Chromothermal oscillations and collapse of strange stars to black holes: astrophysical implications

Manjari Bagchi, 1,2,3★ Rachid Ouyed, 3 Jan Staff, 3,4 Subharthi Ray, 5 Mira Dey 2† and Jishnu Dey 2‡

1 Tata Institute of Fundamental Research, Homi Bhabha Road, Colaba, Mumbai 400 005, India
2 Department of Physics, Presidency College, 86/1, College Street, Kolkata 700 073, India
3 Department of Physics and Astronomy, University of Calgary, Canada AB T2N 1N4
4 Department of Physics, Purdue University, 525 Northwestern Avenue West Lafayette, IN 47907-2036, USA
5 Inter University Centre for Astronomy and Astrophysics, Ganeshkhind, Pune 411 007, India

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ABSTRACT

We study the effects of temperature on strange stars. It is found that the maximum mass of the star decreases with the increase of temperature, as at high temperatures the equations of state become softer. Moreover, if the temperature of a strange star increases, keeping its baryon number fixed, its gravitational mass increases and its radius decreases. This leads to a limiting temperature, where it turns into a black hole. These features are the result of a combined effect of the change of gluon mass and the quark distribution with temperature. We report on a new type of radial oscillation of strange stars, driven by what we call ‘chromothermal’ instability. We also discuss the relevance of our findings in the astrophysics of core collapse supernovae and gamma-ray bursts.

Key words: black hole physics – dense matter – equation of state – instabilities – stars: neutron – stars: oscillations.

1 INTRODUCTION

The concept of a strange star is not new. Itoh (1970) first proposed a model for this, even before the theory of quantum chromodynamics (QCD) had reached its current status. At the same time, Bodmer (1971) discussed an astrophysical object that had collapsed from its usual state formed by nucleonic matter. He argued that collapsed nuclei have radii much smaller than ordinary nuclei. Then, Witten (1984) suggested that the early Universe may have undergone a first-order phase transition from a high-temperature dense quark phase to a low-temperature dilute baryonic phase, with both phases being stable with local minima. The low-temperature phase grows and gradually occupies more than half of the volume. At this point, the high-temperature regions detach from each other into isolated bubbles. Then, further expansion of the Universe results in cooling at the low-temperature phase. These bubbles may survive today in the form of strange stars. He also conjectured that the true ground state of matter is ‘strange quark matter’ (SQM), not Fe56. SQM is a bulk quark matter phase, consisting of roughly equal numbers of up, down and strange quarks, plus a small number of electrons to guarantee charge neutrality. SQM would then have a lower energy per baryon than ordinary nuclei and it manifests in the form of strange stars. However, the strange star hypothesis is still not beyond skepticism. The maximum mass–radius obtained in strange star models is usually lower than that obtained from neutron star models. So, strange star models face difficulties in explaining high-mass stars such as PSR J0751+1807 (Nice et al. 2005) and EXO 0748−676 (Özel 2006), which have masses ~2.1 M⊙. Only a very few stiff neutron matter equations of state (EOSs) can explain the estimated mass–radius of EXO 0748−676 (Özel 2006). However, there are some observational features that are easier to explain with the strange star model rather than the neutron star model. For example, the harmonic absorption lines in the X-ray spectrum of compact stars such as 1E 1207.4−5209, J1210−5226, RX J1856.−3754, etc., can be explained as the consequences of compressional modes of surface vibrations of strange stars (Sinha et al. 2003). Strange stars can produce such oscillations as they have sharp surfaces and are self-bound with zero pressure at the surface, where energy per baryon (E/A) is minimum and the density is non-zero. Such harmonic compressional modes are not possible for a neutron star because of the lack of minimum in E/A. Another observed feature, the superburst, faces difficulties in using the standard carbon-burning scenario within neutron star models. Sinha et al. (2002) proposed an alternative scenario as the formation of diquark pairs on the strange star surface and their subsequent breaking, giving a continuous and prolonged emission of energy comparable with that emitted during superbursts.

