Formation of quark phases in compact stars and SN explosion

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Abstract. We describe possible scenarios of quark deconfinement in compact stars and we analyze their astrophysical implications. The quark deconfinement process can proceed rapidly, as a strong deflagration, releasing a huge amount of energy in a short time and generating an extra neutrino burst. If energy is transferred efficiently to the surface, like e.g. in the presence of convective instabilities, this burst could contribute to revitalize a partially failed SN explosion. We discuss how the neutrino observations from SN1987A would fit in this scenario. Finally, we focus on the fate of massive and rapidly rotating progenitors, discussing possible time separations between the moment of the core collapse and the moment of quark deconfinement. This mechanism can be at the basis of the interpretation of gamma ray bursts in which lines associated with heavy elements are present in the spectrum.

Keywords: Quark Matter, Deconfinement Transition, Supernovae, GRB
PACS: 25.75.Nq, 26.50.+x, 97.60.Bw, 98.70.Rz

INTRODUCTION

The mechanism of core collapse Supernova (SN) explosions has not yet been completely clarified, although relevant progresses have been made in the last years. It is possible that, while SNe with a relatively light progenitor can explode via the standard mechanism, new physical ingredients are needed to explain SNe with progenitor masses larger than ∼ 20M⊙.

In the last years a huge amount of papers has been published, discussing the existence of deconfined quarks inside a compact star. Quark deconfinement inside a compact star is an exothermic process releasing in general a large amount of energy. Thus, it is interesting to explore its astrophysical implications. In this contribution we will first describe possible scenarios of quark deconfinement in compact stars. We will then focus on the impact of this process on SN explosion and on the connection between SNe and Gamma Ray Bursts (GRBs).

WHEN AND HOW TO DECONFINE INSIDE A COMPACT STAR?

In the literature several scenarios of quark deconfinement have been discussed, and they can roughly be grouped in two categories, depending on when the deconfinement
transition takes place:

- Quark Deconfinement Before Deleptonization (QDBD) of the protoneutron star;
- Quark Deconfinement during or After the Deleptonization (QDAD).

Concerning the first possibility, QDBD, the main idea is that during the collapse of the homologous core the first critical density is reached, separating the pure hadronic phase from the mixed phase of quarks and hadrons\(^1\) [1, 2, 3]. Since in the mixed phase the adiabatic index is very low, the collapse continues rapidly through the mixed phase till the central density reaches the second critical density separating mixed phase and pure quark matter. At this point, the adiabatic index becomes large again and the collapse halts. A shock wave is then produced. One feature of this mechanism is that it requires a particularly soft Equation of State (EoS), since the formation of a mixed phase of quarks and hadrons has to take place at the relatively low densities reached at the moment of core bounce (or immediately after, during the fallback but anyway before deleptonization [4]). Since the densities reached at the moment of the bounce are only moderately dependent on the mass of the progenitor, this mechanism is rather “universal”, affecting most of the SNe, although its effect on the explosion can still depend on the mass of the progenitor.

The second possibility, QDAD, is that quark deconfinement takes places only after an at least partial deleptonization [5, 6]. It is well known, in fact, that when the pressure due to leptons decreases, the central baryonic density increases and therefore the deconfinement process becomes easier\(^2\). Clearly, a temporal separation can exist in this second scenario between the moment of core collapse and the moment in which quarks deconfine.

Another important question concerns the way in which the deconfinement transition takes place, either as a smooth transition, in which no surface tension is present and no metastability (of the hadronic phase) can exist or, instead, as a first order transition in which a surface tension exists at the interface between hadrons and quarks.

The first possibility, i.e. no metastability, was analyzed in a QDBD scenario in [1, 2, 3, 4] where the time scale of the formation of the mixed phase depends only on the velocity of compression. Here a very important role is played by the mechanical shock wave which forms at the interface between the mixed phase and the pure quark phase, which could help the SN to explode as shown in [4] for low- and intermediate-mass progenitor stars. Within the QDAD scenario of Ref. [5] deconfinement is also a gradual process, driven in this case by deleptonization. The total thermal energy emitted in neutrinos increases, but the neutrino luminosity is almost unchanged and in particular no new neutrino burst is obtained in association with deconfinement.

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1 An interesting variation of this possibility has recently been discussed [4], in which the mixed phase is mainly produced not at the moment of the core bounce, but during the fallback of the material following a failed SN explosion.

