Thermal relaxation and cooling of quark stars with a strangelet crust

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ABSTRACT

Context. In this article we explore the cooling of isolated quark stars. These objects are structured from a homogeneous quark matter core and crusted by ordinary matter or by strangelets.

Aims. Our main purpose is to quantify the effects of a strangelet crust on the cooling and relaxation times of these strange stars.

Methods. We adopt two kinds of crust: (i) a crust made of purely nuclear matter following the Baym-Pethick-Sutherland equation of state (EOS) and (ii) a crust made of nuggets of strange quark matter (strangelets). Both models have the same quark matter core, described by the MIT bag model EOS. Our study also includes the possible effects of color superconductivity in the quark core.

Results. We have found that objects with a strangelet crust have a significantly different thermal relaxation time.

Key words. equation of state – neutrinos – radiation mechanisms: thermal – stars: interiors

1. Introduction

According to the strange quark matter (SQM) hypothesis (Bodmer 1971; Terazawa 1979; Witten 1984), strange matter that contains roughly equal numbers of up, down, and strange quarks may be the true ground state of strongly interacting matter. If the SQM hypothesis is true, many neutron stars could in fact be strange stars, that is, large (kilometer-scale) compact stars made entirely of SQM (Baym & Chin 1976; Alcock et al. 1986; Weber 2005). In this work we assume the SQM hypothesis to be correct and consider compact stars that are made up of absolutely stable strange matter. Given the self-bound nature of SQM (Alcock & Olinto 1988), many authors (see for instance Weber 2005 and references therein) have considered the possibility of strangelets (droplets or nuggets of SQM). In particular, Farhi & Jaffe (1984) and Berger & Jaffe (1987) assumed that strangelets are uniformly charged (i.e., constant chemical potential within the quark matter strangelet) to calculate a mass formula from them. This approach, however, was later proved to be inconsistent as the electrostatic potential increases toward the strangelet’s center, thus causing quarks to migrate due to the resulting electric field. Improving on the work of Farhi & Jaffe (1984) and Berger & Jaffe (1987), Heiselberg et al. (1993) took the screening effect in strangelets into account and found a more accurate mass formula. They showed that the charge density is found to vary on a scale of the Debye screening length, $A_D \sim 5$ fm, for strangelets with mass number $A < 10^6$. As shown by Alford & Eby (2008), the Debye screening plays a major role in the internal energy of strangelets, as it shuffles the electric charge.

If the SQM hypothesis is true, strange stars would be a new class of astronomical compact objects. Several physical scenarios have been proposed and theoretically discussed as to such possibilities (Witten 1984; Baym & Chin 1976; Weber 2005; Haensel et al. 1986; Alcock et al. 1986). Relevant to the work we present here is the research of Alcock et al. (1986), who considered the possibility for a strange star to maintain a thin crust of normal matter. They pointed out that the crust was mainly influenced by two factors: (i) the tunnel effect through which ions might penetrate the core-crust gap and (ii) that the density at the base of the crust cannot be denser than the neutron drip ($\rho_{\text{drip}}$) since free neutrons would come out of nuclei and fall into the strange core (Alcock et al. 1986; Glendenning & Weber 1992; Glendenning et al. 1995; Huang & Lu 1997). The latter consideration was revised by Huang & Lu (1997), who found that the maximum density at the base of the crust is about $\rho_{\text{drip}}$, giving a mass of $\sim 3.4 \times 10^5 M_{\odot}$ for the crust, which is about one order of magnitude smaller than what had been found before. In the traditional picture, the surface of a bare strange star has a sharp edge of thickness $\sim 1$ fm (Alcock et al. 1986). Below the surface lies quark matter, the outermost layer of which should be positively charged due to the exhaustion of massive strange quarks; above the surface there is a cloud of electrons, which guarantees the star’s charge neutrality (Alcock et al. 1986; Stejner & Madsen 2005; Usov 1997).

