

On the conversion of neutron stars into quark stars

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Abstract. The possible existence of two families of compact stars, neutron stars and quark stars, naturally leads to a scenario in which a conversion process between the two stellar objects occurs with a consequent release of energy of the order of 10^{53} erg. We discuss recent hydrodynamical simulations of the burning process and neutrino diffusion simulations of cooling of a newly formed strange star. We also briefly discuss this scenario in connection with recent measurements of masses and radii of compact stars.

1 Introduction

The equation of state and the properties of nuclear matter at high baryon densities ($n_B > 3n_0$ with the nuclear saturation density $n_0 = 0.16 \text{ fm}^{-3}$) are rather uncertain due to the lack of laboratory experimental data and to the theoretical and computational difficulties in the study of such a quantum many body relativistic problem. On the other hand at high temperature and vanishingly small baryon density a consistent physical picture has emerged in the last years thanks to experiments of heavy ion collisions and to the complicated calculations of lattice QCD. In particular what is now widely accepted is the existence of a cross-over transition from hadronic matter to the quark gluon plasma (a soup of quarks and gluons) at a critical temperature $T_c \sim 170 \text{ MeV}$. While the matter created in the early stages of ultra-relativistic heavy ion collisions is deconfined, the subsequent expansion and cooling down causes hadronization; the production of particles, at the so called freeze-out, is extremely well described by hadron resonance gas models which consist of a mixture of baryons and mesons, with masses up to $\sim 2 \text{ GeV}$, in thermodynamical equilibrium. In particular, in the baryon sector the contribution of hyperons is important and cannot be neglected. It is interesting to notice that the equation of state associated with a hadron resonance gas has an almost constant sound velocity of $\sim \sqrt{1/6}$ and it is therefore *softer* than the equation of state of the quark gluon plasma which, at least in the limit of very high temperatures, can be modelled by a gas of massless quarks and gluons with a corresponding sound velocity of $\sim \sqrt{1/3}$ (see [1] for a review).

While, as explained before, at high baryon densities there are huge uncertainties on the equation of state, from the high temperature regime one can learn two important lessons: i) at high energy densities a phase transition to quarks and gluons matter occurs ii) at smaller energy densities not only pions and nucleons are present but also hyperons, resonances and strange mesons. Moreover the equation of state of the hadronic phase is softer than the one of the quark phase due to the appearance of new degrees of freedom when increasing the temperature. A natural place in which nuclear matter at high density

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exists is the core of neutron stars. Recent studies and observations of these stellar objects have severely challenged nuclear physics. We refer in particular to the very precise measurements of neutron stars with masses up to two solar masses [2]. Moreover, although the corresponding measurements are still affected by large uncertainties, there are several indications of stars having a radius smaller than about 10 km [3, 4]. It is not easy to explain the existence of massive neutron stars and very compact stars with only one family of compact objects, indeed a star with a mass of $2M_{\odot}$ and a radius of 9 km would be close to the causal limit (i.e. sound velocity equal to c) and thus unlikely [5]. It is possible instead that two families actually exist differing from each other for the composition : hadronic stars made of baryonic matter and stars made of quark matter [6–8]. If these two families exist, there must be a mechanism for populating the quark star branch of compact stars. We do not investigate here in detail the astrophysical scenario of the conversion of a neutron star into a quark star but just assume that it can take place and discuss instead if such a process can be phenomenologically relevant.

2 Hydrodynamical conversion and neutrino emission

The conversion of a neutron star into a quark star has been investigated in many papers (see [9, 10] and references therein) and it has been shown to proceed as a strong deflagration i.e. it is similar to a burning process which is sustained by the energy released in the conversion and does not propagate as a shock wave. Interestingly, the hydrodynamical instabilities which develop, mainly because of the gradient of the gravitational potential inside the star, significantly increase the rate of conversion. In [11, 12] full 3+1D hydrodynamical simulations of the burning process have been performed in which the conversion is described in a discontinuity approximation, meaning that the unburned material (nucleonic matter) and the newly converted strange quark matter are separated by a conversion front. The conversion process is triggered by a strange quark matter seed in the center of the initial stellar configuration : a volume in the center is converted instantly and the conversion front subsequently propagates as a deflagration wave. The development of a turbulent flow strongly enhances the velocity of conversion.

The neutron star is modeled by use of the Lattimer-Swesty equation of state with compressibility $K = 240$ MeV [13] and for quark stars, as customary, we adopt the simple MIT bag model picture. We consider in particular two sets of parameters, taken from [14], both allowing to reach a maximum mass for strange quark stars of $2M_{\odot}$. We fix the current mass of the strange quark to $m_s = 100$ MeV, and we then consider $B_{eff}^{1/4} = 142$ MeV - $a_4 = 0.9$ (Set1) and $B_{eff}^{1/4} = 141$ MeV - $a_4 = 0.65$ (Set2) where B_{eff} and a_4 represent the effective bag constant and the coefficient of the μ^4 term in the pressure of the quark phase, respectively (μ is the quark chemical potential), as in Ref. [15]. The two sets provide almost the same mass radius relation, as one can notice in Fig.1, but they correspond to different values of the energy per baryon of the ground state of strange quark matter : for Set1 $E/A = 860$ MeV and for Set2 $E/A = 930$ MeV implying that the former provides quark bags with a larger binding energy. The larger binding energy of quarks in bulk matter obtained with Set1 is then responsible for the larger total binding energy (the difference between the baryonic mass M_B and the gravitational mass M_G [16]) of quark stars : for instance the stellar configuration labelled with M, which lies on the two gravitational mass radius curves, has a larger baryonic mass (the point on the thick dashed line) in the case of Set1. In turn, this means that a larger energy is available for the conversion of a neutron star when the equation of state of Set1 is adopted. As previously discussed, the burning proceeds thanks to the energy released in the conversion and indeed while for Set1 a successful conversion is obtained, for Set2 the energy released in the conversion is not sufficient to power the conversion front and the burning stops immediately after the initialisation. The conversion, when successful, is very efficient : turbulence indeed leads to very high conversion velocities and on a time scale of few milliseconds almost the whole star is converted.