Thus, we support the view that both strange stars and neutron stars exist in nature, and under suitable physical conditions a neutron star may convert to a strange star, leading to energy outburst (Bombaci, Parenti & Vidaa 2004; Staff, Ouyed & Bagchi 2007). However,
further study is needed to pinpoint the condition that will give rise to such a transition.

With this view, we feel it is intriguing to study the properties of strange stars by matching theoretical predictions (of mass, radius, etc.) with astronomical observations. One such property is the temperature dependence of the mass and the radius of a strange star as it cools (by neutrino or photon emission) or heats up (by accreting matter). In this paper, we study the effect of temperature on the SQM EOS. We show that an increase in temperature leads to a softening of the SQM EOS, giving rise to a decrease in the maximum mass of the strange star. When the temperature drops, the EOS stiffens again. We show that this leads to chromothermal instability, which has interesting implications in astrophysics.

There are several EOSs for SQM, such as the Bag model (Alcock, Farhi & Olinto 1986; Haensel, Zdunik & Schaeffer 1986; Kettner et al. 1995), the perturbative QCD model (Fraga, Pisarski & Schaffner-Bielich 2001), the chiral chromodielectric model (Malheiro, Fiolhais & Taurines 2003), etc. However, in all these models, the effect of finite temperature was not sufficiently studied. Such a study has been performed in the present work using the relativistic mean field model (Dey et al. 1998; Bagchi et al. 2006) for SQM. The other novelty in this model is that here chiral symmetry is restored at high densities as a result of the introduction of a density dependence of quark masses. The paper is organized as follows. Our strange star model is briefly discussed in Section 2. Section 3 is devoted to the study of strange star properties at finite temperatures including the chromothermal instability and the possible collapse of a strange star to a black hole. In Section 5, we discuss the relevance of our results in the astrophysics of core collapse supernovae and gamma-ray bursts (GRBs). We conclude in Section 6 with a suggestion on how these oscillations can be observed.

2 MEAN FIELD MODEL FOR STRANGE STARS

Strange stars are more compact than neutron stars and fit into the Bodmer–Witten hypothesis for the existence of SQM. In the relativistic Hartree–Fock calculation for the SQM EOS, Dey et al. (1998) used a phenomenological interquark interaction, namely the Richardson potential (Richardson 1979). This potential takes care of two features of the interquark force, namely asymptotic freedom (AF) and confinement with the same scale, which is not true from theoretical considerations.

Since then, strange star properties have been calculated with a modified Richardson potential, which has different scales for AF and confinement. The scale values were obtained from baryon magnetic moment calculations (Bagchi et al. 2004). In this model, chiral symmetry restoration at high density is incorporated by introducing density-dependent quark masses. A temperature dependence of gluon mass is considered, in addition to its usual density dependence. The gluon mass represents the medium effect, resulting in the screening of the interquark interaction. The temperature effect through the Fermi function is also incorporated. At non-zero temperature, free energy $F = E - TS$ is used instead of energy $E$ while calculating the EOS. It is also ensured that in SQM, the chemical potentials of the quarks satisfy $\beta$ equilibrium and charge neutrality conditions. The parameters of the model are adjusted in such a way that the minimum value of $E/A$ for $u,d,s$ quark matter is less than that of $Fe^{56}$, so that $u,d,s$ quark matter can constitute stable stars. The minimum value of $E/A$ is obtained at the star surface where the pressure is zero. However, the minimum value of $E/A$ for $u,d$ quark matter is greater than that of $Fe^{56}$, so $Fe^{56}$ remains the most stable element in the non-strange world. With the obtained EOS, Tolman–Oppenheimer–Volkov equations for hydrostatic equilibrium are solved to obtain the structures of the stars at different temperatures (Bagchi et al. 2006).

