QUARK MATTER FORMATION IN EXPLOSIVE ASTROPHYSICAL PHENOMENA*

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Neutron stars represent excellent physical systems for the study of the high density QCD phase transition that might occur in their core. A promising line of research concerns the possible signatures of the dynamics of the formation of quark matter in a neutron star. We review the different signatures that have been recently proposed in connection with explosive phenomena such as supernovae, gamma-ray-bursts, merger of neutron stars.

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1. Introduction

Neutron stars, with their core having densities as high as ten times the density of nuclear matter, represent excellent physical systems to understand the properties of strongly interacting matter at extreme conditions. Particularly exciting is the possibility that in their core a first order phase transition from nuclear matter to quark matter takes place [1]. From the theoretical point of view, a crucial uncertainty concerns the numerical value of the critical density for the transition: since lattice QCD is not yet capable of investigating the equation of state at large densities, one has to rely to simple models for strongly interacting matter which can provide estimates for the critical density which are, however, parameter and model dependent. In the last 20 years, a big effort has been put to find signatures of quark matter in compact stars and to get therefore informations on the properties of QCD matter from the astrophysical observations of these stellar objects. There are many possible interesting observables: the structure of compact stars, mainly the mass radius relation, which is strongly correlated with

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the stiffness of the equation of state; the cooling history, which depends on the transport properties of stellar matter (heat capacity, thermal conductivity, neutrino emissivity); the stability with respect to the r-modes, which depends on the shear and bulk viscosities, *etc.* (see Ref. [1]). Due to the poor predictive power of the models used to calculate the equation of state (too many free parameters that can be adjusted to reproduce the observational data) and due to the intrinsic difficulties of astrophysical measurements (data with large error bars) no firm conclusions can be drawn yet concerning the occurrence of a quark matter core in neutron stars. There is however an alternative strategy: instead of studying the signatures associated with stars in which quark matter is already present, one can investigate what are the signatures of the formation process itself of quark matter during the life of a neutron star. A wonderful example of this kind of signatures is the strong variation of the braking index of an old spinning down neutron star when a quark core, or a mixed phase starts to be formed [2]. Quark matter could also be formed during the first instants of life of a neutron star in a core collapse supernova event (eventually associated with a Gamma-Ray-Burst (GRB)) or during the final stage of the life of neutron stars in binary systems when the merger occurs. In the following we review the possible signatures of the formation of quark matter in such explosive phenomena.

2. Signatures of quark matter in explosive phenomena

Let us first state clearly our assumptions for the QCD phase transition in compact star matter. As customary, we assume that the phase transition at high density and small temperature is a first order phase transition. As such, a mixed phase is present between the pure nuclear and quark phases. Within the mixed phase the pressure is not constant because neutron star matter is a multicomponent system: baryon number and electric charge are conserved charges (in addition, lepton number is also conserved during the protoneutron star stage) [3, 4]. The process which initiates the formation of the quark phase within the nuclear phase is nucleation (thermal or quantum nucleation) [5, 6]. The conversion of nuclear matter into quark matter has been studied in detail in Ref. [7] and references therein, where it has been shown that it can be a very fast process (time scales of conversion of the order of the ms) proceeding as a strong deflagration. Moreover, depending on the temperature T and proton fraction Y_p and thus on the stage of life of the star during which quark matter is formed, there can be different color superconducting phases of quark matter as the 2SC phase or the CFL phase or just the unpaired phase [8–12]. The equations of state of nuclear and quark matter at high density are quite uncertain, there are however a few quantities which strongly characterize the scenario of the formation of the quark phase and the possible associated signatures: the critical density $n_{\rm crit}$ and the surface tension σ between nuclear and quark matter. Depending on the value of the critical density, the formation of quark matter can occur already during the early post-bounce phase of a supernova explosion as proposed in [13], just after the explosion during the protoneutron star evolution [14], in old stars spinning down or stars which are accreting mass in binary systems or finally during the merger of two neutron stars. The value of the surface tension regulates instead the degree of metastability of neutron star: when its central density exceeds the critical density, the star becomes metastable [15, 16] and its decay time is determined mainly by the value of σ.

