Article

Reduction of the Mass of the Proto-Quark Star during Cooling

Gevorg Hajyan

Yerevan State University, Alex Manoogian str.1, Yerevan 0025, Armenia; ghajyan@ysu.am

Abstract: The integral parameters (mass, radius) of hot proto-quark stars that are formed in supernova explosion are studied. We use the MIT bag model to determine the pressure of up-down and strage quark matter at finite temperature and in the regime where neutrinos are trapped. It is shown that such stars are heated to temperatures of the order of tens of MeV. The maximum possible values of the central temperatures of these stars are determined. It is shown that the energy of neutrinos that are emitted from proto-quark stars is of the order of $250 \div 300$ MeV. Once formed, the proto-quark stars cool by neutrino emission, which leads to a decrease in the mass of these stars by about 0.16–0.25 $M_\odot$ for stars with the rest masses that are in the range $M_b = 1.22 - 1.62 M_\odot$.

Keywords: proto-quark stars; maximum temperature; mass reduction

1. Introduction

The neutron and quark stars are formed during the explosion of a supernova star (SN), according to modern concepts. The first numerical simulations of the explosion of SN were carried out in the middle of the last century [1–4]. Despite the tremendous progress of computer technology and the presence of numerous works on explosion modeling of SN, the mechanism of explosion and many related issues have not been completely understood. More recently, the problem of binary neutron star mergers and proto-neutron star evolution has gained attention, which, like the SN explosion problem, requires knowledge of the equation of state of matter at a finite temperature as an input in numerical simulations [5–16]. In addition, the discovery of $M \approx 2M_\odot$ pulsars during the last decade has put strong constraints on the properties of the dense matter, indicating that the equation of state at high densities must be stiff [17]. Furthermore, the NICER experiment has measured the radius of PSR J0030+0451, thus constraining the equation of state of dense matter at intermediate densities [18,19].

Although it is impossible to determine the evolution of the physical system while using conservation laws, nevertheless in some cases they allow for one to obtain a relation between the initial and final values of some physical parameters of the examined object. The purpose of present work is to calculate the temperature and the energy content of a proto-quark star (PQS), which was formed during a SN explosion. This is done by using only the energy and lepton charge conservation laws. We also determine the decrease in its mass during the cooling. When the central dense core of a massive star loses its mechanical stability (due to neutronization or the dissociation of iron nuclei), it begins to shrink rapidly. The timescale for the core to shrink to nuclear density is given by the free fall time $\tau_0 \sim (R^3/GM)^{1/2} \sim 1$ s, assuming that the iron core has a radius $R \approx 5000$ km and the mass $M \approx 2M_\odot$, where G is a gravitational constant. During this process, atomic nuclei dissociated into nucleons. A proto-neutron star (PNS) is formed if the pressure of the matter stops the further compression. Otherwise, the compression continues until the nucleons dissociate into quarks, i.e., a deconfinement phase transition takes place. Consequently, a proto-quark star is formed. In principle, the compression may continue until a black hole is formed.

The mechanism of explosive ejection of the main mass of the star is not considered here. We only note here that one of the promising mechanisms that accounts for the explosive

nature of the ejection of the bulk of the pre-supernova matter is the magnetorotational mechanism [20,21]. The current state of the problem is described in detail in [22]. The purpose of our work is to define the maximum value of the temperature of the proto-quark star, which has been formed after SN explosion, and to calculate the decrease of its mass during subsequent cooling.

Our main working assumption are as follows: (1) the matter of the central core of the pre-supernova before collapse is opaque for neutrinos. (2) The process of compression of the central core of a pre-supernova before the formation of PQS occurs so rapidly that its total energy and lepton charge remain unchanged. As a consequence of this assumption, the lepton charges of the central core of a pre-supernova and a proto-quark star are (almost) the same. After the successive disintegration of atomic nuclei into nucleons, and thereafter nucleons into quarks, we expect that a PQS, completely, or at least its central region, consists of a hot superdense up (u), down (d) quarks, and electron-position (e^-, e^+) plasma, which is out of the β-equilibrium.

