Strange Quark Matter in Stars: A General Overview

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Abstract. The physics of strange quark matter in the core of compact stars and recent compact star data is reviewed. Emphasis is put on the possible existence of a third family of strange quark stars.

1. Introduction

The study of the QCD phase diagram encompasses a plethora of phenomena. High temperatures and low baryon number densities are realized in the early universe and in the mini-bang in the laboratory, i.e. relativistic heavy–ion collisions. On the other hand, low temperatures and high baryon number densities are the realm of compact stars, neutron stars and quark stars. In the following, we address the physics of the latter area of the QCD phase diagram, in the spirit of this meeting focusing on the rôle of strangeness.

Neutron stars are the endpoint of stellar evolution of massive stars with $M > 8M_\odot$. They are compact, massive objects with typical radii of about 10 km and masses of $(1 - 2)M_\odot$. Presently, more than 1500 pulsars, rotating neutron stars, are known. So far, the best determined mass is the one of the Hulse-Taylor pulsar with $M = 1.4411 \pm 0.00035M_\odot$[1]. We will discuss more recent developments in the determination of neutron star masses and radii in section 3.

Let us explore the composition and structure of neutron stars starting from the surface. There is a thin atmosphere up to a density of about $10^4$ g/cm$^3$ of atoms, the outer crust has a density between $10^4$ g/cm$^3$ and $4 \cdot 10^{11}$ g/cm$^3$ and consists of a lattice of nuclei surrounded by free electrons. The inner crust starts beyond the drip-line density with densities of $4 \cdot 10^{11}$ g/cm$^3$ to $10^{14}$ g/cm$^3$, where the lattice of nuclei is now immersed in a gas of neutrons and electrons. At even larger densities, one reaches the core of the neutron star, a liquid of neutrons, protons, electrons and other particles. The composition of the core of a neutron star is a matter of intense debate. Several more or less exotic phases have been proposed to exist: pion condensation, kaon condensation, hyperon matter, and finally quark matter including strange quarks (see e.g. [2, 3] for
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a discussion on the various phases). The Bodmer–Witten scenario, that strange quark matter can be more stable than ordinary nuclear matter, suggests that there exists a corresponding class of compact stars, so called strange stars \cite{4,5}, where the core consists of about equal amounts of up, down and strange quarks. Only an outer crust can exist for this kind of compact star, as unbound neutrons are converted to more stable strange quark matter. Let us start more conventional and look at a free gas of particles of known hadrons, including pions, kaons and hyperons. It turns out, that in $\beta$-equilibrium the first “exotic” hadron beside nucleons and leptons are hyperons: the $\Sigma^-$ appears at $4n_0$, the $\Lambda$ at $8n_0$, where $n_0 = 0.15$ fm$^{-3}$ is normal nuclear matter density \cite{6}. The maximum mass, however, will be around $M = 0.7M_\odot$ for a free gas of neutrons \cite{7} substantially smaller than the required $M = 1.44M_\odot$. Hence, taking into account interactions (and interaction energy) is crucial to describe neutron stars. Note, that this in contrast to the case of white dwarfs, which can be well described by a free gas of electrons and a lattice of nuclei.

2. Neutron Star Modelling

Motivated by the results for a free gas of hadrons, implementing hyperons into the composition of neutron star matter besides nucleons and leptons seems to be a reasonable first step. Indeed, modern models, of the equation of state for neutron stars confirm that the hyperons $\Lambda$ and/or the $\Sigma^-$ appear first around $2n_0$, see e.g. \cite{8} and references therein. Most notable, what one learns from these calculations is, that neutron stars are most likely strange in the interior! The story about matter with strangeness in neutron stars does not end here. Increasing the strength of the basically unknown interaction between hyperons reveals a new aspect of compact star physics: the possible existence of a new class of family of compact stars besides white dwarfs and ordinary neutron stars (see figure 1)! This new stable solution to the Tolman–Oppenheimer–Volkoff (TOV) equations is characterised by an increased compactness compared to ordinary neutron stars. The mass-radius curve shows an instability at the onset of the phase transition to hyperon matter which vanishes once a core of pure hyperon matter is present \cite{9}. Increasing the attraction between hyperons even further, the mass-radius curve changes its characteristics completely: hyperon matter gets absolutely stable and corresponding hyperon stars can become arbitrarily small in radii and mass. Typical radii even when including an (outer) crust are in the range $R = 7 \text{ – } 8 \text{ km}$. Such compact stars are generically dubbed selfbound stars. Figure 1 shows the mass-radius relation for the various cases. Note, that all these cases and phases are described within one single Lagrangian!

