STRANGE MATTER IN CORE-COLLAPSE SUPERNOVAE *

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We discuss the possible impact of strange quark matter on the evolution of core-collapse supernovae with emphasis on low critical densities for the quark–hadron phase transition. For such cases the hot proto-neutron star can collapse to a more compact hybrid star configuration hundreds of milliseconds after core-bounce. The collapse triggers the formation of a second shock wave. The latter leads to a successful supernova explosion and leaves an imprint on the neutrino signal. These dynamical features are discussed with respect to their compatibility with recent neutron star mass measurements which indicate a stiff high density nuclear matter equation of state.

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1. Introduction

A core-collapse supernova (SN) explosion marks the disruption of a massive star by an energetic shock wave followed by the formation of a neutron star or a black hole. In the first hundreds of milliseconds (ms) of a supernova, temperatures in the range of tens of MeV, densities beyond nuclear matter saturation density $n_0 \sim 0.145$ fm^{-3} and proton fractions $Y_p \leq 0.3$

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are reached. With such properties, supernovae (SNe) are astrophysical laboratories for dense nuclear matter which, in the phase diagram of strongly interacting matter, possess overlap regions with heavy-ion experiments, such as in the future FAIR facility at GSI, Darmstadt (Germany) and the NICA facility at the JINR in Dubna (Russia). The modeling of core-collapse SNe represents a great computational challenge. It requires as input amongst others a nuclear matter equation of state (EoS), which provides information about the thermodynamic properties and compositions of matter for a large range of baryon number densities n_b, temperatures T, and isospin states, characterized by Y_p. Being discussed to populate neutron star interiors, hyperons and quark matter can also be included in SN equations of state (EoSs). At present, both components are tested on their impacts in SN simulations. Hereby, the applied quark and hyperon EoSs should be compatible with observed neutron star properties, *e.g.* pulsar masses. As we will argue in the next section, the latter indicate a stiff nuclear matter EoS at high density.

In the following, we will give a short summary on recent pulsar mass measurements and their implications for quark matter in neutron star interiors. We will proceed with an overview of quark matter studies in core-collapse SNe. In the last section, we will focus on the impact of low density quark–hadron phase transitions on the gravitational collapse of light and intermediate mass progenitor stars.

2. Strange quark matter in massive neutron stars

Neutron star masses can be deduced for pulsars in binary systems, if effects from general relativity such as the advance of periastron $\dot{\omega}$ and Shapiro delay are observable in the pulsar signal [1]. For a long time the Hulse–Taylor pulsar PSR B1913+16 had the highest precisely known mass of $M = 1.4414 \pm 0.0002\, M_\odot$, with most pulsars clustering around this value [2]. However, the observation of $\dot{\omega}$ and Shapiro delay in the low mass X ray binary J1903-0327 [3] allowed the determination of the mass for the corresponding millisecond pulsar to $M = 1.667 \pm 0.021\, M_\odot$. In 2010, an even higher pulsar mass was obtained for the millisecond pulsar PSR J1614-2230. A massive binary partner and the large inclination angle of the system allow the measurement of the Shapiro delay to a high accuracy and reveal a pulsar mass of $M = 1.97 \pm 0.04 M_\odot$ [4]. At present, this value represents the highest robust mass ever measured for a compact star and poses tight constraints on the nuclear matter EoS restricting it to stiff models. Hybrid and strange stars are only compatible with such a high mass if stiffening effects from the strong interaction between the quarks, *e.g.* in form of the strong interaction coupling constant α_s and/or color superconductivity, have a large impact on the quark matter EoS (see [5] and references therein).