Note that the formation of the ud phase can be accompanied by a decrease in the temperature of the medium. The equilibrium between electrons and positrons is established through fast (as compared to weak interactions) electromagnetic interaction. According to the SN collapse scenarios, the matter becomes opaque for neutrinos before the dissociation of the atomic nuclei in nucleons. Accordingly, the chemical equilibrium (equilibrium with respect to β-processes) in PQS is established in a matter that is opaque for neutrinos, which implies that the lepton charge is conserved. The β-equilibrium in ud quark matter is established through the reactions $u + e^- \longrightarrow s + \nu_e$ and $d \longrightarrow u + e^- + \widetilde{\nu}_e$, which can lead to a heating of the star. This heating resembles the mechanism of heating of matter through non-equilibrium β processes on atomic nuclei that was proposed in [23]. It will be shown below that, due to these processes, the temperature of the proto-quark star can rise up to $7 \cdot 10^{11}$ K.

2. The Equation of State of Hot Quark Matter

The composition, thermodynamic characteristics, and the equation of state of a hot strange quark matter (HSQM) in the regime where neutrinos are trapped in matter where studied in [24,25], within the MIT quark bag model. In these studies, it was shown that the amount of thermal energy of HSQM is weakly dependent on the lepton composition. Taking the presence in HSQM of muons, muon-, and tau-neutrinos, as well as their antiparticles and the possibility of the neutrino oscillations, into account, only slightly changes the thermal energy. Therefore, in determining the integral parameters of the proto-quark star, only the electrons, electron-neutrinos, and the corresponding antiparticles will be taken into account, which significantly reduces the numerical effort.

After the "breakdown" of the baryons and before the establishment of β-equilibrium in the quark matter, the concentrations of u and d quarks, denoted by n_u and n_d, will be

$$n_u = n(Z + A)/A, \qquad n_d = n(2A - Z)/A,$$

where A and Z are the mass and atomic numbers of the atomic nucleus at the moment of their disintegration, n is the concentration of the baryonic charge. The concentrations of electrons and positrons are determined by the conditions of local electro-neutrality and the chemical equilibrium. Assuming that quarks are massless, the pressure P and energy density ε are related by the simple relation

$$\varepsilon = 3P + 4B, \tag{1}$$

where B is the bag constant of the MIT bag model. Taking the s quark mass (m_s) into account, the relationship between the energy and pressure changes slightly [24,25]:

$$\varepsilon = 3P + 4B + \Delta(m_s, n_s, T), \tag{2}$$

where n_s is the concentration of the *s*-quark and T is the temperature. The correction $\Delta(m_s, n_s, T)$ arises due to the relatively large mass $m_s = 95$ MeV of the *s*-quark, and our calculations show that $\Delta/\varepsilon < 0.04$ [24,25]. Consequently, the temperature dependence introduced by this term in (2) is small. On the contrary, the energy density and pressure strongly depend on the temperature at a fixed concentration of the baryonic charge. Further details on the particle composition of matter that is composed of quarks and leptons, the condition of thermodynamical equilibrium among their chemical potentials within the MIT model used in this work, can be found in Refs. [24,25].

As is well known, the mass and radius of static isothermal superdense configurations are determined by the equation of state (hereafter EoS), i.e., the relation $P = P(\varepsilon, T)$. If one assumes that $\Delta = 0$, then the dependence of the mass of isothermal PQS on its central density $\rho_c = \varepsilon_c/c^2$ (where ε_c is the energy density of at the center of the star and c is the speed of light in vacuum) is independent of temperature, according to Equation (2), i.e., all mass versus central density curves coincide. Taking the mass of the strange quark into account only leads to insignificant shifts of these curves: the higher the temperature, the greater the shift upward of the $M = M(\rho_c, T_c)$ curve from its zero-temperature counterpart $M = M(\rho_c, T_c = 0)$. The relative shift does not exceed $6 \cdot 10^{-3}$ at the maximum of these curves for central temperature $T_c = 100$ MeV [26].