2 It is also important to recall that a important role is played by strangeness: it is much more easy to deconfine into strange quark matter than into purely up and down quarks. On the other hand one needs to clarify how the strange quarks are produced, if they are not already present in the hadronic phase.
The existence of surface tension between quarks and hadrons opens the possibility that hadronic matter remains metastable for a short or long time period. The duration of the metastable phase depends mainly on: i) the numerical value $\sigma$ of the surface tension; ii) the rate by which the parameter controlling the degree of metastability (for instance the density of the system, or the leptonic content) changes with time. A not too small of $\sigma$ and a slow change in the density can allow the system to remain metastable even for a very long time [7]. On the other hand, even a very short period of metastability (order of seconds) can be extremely important, because it allows the system to evolve on time scale dictated by the velocity of the burning. This point is particularly relevant because we will show that the burning of hadrons into quarks inside a compact star is a strong deflagration and not a detonation.

In the following we will concentrate on the QDAD scenario in presence of surface tension which implies the formation of quarks via drops nucleation.

An important role in the scenarios outlined above is played by the rotation of the star. A rapid rotation produces a very slow variation of the central density of the compact star. The density will increase due to the reduction of the angular momentum or due to the fallback associated with a failed explosion. As a consequence, the high densities necessary for the deconfinement are reached after a relatively long time, even of the order of hours. In Fig. 1 we show an example of the relation between angular momentum and central density of the compact star. Here the slow down is due to $r$-mode instabilities, but a strong magnetic field could play a similar role in rapidly reducing the angular velocity of the star.

**BURNING OF HADRONS INTO QUARKS INSIDE A COMPACT STAR**

Let us recall a few results concerning the hydrodynamics of the combustion of hadrons into quarks in compact stars. Due to the large density of the system and to the relatively
low temperatures involved, the process does not start as a detonation, but as a strong deflagration. This implies that the velocity of the front is subsonic and that no shock wave is associated with the burning. On the other hand a strong deflagration in the presence of gravity is characterized by an unstable front, where wrinkles can form. Since a deflagrative front proceeds due to the transmission of some “fuel” across the surface (in this case the fuel can be strange quarks) and/or the exchange of heat from the burned zone to the unburned zone, the formation of wrinkles can significantly increase the burning velocity, since it increases the area of the surface separating burned and unburned material.

In Ref. [10] the velocity of the front has been estimated taking into account the hydrodynamical instabilities of the burning front. The net effect of the wrinkles is to increase the burning velocity up to $10^3 - 10^4$ km/s, so that the central region of the compact star can transform into quarks or into a mixed phase on a time scale of the order of $10^{-3} - 10^{-2}$ s. These velocities, although very large, are clearly subsonic (the velocity of sound in a compact star is of the order of $10^5$ km/s) and therefore the deflagration does not transform into a detonation due to the hydrodynamical instabilities (at variance with what happens in SNIa). It is also important to note that the velocity slows down while the combustion front approaches the surface of the star.

Finally, we remark that convective instabilities can develop close to the center of the star, due to the different EoS describing a newly formed bubble of quarks with respect to the surrounding hadronic material. This type of convection (not based on a thermal gradient) can develop, however, only in a relatively narrow range of parameter values, typically the ones which lead to the formation of a quark star and not of a hybrid star.

HEAT TRANSPORT INSIDE A NEWLY FORMED HYBRID STAR

The combustion of hadrons into quarks releases a substantial amount of energy \cite{11,12}, $E_{\text{dec}} \sim 10^{53}$ erg, in the central region of the star and in a time scale of the order of $\tau_{\text{dec}} \sim 10^{-3} - 10^{-2}$ s. To consider specific models, we can see in the left panel (middle plot) of the Fig. 2 the energy difference between the combusted and the uncombusted phases as a function of the baryonic density and for three values of the MIT bag model parameter $B$. In the right panel we also show the baryonic density profiles of different compact stars. For definiteness, we select the specific case of a hybrid star corresponding to a quark phase described by the MIT bag model with $B^{1/4} = 165$ MeV. We consider normal not-superconducting (“H-uds” line) as a reference model.

The combustion occurs in the region where $(\Delta E/A) \geq 0$ which corresponds to density $\rho_B \geq 2 - 3 \rho_0$ and extends out to a radius of $\sim 8$ km (see the kink in the ”H-uds” curve in Fig. 2). One can estimate that most of the energy is released in radial shells at a distance of $D \sim 5$ km from the surface. This region is heated to temperatures which can be as large as $T \sim 30$ MeV, much larger than the temperature of the external hadronic region.