3. Strange quark matter in core-collapse supernovae

The dynamical effects of phase transitions on neutron stars and core-collapse SNe were first discussed by Migdal [6] in 1979, and later studied by Takahara and Sato [7] as well as Brown [8]. In the early 90s, Gentile *et al.* [9] performed general relativistic hydrodynamic core-collapse SN simulations including a phase transition to strange quark matter for critical densities of $\sim$ (2–3) n_0. The authors tested different setups of the quark–hadron mixed phase, finding the formation of two shock waves. The first shock wave is caused by the usual stiffening of the hadronic EoS for $n_b > n_0$, which halts and reverts the infall of matter in the center of the collapsing iron core (core-bounce). The second wave is formed due to the softening of the EoS in the quark–hadron mixed phase together with the subsequent stiffening in pure quark matter. As neutrino transport was not included in the calculations, the dynamics of the shock waves could only be followed for a few ms. Simulations including neutrino transport were performed by *e.g.* Nakazato *et al.* [10,11]. The authors applied the hadronic Shen SN EoS [12] extending it by the inclusion of quark matter at higher densities as well as thermal pions. For the quark matter EoS, Nakazato *et al.* chose the simple bag model [13] with a bag constant of $B^{1/4} \sim 209$ MeV. The quark–hadron phase transition was modeled by a Gibbs construction [14]. The studied progenitor stars had masses of $\geq 40\, M_\odot$, whereas the gravitational collapse of such massive stars usually ends with the production of a black hole [15]. Due to the softer hybrid EoS, the onset of quark matter accelerates the black hole formations by tens to hundreds of ms in comparison to simulations with the original Shen EoS. While the earlier collapse results in a shortening of the neutrino emission, the softening of the EoS influences the neutrino spectra. Both effects can be used as indicators for a quark matter phase transition. However, as hyperons and different nuclear interactions [16, 17] can have similar imprints on the neutrino signal, further studies are required.

In this work, we focus on quark matter phase transitions with low critical densities around n_0 for SN conditions. It was shown by Drago *et al.* [18] and later argued in Sagert *et al.* [19] and Fischer *et al.* [20] that quark models with such low $n_{\rm crit}$ for SN conditions can be compatible with higher transition densities in heavy ion collisions, caused by the larger Y_p in the latter and different strangeness production mechanisms.

4. Early quark–hadron transition in core-collapse supernova

In our study, we implement a quark–hadron phase transition into the Shen EoS via the Gibbs construction. For the quark matter EoS, we apply a quark bag model which is extended by first order corrections in $\alpha_{\rm s}$. The thermodynamic grand potential is given by [20]

$$\Omega_{\rm QM} = \sum_{i=u,d,s} \left[\Omega_i + \frac{\alpha_{\rm s}}{\pi} \left(T^2 \mu_i^2 + \frac{\mu_i^2}{2\pi^2} \right) + \frac{35\pi}{126} T^4 \alpha_{\rm s} \right] + B \,. \qquad (1)$$

Hereby, Ω_i are the Fermi–Dirac contributions for the up, down, and strange quarks. First order corrections from $\alpha_{\rm s}$ are given by the second and third terms, while B is the bag constant which represents all non-perturbative effects of the strong interaction. The quark masses are chosen to m_s = 100 MeV for strange quarks and $m_u = m_d = 0$ MeV for up and down quarks. In the very simple bag model, first order corrections from $\alpha_{\rm s}$ are not present. As a consequence, the corresponding quark EoS is very soft. The maximum masses of the resulting hybrid stars are low and do not fulfill the mass constraint of PSR J1614-2230 [5]. The inclusion of $\alpha_{\rm s}$ correction terms stiffen the quark EoS and can increase the hybrid star maximum masses up to $\geq 2\, M_\odot$ [5]. For low critical densities, the resulting hybrid stars have an extended quark–hadron mixed phase in their interior and only for sufficiently stiff hadronic EoSs possess a pure quark matter core [5]. Figure 1 shows the mass-radius relations for different parameter sets in Eq. (1). Hadronic matter is described by the relativistic mean field model TM1 [21] which is also the basis for the Shen EoS. The three parameter sets with $\alpha_{\rm s} = 0$ and $\alpha_{\rm s} = 0.3$, shown in Fig. 1, have been tested on their impact in one-dimensional SN simulations based on general relativistic radiation hydrodynamics and three flavor Boltzmann neutrino transport [22]. The

