protect the surface temperature from dropping at early time, or even cause its surface temperature to increase instead of decreasing. Therefore, if a heating period of a very young pulsar, such as that of SN 1987A, is observed, it signals the existence of strange star. This conclusion is completely contrary to the previous discussions. We will perform the relevant calculations in detail later by calculating the thermal transfer equation in general relativity.

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