The Strange Prospects for Astrophysics

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Abstract. The implications of the formation of strange quark matter in neutron stars and in core-collapse supernovae is discussed with special emphasis on the possibility of having a strong first order QCD phase transition at high baryon densities. If strange quark matter is formed in core-collapse supernovae shortly after the bounce, it causes the launch of a second outgoing shock which is energetic enough to lead to an explosion. A signal for the formation of strange quark matter can be read off from the neutrino spectrum, as a second peak in antineutrinos is released when the second shock runs over the neutrinosphere.

1. Introduction

The exploration of the QCD phase diagram is not only a task for heavy-ion physics as there are strong relations to astrophysics of extremely dense matter and even to cosmology. The conditions in the early universe are similar to the ones probed at the heavy-ion collisions at RHIC and LHC, high temperatures and low net baryon densities. Supernova matter and neutron star matter is located in the QCD phase diagram at moderate temperatures and high net baryon densities. In this region of the QCD phase diagram one expects to have a strong first order phase transition which is related to the restoration of chiral symmetry+. QCD matter at extreme baryon densities will be investigated by heavy-ion experiments with FAIR at GSI Darmstadt.

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+ In the following, we will refer to the new phase at high densities generically to ‘quark matter’ although matter is not necessarily deconfined as the phase transition is related to chiral symmetry restoration.
The QCD equation of state (EoS) is an essential input in astrophysical systems. In core-collapse supernovae simulations temperatures of about $T = 10 - 20$ MeV with densities slightly above normal nuclear matter density are reached at core bounce, the newly born proto-neutron star is heated up to $T = 50$ MeV with densities a few times normal nuclear matter densities, the final cold neutron stars then has central densities of up to ten times normal nuclear matter densities for a soft equation of state. Finally, neutron star mergers simulations can achieve temperatures of typically $T = 30$ MeV, even higher temperatures have been noticed for some equations of states. Note, that the dynamical timescales involved are usually not much less than around a few 100 microseconds so that they are always much larger than the timescale to establish equilibrium with respect to weak interactions involving strange particles of about $10^{-8}$ seconds or less. Hence, the matter for astrophysical applications is necessarily in weak equilibrium with respect to strangeness and always includes strange matter! Except for cold neutron stars, there is a subtlety here, as protons and neutrons are not in weak equilibrium. Hence, for dynamical astrophysical scenarios, the matter is characterized by a given temperature $T$, baryon density $n$ and proton fraction $Y_p$.

For hunting down strange quark matter in the heavens several signals have been suggested in the literature as exotic mass-radius relation of compact stars, rapidly rotating pulsars due to r-mode stability window, enhanced cooling of neutron stars, and gamma-ray bursts by transition to strange quark matter. Let us first concentrate on strange quark matter in neutron star before we discuss the implications of the formation of strange quark matter for core-collapse supernovae.
2. Strange Quark Matter in Neutron Stars

Neutron stars are produced in core-collapse supernova explosions and are extremely compact, massive objects with radii of $\approx 10$ km and masses of $1 - 2M_\odot$, involving extreme densities, several times nuclear density: $n \gg n_0 = 0.16$ fm$^{-3}$.

More than 1700 pulsars, rotation-powered neutron stars, are presently known. The best determined mass is the one of the Hulse-Taylor pulsar, $M = (1.4414 \pm 0.0002)M_\odot$ [2], the smallest known mass is $M = (1.18 \pm 0.02)M_\odot$ for the pulsar J1756-2251 [3]. Note, that the mass of the pulsar J0751+1807 has been corrected from $M = 2.1 \pm 0.2M_\odot$ to $M = 1.14 - 1.40M_\odot$[4]. We note that the extremely large neutron star masses extracted from pulsars found in globular clusters [5] can only give an upper bound. Only the periastron advance of the pulsar PSR J1748-2021B has been determined so far, the inclination angle $i$ of the orbital plane is still unknown. A statistical analysis for that angle is not really appropriate for one pulsar. For an inclination angle of $i = 4 - 5$ degrees, two neutron stars with a mass of $M \sim 1.4M_\odot$ are possible. A measurement of a second effect from general relativity is needed to draw a firm final conclusions.

The spectral analysis of the closest isolated neutron star known, RX J1856.5-3754, hints at more complex surface properties than initially expected. Fits with a two-component blackbody as well as with a condensed surface and a small layer of hydrogen result in rather large radiation radii $R_\infty = R/\sqrt{1 - 2GM/R} = 17(d/140\text{pc})$ km. With an inferred gravitational redshift of $z_g \approx 0.22$, the neutron star would have a true radius of $R \approx 14$ km and a mass of $M \approx 1.55M_\odot$ [6]. A large uncertainty resides in the still not well known distance $d$, but clearly more data and analysis is needed to understand the atmosphere and the radiation of neutron stars.