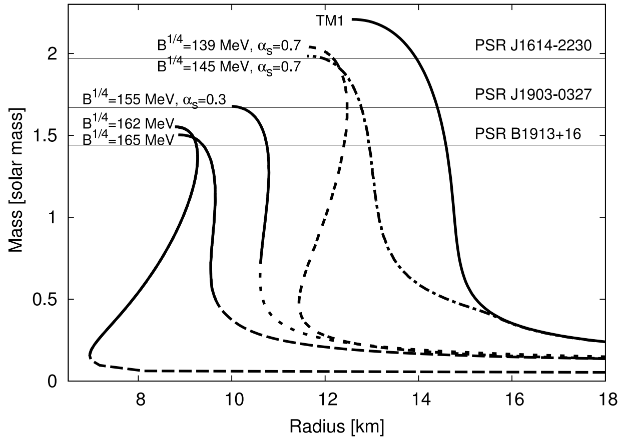

Fig. 1. Hybrid star mass radius relations for the quark bag model in Eq. (1) and the hadronic EoS TM1. Solid lines are stars with a pure quark matter core, while dashed lines indicate mixed phase cores. The horizontal lines show pulsar mass measurements discussed in the text.

simulations show that due to the low critical densities, the quark–hadron mixed phase sets in already at core-bounce, when matter in the center of the collapsing iron core reaches densities around n_0. However, as the quark fraction is small and $Y_p \sim 0.3$, the hybrid EoS is very similar to the one of hadronic matter [20], and the dynamics proceed like in a normal core-collapse SN for the first (200–400) ms. The core-bounce launches a hydrodynamic shock wave which starts to propagates outwards. On its way, it loses energy due to the disintegration of infalling heavy nuclei and production of neutrinos. As the shock wave moves across the neutrinospheres, the neutrinos are emitted in a burst dominated by electron neutrinos ν_e. This energy loss turns the expanding shock into a standing accretion shock (SAS). As shock-heated matter continues to be accreted through the SAS on the surface of the proto neutron star (PNS), the density and temperature in its interior rise and a growing volume of the PNS enters the mixed phase. The quark fraction in the mixed phase increases which leads to a softening of the EoS. This, together with the growing gravitational mass of the PNS eventually triggers its collapse to a more compact hybrid star configuration. Similar to the study of Gentile *et al.* [9], a second shock wave forms and propagates outwards. Shock heating of the infalling neutron rich matter leads to the production of $\bar{\nu}_e$, as well as $\nu_{\mu/\tau}$, and $\bar{\nu}_{\mu/\tau}$, which are released in a second burst as the second shock wave propagates across the neutrinospheres. For all three parameter sets the second shock wave eventually leads to an SN explosion, whereas the explosion energy and the time difference between the first and second neutrino bursts depend on $n_{\rm crit}$ and the model of the progenitor star [19, 20]. To test the effects of a stiffer quark EoS on the SN dynamics we chose $B^{1/4} = 145$ MeV and $\alpha_{\rm s} = 0.7$. As can be seen from Fig. 1, the corresponding hybrid star maximum mass is $\sim 1.97\, M_\odot$ and thereby compatible PSR J1614-2230. Fig. 2 shows the phase diagram for different values of Y_p (for details of phase diagram calculations see [20]). The critical densities for the onset of the mixed phase for $Y_p = 0.3$ are around $n_{\rm crit} < 1.5\, n_0$, however, due to the similar stiffness of the quark and hadron EoSs, the mixed phase extends up to $\geq 10\, n_0$ for low T. As the temperature rises above 60 MeV, the mixed phase experiences a significant reduction and the critical densities become low. However, for such high values of T, the inclusion of pions and hadron resonances becomes important and would most likely change the shape of the phase diagram. Similar to the soft bag EoS parameter sets, we tested the new hybrid EoS in one-dimensional SN simulations for the collapse of a 15 $M_\odot$ and a 30 $M_\odot$ progenitor. In both cases we find that quark matter appears very late — around 1 s after core bounce and does not influence the SN dynamics [23]. The reason for this outcome can be seen in Fig. 3 which shows the onset of the mixed phases for the discussed quark EoSs. Though the critical densities for $B^{1/4} = 145$ MeV