3 TEMPERATURE EFFECT ON STRANGE STAR PROPERTIES

The increase of temperature softens the SQM EOS (i.e. $p = p(\epsilon)$, where $p$ is the pressure and $\epsilon$ is the energy density; see Fig. 1a), resulting in a different curve in the mass–radius plane with a lower value of maximum mass (Fig. 1b). These figures also reveal the fact that if an EOS is stiffer than another at a given temperature, then it will remain stiffer even at a different temperature. Here we have used the stiffest (EOS A) and the softest (EOS F) EOSs in our model (Bagchi et al. 2006). The change in EOS is a result of the combined effect of the change of gluon mass and the quark distribution function (Fermi function) with temperature, which also changes the number densities ($n$) of the quarks. Both the energy density and number density increase with temperature. However, the increase in energy density is more dominant than that in number density (see Bagchi et al. 2006 for expressions of $\epsilon$ and $n$). So $E/A$ increases with rising temperature, resulting in an increase of the mass of the star for a fixed baryon number. We find a softening of the EOS at a higher temperature, in contrast to other models showing the opposite behaviour (Kettner et al. 1995). Moreover, all models consider the effect of temperature through Fermi function; however, in addition to this, our model incorporates the temperature dependence of the interquark interaction.

In our model, while establishing beta equilibrium conditions, we have assumed that neutrinos have escaped from the star. This is true in the low-temperature regime. However, at high temperatures (e.g. 50–80 MeV), some of the neutrinos will be trapped inside the

![Figure 1](https://example.com/figure1.png)

**Figure 1.** Temperature effect on SQM EOSs. Here we choose the stiffest (EOS A) and softest (EOS F) EOSs in our model. (a) Plot of pressure versus energy density (EOS). The upper two lines are the EOSs at 0 MeV (dashed-dotted line is EOS A and dotted line is EOS F) and the lower two lines are the EOSs at 50 MeV (dashed line is EOS A and solid line is EOS F). (b) Corresponding mass–radius curves (with the same line symbols).
Different EOSs will give different values for
\[ M_{\text{max}} \]
where \( M \) gives for any SQM EOS with an average value of \( 0.0054 \). As EOS A is the stiffest and EOS F is the softest in our model, we conclude that equation (1) can be used the maximum mass of strange stars with the increase of temperature.

Another interesting property (shown in Fig. 2a) is the decrease of the maximum mass of strange stars with the increase of temperature. This can be fitted as

\[ M_{\text{max},T}(M_{\odot}) = \frac{M_{\text{max},0}(M_{\odot})}{1 + a T_{\text{MeV}}}, \tag{1} \]

where \( M_{\text{max},T}(M_{\odot}) \) is the maximum mass (in units of solar mass), \( T_{\text{MeV}} \) is the temperature of the star in units of MeV, \( M_{\text{max},0}(M_{\odot}) \) is the maximum mass at a temperature of 0 MeV and \( a \) is a parameter. As an example, EOS F gives \( M_{\text{max},0}(M_{\odot}) = 1.4485 \) and \( a = 0.0047 \).

The fit quality is good, as depicted in Fig. 2(b), where the solid line represents the fit and the + signs indicate maximum masses at different temperatures.

The maximum mass point in a given mass–radius curve also corresponds to maximum baryon number. We find that the baryon number of a maximum mass star at a certain temperature is greater than that of a maximum mass star at higher temperatures (Table 1).

3.1 Chromothermal oscillations and collapse to a black hole

Now let us discuss the chromothermal instability. Initially, the strange star is at a low temperature (the reason for this is discussed in Section 4.1) around 0–10 MeV. At such a low temperature, all the neutrinos escape from the star. Then, if there is hyper-accretion on to such a low-temperature strange star, the star will be heated to 20–30 MeV. As this temperature is not too high, there will be no generation of neutrinos in copious amounts to affect the EOS. There will be emission of a gamma-ray fireball from the hot star, which will halt the accretion. During this period, the star cools. Then the process repeats. Here, we can take the baryon number of the star to be constant for a few accretion episodes as the SQM is much more dense than normal accreting matter.