2.1. Supernovae, GRBs, protoneutron stars

Let us discuss first the scenario of a phase transition occurring during the early post-bounce phase of a core collapse supernova studied in [13]. The quark matter equation of state was derived from the MIT bag model. By adopting a small value of the bag constant it is possible to obtain a critical density for supernova matter ($T \sim 10$ MeV and $Y_p \sim 0.3$) close to nuclear saturation density $n_0 = 0.16\ \mathrm{fm}^{-3}$. When the mixed phase starts to be produced after bounce, due to its softness and due to the compression exerted onto the protoneutron by the still falling material, a new collapse is obtained followed by a second shock wave that triggers a delayed supernova explosion. Moreover, a second burst (after the first neutronization burst) is present in the neutrino signal which can be detected by SuperK and Icecube [17]. Within this scenario, due to the small value of the critical density, all neutron stars would actually be hybrid stars and the formation of quark matter is at the origin of the explosion mechanism of the star. Notice that in this calculation the effects of the surface tension and nucleation were neglected and, as shown in [6], only in if $\sigma \lesssim 10\ \mathrm{MeV/fm}^2$ the nucleation of quark matter can be fast enough for this scenario to be conceivable.

A different scenario arises if $n_{\rm crit}$ is larger than $\sim 2n_0$ and cannot be reached during the early post-bounce phase; the formation of quark matter is delayed for a few seconds with respect to the core bounce and it can help the explosion of the star for large mass progenitors stars [18]. There is a number of papers discussing this scenario following the first numerical study on the formation of quark matter during the deleptonization of the star [14]. The main idea is that there exist two families of compact stars: neutron stars and hybrid or quark stars. Neutron stars can convert into a star containing quark matter only if its mass is larger than a critical mass [5, 15, 16, 18]. The conversion of nuclear matter into quark matter is then proven to be a powerful source of energy which can have a role in many different explosive phenomena: the explosion of massive progenitor stars (with masses of roughly 20 $M_{\odot}$) as proposed for the SN1987A in [18] and the long GRBs [5, 15, 16]. The temporal structure of some long GRBs turns out to be rather complex with the presence of precursors, long quiescent times, long time delays with respect to the associated supernova and finally the prolonged emission periods during the early afterglow stage and the X-ray flares. In [19, 20] the rich structure of the light curves of long GRBs has been associated with the progressive compactification of the star via formation of strangeness and color superconducting quark phases.

During the protoneutron star stage, with its still strong neutrino emission due to the gradual deleptonization of matter, some important changes of the equation of state could occur. The deleptonization is in fact accompanied by a gradual reduction of the proton fraction which, in quark matter, implies a change in the ratios of up, down and strange quark densities. This opens the possibility of forming, during the evolution of the protoneutron star, first a 2SC phase (which is favored for matter with high Y_p [11]) then the unpaired quark phase when the mismatch between up and down is too large and finally the CFL phase when matter is completely deleptonized [9, 10]. Another interesting possibility proposed in [4] is that in the case in which σ is very large ~ 50 MeV/fm^2, the mixed phase, which is present in a protoneutron star during deleptonization because of the conservation of lepton number, disappears at the end of the deleptonization. Sizable changes of the structure of the protoneutron star occurs during this peculiar temporal evolution. The dynamical evolution of protoneutron stars is very rich and could offer new signatures of quark matter formation which are presently under investigation by studying the diffusion of neutrinos in the quark phases.

2.2. Gravitational waves and merger

Besides neutrino and gamma-ray signals also gravitational waves could bring us important informations on the formation process of quark matter. There have been different numerical simulations on the process of formation of quark matter in rotating neutron stars [21–24] in which the scenario consists of an old neutron star whose central density increases due to spinning down or to mass accretion from a companion. At some point the critical density is reached and the phase transition induces then a collapse of the star with subsequent gravitational waves radiating oscillation modes. Interestingly, the signal emitted in gravitational waves is enough powerful to be detected by the second generation interferometers for galactic events.

Finally, a less explored scenario for the QCD phase transition is the merger of two neutron stars. In this process the highest possible densities are reached (indeed in most cases a black hole is left after the merger) and it is, therefore, the right system to look for signatures of the formation of quark matter in the case in which $n_{\rm crit}$ is very high. There have been a few studies on the merger of compact stars containing quark matter in the core, hybrid stars [25], or completely composed by strange quark matter, strange stars [26, 27]. The temporal evolution of the merger process of hybrid or strange stars shows some differences with respect to the case of neutron stars and some distinctive features are present in the gravitational waves signal: for instance the maximal frequency during the inspiral and the frequencies emitted by the merger remnant are in general higher in the case of strange stars mergers in comparison to neutron stars mergers. Important differences are also demonstrated for the mass ejected during the merger: for very compact configurations a prompt collapse to a black core occurs before matter is ejected. In turn, this result is also relevant for the study of cosmic rays.

