Effects of quark matter and color superconductivity in compact stars

D. Blaschke*, H. Grigorian***, D.N. Aguilera‡, S. Yasui§ and H. Toki§

* Fachbereich Physik, Universität Rostock, D-18051 Rostock, Germany
† Bogoliubov Laboratory of Theoretical Physics, Joint Institute for Nuclear Research, 141980, Dubna, Russia
‡ Department of Physics, Yerevan State University, 375025 Yerevan, Armenia
§ Instituto de Física Rosario, Bv. 27 de febrero 210 bis, 2000 Rosario, Argentina
§ Research Center for Nuclear Physics, Osaka University, Ibaraki 567 - 0047, Japan

Abstract. The equation of state for quark matter is derived for a nonlocal, chiral quark model within the mean field approximation. We investigate the effects of a variation of the form factors of the interaction on the phase diagram of quark matter under the condition of $\beta$-equilibrium and charge neutrality. Special emphasis is on the occurrence of a diquark condensate which signals a phase transition to color superconductivity and its effects on the equation of state. We calculate the quark star configurations by solving the Tolman-Oppenheimer-Volkoff equations and obtain for the transition from a hot, normal quark matter core of a protoneutron star to a cool diquark condensed one a release of binding energy of the order of $\Delta M c^2 \sim 10^{53}$ erg. We study the consequences of antineutrino trapping in hot quark matter for quark star configurations with possible diquark condensation and discuss the claim that this energy could serve as an engine for explosive phenomena. A "phase diagram" for rotating compact stars (angular velocity-baryon mass plane) is suggested as a heuristic tool for obtaining constraints on the equation of state of QCD at high densities. It has a critical line dividing hadronic from quark core stars which is correlated with a local maximum of the moment of inertia and can thus be subject to experimental verification by observation of the rotational behavior of accreting compact stars.

INTRODUCTION

Color superconductivity in quark matter is one interesting aspect of recent discussions devoted to the physics of compact star interiors. Since calculations of the energy gap of quark pairing predict a value $\Delta \sim 100$ MeV and corresponding critical temperatures for the phase transition to the superconducting state are expected to follow the BCS relation $T_c = 0.57 \Delta$, the question arises whether diquark condensation can lead to remarkable effects on the structure and evolution of compact objects. If positively answered, color superconductivity of quark matter could provide signatures for the detection of a deconfined phase in the interior of compact objects (pulsars, Low-mass X-ray binaries) via observations. Hong, Hsu and Sannino have conjectured that the release of binding energy due to Cooper pairing of quarks in the course of protoneutron star evolution could provide an explanation for the unknown source of energy in supernovae, hypernovae or gamma-ray bursts, see also. Their estimate of energy release did not take into account the change in the gravitational binding energy due to the change in the structure of the stars quark core. We reinvestigate the question of a pos-
possible binding energy release due to a color superconductivity transition by taking into account changes in the equation of state (EoS) and the configuration of the quark star selfconsistently and by including the effects of antineutrino trapping [5].

As a first step in this direction we will discuss here the two flavor color superconducting (2SC) quark matter phase which occurs at lower baryon densities than the color-flavor-locking (CFL) one, see [6, 7]. We will investigate the influence of the formfactor of the interaction on the phase diagram and the EoS of dense quark matter under the conditions of charge neutrality and isospin asymmetry due to $\beta$-equilibrium relevant for compact stars.

Finally we consider the question whether the effect of diquark condensation which occurs in the earlier stages of the compact star evolution ($t \simeq 100$ s) [8, 9] at temperatures $T \sim T_c \sim 20 \div 50$ MeV can be considered as an engine for explosive astrophysical phenomena like supernova explosions due to the release of a binding energy of about $10^{52} \div 10^{53}$ erg, as has been suggested before [3, 4].