3. Methods

The integral parameters of PQS, such as the gravitational and baryonic masses and the radius, are determined by numerical integration of the relativistic equations of hydrostatic equilibrium (3), the mass (4), the time component of the space-time metric inside the star $g_{00} = e^\nu$ (5), and the baryonic charge N (6)

$$\frac{dr}{dP} = -\frac{r^2 c^2}{Gm\varepsilon}(1 - \frac{2Gm}{rc^2})\frac{1 + \frac{4\pi r^3 P}{mc^2}}{1 + \frac{P}{\varepsilon}} , \tag{3}$$

$$\frac{dm}{dP} = 4\pi r^2 \frac{\varepsilon}{c^2}\frac{dr}{dP} , \tag{4}$$

$$\frac{d\nu}{dP} = -\frac{2}{\varepsilon + P} , \tag{5}$$

$$\frac{dN}{dP} = 4\pi r^2 \frac{n}{(1 - \frac{2Gm}{rc^2})^{1/2}}\frac{dr}{dP} , \tag{6}$$

with conditions in the center of the star $r = 0, P = P_c, m = 0, N = 0, T = T_c$. The distribution of temperature is determined by the relation

$$T(r) = T_c \sqrt{g_{00}(0)/g_{00}(r)} = T_c \exp[(\nu_c - \nu(r))/2]. \tag{7}$$

The difference $\nu_c - \nu(r)$ does not depend on the central value of ν_c, since Equation (5) is linear. Therefore, in order to determine the temperature distribution, it is enough to take, for example, $\nu_c = 1$, which need not correspond to actual physical value of ν at the center of the star.

As mentioned above, we assume massless *u* and *d* quarks in our MIT bag model based EoS. The remaining parameters are the *s* quark mass m_s, the bag constant B, and the quark-gluon interaction constant α_c, which are assumed to have the values $m_s = 95$ MeV, $B = 80$ MeV, $\alpha_c = 0$. The surface where $P = 0$ is considered to be the outer boundary of the PQS, which defines its radius. Of course, the newborn PQS will be surrounded by normal stellar matter. However, the pressure of this substance cannot significantly change the density of the quark matter on the PQS surface; therefore, our choice of the PQS surface is justified. The radius, R, the gravitational mass, M, the baryonic mass, M_b, and the baryonic charge, N_b, of the PQS are determined by the relations

$$R = r(P = 0), \quad M = m(P = 0), \quad M_b = m_n N_b, \quad N_b = N(P = 0),$$

where m_n is the mass of neutron.

In our calculations, the PQS is assumed to be isothermal, i.e., $T\sqrt{(g_{00})}$ = const within the star. If the energy losses are insignificant during the entire compression of the central core of the pre-supernova star before the formation of a PQS, then the difference between the baryonic mass M_b and gravitational mass M of the collapsing core will remain almost unchanged. At the moment of loss of stability of the central core of the pre-supernova, one has $(M_b - M)/M_b \approx 10^{-4} \div 10^{-3}$. The change in gravitational energy during the collapse is spent on changing the composition and heating the matter. Moreover, the heating of the matter will be maximal if the energy is fully conserved. The maximum temperature of PQS is determined from the condition of equality of the masses of the central core of the pre-supernova star and the newborn PQS at the same baryonic masses. If, after the formation of the PQS, part of the matter that is ejected during the SN explosion does not settle back by accretion on the PQS, then all of the the emitted energy (mainly in the form of neutrinos) will be equivalent to the difference in the masses of the PQS and a cold quark star of the same baryonic mass.