It has been shown, however, that if the surface tension, $\sigma$, of the interface between quark matter and the vacuum is less than a critical value, $\sigma_{\text{crit}}$, then large lumps of strange matter become unstable against fission into smaller pieces (Jaikumar et al. 2006; Alford et al. 2006). As a result, the lower-density surface region is replaced by a “mixed phase” that involves nuggets (strangelets) of positively charged strange matter in a neutralizing background of electrons. Jaikumar et al. (2006), assuming zero surface tension and neglecting Debye screening, estimated that the mixed-phase crust might be $40-100$ m thick. Later, Alford & Eby (2008) found that if the surface tension of quark matter is low enough, the surface of a strange star will be a crust consisting of a crystal of charged strangelets in a neutralizing background of electrons. They calculated the thickness of the crust taking the effects of surface tension and the Debye effects of color superconductivity in the quark core.
screening of electric charges into account. Their results showed that the strangelet crust size can range from zero to hundreds of meters thick and that the thickness is greater when the strange quark is heavier and the surface tension is lower (Alford & Eby 2008). In this work we further explore the possibility of a strangelet crust on strange stars and the implications for the thermal evolution of such stars.

Since the proposal of strange stars, many efforts have been devoted to determining the observational properties (if any) that may be useful in distinguishing strange stars from neutron stars, as they share many similar observable macroscopic properties, such as gravitational mass. One such possibility is thermal evolution since quark stars (QSs) can exhibit cooling that is fairly distinct from that of ordinary neutron stars. The cooling of neutron stars is mainly dominated by neutrino emissions for the initial \( \sim 1000 \) years, later being replaced by surface photon emissions (Page et al. 2006; Tsuruta 1998). Due to the very different compositions and morphologies of neutron star cores, it is unlikely that they would strongly modify the thermal relaxation of QSs, which, to the extent of our knowledge, has never been studied in detail.

The remainder of this paper is organized as follows: in Sect. 2 we describe the microscopic model for crusted strange stars, and we present the results for the macroscopic structure of our models of QSs. In Sect. 3 we explore the thermal evolution of these stars and discuss their principal characteristics. Furthermore, we include superconductivity effects on QSs and compare the resulting thermal evolution with observations. Finally, our conclusions and perspectives are presented in Sect. 4.

2. Microscopic model

We adopted the structure of a QS that consists of two parts: the crust and the core of the star (obviously, we are not considering bare QSs, in which case they would not be crusted). The crust is characterized by a low-density regime. Thus, we contemplate two scenarios: (i) the (traditional) nuclear Baym-Pethick-Sutherland (BPS) equation of state (EOS; Baym et al. 1971; Glendenning & Weber 1992) – in which case the crust must necessarily have a maximum density limited by approximately the neutron drip density \( \rho_{\text{drip}} \) and (ii) a strangelet crust as described by Jaikumar et al. (2006), that is, if the surface tension of the interface between quark matter and the vacuum is less than a critical value, then large lumps of strange matter become unstable against fission into smaller pieces. As a result, the crust consists of a crystalline structure of charged spherical strangelets in a neutralizing background of electrons. On the other hand, for the star’s core we adopted a traditional MIT bag model EOS in which the parameters are set as \( m_s = 100 \text{ MeV}, \quad \rho_{\text{drip}} = 128.9 \text{ MeV} \text{fm}^{-3} \), and \( \alpha_s = 0.4 \) (the strong interaction coupling constant). We note that such a model was chosen for its simplicity. It is important to mention that more sophisticated quark models have been proposed, such as the Nambu-Jona-Lasinio (NJL) model (Nambu & Jona-Lasinio 1961a,b) and the Polyakov-loop-extended Nambu-Jona-Lasinio (PNJL) model (Fukushima 2003, 2004; Ratti et al. 2006, and references therein). It is also important to point out that there has been great improvement in the modeling of quark matter in compact objects, accomplished by modern perturbation calculations (see, for instance, the parametrized EOS described in Fraga et al. 2014). We remark, however, that such improved and more sophisticated models lead to qualitatively similar compositions; thus, it is unlikely that they would strongly modify the thermal evolution, which is the focus of our research.