**THERMODYNAMICS OF A NONLOCAL CHIRAL QUARK MODEL**

The phase structure of electrically and color neutral quark matter in $\beta$-equilibrium has been studied in [7] and it has been shown that at densities relevant for compact star interiors the 2SC phase should be dominant over the CFL phase. The latter one could only be stable in the very inner core and thus does not occupy a large enough volume in order to cause observable effects. Therefore, we consider in the present work two flavor quark matter in with 2SC superconductivity only. The more general case which includes the CFL phase does not invalidate the scenario developed in the following and will be studied in a subsequent work. We consider the grand canonical thermodynamical potential for 2SC quark matter within a nonlocal chiral quark model [10] where in the mean field approximation the mass gap $\phi$ and the diquark gap $\Delta$ appear as order parameters which can be expressed as in [11] by

$$\Omega_q(\phi, \Delta; \mu_q, \mu_I, T) = \frac{\phi^2}{4G_1} + \frac{\Delta^2}{4G_2} - \frac{1}{\pi^2} \int_0^\infty dq q^2 \{ \omega \left[ \varepsilon_r(-\mu_q - \mu_I), T \right] + \omega \left[ \varepsilon_r(-\mu_q + \mu_I), T \right] + \omega \left[ \varepsilon_r(\mu_q + \mu_I), T \right] - \frac{2}{\pi^2} \int_0^\infty dq q^2 \{ \omega \left[ \varepsilon_b(E(q) - \mu_q) - \mu_I, T \right] + \omega \left[ \varepsilon_b(E(q) + \mu_q - \mu_I, T \right] + \omega \left[ \varepsilon_b(E(q) + \mu_q + \mu_I, T \right] \} + \Omega_{vac},$$

(1)

where we have introduced the quark chemical potential $\mu_q = (\mu_u + \mu_d)/2$ and the chemical potential of the isospin asymmetry $\mu_I = (\mu_u - \mu_d)/2$ instead of the chemical potentials of up and down quark flavors. We neglect here a possible difference between the chemical potentials of paired and unpaired colors for the same quark flavor. For a more general approach see [7, 12]. The factor 2 in the last integral comes from the
Degeneracy of the blue and green colors \((\varepsilon_b = \varepsilon_g)\). We have introduced the notation

\[
\omega [\varepsilon_c, T] = T \ln \left[1 + \exp \left(-\frac{\varepsilon_c}{T}\right)\right] + \frac{\varepsilon_c}{2},
\]

where the first argument is given by

\[
\varepsilon_c(x) = x \sqrt{1 + \Delta_c^2/x^2},
\]

with the color index \(c = r, g, b\) and we assume that the green and blue colors are paired while the red one remains unpaired, so that we have

\[
\Delta_c = g(q)\Delta(\delta_{c,b} + \delta_{c,g}).
\]

The dispersion relation for unpaired quarks with dynamical mass function \(m(q) = m + g(q)\phi\) is given by

\[
E_f(q) = \sqrt{q^2 + m^2(q)},
\]

where \(g(q)\) denotes the formfactor of the quark interaction, for which we employ the following models

\[
g_L(q) = [1 + (q/\Lambda_L)^{2\alpha}]^{-1}, \quad \alpha > 1,
\]

\[
g_G(q) = \exp(-q^2/\Lambda_G^2),
\]

\[
g_{NJL}(q) = \theta(1 - q/\Lambda_{NJL}).
\]

Depending on the parameter \(\alpha\), the Lorentzian (L) momentum distribution can interpolate between a soft Gaussian (G) formfactor (for \(\alpha \sim 2\)) and a hard cutoff (NJL) one (for \(\alpha > 30\)). The parametrization of the model can be found in Refs. [13, 10]. The contribution from the leptons should be added to the quark thermodynamical potential \(\Omega_q\) in order to obtain the total one

\[
\Omega(\phi, \Delta; \mu_q, \mu_I, \mu_e, \mu_{\bar{\nu}_e}, T) = \Omega_q(\phi, \Delta; \mu_q, \mu_I, T) + \sum_{l \in \{e, \bar{\nu}_e\}} \Omega^{id}(\mu_l, T),
\]

where

\[
\Omega^{id}(\mu, T) = -\frac{1}{12\pi^2} \mu^4 - \frac{1}{6} \mu^2 T^2 - \frac{7}{180} \pi^2 T^4
\]

is the thermodynamical potential for an ideal gas of massless fermions. The stellar matter in the quark core of compact stars consists of \(u\) and \(d\) quarks, electrons \(e\) and antineutrinos \(\bar{\nu}_e\) under the conditions of \(\beta\)-equilibrium: \(d \longleftrightarrow u + e^- + \bar{\nu}_e\), which in terms of chemical potentials reads \(\mu_e + \mu_{\bar{\nu}_e} = -2\mu_u\), and charge neutrality: \(\frac{2}{3}n_u - \frac{1}{3}n_d - n_e = 0\), which also could be written as \(n_q + 3n_I - 6n_e = 0\). The number densities \(n_j, j \in \{u, d, e, \bar{\nu}_e, q, I\}\) are defined as