4. Results

Figure 1 and Table 1 provide the results of numerical calculations for the two values of the baryonic mass $M_b/M_\odot = \{1.22; 1.62\}$ and initial relative lepton charge $L = \{1/2; 26/56; 0.4\}$ (defined as the ratio of the lepton and baryonic charges of quark matter).
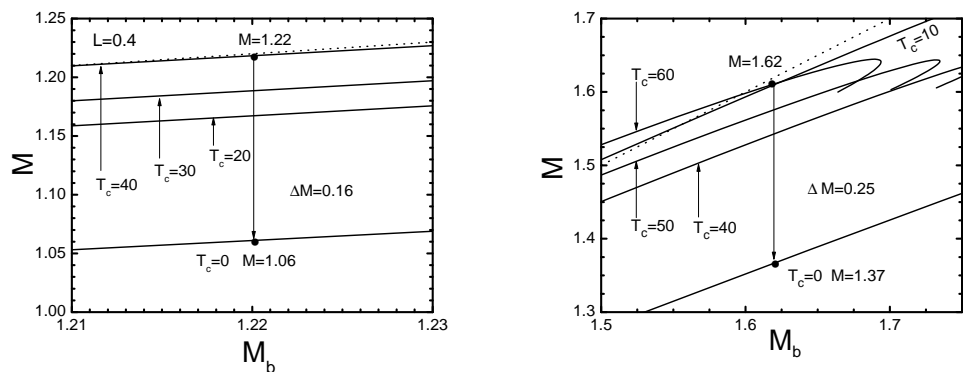

Figure 1. The dependence of the mass of the quark star M on the baryonic mass M_b for different central temperatures T_c for regions $1.21 \leq M_b \leq 1.23$ (left panel) and $1.5 \leq M_b \leq 1.75$ (right panel). The relative lepton charge is $L = 0.4$, which is less than $26/56$ (corresponding to the Z/A-ratio for iron) to compensate the partial escape of neutrinos before the formation proto-quark star (PQS). We also show the same dependence for cold (zero-temperature) quark stars. All of the masses are given in units of the solar mass and the temperatures are given in MeV. The circles mark the positions of stars with masses of 1.22 and 1.62. All curves correspond to the *uds* quark stars, except the $T_c = 10$ MeV curve, which corresponds to *ud*-PQS. The dotted line corresponds to the line $M = M_b$.

Table 1. Integral parameters of PQS. M_b is the baryonic mass, M is the gravitational mass, L is the initial relative lepton charge, T_c, ρ_c, and n_c are, respectively, the temperature, the density, and concentration of the baryonic charge in the center of the star, $n_0 = 0.15$ fm^{-3} is the nuclear saturation density, R is the PQS radius, ΔM - the decrease in the mass of the PQS with cooling to $T \to 0$, E_ν is the energy of neutrino gas, and ε_ν is the average neutrino energy. The table also lists the parameters of this star in the cold state.

$\frac{M_b}{M_\odot}$	L	$\frac{M_b}{M_\odot}$	$\frac{T_c}{10^{11}}$ [K]	T_c [MeV]	$\frac{n_c}{n_0}$	$\frac{\rho_c}{10^{15}}$ [g/cm^3]	R [km]	$\frac{\Delta M}{M_\odot}$	$\frac{E_\nu}{Mc^2}$	ε_ν [MeV]
1.22	0.5	1.22	3.48	30	3.64	1.10	9.15	0.16	5	260
1.22	26/56	1.22	3.94	34	3.64	1.10	9.15	0.16	4.5	257
1.22	0.4	1.22	4.64	40	3.65	1.10	9.15	0.16	3.7	250
1.22	-	1.06	0	0	3.89	0.99	8.83	-	-	-
1.62	0.5	1.62	6.15	53	6.06	2.12	9.29	0.25	5.2	293
1.62	26/56	1.62	6.38	55	5.99	2.08	9.31	0.25	4.7	288
1.62	0.4	1.62	6.69	60	5.95	2.06	9.31	0.25	3.9	280
1.62	-	1.37	0	0	4.9	1.30	9.30	-	-	-