Figure 1 shows the EOS of a QS with a nuclear (BPS) matter (labeled “BPS”) and strangelet crust (labeled “Strangelets”). The transition point between core and crust occurs at \( \epsilon_{\text{tr}} \sim 153.76 \text{ MeV fm}^{-3} \). With the EOSs in Fig. 1, we can solve the Tolman-Oppenheimer-Volkoff (TOV) equations (Tolman 1939; Oppenheimer & Volkoff 1939) and find the structure of the QSs. In Fig. 2 we show the sequences of QSs obtained from the EOSs. We note that, as expected, the only difference between the models studied is the description of the crust: both sequences have the same maximum mass, \( \sim 2.41 M_\odot \). Furthermore, due to the different crust modeling, we also see a significant difference between the stellar radius in each sequence. We summarize the macroscopic properties found for the two models in Table 1. The most notable distinction between them is that QSs with nuclear (BPS) matter crusts have larger radii as well as thicker crusts and higher masses, \( \Delta R_{\text{crust}} \sim 500 \text{ m} \) and \( \sim 10^{-4} M_\odot \), respectively. Quark stars with strangelet crusts, on the other hand, have smaller radii as well as thinner crusts and lower masses, \( \Delta R_{\text{crust}} \sim 20 \text{ m} \) and \( \sim 10^{-5} M_\odot \), respectively.
Table 1. Properties of some QSs from Fig. 2.

<table>
<thead>
<tr>
<th>( \epsilon_c ) (MeV/fm(^3))</th>
<th>( M ) (( M_\odot ))</th>
<th>( \bar{R} ) (km)</th>
<th>( R ) (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>237.24</td>
<td>1.42</td>
<td>12.78</td>
<td>13.27</td>
</tr>
<tr>
<td>257.49</td>
<td>1.60</td>
<td>13.19</td>
<td>13.62</td>
</tr>
<tr>
<td>288.59</td>
<td>1.82</td>
<td>13.55</td>
<td>13.93</td>
</tr>
<tr>
<td>327.36</td>
<td>2.00</td>
<td>13.77</td>
<td>14.11</td>
</tr>
</tbody>
</table>

**Notes.** We differentiate them with the labels “strangelet crusts” or “nuclear (BPS) crusts”. \( \epsilon_c \) is the central density.

Subsequently, in our study of these QSs, we considered the possibility of color superconductivity. The pattern considered is the color-flavor-locked (CFL) phase (Alford 2001), where all quarks of all colors are paired to form Cooper pairs. The CFL phase is the most likely condensation pattern at densities of \( >2\epsilon_0 \) (where \( \epsilon_0 \) is the nuclear matter density) (Alford et al. 2008). Intermediate-density (\( \sim 2\epsilon_0 \)) model calculations indicate that quark matter is in a two-flavor color superconducting (2SC) phase (Alford et al. 2008). Another possibility is that quark matter forms a crystalline superconductor, where the momenta of the quark pairs do not add to zero (Alford et al. 2001; Bowers & Rajagopal 2002). Given the densities of the quark cores in our model, we considered only the CFL phase. It should be noted that one expects corrections to the quark matter EOS when pairing is present; however, the effects of such corrections to the structure of the star are only noticeable for pairing gaps \( \Delta > 50 \) MeV, where \( \Delta \) is the gap parameter for the CFL phase (Alford & Reddy 2003). Therefore, for the values of \( \Delta \) considered here (0.1–10 MeV) they can be safely ignored.