The produced energy is transported to the surface by neutrinos that reach thermal equilibrium on weak interaction time scales which are much shorter than $\tau_{\text{dec}}$. We

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\[3\] The estimated average temperature of the quark phase after the burning is typically below 50 MeV.
indicate with $\gamma = E_\nu / E_{\text{dec}}$ the fraction of the total energy which is stored in neutrinos at a given moment (before the star cools down significantly). This quantity depends on temperature and chemical potentials and it is typically of the order of few percent.

Neutrinos diffuse outwards with a time scale $\tau_{\text{diff}} \sim D^2/\lambda \sim 10s (D/5\ \text{km})^2/(\lambda/1\text{cm})$ where $\lambda$ is the neutrino mean free path. After the combustion, we thus expect an extra neutrino burst with a risetime $\tau_{\text{rise}} \sim \tau_{\text{diff}}$ and a peak luminosity equal to about $L_\nu \sim E_\nu / \tau_{\text{diff}} \sim 10^{52}\text{erg s}^{-1}\gamma(\lambda/1\text{cm})$. Due to neutrino emission the star will cool (and the neutrino luminosity will decrease) with a time scale $\tau_{\text{cool}} \sim \tau_{\text{diff}}/\gamma$.

It should be noted that the burning of hadrons into quarks produces a large temperature gradient between the combusted and the uncombusted region which can lead to a convective instability. The existence of a convective motion which mixes the upper layers of the burned zone with the unburned region is an interesting possibility which will be explored quantitatively in a future paper. Convection is a very efficient heat transport mechanism. If the convective layer is sufficiently extended, the energy released by combustion is transported to the surface much faster than in the non-convective case. Moreover, convection brings hot material to the surface which can be heated to a temperature of the order of few MeV. As a consequence, the neutrino luminosity is expected to increase on the time scale of convective heat transfer, reaching a much larger peak value than in the normal diffusive case described above. If a luminosity equal to about $10^{53}\text{erg s}^{-1}$ is achieved, the extra $\nu_e\bar{\nu}_e$-neutrino burst could revitalize the SN explosion.

### COMPARING WITH SN1987A OBSERVATIONS

The only SN neutrinos detected till now are those from SN1987A. Indeed, on February 23, 1987, at 2 h 53 m (UT) LSD detector observed 5 events [13]; at 7 h 36 m (UT) IMB, Kamiokande-II and Baksan [14] detectors observed 8, 11 and 5 events respectively. The

*FIGURE 2.* Left panel: Burning of hadrons into quarks. Right panel: Baryon density profile of compact stars in various models. See text for details.
progenitor was a blue supergiant with estimated mass of $\sim 20 \, M_\odot$.

The observations of Kamiokande-II, IMB and Baksan can be explained very well within the standard scenario for core collapse SNe, assuming that the events are due to $\bar{\nu}_e p \to ne^+$. The observations are consistent with the presence of an initial, high luminosity phase of neutrino emission, followed by a thermal phase due to the cooling of the newborn neutron star [15]. Such an initial and luminous phase is expected; indeed, it should trigger the subsequent explosion of the star. The standard scenario for core collapse SNe does not predict the existence of multiple pulses of neutrino emission and thus cannot accommodate LSD data.

Non-standard scenarios with multiple phases of neutrino emission have been proposed [16, 17]. An interesting possibility is that the first burst is due to a very intense neutronization phase by $e^- p \to n\nu_e$; it was noted in [17] that electron neutrinos with an energy of 30 – 40 MeV can be more easily seen in LSD detector than in the other detectors. In the astrophysical scenario of [17], the rapid rotation of the collapsing core leads to a delay between the first and the second burst. However, the nature of the second burst is not discussed in [17] and one could doubt whether the beginning of the second burst includes a phase of initial luminosity.

Here, we consider the possibility that Kamiokande-II, Baksan and IMB observations are due to the burning of hadrons into quarks. More specifically, the process of quark deconfinement can provide the necessary amount of energy in neutrinos, and the occurrence of convective processes can release a part of this energy in a short time scale. The intense neutrino luminosity obtained in this way could not only meet the observations, but also play a key role for the explosion of the star.