\[
n_j = -\frac{\partial \Omega}{\partial \mu_j} \bigg|_{\phi_0, \Delta_0, T}.
\]
The conditions for the local extrema of $\Omega_q$, correspond to coupled gap equations for the two order parameters $\phi$ and $\Delta$

$$\frac{\partial \Omega}{\partial \phi} \bigg|_{\phi=\phi_0, \Delta=\Delta_0} = \frac{\partial \Omega}{\partial \Delta} \bigg|_{\phi=\phi_0, \Delta=\Delta_0} = 0 .$$

(12)

The global minimum of $\Omega_q$ represents the state of thermodynamical equilibrium from which all equations of state can be obtained by derivation. In the following subsections we want to comment on aspects of this stellar matter model which turns out to be essential for the discussion of quark matter in compact stars.

**Effect of formfactors**

The nonvanishing of the order parameters $\phi$ or $\Delta$ signals the presence of a phase with broken chiral symmetry or color superconductivity, respectively. In Fig. 1 we show the resulting phase diagram of quark star matter under the above constraints and neglecting the CFL phase which should appear only at such high densities that it will at best occupy a negligible volume in the very inner core of a compact star configuration. From Fig. 1

![Phase Diagram](image)

FIGURE 1. Phase diagrams for different form factors: Gaussian (solid lines), Lorentzian $\alpha = 2$ (dashed lines) and NJL (dash-dotted). In the upper panel the comparison with the BCS formula for $T_c = 0.57 \Delta(T = 0, \mu_q) g(\mu_q)$ is shown for the Gaussian model.

we see that the softer the formfactor $g(q)$ the lower the critical temperatures and chemical potentials for the phase transition to quark matter with vanishing order parameters or to color superconducting quark matter at low temperatures. It is remarkable that a modified BCS relation for the critical 2SC temperature holds [10].
Antineutrino trapping

The results for the solution of the gap equations (12) are shown in Fig. 2 (left panel) for different values of the antineutrino chemical potential which is a measure for the density of trapped antineutrinos in a hot, young protoneutron star. For values $\mu_{\bar{\nu}e} > 72$ MeV the flavor asymmetry becomes large enough to prevent diquark pairing and therefore color superconductivity at low densities. Simultaneously, the onset density for quark matter occurrence is shifted to higher densities, see Fig. 2 (right panel). These solutions will be used for the discussion of a scenario of hot quark star evolution in the next Section. Before that we have to consider the question whether the quark-hadron phase transition would occur at too high energy densities so that no quark core could exist in a hybrid compact star.

Quark hadron phase transition

We construct a quark hadron phase transition at zero temperature using a linear and a nonlinear Walecka model for the hadronic phase and perform a Maxwell construction for the phase transition. Although it has been claimed that this procedure might be in contradiction with the Gibbs conditions for phase equilibrium when more than one conserved charge exists in the system [14], a recent investigation including charge screening has revealed the opposite [15]. The resulting EoS with a deconfinement transition confirms that the lowest critical phase transition (energy) density is obtained for the softest (Gaussian) formfactor model, see Fig. 3.

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FIGURE 2. Left panel: Mass gap $\phi$, diquark gap $\Delta$ and isospin chemical potential $\mu_I$ as a function of the quark chemical potential $\mu_q$ for different values of the antineutrino chemical potential $\mu_{\bar{\nu}e}$. Solutions obey $\beta$-equilibrium and charge neutrality conditions. Right panel: Pressure vs. energy density for different values of the antineutrino chemical potential $\mu_{\bar{\nu}e}$. The onset of the appearance of quark matter is shifted to higher energy densities due to antineutrino trapping.
FIGURE 3. EoS of compact star matter with quark hadron phase transition. Hadronic EoS: linear (LW) and nonlinear (NLW) Walecka model, quark matter: nonlocal separable model with 2SC quark matter and different form factors: Gaussian (Gauss), Lorentzian $\alpha = 2$ (L2) and cutoff (NJL).