Our study is still valid for any quark pairing scheme (though not necessarily color superconductivity) as long as it affects all quark flavors similarly (Negreiros & Dexheimer 2012). In the next section we analyze the thermal evolution of our two models of QSs from Table 1 and thereby determine the differences between them. Additionally, we consider the superfluidity possibility and the thermal relaxation analysis. At the end, our results are compared with the prominent thermal observations.

3. Cooling

In this section we study the thermal evolution of our two models. The cooling of a compact star is governed by the general relativistic thermal balance and transport equations given by (\( G = c = 1 \)) (Thorne 1977; Van Riper 1991; Weber 1999)

\[
\frac{\partial (\epsilon e^{\nu \theta})}{\partial m} = -\frac{1}{\epsilon \sqrt{1 - 2m/r}} \left( \epsilon \epsilon_c e^{\nu \theta} + \frac{\partial (T e^{\nu \theta})}{\partial t} \right),
\]

\[
\frac{\partial (T e^{\nu \theta})}{\partial m} = -\frac{(l e^{\nu \theta})}{16\pi^2\kappa \epsilon \sqrt{1 - 2m/r}}.
\]

where the macroscopic dependences are: the radial distance, \( r \), the energy density, \( \epsilon (r) \), and the stellar mass, \( m(r) \). Since the central star temperature at the beginning of its thermal life is not higher than \( 10^{11} \) K \(-1-10\) MeV, the effects of finite temperatures on the EOS can be neglected to a very good approximation. Consequently, the TOV equations do not depend on time and thus need to be solved only once, which is fortunate as the thermal and structural properties are then uncoupled. Moreover, the thermal properties are represented by the temperature, \( T (r, t) \), luminosity, \( l (r, t) \), neutrino emissivity, \( \epsilon (r, T) \), thermal conductivity, \( k (r, T) \), and specific heat, \( c_c (r, T) \). The boundary conditions of Eqs. (1) and (2) are determined by the luminosity at both the stellar center and the stellar surface. The luminosity vanishes at the stellar center, since at this point the heat flux is zero. At the surface, the luminosity is defined by the relationship between the mantle temperature and the temperature outside the star (Page et al. 2006; Blaschke et al. 2000). The microscopic input in Eqs. (1) and (2) are the neutrino emissivities, specific heat, and thermal conductivity. For the quark core, we considered the processes that involve quarks: the quark direct Urca (QDU), quark modified Urca (QMU), and quark bremsstrahlung (QBM) processes. If the electron fraction vanishes entirely in quark matter \( (Y_e = 0, \text{in the limit in which } m_s \to 0) \), both the QDU and QMU processes become unimportant, and the neutrino emission is thus dominated by QBM processes only. The emissivities of such processes were calculated in Iwamoto (1982). We used the specific heat for the quark phase as calculated in Iwamoto (1982), and the thermal conductivity comes from Haensel (1991). At the crust (both strangelet and nuclear), we considered all expected thermodynamic processes with thermal conductivity dominated by the electrons and specific heat connected to the \( A, Z \) of the nuclei (or strangelets). A description of the thermal processes taking place in the crust can be found in Kaminker et al. (1998), Yakovlev et al. (2001), and Potekhin et al. (1999).

To investigate the difference between a QS with nuclear (BPS) crust and those with strangelet crusts, we analyzed the cooling of QSs of the same mass for both. The thermal evolution of our models is illustrated in Fig. 3, where we show a typical cooling curve, that is, the redshifted surface temperature \( (T_s) \) as a function of the age \( (t) \) of the star. The results indicate that there is little difference between the cooling of stars with different gravitational masses within the same model, both for stars with nuclear (BPS) crusts and for stars with strangelet crusts. Additionally, for each model, as the star’s gravitational mass increases, the surface temperature becomes slightly lower. On the other hand, we can notice a significant difference when comparing the cooling behavior exhibited within each model. Most noticeably, QSs with strangelet crusts cool down significantly faster than QSs with nuclear (BPS) crusts. We think that this is due to the thinner nature of the strangelet crust.