Let us first consider the case where heating and cooling are not simultaneous (as mentioned above) but are equal in magnitude. In this case, as the star heats up during an accretion event, it will move from one mass–radius curve at a lower temperature to another at a higher temperature following an ‘iso-baryon’ line, in such a way that the mass of the star increases and the radius decreases. This is depicted in Fig. 3, which shows different probable paths or iso-baryon lines (dashed lines) corresponding to the different initial masses and temperatures of the star. Then, cooling starts and the star will move to a lower temperature mass–radius curve through the same iso-baryon line. Its mass will decrease and its radius will increase. Because the time-scales of these phenomena are set by quark interactions, the adjustment of the star’s mass and radius is to a first approximation of the same order as the signal crossing time of the star, or \( R/c_s \sim 0.04 \) ms, where \( c_s \) is the speed of sound in SQM (for an estimate of \( c_s \), see Sinha et al. 2004); that is, the changes in the star’s mass and radius are almost instantaneous. In the case of continuous accretion, these processes will repeat, making the star oscillate along an iso-baryon line between two mass–radius curves.

Table 1. Maximum mass strange stars at different temperatures for EOS F.

| Temperature (MeV) | \( M_{\text{max}} \) (M\(_{\odot}\)) | Radius (km) | Baryon number (10\(^{57}\)) |
|------------------|-------------------------------|-------------|-----------------------------|
| 0                | 1.44                          | 6.96        | 2.17                        |
| 10               | 1.38                          | 6.72        | 2.00                        |
| 20               | 1.32                          | 6.44        | 1.81                        |
| 30               | 1.27                          | 6.21        | 1.64                        |

Figure 2. (a) Strange star masses plotted against radii at different temperatures for EOS F. The straight inclined line on the left represents the Schwarzschild limit, so the objects located to the left of this line are black holes. For each horizontal dashed line, the right end corresponds to the strange star and the left end corresponds to the black hole that is formed by the collapse of that strange star. (b) A fit to the maximum mass of strange stars with temperature. Here the solid line represents the fit (equation 1) while the diamond symbols indicate the obtained values.

\( c_s \) is a parameter. As mentioned above, in such a way that the mass of the star increases and the radius decreases. This is depicted in Fig. 3, which shows different probable paths or iso-baryon lines (dashed lines) corresponding to the different initial masses and temperatures of the star. Then, cooling starts and the star will move to a lower temperature mass–radius curve through the same iso-baryon line. Its mass will decrease and its radius will increase. Because the time-scales of these phenomena are set by quark interactions, the adjustment of the star’s mass and radius is to a first approximation of the same order as the signal crossing time of the star, or \( R/c_s \sim 0.04 \) ms, where \( c_s \) is the speed of sound in SQM (for an estimate of \( c_s \), see Sinha et al. 2004); that is, the changes in the star’s mass and radius are almost instantaneous. In the case of continuous accretion, these processes will repeat, making the star oscillate along an iso-baryon line between two mass–radius curves.

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The nature of these oscillations is different from the well-known ‘radial oscillation’ arising as a result of perturbations in the hydrostatic equilibrium at a constant temperature (Chandrasekhar 1964). There are two fundamental differences between these oscillations and chromothermal oscillation. First, in the ‘Chandrasekhar’ oscillations, the mass of the star remains constant, and secondly the radial oscillations are very small in magnitude. In our case, both the mass and radius oscillate and up to 10 per cent change in radius and mass is possible.

For the purpose of illustration, let us take the softest EOS F; a stiffer EOS will give higher values of masses than quoted below. With this EOS, as an example let us consider a strange star with an initial mass of $1.0 \, M_\odot$ and an initial temperature of 10 MeV with total baryon number $N_{B,1.0,10} = 1.36677 \times 10^{57}$ (point i in Fig. 3). When it is heated to a temperature of 30 MeV, it will come to a point where the mass is 1.099 $M_\odot$ (point ii in Fig. 3), which has the same baryon number. During this phase, the star’s radius would have instantaneously decreased by ~4 per cent and the gravitational mass increased by ~10 per cent. Then cooling starts and the star returns to point (i). If accretion is still occurring, the process starts again, and continues until the baryon number increases significantly, at which point the star finds itself on another iso-baryon line. These large oscillations in radius and mass, we expect, could have unique observational signatures (see Section 6).