COMPACT STAR CONFIGURATIONS

What compact star configurations will result from the use of the above EoS? Will a stable compact star with quark matter core be obtained? We will answer these questions in the present Section by solving the Tolman-Oppenheimer-Volkoff equations for the case without rotation and by applying the perturbative method of solution of Einstein equations for stationary rigid rotation. First we consider quark stars without hadronic shell which can be thought of as the simplified models for a compact star interior and after that we discuss hybrid stars.

Quark stars - engine for explosive phenomena?

The engine which drives supernova explosions and gamma ray bursts being among the most energetic phenomena in the universe remains still puzzling. The phase transition to a quark matter phase may be a mechanism that could release such an amount of energy [16,17]. It has been proposed that due to the Cooper instability in dense Fermi gas cold dense quark matter shall be in the color superconducting state with a nonvanishing di-quark condensate [18,2]. The consequences of diquark condensation for the cooling of compact stars due to changes in the transport properties and neutrino emissivities have been investigated much in detail, see [19,20,8,10], and may even contribute to the explanation of the relative low temperature of the pulsar in the supernova remnant 3C58.
Unlike the case of normal (electronic) superconductors, the pairing energy gap in quark matter is of the order of the Fermi energy so that diquark condensation gives considerable contributions to the equation of state (EoS) of the order of $\left(\frac{\Delta}{\mu}\right)^2$. Therefore, it has been suggested that there might be scenarios which identify the unknown source of the energy of $10^{53}$ erg with a release of binding energy due to Cooper pairing of quarks in the core of a cooling protoneutron star [3]. In that work the total diquark condensation energy released in a bounce of the core is estimated as $\left(\frac{\Delta}{\mu}\right)^2 M_{\text{core}}$ corresponding to a few percent of a solar mass, that is $10^{52}$ erg. It has been shown in [10] by solving the selfconsistent problem of the star configurations, however, that these effects due to the softening of the EoS in the diquark condensation transition lead to an increase in the gravitational mass of the star contrary to the naive estimates and that no explosion occurs.

Therefore, we have suggested a new mechanism of energy release [5] which involves a first order phase transition induced by antineutrino untrapping. The trapping of antineutrinos occurs in hot compact star configurations at temperatures $T \geq 1$ MeV where the mean free path of (anti-)neutrinos becomes smaller than the typical size of a star [22]. During the collapse in the hot era of protoneutron star evolution, antineutrinos are produced due to the $\beta$-processes. Since they have a small mean free path, they cannot escape and the asymmetry in the system is increased. This entails that the formation of the diquark condensate is shifted to higher densities or even inhibited depending on the fraction of trapped antineutrinos. As the quark star cools, a two-phase structure will occur. Despite of the asymmetry, the interior of the quark star (because of its large density) could consist of color superconducting quark matter, whereas in the more dilute outer shell, diquark condensation cannot occur and quark matter is in the normal state, opaque to antineutrinos for $T \geq 1$ MeV. When in the continued cooling process the antineutrino mean free path increases above the size of this normal matter shell, an outburst of antineutrinos occurs and gives rise to an energy release of the order of $10^{53} - 10^{54}$ erg. This untrapping transition is of first order and could lead to an explosive phenomenon. Three stages of this scenario of hot quark star evolution are illustrated in Fig. 4. In Fig. 5 these

![FIGURE 4.](image)

Left two graphs: Quark star cooling by neutrino and photon emission from the surface in the case of antineutrino trapping when $T > 1$ MeV. Right graph: Antineutrino untrapping and burst-type release.
FIGURE 5. Three stages of quark star cooling in the phase diagram corresponding to Fig. 4.

stages are shown schematically in the quark matter phase diagram. From Fig. 2 (right panel) we can see that the EoS without antineutrinos is softer than with antineutrinos (it has a lower pressure at a given energy density) and therefore allows more compact configurations (Fig. 4 left part of left panel). The presence of antineutrinos tends to increase the mass of the star for a given central density (Fig. 4 right part of left panel).