We now consider a scenario, in which, due to an collapse of the central core of the pre-supernova star, its baryonic matter under gravitational compression turns into the *ud* quark matter. If the gravitational energy (mass) of the collapsing matter is high enough, then all of the central core matter would become *ud* quark matter and a *ud*-PQS will be formed. Within this scenario a 1.62 $M_\odot$ PQS, as listed in Table 1 is born. Its temperature is $T_c = 10$ MeV. During the subsequent transition of the star to the *uds* state, its temperature increases to $T_c = 60$ MeV. This heating is similar to the heat release process that was proposed in [27]. Afterwards, the star is cooling down, loses its mass, and becomes a cold quark star with a mass of 1.37 $M_\odot$. Figure 1 illustrates these scenarios.

Now consider the case where the mass of the collapsing matter is not large enough and a PQS with a mass of 1.22 $M_\odot$ is formed, which, at the initial moment of its life, only partially consists of *ud* quark matter. The change in gravitational energy turns out to be insufficient for the desintegration of all the baryons of the star in *ud* quarks. This only happens in the central region of the star. After the transition of this region into the *uds* state, it will become a seed center for the transition of the entire star into the *uds* quark state. While cooling down, this star loses mass and becomes a cold quark star with a mass of 1.06 $M_\odot$. Figure 1 illustrates this scenario.

If, during the collapse of the central core of a pre-supernova star, the decomposition of baryons into *ud* quarks does not occur, then a proto-neutron star will be formed. The high energy barrier between the baryonic and strange *uds* quark matters [28] will prevent the transformation of the proto-neutron star into a PQS. The final state of the central regions of the pre-supernova will primarily depend on its mass. This question is a topic for a separate study.

The gravitational and baryonic masses of the newborn PQS differ in the third or fourth digits, so they are just equal in Table 1. According to the above, for each PQS, the T_c listed in the Table 1 are the maximum possible values for their central temperatures. In this state, the portion of the energy of the neutrino component, depending on the baryonic mass and the lepton charge, is $4 \div 5$ percent of the total energy Mc^2, and the average energy of the neutrino is $250 \div 290$ MeV. The mass of the PQS decreases with the loss of neutrinos. The change in mass after the complete cooling of the star is 16 and 25 percent for $M_b = 1.22\ M_\odot$ and $M_b = 1.62\ M_\odot$, respectively. This mainly happens due to neutrino radiation.

A similar scenario has been explored in the case of a proto-neutron star [29–31]. The energy loss of the PNS during cooling is of the same order. However, the energy of individual neutrinos is approximately 10 MeV [29–31]. In contrast to these neutrinos, the energy of neutrinos from PQS is by an order of magnitude larger. Therefore, the transfer of the energy of the neutrino flux from the PQS to the surrounding matter (deposition) will be more effective due to an increase in the cross-section for the interaction of neutrinos

with electrons and nucleons. This may provide the explosive nature of the ejection of the pre-supernova matter.

During the cooling, the radius of PQS changes both due to a decrease in the pressure of the matter and due to a decrease in gravitational forces. The PQS radius can either decrease or increase, depending on the ratio of these changes. After complete cooling, the radius of PQS with $M_b = 1.22\ M_\odot$ decreases by 3.5 percent, and the radius of PQS with $M_b = 1.62\ M_\odot$ remains almost unchanged.

The central concentrations n_c of the baryonic charge of the considered configurations change in different ways. After cooling, for PQS with masses of $M_b = 1.22\ M_\odot$ and $n_c = 3.64\ n_0$, the concentration of the baryon charge at the center increases to a value of $n_c = 3.85\ n_0$. For PQS with mass $M_b = 1.62\ M_\odot$, on the contrary, the central concentration of the baryonic charge after cooling of the star decreases from $n_c \approx 6\ n_0$ to $n_c \approx 5n_0$, although the radii in both of the states are the same. At first glance, such a paradoxical result can be easily explained. On one hand, as the PQS with masses $M_b = 1.22\ M_\odot$ cools down, the decrease in the gravitational and pressure forces of the stellar matter leads to the fact that the radii of PQS and the cold quark star remain almost unchanged. On the other hand, the concentration of the baryonic charge HSQM in the surface layers of the star, where the pressure is close to zero, should increase with cooling to compensate for the decrease in thermal corrections to the pressure. While, in PQS with $M_b = 1.22\ M_\odot$, this is achieved by decreasing the radius, in PQS with $M_b = 1.62\ M_\odot$ this is provided by the outflow of quarks from the inner regions to the outer layers.