This oscillation will affect observational features in different ways; the gravitational redshift $z$ increases by 22 per cent when a star comes from point (i) to point (ii) of the above example. Moreover, the sudden changes in the star’s radius and mass may alter the properties of the star, such as its Schwarzschild radius and its innermost stable circular orbit (ISCO), in such a way that it might affect the accretion process and lead to disc instabilities, which may be observed by observing processes related to accretion.

We have also calculated the amount of energy needed for such oscillations to occur. During each half oscillation, the energy input to the star (during heating) or the energy emission from the star (during cooling) is equal to the change in its free energy ($\Delta F$). For the above example of oscillation between points (i) and (ii)

$$\Delta F = F_2 - F_1 = (E_2 - T_2S_2) - (E_1 - T_1S_1)$$

$$= (M_2 - M_1)c^2 + (T_1S_1 - T_2S_2)$$

$$= 0.03273 \times 10^{60} \text{MeV} = 0.02933 \, M_\odot c^2,$$

(2)

where $S_1$ and $S_2$ are the total entropies of the star at points (i) and (ii). The entropy density $s(r)$ is estimated during calculation of the EOSs (equation 8 of Bagchi et al. 2006). $s(r)$ is in units of fm$^{-3}$ and the unitless total entropy $S$ is obtained by integrating $s(r)$. We found $S_1 = 9.736 \times 10^{68}$ and $S_2 = 29.3711 \times 10^{68}$. The amount of accretion needed during heating is determined by $\eta M_{\text{accr}} = \Delta F$, where $\eta$ is the efficiency for the accreting matter to give energy to the star (as some of the energy from the accreting matter will be emitted in the form of X-rays, and so on). The exact value of $\eta$ is not known, but we assume that only a small portion of the energy of the accreting matter will dissipate. So, taking $\eta = 0.8$, we obtain $M_{\text{accr}} = 0.0366625 \, M_\odot$ needed to bring the star from point (i) to point (ii). During cooling (i.e. when the star comes from point ii to point i), $\Delta F = 0.03273 \times 10^{60} \text{MeV}$ energy will be emitted by the energetic photons. As $0.0366625 \, M_\odot$ normal matter contains 0.0366625 $\times 1.116 \times 10^{69}/939 = 0.04357 \times 10^{57}$ baryons, after two or three cycles, the star will start to oscillate along the next higher iso-baryon line. As the initial baryon number of the star was 1.36678 $\times 10^{57}$ and the maximum baryon number at 30 MeV is 1.64 $\times 10^{57}$, after $(1.64 - \Delta T)/1.64 = 0.04357 \sim 6$ oscillations the star will collapse to a black hole. This example is an extreme case. It is more probable that the accretion rate is lower and the star is oscillating for a long time between two close temperatures (e.g. 10 and 12 MeV). In this case, the change in mass and radius will be very small and difficult to detect. However, the effect of this breathing process is still possible to detect by observing other properties of the star, which are affected by these oscillations, such as gravitational redshift, disc properties, etc.

A more complex oscillatory behaviour will result in situations where heating and cooling rates (i.e. time-scales) are not equal.

The feedback mechanism between heating/cooling (the external drive) and the star’s response through chromothermal oscillations, and the consequences for the star properties and the underlying accretion process are currently being explored in more detail.

The collapse to a black hole occurs when the star reaches such a high temperature that the maximum baryon number at that temperature is less than the baryon number of the star. For example, if a strange star has an initial mass of $1.3 \, M_\odot$ at 0 MeV (with baryon number $N_{B,1.3,0} = 19.24 \times 10^{56}$), it will remain a strange star when heated to 10 MeV ($N_{B,1.3,10} = 20.00 \times 10^{56} > N_{B,1.3,0}$). However, it will collapse to a black hole before reaching 30 MeV (as $N_{B,1.3,30} = 16.40 \times 10^{56} < N_{B,1.3,0}$). The lower the initial mass of the strange star, the higher the temperature it can sustain.