To estimate the effect of antineutrinos on star configurations we choose a reference configuration without antineutrinos with the mass of a typical neutron star $M_f = 1.4 M_\odot$ (see Fig. 6). The corresponding radius is $R_f = 10.29$ km and the central density $n_q = 10.5 n_0$, where $n_0 = 0.16$ fm$^{-3}$ is the saturation density. The configurations with trapped antineutrinos and nonvanishing $\mu_{\bar{\nu}_e}$ to compare with we choose to have the same total baryon number as the reference star: $N_B = 1.48 N_\odot$, where $N_\odot$ is the total baryon number of the sun. For $\mu_{\bar{\nu}_e} = 72$ MeV we obtain $M_A = 1.47 M_\odot$ and for $\mu_{\bar{\nu}_e} = 150$ MeV, $M_B = 1.72 M_\odot$. The differences in the radii are $R_A - R_f = 0.1$ km and $R_B - R_f = 0.3$ km and in the central densities $n_q^A - n_q^f = 0.6 n_0$ and $n_q^B - n_q^f = 2.1 n_0$, respectively. This is a consequence of the hardening of the EoS due to the presence of antineutrinos. The mass defect $\Delta M_{ij} = M_i - M_f$ can be interpreted as an energy release if there is a process which relates the configurations with $M_i$ and $M_f$ being the initial and final states, respectively. In the right panel of Fig. 6 we show limits for the binding energy release as a function of the final state mass when conservative values for the antineutrino chemical potential during the trapping are chosen. The antineutrino untrapping transition results in a first order phase transition which gives rise to an explosive release of the binding energy, as required for a scenario which should explain the engine of supernovae or gamma-ray bursts [5].
FIGURE 6. Left panel: Quark star configurations for different antineutrino chemical potentials $\mu_{\bar{\nu}_e} = 0, 72, 150$ MeV. The total mass $M$ in solar masses $M_\odot$ is shown as a function of the radius $R$ (left panel) and as a function of the central number density $n_q$ in units of the nuclear number density $n_0$ (right panel). Asterisks denote configurations with the same total baryon number. Right panel: Mass defect $\Delta M$ and corresponding energy release $\Delta E$ due to antineutrino untrapping as a function of the mass of the final state $M_f$. The shaded region is defined by the estimates for the upper and lower limits of the antineutrino chemical potential in the initial state $\mu_{\bar{\nu}_e} = 150$ MeV (dashed-dotted line) and $\mu_{\bar{\nu}_e} = 72$ MeV (dashed line), respectively.

Hybrid stars

Once the EoS with a quark-hadron phase transition is defined and the constraints of beta equilibrium and charge neutrality are obeyed (see previous Section), the corresponding hybrid star configurations are obtained from the solution of Einstein's equations [23].

Is a quark core possible?

The answer to this question depends crucially on the employed EoS. Within the setting of the present model, stable quark matter cores are possible for a Gaussian formfactor model but not for a cut-off one (NJL). This confirms on the one hand conclusions previously obtained within other approaches using an NJL model [24, 25] for quark matter but on the other hand presents an alternative quark matter model for which quark cores are possible, see Fig. 7.

Cooling curves and the compact star in 3C58

In order to obtain the cooling behavior of the presented hybrid star model, we employ the program code developed recently [19, 8] so as to describe 2SC quark matter and
investigate the dependence on the compact star mass [21]. The result shown in Fig. 8 demonstrates that a massive star may have a large enough quark core to entail an enhanced cooling behavior in accordance with the recent data point reported by CHANDRA measurements of the pulsar in the supernova remnant 3C58. This is, however, not a unique feature of a quark matter interior and could also be explained by other exotic phases of dense matter [26].

Population gap for accreting LMXBs

Our focus is on the elucidation of qualitative features of signals from the high density phase transition in the pulsar timing, therefore we use a generic form of an equation of state (EoS) with such a transition. We use the polytropic type equation of state for different values of the incompressibility [23] \( K_{L,H}(n) = 9 \frac{dP}{dn} \) at the saturation density, see Ref. [27]. The phase transition between the lower and higher density phases is made by the Maxwell construction and compared to a relativistic mean field model consisting of a linear Walecka plus dynamical quark model EoS with a Gibbs construction, Fig. 9.

We introduce a classification of rotating compact stars in the plane of their angular frequency \( \Omega \) and mass (baryon number \( N \)) which we will call phase diagram. In this diagram, configurations with high density matter cores are separated from conventional
ones by a critical phase transition line. The position and the form of these lines are sensitive to changes in the equation of state of stellar matter [2].