3.1. Thermal relaxation

In order to quantify the faster cooling exhibited by QSs with strangelet crusts, we now discuss their thermal relaxation.

Fig. 3. Cooling of QSs with gravitational masses from Table 1. \( T_s \) denotes the redshifted temperature, and the x axis is the age, \( t \), in years. Solid lines (upper band) represent QSs with a nuclear (BPS) crust, and dashed lines (lower band) are stars with a strangelet crust.
As shown by Lattimer et al. (1994), the thermal relaxation timescale, \( t_{\text{rel}} \), is defined as the moment of the most negative slope of the cooling curve of a young neutron star. It is given in Gnedin et al. (2001) as

\[
\ln(T_s) = \ln(T_0) + \frac{\Delta R_{\text{cru}}}{|\ln(t)|},
\]

where \( T_0 \) is the temperature as measured by a distant observer, and the \( x \) axis is the age in years. Solid lines represent QSs with nuclear (BPS) crusts, and dashed lines are stars with strangelet crusts.

3.2. Superfluidity effects

As mentioned in Negreiros & Dexheimer (2012) and references therein, we expect the strange matter to be in a superconducting phase. The most likely condensation pattern for strange matter in the high-density cores of QSs is that of the CFL phase (Alford 2001), in which all quarks are paired. Because of pairing, the QDU process is suppressed by a factor of \( e^{-\Delta/T} \) and the QMU and QBM processes by a factor of \( e^{-2\Delta/T} \) for \( T \leq T_c \), where \( \Delta \) is the gap parameter for the CFL phase and \( T_c \) is the pairing critical temperature (Alford 2001; Alford et al. 2008). Moreover, the specific heat of quark matter is also modified by the factor \( 3.2(T_c/T)^2(2.5 - 1.7(T/T_c) + 3.6(T/T_c)^2)e^{-\Delta/T} \) (Blaschke et al. 2000). The critical temperature for the CFL phase is currently not known; however, it is believed to be lower than the standard Bardeen-Cooper-Schrieffer temperature \((T_c \simeq 0.57\Delta)\) due to instanton-anti-instanton effects (Blaschke et al. 2000; Negreiros & Dexheimer 2012). Here, we used \( T_c \sim 0.4\Delta \).

We have plotted the cooling curve for QSs whose quark cores are only composed of SQM in the CFL phase for different gap values (\( \Delta \)) in Figs. 6, 7, and we compare them with stars without superfluidity. These QSs have masses of \( \sim 1.4 M_\odot \) and \( \sim 2.0 M_\odot \), respectively. In this paper we limit our study to pairings with small gaps given by \( \Delta = 0.1, 1.0, 10.0 \) MeV. We have not considered cooling from processes involving Goldstines bosons in the CFL phase. Although these processes are important for the core, they are not effective at cooling stars with a crust, and thermal relaxation of the crust is still the key factor. We note a very distinctive behavior that depends on the value chosen for the superconductivity gap. We see that objects with a higher \( \Delta \), and thus stronger pairing, will have slower cooling. For completeness, we also studied scenarios in which \( \Delta \geq 10 \) MeV and

Fig. 4. \( \ln(T_s) \) variation rate with respect to \( \ln(t) \) versus age for our QSs from Fig. 3. Solid lines are QS (BPS) crusts, and dashed lines are strangelet crusts. The highlighted diamond and star points represent the moment of the most negative slope, i.e., their relaxation times.

Fig. 5. Relaxation time versus gravitational mass. The blue line is for QS (BPS) crusts, and the red line is for strangelet crusts. The two models have the same linear behavior, though the gravitational mass increases as the relaxation time decreases.

Fig. 6. Cooling of quark stars with a gravitational mass of \( \sim 1.4 M_\odot \). \( T_s \) denotes the temperature as measured by a distant observer, and the \( x \) axis is the age in years. Solid lines represent QSs with nuclear (BPS) crusts, and dashed lines are stars with strangelet crusts for different values of the CFL gap (\( \Delta \)).