Throughout this work, we have assumed that the stars are isothermal even at higher temperatures. Random motions of quarks at very high velocities (0.5–0.7) as quoted in Bagchi et al. (2007) will facilitate isothermal configurations. For theoretical interest, we discuss isentropic configurations in Section 4.

4 ISENTROPIC CONFIGURATIONS

Until now, we have considered strange stars to be isothermal. However, extensive study of neutron star evolution shows that a few seconds after its birth, a neutron star will come to an isentropic configuration (see fig. 2 of Burrows & Lattimer 1986). Although we have not performed such a study of strange star evolution, for the
value from 1.2 to 1.8 and keeping its total baryon number fixed at 1.318 × 10^{37}, its mass increases by 3.88 per cent and its radius decreases by 1.82 per cent. Similarly, when the star comes from point (iii), having mass 0.802 M⊙ and radius 6.036 km, to point (iv), having mass 0.854 M⊙ and radius 5.96 km, by changing the S/nB value from 1.2 to 1.8 and keeping its total baryon number fixed at 1.026 × 10^{37}, then its mass increases by 6.46 per cent and its radius decreases by 1.26 per cent. The change in free energy (see equation 2) is ΔF = 0.044 MeV = 0.0395 M⊙ c^{2} for a transition (i)–(ii), and it is ΔF = 0.0399 MeV = 0.0357 M⊙ c^{2} for a transition (iii)–(iv). These values are equal to the amount of accretion needed when the star is being heated and comes from a lower S/nB curve to a higher S/nB curve (i.e. transitions (i)–(ii) or (iii)–(iv)). Alternatively, these are the amounts of energy emitted by the stars during cooling (i.e. transition from a higher S/nB curve to a lower S/nB curve, such as transitions ii–i or iii–ii).

5 ASTROPHYSICAL IMPLICATIONS

5.1 Core collapse supernova

In a core collapse supernova, the possibility of the production of a neutron star, a strange star or a black hole is guessed. We model that first a neutron star is born during the supernova, which rapidly comes to a low temperature by neutrino cooling and then converts to a strange star (e.g. Staff, Ouyed & Jaikumar 2006). The intermediate neutron star stage may lead to a delay between a supernova and the subsequent strange star formation, which has interesting implications for the model of GRBs involving strange stars (Staff et al. 2007).

Here, we should remember that our SQM EOSs, which ignore neutrino effects, might not be appropriate at the very high temperature created by the supernova. However, as we are modelling that first a neutron star is born during the supernova and then it converts to a strange star at a low temperature, the simplification in the EOS does not affect the physics.

5.2 Gamma-ray bursts

The recent launch of the Swift satellite has revealed some new interesting features of GRB afterglows, which cannot be easily explained by current models. If a strange star forms inside a collapsar, then a new model involving a three-step process in the framework of the ‘Quark Nova’ scenario (Ouyed, Dey & Dey 2002; Keränen, Ouyed & Jaikumar 2005) is one possible way of explaining recent Swift data. In this model, the conversion of a neutron star to a strange star, followed later by the conversion of the strange star to a black hole (as suggested in this paper) is involved. Here, a GRB occurs as a result of the jet from the accreting strange star (Ouyed et al. 2005). Depending on the initial mass, temperature and the accretion rate, a strange star may collapse to a black hole, and the accretion on to the black hole gives rise to an ultrarelativistic jet causing the giant
flares observed in some GRB afterglows (see Staff et al. 2007 for details).

6 CONCLUSION

In this paper we have studied the effects of temperature on the SQM EOS. A novelty in our model is the increase of the softness of the EOS at high temperatures. This feature reveals the dependence of the maximum allowable mass on the temperature and the change of the star’s mass and radius with temperature. This suggests that the collapse of a strange star to a black hole is more intricate than previously thought. It might have interesting astrophysical applications, specifically in situations involving an accreting strange star with applications to GRBs.

We have also isolated a new type of radial oscillation, which we have called chromothermal. As the increase in mass is accompanied by a decrease in radius, and vice versa, the value of gravitational redshift \( z \) will also oscillate. This effect could, in principle, be detected through spectral or timing analysis techniques and should test our model.

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