In the following, let us summarise in some detail the properties of selfbound stars and the third family. For neutron stars we note:
- they are bound by gravity, there is a finite pressure for all energy density
- their mass–radius relation starts at large radii,
- the minimum neutron star mass is $M \approx 0.1M_\odot$ with $R \approx 200$ km
while for selfbound stars:

- there is a vanishing pressure at a finite energy density
- the mass-radius relation starts at the origin (ignoring a possible outer crust)
- arbitrarily small masses and radii are possible.

At first glance, the global properties of neutron stars and selfbound stars, in particular those made out of absolutely stable strange quark matter [4, 5], are quite similar, like the maximum mass and the corresponding radius, or the surface properties due to the same outer crust. There are, however, unique features of strange stars, which can have spectacular effects for astrophysical systems as e.g.: compact stars with arbitrarily small masses and small radii (dubbed golf balls in [10]), collapse of neutron stars to quark stars [11], explosive conversion of neutron stars to strange stars [12], generation of a secondary shock wave in supernova explosions [13, 14], strange dwarfs: small and light white dwarfs with a strange star core [15], super-Eddington luminosity from bare, hot strange stars [16].

We stress, that the existence of strange stars hinges on the underlying assumption that strange quark matter is more stable than ordinary nuclear matter. On the other hand, the criteria for the existence of the third family of compact stars is less stringent: there has to be a strong first order phase transition in $\beta$-equilibrated matter [17]. The new solution to the TOV equation is stable and generates compact stars which are more compact than neutron stars. Note, that any first order phase transition can possibly produce a third family. Signals for a first-order phase transition in compact stars and/or a third family in general proposed in the literature are e.g.: delayed collapse of a proto-neutron star to a black hole [18], spontaneous spin–up of pulsars [19], generation of a
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secondary shock wave in supernova explosions (as proposed for strange stars), specific
waveforms of gravitational waves from colliding neutron stars [20], collapse of a cold
neutron star to the third family [21, 22] with possible emission of gravitational waves,
γ-ray bursts, and neutrinos, rising twins in the mass–radius diagram: compact stars
with \( M_1 < M_2 \) and \( R_1 < R_2 \) (see e.g. [23]), delayed collapse of a cold neutron star and
gamma-ray bursts [24].

The third family of solution was considered before for hyperon matter [25] (so
called hyperon stars), pion-condensed stars [26, 27] and also for stars with a quark core
[28, 29]. Note, that Kämpfer used polytropic equation of states to derive conditions for
the existence of a third family for pion-condensed stars and stars with a quark core, so
that his results can be generalised in principle for an arbitrary exotic phase in the core
of compact stars. A modern treatment investigating the appearance of the third family
with parametric equation of states can be found in [30]. The third family solution
was rediscovered only recently. Its properties are now discussed in terms of modern
equation of states which take into account the Gibbs criteria for phase transitions in
compact stars [31, 23] and for stars with a quark core [32, 33, 34, 35]. There is even a section devoted to the third
family in the second edition of Glendenning’s textbook [2]. Contrary to earlier findings
within Bose-condensed stars but consistent with the results of Kämpfer [28, 29], the
third family has similar masses compared to the ordinary neutron star branch and
constitutes a truly new branch for compact stars. One should stress again, that the
existence of the third family of compact stars depends on a strong first order phase
transition of the equation of state (see e.g. the general discussion in [17, 28, 27, 23, 36]).
The underlying micro-physical form of the phase transition is not relevant for the global
properties (mass–radius) of compact stars by solving the TOV equations. So a third
family has been found for a phase transition using the MIT bag model for quark matter
[31, 34], massive quasi-particles of quarks [23], hyperon matter [9], interacting quarks in
perturbative QCD [32], kaon condensates [33], and colour-superconducting quarks [35].
The third family has been also studied for rotating compact stars in [37, 38].