Fig. 7. Cooling of QSs with a gravitational mass of \( \sim 2.0 M_\odot \). \( T_s \) denotes the temperature as measured by a distant observer, and the \( x \) axis is the age in years. Solid lines represent QSs with nuclear (BPS) crusts, and dashed lines are stars with strangelet crusts for different values of the CFL gap (\( \Delta \)).
have found that the resulting thermal evolution is essentially the same, $\Delta = 10$ MeV. This comes from the fact that the exponential $\exp(-\Delta/T)$ effectively saturates for $\Delta > 10$ MeV. At this point, we would like to note the following: as the cooling of the core is mainly driven by the exponential suppression of the gap, we believe that the value of $T_c$ is not so relevant, so we focused on varying the gap instead. The large value of the CFL gap (0.1–10 MeV) compared to typical core temperatures implies that the cooling behavior should be relatively insensitive to $T_c$ (some updated references to the instanton suppression of pairing in dense quark matter are found in Ferrer et al. 2006; Alford et al. 2007; and Gerhold & Schäfer 2006). For the specific heat of the CFL phase, we used the fitted forms that are simply extensions of nuclear matter. For CFL matter, in principle, one should include the contribution from the (massless) Goldstone boson of the CFL phase. However, such “bare” CFL stars can store a lot of heat and would remain hot for a very long time, in disagreement with the data. Adding a crust allows them to cool, but the large thermal conductivity due to the same bosons basically means that the crust determines the cooling rate. In either case, we return to the same conclusion, that the nature of the crust (nuclear or strangelet) plays the main role in cooling strange stars. Also, we note that superconductivity effects were only considered in the quarks at the stellar core. Although there could be pairing in the strangelets, we believe it would not affect the thermal evolution as they have only a passive role – with the electrons dominating the thermal conduction (the strangelets being analogous to the role of ordinary ions in traditional crust models).

### 3.3. Comparison with observed data

We can now compare our previous results with the current observations. In Fig. 8 we compare our theoretical results with a set of observed data as described in Potekhin et al. (2020), in which the thermally observable neutron stars are grouped in different classes: (i) the weakly magnetized thermal emitters, including central compact objects and other thermally emitting isolated neutron stars, which mostly emit soft X-ray thermal-like radiation and do not seem to be very strongly magnetized (surface fields below $5 \times 10^{12}$ G or non-determined); (ii) ordinary pulsars, which comprise thermal data associated with rotation powered pulsars with moderate magnetic fields ($B \sim 10^{12} - 10^{13}$ G); (iii) high-B pulsars, objects with strong estimated magnetic fields ($B \sim 10^{13} - 10^{14}$ G); and finally (iv) neutron stars whose temperatures can only be estimated as an upper limit and are thought to be associated with relatively young objects (see Potekhin et al. 2020 for more details).

In Fig. 8 we show the cooling of $1.4 M_\odot$ QSs – with different pairing gaps – against the observed data described above. It quickly becomes evident that without pairing the QSs cool down too quickly, which does not line up with the observed data. Such behavior is not unexpected and has been pointed out in previous works (Negreiros & Dexheimer 2012; Alford 2009). This situation is changed when pairing is included, as the cooling slows down and matches a few of the observed stars. Our results seem to indicate that a moderate pairing with $\Delta \sim 1-10$ MeV is favored if the cooling tracks are to go through the data points. At this point, it is opportune to make a few remarks. First, Fig. 8 shows that a large set of the data points (mostly in the ordinary pulsars group) lies to the right of the cooling tracks, indicating old objects. One must note, however, that unless a neutron star is associated with a supernova remnant (not usually the case for ordinary pulsars, with a few exceptions), one can only estimate its age by its spin-down properties. Such estimates should be regarded mostly as an upper limit, as the spin-down age is known to be a very crude estimate (in the few cases in which both spin-down and kinematic ages can be estimated simultaneously, they vary drastically). Second, the observed data unfortunately does not help in differentiating between the nuclear and strangelet crusts studied. As explained in the previous section, the difference in the crust composition is more strongly manifested in the process of thermalization of the star, and thus only observations of young stars undergoing such processes, which is not the case with the available observed data, would aid us in differentiating between these models.