5. Conclusions and Critical Remarks

For sure, during the collapse, the central regions of the pre-supernova star lose both energy and lepton charge. Therefore, the numerical values of the temperature and energy of PQS neutrinos in Table 1 are the maximum possible values of these parameters. However, the collapse occurs so quickly that these losses can be neglected in the first approximation.

Of course, the model of quark matter that is used in this work is simple. There exists more sophisticated models, such as the NJL model of quark matter, which includes the dynamical mass generation of quarks and restoration of chiral symmetry. Although such models better describes the physical reality, the simplicity of the MIT bag model allows for us to determine, in an easy way, the thermodynamic characteristics of the HSQM.

If the lepton charge and energy are conserved during the collapse of the central regions of a pre-supernova star, then a very hot PQS that is enriched with leptons can be formed. The energy of such a star can reach up to 0.25 Mc^2, which will lead to a decrease in its mass by the same amount when it cools. This energy is mainly carried away by neutrinos. If we take the gravitational redshift for a distant observer into account, then the energy of these neutrinos will be around 200 MeV. However, we need to keep in mind that this estimate has been obtained under some assumptions, which most likely overestimate the value of the neutrino energy. If the neutrinos of such large energy are detected, then the could be a signal of a birth of PQS. So far, the only neutrinos that were detected by neutrino observatories are those from the SN1987A. These neutrinos have an energy of the order of tens of MeV. It should be assumed that a PQS was not formed in this supernova event. As noted above, in the case of $1.62M_\odot$ PQS, the transition from the baryonic to ud then to the uds quark matter occurs in the entire star. On the contrary, in the case of $1.22M_\odot$, the transition can only occur after a core of ud quark matter is formed in the central region of the collapsing core of the pre-supernova star. The less the mass of this star, the less the mass of the ud quark core. In both cases, this transition will be accompanied with structural changes that may cause weak (but noticeable) secondary activity of supernova. Note that the minimum value of the mass of the collapsing core of the PQS at which the ud quark phase is still formed coincides with the value of the PQS mass that can be formed in the supernova explosion. The precise value of this limit can only be obtained through detailed numerical computations. The neutrino flux from PQS with energies of 250 ÷ 300 MeV can possibly provide the transfer of the energy that is accumulated in the PQS to the

surrounding non-degenerate matter. This could be very important for explaining the nature of the explosive ejection of pre-supernova matter.

Because the values of the maximum masses M_{max} of hot and cold quark stars do not practically differ [26], the maximum value of the mass of the cooled PQS will be $\approx 0.75\, M_{max}$. Only the accretion of matter can increase this value. If cold quark stars are formed only after a supernova explosion, then their number in the mass range $\sim(0.75 \div 1)\, M_{max}$ will be significantly less than those stars with $M < 0.75\, M_{max}$.

It is useful to compare our discussion of PQS to ordinary baryonic proto-neutron stars. Firstly, the energy losses of proto-neutron stars during the cooling are of the same order of magnitude, as in the case of PQS. Therefore, it is likely that the scenarios that are discussed above will also apply to proto-neutron stars. This can partially explain the relatively small number of pulsars with $M > 1.5\, M_\odot$ if the value $M_{max} \approx 2M_\odot$ [32] is taken as maximum for the mass of cold neutron stars. Of course, this can only be confirmed by detailed calculations.

Our static calculations and the conclusions that are drawn from them can be tested and confirmed by solving numerical the time-evolution problem. We hope that our work will stimulate such work.

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