This becomes even more interesting in the presence of a rapid rotation. The sequence of events, in this case, could be the following: (1) an initial intense phase of neutronization accounts for LSD observations as in [17]; (2) the rapid rotation of the core leads to the formation of a metastable neutron star, that looses its angular momentum in a time scale of several hours; (3) the central density of the metastable star becomes large enough that deconfinement can take place. Again, the rapid release of energy at the beginning of the last stage could be sufficient to lead to the explosion of the star.

**ASTROPHYSICAL SCENARIOS OF EXPLOSIONS DRIVEN BY QUARK DECONFINEMENT**

In this section we discuss how quark deconfinement can affect the standard scenario of the fate of massive stars, as e.g. outlined in the classical paper of Heger et al. [18]. In Fig. 3 there is a line separating the stars which end up their life as neutron stars and the ones which produce a black hole by the fallback of the material not ejected due to a (partially) failed SN explosion. This line is particularly relevant to our discussion because it is located inside the region of large progenitor masses where the standard mechanism has difficulties in exploding SNe: the explosion needs to be revitalized by some new injection of energy. We suggest that the mechanism providing the new energy is based on quark deconfinement [19].

In the scenario described in Fig. 3 the rotation of the star is crucial and it plays a double role: it slows down the fallback and it allows the formation of a jet which, for
high metallicity stars, is at the basis of the mechanism of formation of a GRB. Let us clarify which scenarios can open when quark deconfinement takes place inside a rapidly rotating star:

- if the rotation velocity is large but not extreme, the main effect is the reduction of the fallback rate. From one side, this reduces the luminosity of the neutrino burst typically associated with the fallback of the material on the protoneutron star (therefore making the SN more difficult to explode); on the other hand, preventing the immediate formation of a black hole, the rotation allows the neutrino produced by quark deconfinement to play a important role, since they can have the time to be produced and to push the star envelope halting the collapse;

- if the rotational velocity of the central region is extreme, the duration of the collapse of the core before the formation of the protoneutron star can be significantly extended. The peak in neutrino luminosity associated with electron capture can be temporally separated from the peak due to quark deconfinement. In principle these two peaks can be separated by time intervals ranging from minutes to hours to days or more, depending on the rotational velocity and on the rate of the fallback.

Are there any observational hints of the scenario outlined above? We are clearly looking for events in which a first (partially failed?) SN explosion is followed by a new neutrino outburst. A possible example is the one already discussed, i.e. the neutrino signals possibly associated with SN1987A. There, the first partially failed SN is due to

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4 Interestingly, a neutrino burst associated with quark deconfinement and temporally separated from the first neutronization burst was recently discussed in [4] in a non-rotating scenario.
the neutrinos produced at the moment of the prolonged neutronization which takes place (in the scenario of Ref. [17]) inside the rapidly rotating disk collapsing at the core of the progenitor star. The moderate fallback due to the rapid rotation allows the central density of the protoneutron star to gradually increase till a critical density is reached and a new burst of neutrinos is generated due to deconfinement. The time interval between the first and the second burst is regulated by the slowdown of the protoneutron star, due e.g. to r-mode instabilities or to the presence of a strong magnetic field.

A second example is provided by GRBs. There have been in the past several hints of a presence of iron lines in GRBs (either in absorption or in emission [20]). Since iron can only be produced at the moment of a SN explosion, then the SN (even if marginally failed) has to precede the GRB by a time interval which can be estimated from data. In our scenario such a delay between SN and GRB can again be due to the time separation between a (partially failed) SN explosion and the gamma burst produced by the quark deconfinement neutrinos. A recent observation based on a Nickel line [21] indicates a time interval of the order of one hour. Other hints of GRBs in which the SN explosion precedes the GRB are:

• the possible association of GRB with SNIIn [22]. In the standard scenario of GRBs this association should not be possible, since the GRB would be absorbed by the external shells of the progenitor; in our case, the time separation between the two events can help the GRB to emerge from the thick environment;
• the evidence of GRBs where no SN is observed [23]. In our scenario, a time delay between the SN and the GRB of several days or longer would not allow to observe any signal associated with the SN, which would be too weak when the GRB signal fades away [24].

Finally, a well known problem is the difficulty to produce the heaviest elements through r-processes taking place at the moment of a SN explosion. It is tempting to imagine that the ejection of a fraction of hot and neutron rich material after the first explosion can allow the production of the heaviest elements via revitalized r-processes [25, 4].

A preliminary version of this work was presented at the Workshop "The complex physics of compact stars", Ladek Zdroj - Poland, February 2008.

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