### 4. Conclusions

In this article we have studied the structure and cooling behavior of QSs with two different crust models: (i) nuclear (BPS) matter crust and (ii) strangelet crust. Our goal was to identify possible differences in the cooling behavior of each model, as well as to quantify the thermal relaxation properties of QSs. Quark stars with nuclear crusts were modeled traditionally, assuming a BPS EOS for the crust beginning at the neutron drip density. As for the strangelet crusts, we followed the foundations laid out in Alford & Eby (2008), Jaikumar et al. (2006), and Alford et al. (2006), which is to say we considered the possibility that the surface tension of quark matter is low enough to allow for the formation of strangelets. Under this hypothesis, it would be energetically favorable for the quark matter at the low densities of a QS to rearrange itself into a lattice – akin to how the nuclei organize themselves in the traditional crust model for neutron stars. As shown in Jaikumar et al. (2006), strangelet crusts, with spatial extents of $\sim 20$ m, tend to be thinner than their nuclear matter counterparts, which have thicknesses of $\sim 0.5$ km. Furthermore, according to Jaikumar et al. (2006), the small mean free path for electrons scattering off nuggets implies that the thermal conductivity in the crust is much lower than in the core, and they pointed out that the thermal conductivity of strangelet crusts is similar to that of nuclear crusts. This will influence thermal evolution since the crust will act as an insulator, effectively keeping the surface temperature low (Jaikumar et al. 2006; Gnedin et al. 2001). Given such differences, we sought to quantify how they manifest themselves in a thermal evolution context.

Our results indicate that most of the thermal differences between the two studied models are manifested in the initial years of cooling. We have found that QSs with nuclear (and thus thicker) crusts display a slower cooling behavior when compared with QSs with strangelets (thinner crusts). Our assessment is that such behavior is mostly due to the difference in crust thicknesses,
as the crust acts as a blanket for the initial years of thermal evolution (Lattimer et al. 1994; Gnedin et al. 2001; Sales et al. 2020). We have also found that the fact that the crust of the QSs studied is populated with strangelets (as opposed to the traditional ions) does not seem to affect the cooling in any major manner. The reason is that, as is the case for the ions in regular neutron stars, the strangelets are mostly inert in the context of thermal processes, with the free electrons being the major agents of heat conduction. In order to quantify our findings, we investigated the thermal relaxation time of QSs under both models. Following the study of Sales et al. (2020), we have found that the star’s relaxation time is linearly dependent on the gravitational mass – with a more sloped curve for the QSs with strangelet crusts (thus indicating a faster relaxation time). Overall, we have found that QSs with strangelet crusts thermalize in ~1 yr, whereas QSs with ordinary crusts do so in ~100 yr. We have found that this is mostly due to the fact that strangelet crusts are significantly thinner than ordinary hadronic ones. The different masses of the strangelets (in comparison to the ordinary nuclei that comprise the crust) also affect the specific heat in the region, although this does not seem to affect the thermal evolution in any major way.

With this work we aimed to investigate the thermal relaxation of QSs as well as to explore the thermal properties of previously proposed strangelet crust models. We have found that there is a significant decrease in the relaxation time of QSs with strangelet crusts (corresponding to a faster thermal evolution). We have also presented the thermal relaxation times of QSs as a function of their mass, which, as far as we know, has not been studied before. Finally, we are currently expanding this study to consider the effects of rotation and high magnetic fields in the structure of the stars we discussed in this work.

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