In the following, we take a closer look at the QCD phase transition at finite chemical
potential and zero (or small) temperature focusing on the chiral phase transition. For
dense matter, there is a naive argument why the chiral phase transition should happen
after deconfinement. Consider the counter-situation, assume that the hadrons are in
the chirally restored phase and hypothesise that the hadrons are massless (which is not
necessarily implied by chiral symmetry restoration!). Then compare the pressure with
that of free, massless quarks at the same baryochemical potential and one finds that
(see e.g. [32]):

\[
P_h(\mu_B) = N_h/(12\pi^2)\mu_B^4 = N_h/(12\pi^2)N_f^4\mu_q^4 = N_h/N_f N_q^3 P_q(\mu_B)
\]

Hence, the hadron pressure will be always larger than the quark pressure and there
will be no transition to quark matter possible! Therefore, hadrons must transform to
massive quarks first and then the chiral phase transition to (nearly) massless quarks
happens. Of course, this line of arguments relies heavily on the tacit assumption that
interactions can be ignored!

The order and strength of the chiral phase transition actually determines whether or not there is a third family of compact stars \[32, 39\]. For a cross-over or a weak first-order phase transition, there will be only one solution to the TOV equations for ordinary neutron stars. For a strong first-order phase transition, however, there will be two solutions, an additional one with smaller radii (and probably smaller masses). These two scenarios outlined here actually depends crucially on the low-density hadronic equation of state! If the hadronic pressure rises strongly with the baryochemical potential, the crossing with the quark pressure appears at large values of the baryochemical potential and the change of the slope of the curves, which is just the baryon number density, will be moderate. Hence, the transition will be at most weakly first order. On the other hand, if the hadron pressure increases weakly with the baryochemical potential, the phase transition will happen at smaller baryochemical potential and the change of the slope changes drastically. In that case, the transition will be strongly first order. Unfortunately, the low-density equation of state of hadronic matter is still not well determined. The only thing one can state is that a strong first order phase transition is not ruled out by calculations of asymmetric nuclear matter up to \(2n_0\) \[40\]: the hadronic pressure increases slowly and is still considerably smaller compared to that of free quarks, i.e. only about 4% of \(P_q\) at \(n_0\) \[39\].

Using perturbative QCD as a model for dense QCD, the matching to the hadronic equation of state indeed can produce a third family of compact stars with a large quark core for reasonable transition densities \[39\]. Note that the maximum mass configuration of ordinary neutron stars contains then also a mixed phase of hadrons (or massive quarks) and chirally restored quarks in the core. The difference to the quark star solution of the third family is that their core consists of pure (chirally restored) quark matter surrounded by layers of a mixed phase and a hadronic (chirally broken) phase.

Recently, the study of quark stars has been refined by including effects from colour-superconductivity (see \[41, 42, 43, 35, 44, 45, 46, 47, 48, 49, 50\]). Here we just quote some of the recent findings and refer the interested reader to the contribution of Shovkovy, Rüster and Rischke for more details \[51\]. It was shown by Rüster and Rischke, that an increased interaction between quarks results actually in an increased mass for quark stars \[47\]. On the other hand, matching of an hadronic equation of state with a quark matter equation of state, which incorporates features of perturbative QCD and colour-superconductivity, can give mass-radius relations which are indistinguishable from ordinary purely hadronic stars \[50\]. Most recently, the phase diagram of colour-superconducting matter in \(\beta\) equilibrium has been studied at finite temperature \[52, 53\]. Besides the more standard two-flavour colour-superconducting (2SC) phase and the colour-flavour-locked (CFL) phase a rich variety of new phases appears, like the gapless CFL phase and the metallic CFL phase with exotic properties. The ungapped normal quark phase is present only at quite large temperatures of more than 50 MeV. If quark matter is formed during cool-down of a hot proto-neutron star, the matter in the core will pass through these phases, experiencing various phase transitions. Hence, those
exotic phases are important for the physics of newly born proto-neutron stars!