In Fig. 10 we display the phase diagrams for the rotating star configurations, which correspond to the three model EoS of Fig. 9. These phase diagrams have four regions: (i) the region above the maximum frequency $\Omega > \Omega_K(N)$ where no stationary rotating configurations are found, (ii) the region of black holes $N > N_{\text{max}}(\Omega)$, and the region of stable compact stars which is subdivided by the critical line $N_{\text{crit}}(\Omega)$ into (iii) the region of hybrid stars for $N > N_{\text{crit}}(\Omega)$ where configurations contain a core with a second, high density phase and (iv) the region of mono-phase stars without such a core.

From the comparison of the regional structure of these three different phase diagrams in Fig. 10 with the corresponding EoS in Fig. 9 we conclude that there are the following correlations between the topology of the lines $N_{\text{max}}(\Omega)$ and $N_{\text{crit}}(\Omega)$ and the properties of two-phase EoS:

- The hardness of the high density EoS determines the maximum mass of the star, which is given by the line $N_{\text{max}}(\Omega)$. Therefore $N_{\text{max}}(0)$ is proportional to the parameter $K_H(n_H)$, where $n_H$ is the density of the transition to high density phase.
- The onset of the phase transition line $N_{\text{crit}}(0)$ depends on the density $n_H$ and $K_L(n_L)$ where $n_L$ is the density of the transition to the low density phase.
FIGURE 9. Incompressibilities for Relativistic Mean Field (RMF) and polytropic EoS models with a phase transition, see [27].

- The curvature of the lines $N_{\text{max}}(\Omega)$ and $N_{\text{crit}}(\Omega)$ is proportional to the compressibility of the high and low density phases, respectively.

Therefore, a verification of the existence of the critical lines $N_{\text{crit}}(\Omega)$ and $N_{\text{max}}(\Omega)$ by observation of the rotational behavior of compact objects would constrain the parameters of the EoS for neutron star matter. We have investigated different trajectories of rotating compact star evolution in the phase diagram in order to identify scenarios, which result in signatures of the deconfinement phase transition [27]. A key evolutionary track corresponds to accretion with strong magnetic fields [28]. For this case the $\dot{\Omega}$ first decreases as long as the moment of inertia monotonously increases with $N$. When passing the critical line $N_{\text{crit}}(\Omega)$ for the phase transition, the moment of inertia starts decreasing and the internal torque term $K_{\text{int}}$ changes sign. This leads to a narrow dip for $\dot{\Omega}(N)$ in the vicinity of this line. As a result, the phase diagram gets overpopulated for $N \lesssim N_{\text{crit}}(\Omega)$ and depopulated for $N \gtrsim N_{\text{crit}}(\Omega)$ up to the second maximum of $I(N, \Omega)$ close to the black-hole line $N_{\text{max}}(\Omega)$. A population gap in the phase diagram of compact stars appears as a detectable indicator for hybrid star configurations.

CONCLUSIONS

We have investigated the influence of the diquark condensation on the thermodynamics of the quark matter under the conditions of $\beta$-equilibrium and charge neutrality relevant for the discussion of compact stars. The EoS has been derived for a nonlocal chiral quark model in the mean field approximation, and the influence of different formfactors...
(Gaussian, Lorentzian, NJL) has been studied. We have shown that the smoothness of the interaction changes the critical temperatures and chemical potentials for the onset of the phase transition to lower values.

The phase transition to color superconducting quark matter from the lower density regions at small temperatures \( T < 5 \div 10 \text{ MeV} \) is of first order, while the melting of the diquark condensate and the corresponding transition to normal quark matter at high temperatures is of second order. The presence of flavor asymmetry due to \( \beta \)-equilibrium in quark matter does not destroy the diquark condensate since the electron fraction \( n_e/n_{\text{total}} < 0.01 \) is too small. The masses of the quark core configurations could be up to \( 1.7 \, M_\odot \) and the radii could be up to 11 km.

We have investigated the effects of trapped antineutrinos on the asymmetry and diquark condensates in a quark star configurations. By comparing configurations with fixed baryon number the release of energy in an antineutrino untrapping transition is estimated to be of the order of \( 10^{53} \) erg. Such a transition is of first order so that antineutrinos can be released in a sudden process (burst). This scenario could play an important role to solve the problem of the engine of supernova explosions and gamma ray bursts. A detailed neutrino transport and cooling calculation should be taken into account in a future work. A second antineutrino pulse is suggested as an observable characteristics of the present scenario.