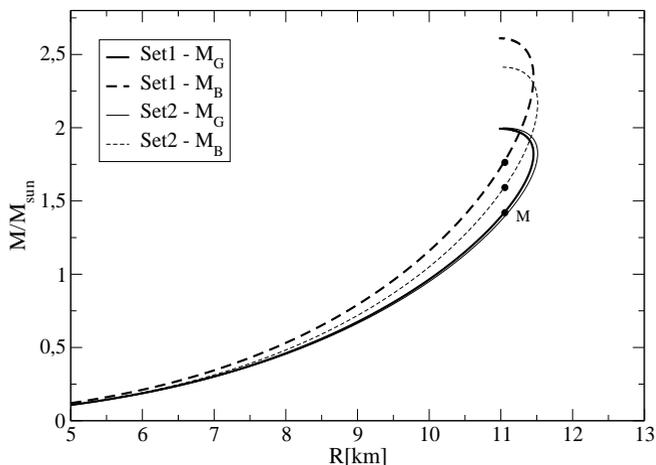


FIGURE 1. Gravitational mass and baryonic mass of quark stars obtained with two parametrized equations of state. The larger value of quarks binding energy in bulk matter at zero pressure obtained with Set1 provides, correspondingly, a larger value of the total binding energy of quark stars.

The newly born strange quark star is hot due to the huge energy released during the conversion process. The temperature at the center of the star reaches values up to 40 MeV and decreases smoothly as a function of the radius until the layer separating the burned from the unburned material. In correspondence of this interface a steep temperature gradient is obtained (see Ref.[12]) which, within the diffusion approximation, leads to a fast neutrino cooling.

For an order of magnitude estimate let us consider the inverse mean free path for the scattering of neutrinos off degenerate quarks [17] $\frac{1}{\lambda_s} = \frac{G_F^2 E_\nu^3 \mu_i^2}{5\pi^3}$ where $G_F = 1.17 \times 10^{-5} \text{ GeV}^{-2}$ is the Fermi constant, E_ν is the energy of the neutrino/antineutrino and μ_i is the chemical potential of the particle involved in the scattering (up, down, strange quarks). For mean thermal energy neutrinos, $E_\nu = \pi T$, with $T \sim 50 \text{ MeV}$ and $\mu_i \sim 500 \text{ MeV}$ at the center of the star, thus one can estimate the diffusion time as $\tau \sim R^2/\lambda_s$ where $R \sim 10 \text{ km}$ is the radius of the star. We obtain a time scale of the order of 1s. Actually in the diffusion calculations presented in [12] the star cools down to temperatures below 1 MeV after about 10 – 15 s with a initial neutrino luminosity of 10^{52} erg/s . Such a high neutrino luminosity is typical of core collapse supernovae and protoneutron stars and can be therefore detectable by the present neutrino telescopes for events occurring in our galaxy. Notice that, differently from a supernova, the process of conversion of a neutron star into a quark star would be a powerful neutrino source but lacking an optical counterpart. In general, a direct detection of neutrinos from protoneutron stars would be an excellent opportunity to test the existence of quark matter in compact stars [18–20]

A final comment concerning the composition of the two stars is needed : while the initial configuration, the neutron star, is rich of leptons (the electron fraction is of order 0.1 at the center of the star), the final strange quark star is almost lepton free. In the presently available simulations indeed no conservation of lepton number is imposed during the conversion. We expect that, if included, the conservation of lepton number would lead to non-beta stable strange quark matter. The cooling would be then accompanied by deleptonization and the neutrino signal could be actually longer and more powerful.

3 Conclusions

A part from the neutrino signal itself, the process here considered represents a new astrophysical energy source which could have a connection with some of the most powerful explosions of the universe i.e. gamma-ray-bursts. In particular, in some of these events the light curve shows some non-trivial temporal structures, the so-called quiescent times. These correspond to periods of tens of seconds during which it is likely that the inner engine of the gamma-ray-burst is not active at all [21]. After the quiescent time the inner engine emits a new burst which has almost the same temporal and spectral structure of the first emission episode. In a spectacular event detected by the Swift satellite, the GRB 110709B [22], the quiescent time lasts about 10 min, which is probably a too long time of inactivity for a collapsar like inner engine. It is now widely accepted that at least some gamma-ray-bursts are produced by highly magnetised proton-neutron stars [23]. We speculate that a possible energy source for the second emission episode seen in some light curves is the conversion of nucleonic matter to strange quark matter. A detailed calculation showing that it is indeed possible to emit part of energy released in the conversion in gamma-rays is clearly needed.

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