### 3. Neutron Star Data

The recent years have shown many surprises in the observations of compact stars. There are trivial constraints on the mass and radius of a compact star. Besides the Schwarzschild radius of \( R_s = 2GM \) a compact star has to be larger than about \( 3GM \) for causal equations of state [54]. The radius for a \( 1.4M_\odot \) star has to be smaller than 15.5 km to be compatible with the fastest rotating pulsar PSR 1937+21 with a spin frequency of 641 Hz [55, 56].

The x-ray pulsar Vela X–1 has a measured mass of \( M = 1.88 \pm 0.13M_\odot \) [57]. If confirmed, the measurement would constitute a new lower limit to the maximum mass of neutron stars. The mass measurement for the high-mass x-ray binary U1700-37 with \( M = 2.44 \pm 0.27 \) is well above \( M(2\sigma) > 2M_\odot \) but it can not be ruled out that this is a black hole and not a neutron star [58]. An interesting candidate for a heavy neutron star has been reported in [59, 60]: the pulsar PSR J0751+1807 with a white dwarf companion has a measured mass limit of \( M > 1.6M_\odot \) (within \( 2\sigma \))! The error bars are still quite large but will be reduced as more data is collected.

A highly debated compact star is the isolated neutron star RX J1856.5-3754 which is the closest one known. The x-ray data shows a perfect black-body spectra [61]. However, no spectral lines are detected and the optical flux is not compatible with the extrapolated simple black-body formula. All classical neutron star atmospheres are basically ruled out (hydrogen as well as heavy element atmospheres) [62]. An alternative description with a two-component black-body fit comes to a surprising conclusion: the soft temperature must be small so that the x-ray part of the spectra is not spoiled. This on the other hand implies a lower limit for the emitting radius to get the optical flux right: \( R_\infty > 16.5 \text{ km}(d/117 \text{ pc}) \), where \( R_\infty \) is the radius measured by an observer at infinite distance [63]. As \( R_\infty = R/\sqrt{1 - 2GM/R} \), allowed masses and radii are very large and nearly every equation of state on the market would be ruled out, except for extremely hard equations of state with no phase transition at all to any exotic matter! We stress, however, that this will not rule out a possible third family of compact stars. It might well be that this isolated neutron star has no exotic core, but still there might be compact (quark) stars with a considerably smaller radius (and maybe smaller masses).

There is a promise from x-ray bursters to get another handle on the compactness of a neutron star by measuring spectral lines. In a binary system with a neutron star, the neutron star is accreting material from its companion which ignites a thermonuclear explosion on the surface of the neutron star. Measured spectral lines, if identified correctly, are redshifted and give a direct measure of the \( M/R \)-ratio. For EXO 0748-676 [64] a value of \( z = 0.35 \) was extracted from three different spectral lines which gives \( M/M_\odot = 1.5(R/10 \text{ km}) \). A more independent way to explore the gravitational potential around compact stars is to measure the spectral profile of emitted spectral lines which is modified from the space-time warpage [65]. A constraint of \( 9.5 \text{ km} < R < 15 \text{ km} \) was
found for EXO 0748-676 [66], the same object studied above. Using $z = 0.35$ from [64] implies a mass range of $1.5M_\odot < M < 2.3M_\odot$ [66].

In the future, the observations of compact stars will be revolutionised by the Square Kilometre Array (SKA). The SKA is an international project to built a receiving surface of one million square kilometres. The potential to discover are 10,000 to 20,000 new pulsars, more than 1,000 millisecond pulsars and at least 100 compact relativistic binaries [67]! These future measurements will probe the equation of state at extreme limits! In addition, the SKA can be used as a gigantic cosmic gravitational wave detector by using pulsars as clocks. The design and location is not finalised yet; maybe the host country of this conference, South Africa, being one of the candidates, will be successful! In any case, the future is bright for peering into the heart of compact stars!

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