As there are still many unknowns in the picture we have drawn in this contribution for the possible effects of quark matter and color superconductivity on compact stars we would like to point out that there will not be one “smoking gun” type signal of quark matter but rather the different facets of the picture which emerges for characteristic
features of compact stars containing quark matter should all match in the big puzzle. To bring the pieces together is a task very similar to that of quark gluon plasma search in heavy-ion collision experiments.

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REFERENCES

1. Rajagopal, K., and Wilczek, F., *At the Frontier of Particle Physics / Handbook of QCD*, World Scientific, Singapore, 2000, vol. 3, chap. The Condensed Matter Physics of QCD, p. 2061.
2. Blaschke, D., Glendenning, N. K., and Sedrakian, A., editors, *Physics of neutron star interiors*, Springer, Heidelberg, 2001.
3. Hong, D. K., Hsu, S. D. H., and Sannino, F., *Phys. Lett.*, **B516**, 362 (2001).
4. Ouyed, R., *eConf*, **C010815**, 209 (2002).
5. Aguilera, D. N., Blaschke, D., and Grigorian, H., *arXiv:astro-ph/0212237* (2002).
6. Steiner, A. W., Reddy, S., and Prakash, M., *arXiv:hep-ph/0205201* (2002).
7. Neumann, F., Buballa, M., and Oertel, M., *arXiv:hep-ph/0210078* (2002).
8. Blaschke, D., Grigorian, H., and Voskresensky, D. N., *Astron. Astrophys.*, **368**, 561 (2001).
9. Carter, G. W., and Reddy, S., *Phys. Rev.*, **D62**, 103002 (2000).
10. Blaschke, D., Fredriksson, S., Grigorian, H., and Oztas, A. M., *arXiv:nucl-th/0301002* (2003).
11. Kiriyama, O., Yasui, S., and Toki, H., *Int. J. Mod. Phys.*, **E10**, 501 (2001).
12. Huang, M., Zhuang, P.-f., and Chao, W.-q., *arXiv:hep-ph/0207008* (2002).
13. Schmidt, S. M., Blaschke, D., and Kalinovsky, Y. L., *Phys. Rev.*, **C50**, 435 (1994).
14. Glendenning, N. K., *Phys. Rev.*, **D46**, 1274 (1992).
15. Voskresensky, D. N., Yasuhira, M., and Tatsumi, T., *Phys. Lett.*, **B541**, 93 (2002).
16. Drago, A., and Tambini, U., *J. Phys.*, **G25**, 971 (1999).
17. Berezhiani, Z., Bombaci, I., Drago, A., Frontera, F., and Lavagno, A., *arXiv:astro-ph/0209257* (2002).
18. Alford, M. G., Bowers, J. A., and Rajagopal, K., *J. Phys.*, **G27**, 541 (2001).
19. Blaschke, D., Klahn, T., and Voskresensky, D. N., *Astrophys. J.*, **533**, 406 (2000).
20. Page, D., Prakash, M., Lattimer, J. M., and Steiner, A., *Phys. Rev. Lett.*, **85**, 2048 (2000).
21. Grigorian, H., Blaschke, D., and Voskresensky, D. N., *MPG-VT-UR 231/02* (2002).
22. Prakash, M., Lattimer, J. M., Sawyer, R. F., and Volkas, R. R., *Ann. Rev. Nucl. Part. Sci.*, **51**, 295 (2001).
23. Glendenning, N. K., *Compact stars: Nuclear physics, particle physics, and general relativity*, Springer, New York, 1997.
24. Schertler, K., Leupold, S., and Schaffner-Bielich, J., *Phys. Rev.*, **C60**, 025801 (1999).
25. Baldo, M., et al., *arXiv:nucl-th/0212096* (2002).
26. Yakovlev, D. G., Kaminker, A. D., Haensel, P., and Gnedin, O. Y., *Astron. Astrophys.*, **389**, L24 (2002).
27. Blaschke, D., Grigorian, H., and Poghosyan, G., *arXiv:astro-ph/0208332* (2002).
28. Poghosyan, G. S., Grigorian, H., and Blaschke, D., *Astrophys. J.*, **551**, L73 (2001).