3. Conclusions

We have discussed a strategy for the search of quark matter in compact stars based on the signatures associated with the formation of quark matter during explosive phenomena. In particular, the neutrino signal associated with the QCD phase transition in the early post-bounce phase of a supernova represents a spectacular signature which could be tested by the neutrino detectors for a galactic supernova. Also GRBs might have their origin from the process of formation of quark matter: their complex temporal structure in particular provides hints of a inner engine given by a compact star which modifies its structure during the emission periods. Gravitational waves bursts are expected to be associated with the formation of quark matter in a neutron star or during the merger process which could be eventually detected by the future interferometers. A major drawback of these kind of signatures is that they are associated with events which are quite rare: there are only 2–4 supernovae per galaxy per century for which we could catch the neutrino signal. Also the discussed gravitational waves signal associated with the formation of quark matter could be detected for events in our galaxy, with an estimated rate of events of $\sim 10^{-5}$/yr [23]. Fortunately, the planned future experiments as IceCube and the third generation interferometers will be able to detect also extra-galactic events thus representing a real chance to test the signatures of quark matter previously discussed. On the other hand, a huge statistics of events is available for GRBs, detailed numerical simulations on the formation of quark matter during these events would be extremely interesting.

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REFERENCES

[1] F. Weber, *Prog. Part. Nucl. Phys.* **54**, 193 (2005).

[2] N.K. Glendenning, S. Pei, F. Weber, *Phys. Rev. Lett.* **79**, 1603 (1997).

[3] M. Hempel, G. Pagliara, J. Schaffner-Bielich, *Phys. Rev.* **D80**, 125014 (2009).

[4] G. Pagliara, M. Hempel, J. Schaffner-Bielich, *Phys. Rev. Lett.* **103**, 171102 (2009).

[5] A. Drago, A. Lavagno, G. Pagliara, *Phys. Rev.* **D69**, 057505 (2004).

[6] B.W. Mintz, E.S. Fraga, G. Pagliara, J. Schaffner-Bielich, *Phys. Rev.* **D81**, 123012 (2010) [`arXiv:0910.3927 [hep-ph]`].

[7] A. Drago, A. Lavagno, I. Parenti, *Astrophys. J.* **659**, 1519 (2007).

[8] M.G. Alford, A. Schmitt, K. Rajagopal, T. Schafer, *Rev. Mod. Phys.* **80**, 1455 (2008).

[9] S.B. Ruester *et al.*, *Phys. Rev.* **D73**, 034025 (2006).

[10] F. Sandin, D. Blaschke, *Phys. Rev.* **D75**, 125013 (2007).

[11] G. Pagliara, J. Schaffner-Bielich, *Phys. Rev.* **D81**, 094024 (2010) [`arXiv:1003.1017 [nucl-th]`].

[12] G. Pagliara, J. Schaffner-Bielich, *Phys. Rev.* **D77**, 063004 (2008).

[13] I. Sagert *et al.*, *Phys. Rev. Lett.* **102**, 081101 (2009).

[14] J.A. Pons, A.W. Steiner, M. Prakash, J.M. Lattimer, *Phys. Rev. Lett.* **86**, 5223 (2001).

[15] Z. Berezhiani *et al.*, *Astrophys. J.* **586**, 1250 (2003).

[16] I. Bombaci, I. Parenti, I. Vidana, *Astrophys. J.* **614**, 314 (2004).

[17] B. Dasgupta *et al. Phys. Rev.* **D81**, 103005 (2010) [`arXiv:0912.2568 [astro-ph.HE]`].

[18] A. Drago *et al.*, *AIP Conf. Proc.* **1056**, 256 (2008).

[19] A. Drago, G. Pagliara, *Astrophys. J.* **665**, 1227 (2007).

[20] A. Drago, G. Pagliara, I. Parenti, *Nucl. Phys.* **A782**, 418 (2007).

[21] L.M. Lin, K.S. Cheng, M.C. Chu, W.M. Suen, *Astrophys. J.* **639**, 382 (2006).

[22] N. Yasutake, K. Kotake, M.A. Hashimoto, S. Yamada, *Phys. Rev.* **D75**, 084012 (2007).

[23] E.B. Abdikamalov, H. Dimmelmeier, L. Rezzolla, J.C. Miller, *Mon. Not. R. Astron. Soc.* **392**, 52 (2009).

[24] H. Dimmelmeier, M. Bejger, P. Haensel, J.L. Zdunik, *Mon. Not. R. Astron. Soc.* **396**, 2269 (2009).

[25] R. Oechslin, K. Uryu, G.S. Poghosyan, F.K. Thielemann, *Mon. Not. R. Astron. Soc.* **349**, 1469 (2004).

[26] A. Bauswein *et al.*, *Phys. Rev. Lett.* **103**, 011101 (2009).

[27] A. Bauswein, R. Oechslin, H.T. Janka, *Phys. Rev.* **D81**, 024012 (2010).