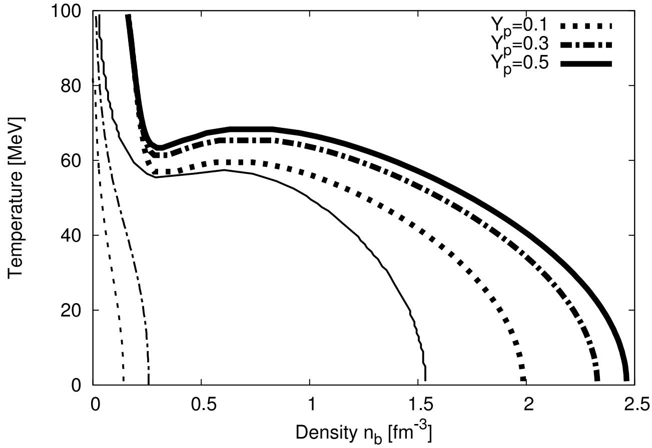

Fig. 2. Phase diagram for transitions from hadronic matter (TM1) to strange quark matter at $Y_p = 0.1, 0.3$, and 0.5. The quark matter parameters are $B^{1/4} = 145$ MeV and $\alpha_s = 0.7$. Thin lines mark the onset of the quark–hadron mixed phase, thick lines give the transition to pure quark matter.

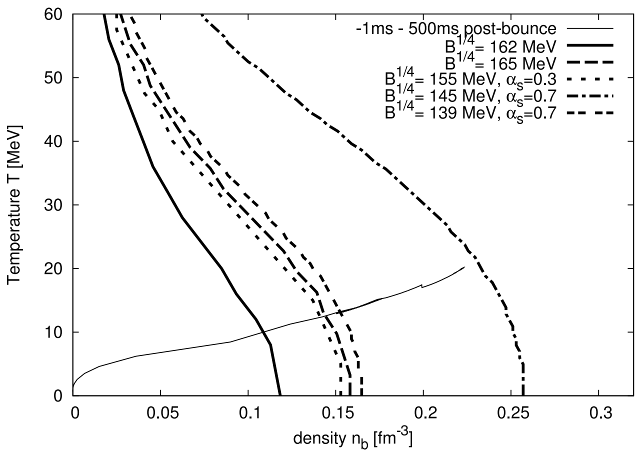

Fig. 3. Onset of the mixed phase for different quark EoS parameter sets and $Y_p = 0.3$. The thin solid line shows the temperatures and densities which are reached in the center of the PNS shortly before and during the first 500 ms after core-bounce.

and $\alpha_s = 0.7$ are low, it can be seen that they are higher in comparison to the soft EoSs. In addition, we plot the densities and temperatures in the center of the PNS shortly before and during the first 500 ms after the core-bounce. While it can be seen that for the soft models, matter in the PNS enters the quark–hadron mixed phase, the critical densities for the new parameter set are too high. However, the reduction of the bag constant to

$B^{1/4} = 139$ MeV leads to sufficiently low values of $n_{\rm crit}$ as is illustrated in Fig. 3 and also fulfills the maximum mass constraint of PSR J1614-2230 (see Fig. 1). This parameter set is currently tested in one-dimensional SN simulations and will give further insights in the role and detectability of a quark matter phase transition in core-collapse SNe.

5. Summary

The onset of strangeness in core-collapse supernovae (SNe) can be studied by implementing hyperons and strange quark matte in SN equations of state (EoSs). Hereby, the chosen parameter sets must fulfill restrictions from the recent finding of a two solar mass pulsar PSR J1614-2230, which is only compatible with a stiff high density nuclear matter EoS. Within currently applied quark EoS models, high critical densities were shown to shorten the time to black hole formation in the gravitational collapse of massive progenitor stars. For the onset of quark matter with a soft EoS at critical densities $n_{\rm crit}$ around nuclear matter saturation density $n_0 \sim 0.145$ fm^{-3}, the proto neutron star collapses to a more compact hybrid star configuration within hundreds of ms after core-bounce. This launches a shock wave which leads to the SN explosion and releases a neutrino burst, dominated by $\bar{\nu}_e$. The properties of the neutrino burst are dependent on $n_{\rm crit}$ as well as the model of the progenitor star. A first study with a stiff quark EoS shows no impacts on the SN dynamics as the critical densities are too high to be reached in the early post-bounce phase. However, studies are on the way, in which we apply a stiff quark EoS parameter set, where SN matter enters the quark–hadron mixed phase at $n_{\rm crit} \sim n_0$.

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