In binary systems of a neutron star with an ordinary star accreting material falling onto the neutron star ignites nuclear burning which is observable as an x-ray burster. The analysis of Özel [7] for the x-ray burster EXO 0748–676 arrived at mass-radius constraints of $M \geq 2.10 \pm 0.28M_\odot$ and $R \geq 13.8 \pm 1.8$ km. The values derived have to be taken with great care, as a multiwavelength analysis of Pearson et al. [8] concludes that the data is more consistent with a mass of $M = 1.35M_\odot$ than with $M = 2.1M_\odot$. Even if such large masses and radii are taken for granted, quark matter can still be present in the interior of neutron stars as demonstrated by Alford et al. [9]. The limits would rule out soft equations of states, not quark stars or hybrid stars, compact stars with a hadronic mantle and a quark matter core.

Future telescopes and detectors will probe compact stars in more details as the International X-ray Observatory IXO, the James Webb Space Telescope JWST, the Square Kilometre Array SKA, LISA and UNO, an underground neutrino observatory. With the future x-ray satellites one can measure the profile of the burst oscillations which is modified from the space-time warpage around the compact star. By this method a model independent measurement of the mass and radius of the compact star can be extracted. It was claimed that one could determine the mass-radius ratio to within 5% with Constellation-X with this method [10].
Quark matter in neutron stars has been widely described by using the MIT bag model with basically one free parameter, the MIT bag constant $B$. The onset of the mixed phase from the hadronic to the quark phase occurs between $(1 - 2)n_0$ even for large values of the bag constant $B$ and then sufficiently high densities are reached in the core of a $1.3M_\odot$ compact star to have quark matter (see Figure 2). Corrections from hard thermal loop calculations do not change these numbers significantly.

So called hybrid stars consist of hadronic matter and quark matter and there are three phases possible: a hadronic phase, a mixed phase and a pure quark phase. The composition depends crucially on the parameters as the bag constant $B$ and the interaction strength $g$ between quarks as well as the total mass of the compact star.

In addition, there exists a third solution to the TOV equations besides the one for the white dwarfs and the one for ordinary neutron stars, which is stabilized by the presence of a pure quark matter phase [12, 13, 14, 15, 11, 16]. The third family of compact stars is generically more compact than ordinary neutron stars and is possible for any first order phase transition.

3. Strange Quark Matter in Supernovae

Stars with a mass of more than 8 solar masses end in a core-collapse supernova (type II, Ib or Ic). New generation of simulation codes now have multidimensional treatments and improved neutrino transport. Still, until recently, no explosions could be achieved (see e.g. [17]) suggesting missing physics either with respect to neutrino transport or to the nuclear equation of state. Only after sufficiently long simulation runs with a quasi unconstrained geometry a standing accretion shock instability could develop which leads to an explosion after 600ms [18].
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The conditions of core-collapse supernova matter at bounce are as follows: energy densities slightly above normal nuclear matter density $\epsilon \sim (1-1.5)\epsilon_0$, temperatures of $T \sim 10-20$ MeV and a proton fraction of $Y_p \sim 0.2-0.3$. The standard lore for the onset of the quark phase in core-collapse supernovae is that it happens during the evolution of the proto-neutron star and not at bounce. The timescale for quark matter to appear would then be typically $(5-20)$ s after bounce [19], which is, however, due to using rather large bag constants of $B > 180$ MeV. Such a large bag constant would hardly allow for a pure quark matter phase to develop in the core of cold neutron stars with a mass of $1.3M_\odot$ (see figure 2). The appearance of quark matter would then be well after the supernova explosion itself. So the question is, can it be possible to produce quark matter much earlier with a smaller bag constant?

Figure 3 shows the phase transition line to quark matter for a given temperature versus the net baryon density (left plot) and versus the baryochemical potential (right plot) for different values of the proton fraction $Y_p$. The hadronic phase is modelled by using the EoS of Shen et al. [20], the quark phase by the MIT bag model with a bag constant of $B^{1/4} = 165$ MeV and a strange quark mass of 100 MeV, the phase transition by a Maxwell construction. Interestingly, the critical baryochemical potential is nearly independent on the proton fraction $Y_p$ and bends towards low chemical potentials for high temperatures as envisioned in the sketch of the QCD phase diagram depicted in figure 1. However, the phase transition occurs at lower densities for lower proton fractions and higher temperatures, so that neutron-rich hot supernova material is favourable for the formation of strange quark matter. Note, that strangeness is not conserved in supernova matter contrary to the situation in heavy-ion collisions. Strange quark matter can be formed via the coalescence of hyperons in supernova matter which are thermally excited in weak equilibrium on timescales of $10^{-8}$ s or less. Hyperon fractions of about 0.1% are already present at bounce, see [21]. The lower critical density in neutron-rich matter is due to the sizable nuclear symmetry energy so that
Figure 4. Mass-radius relation of cold neutron stars for the supernova EoS used for different bag constants. For low bag constants, the maximum mass is again above the mass limit from the Hulse-Taylor pulsar of 1.44 $M_\odot$ which is shown by the horizontal line.

Strange quark matter becomes the energetically preferred phase. For supernova material at bounce ($T = 10 \sim 20$ MeV, $Y_p = 0.2 \sim 0.3$, $n \approx n_0$), one reads from the figure that the immediate production of quark matter is possible!

Two checks have to be performed in order to be consistent with neutron star data and heavy-ion phenomenology. First, the maximum mass of a compact star with the adopted EoS should be at least above 1.44 $M_\odot$. The mass-radius relation is plotted in figure 4 for different values of the MIT bag constant (for simplicity a Maxwell construction is used for the phase transition). For large bag constants, the maximum mass is well above the mass limit from the Hulse-Taylor pulsar. For some intermediate values, here for the cases of $B^{1/4} = 170$ MeV and 175 MeV, the maximum mass is below 1.44 $M_\odot$ because of the large jump in energy density from one phase to the other [22]. That was the reason why smaller values of the bag constants were rejected in the work on proto-neutron stars in ref. [19]. However, for even smaller bag constants of $B^{1/4} = 165$ MeV and below, the maximum mass is again above 1.44 $M_\odot$ owing to the increased stability of the pure quark matter core. The maximum masses are 1.56 $M_\odot$ ($B^{1/4} = 162$ MeV) and 1.5 $M_\odot$ ($B^{1/4} = 165$ MeV). Note, that the maximum mass for pure quark matter stars, selfbound strange stars, is well known to be about 2.1 $M_\odot$ for the original value of the MIT bag constant, $B^{1/4} = 145$ MeV [23, 24, 25].

Secondly, we have to calculate the phase transition line appropriate for matter produced in relativistic heavy-ion collisions. The timescales are too short to generate weak equilibrium in heavy-ion collisions, so the initially produced quark matter has net strangeness zero (of course thermal production of strange quark pairs is possible but highly suppressed for the low temperatures relevant for supernova explosions). Therefore, the quark matter formed consists mainly out of pure up- and down-quarks
and becomes highly unfavoured compared to the case of supernova matter, where strange quark matter is formed. Indeed, we find large critical densities for the phase transition, in particular for isospin-symmetric matter (proton fraction $Y_p = 0.5$) which is relevant for the heavy-ion case. The phase transition occurs at much larger baryon densities, well above five times normal nuclear matter density for low temperatures so that low-energy heavy-ion collisions can not produce quark matter. Also the phase transition line is located at larger chemical potentials for up-down-quark matter. The location of the freeze-out points in statistical approaches is about $\mu_{f.o.} = 700 - 800$ MeV, $T_{f.o.} = 50 - 70$ MeV for SIS energies and $\mu_{f.o.} \sim 500$ MeV, $T_{f.o.} \sim 120$ MeV for AGS energies. These values are lying below the phase transition line in the corresponding right plot of fig. 5. Note, that the hadronic equation of state has been modelled to suit its applications for supernova simulations. Therefore, temperatures of more than 50 MeV can not be handled appropriately in principle, but are also not relevant for our purposes here. For the application to higher temperatures, one needs to improve the hadronic equation of state by e.g. incorporating pions, kaons, hyperons and resonances which would shift the phase transition line to even higher densities and baryochemical potentials.

Now as the supernova EoS has passed these two tests, let us discuss the implications for core-collapse supernovae [26]. The stiffening of the nuclear EoS above normal nuclear matter densities produces a bounce of the supernova material, a shock wave is moving outwards but stalls around 100 km. Afterwards, quark matter is formed in the core and at a few 100ms the mixed phase collapses and an accretion shock develops on the pure quark matter core. The accretion shock turns into an outgoing shock wave which is so energetic that it runs over the stalled first shock leading to an explosion! Note, that normally 1D supernova simulations are not able to achieve an explosion, only
multidimensional codes are presently capable of producing an explosion with the help of the standing accretion shock instability, see [18].

Our supernova simulation runs were performed for different parameters, where the quark core appears at $t_{pb} = 200 \text{ ms to 500 ms}$ post bounce. The results ($t_{pb}$, baryonic mass and explosion energy) are significantly sensitive to the location of the QCD phase transition (i.e. the bag constant in our case). Heavier progenitor masses can lead to the formation of a black hole which could be circumvented by stiffening the quark EoS in order to explain the rather long emission of neutrinos from SN1987A.

Most interestingly, we find that the temporal profile of the emitted neutrinos out of the supernova reflects the features of the QCD phase transition. Figure 6 shows the neutrino luminosity and the mean energy as a function of time. The first peak in electron neutrinos is due to the first shock. When the QCD phase transition is included we find a second peak in electron anti-neutrinos at about the time when the strange quark matter core is created. The pronounced second peak of anti-neutrinos is due to the protonization of the material when the second shock front runs over the neutrinosphere. We note that the location of the second peak and its height is controlled by the critical density and strength of the QCD phase transition!
4. Summary

The QCD phase transition to strange quark matter leads to a rich variety of astrophysical signals involving compact stars and supernovae. Neutron stars with a core of strange quark matter are compatible with present neutron star data. Strange quark matter can be formed in supernovae, even shortly after the first bounce. A second outgoing shock is generated which has enough energy to lead to an explosion. The presence of a strong QCD phase transition can be read off from a second peak in the (anti-)neutrino signal. The formation of strange quark matter will certainly have also significant implications for the gravitational wave signal of core-collapse supernovae and for the r-process nucleosynthesis as core-collapse supernovae are considered to be the prime astrophysical site.

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