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The phase transition from nuclear matter to quark matter during proto-neutron star evolution

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ABSTRACT

We explore the occurrence of a phase transition from nuclear matter to quark matter in proto-neutron stars. To this end, we employ recent results on such a phase transition in the presence of an electron–neutrino–degenerate gas, based on a mean field model nuclear equation of state together with a quark matter equation of state as described by the MIT 'bag model'. Those results show that this neutrino gas does not favour the transition. By comparison with the proto-neutron star evolutionary calculations of Keil & Janka, we find that, if the bag constant B has a value $B \lesssim 126\,\mathrm{MeV\,fm^{-3}}$, the deconfinement transition indeed occurs. We also find that, if $B \gtrsim 100\,\mathrm{MeV\,fm^{-3}}$, the phase transition is delayed by the presence of neutrinos by a few seconds after core bounce, thus providing a natural explanation for the second peak of neutrino emission detected in SN 1987A by the Kamiokande Group. The transition to quark matter and its subsequent decay should affect proto-neutron star evolution and supernova explosions in a non-trivial way.

Key words: equation of state – stars: neutron – supernovae: general – supernovae: individual: SN 1987A.

1 INTRODUCTION

It is widely accepted that a neutron star (NS) interior is one of the few places in the Universe where a phase transition from nuclear matter to quark matter may be expected. This being the case, NSs would be mostly made up of quark matter. Since Witten (1984) proposed that strange matter (a kind of quark matter composed of roughly equal abundances of u, d and s quarks) could be absolutely stable, considerable effort has been devoted to analysing whether such a fundamental proposal is indeed correct. For reviews on this topic see e.g. Alcock & Olinto (1988) and Benvenuto, Horvath & Vucetich (1998). For more recent work on this problem see Anand et al. (1997), Grassi (1998), Goyal & Chandra (1998) and references therein.

The transition to quark matter should produce a major rearrangement of the NS interior structure and the release of a large amount of energy as well, yielding, in principle, some detectable consequences. Moreover, if the transition to quark matter occurs somewhere in the NS interior, it should happen soon after its birth.

It is well known that the structure of a proto-neutron star (PNS) changes dramatically in the few seconds after formation, as a result of the release of most of its energy and lepton excess by means of neutrino emission (Burrows & Lattimer 1986; Keil & Janka 1995, hereafter KJ95). After this PNS stage, the evolution of the NS may be described as basically a cooling process in which the thermal and structural properties are almost decoupled. If we want to look for some signal of quark deconfinement, we should search for it during the short PNS evolution time-scale, which is intimately related to the supernova event itself. If an NS does not reach transition conditions during PNS evolution but suffers mass accretion, then the transition may be induced for much older NSs (see e.g. Grassi 1998). In the case of an isolated NS, a delayed deconfinement, driven by cooling or rotational braking, seems much more unlikely because of the modest increase in the internal density during such processes.

The effect of the transition to quark matter on the dynamical properties of core-collapse supernovae has been addressed in numerous studies. Such studies were motivated by the difficulties of the standard theoretical models in accounting for the observed explosions [for more details, see e.g. Mezzacappa et al. (1998) and Janka (1996)]. Most of these models considered the transition to quark matter by incorporating it as a further core collapse, which releases more gravitational binding energy than in the standard case (Takahara & Sato 1985; Gentile et al. 1993). Perhaps the most extreme scenario has been proposed by Benvenuto & Horvath (1989) and Benvenuto et al. (1991), who presented a mechanism by which quark matter is deconfined some seconds after core bounce. Its subsequent decay to strange matter prompts a detonation wave

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which blows up the mantle and envelope of a massive star. In such a framework, the detonation wave is responsible for the ultimate success of the core-collapse supernova explosion.

It is the purpose of this work to study the viability of the transition from nuclear matter to quark matter in the conditions prevailing in a PNS during the first tens of seconds since its birth. In doing so, we consider a hyperonic equation of state (EOS) for the nuclear phase and the 'bag model' EOS for the quark matter. In addition, we include the effects induced by the presence of a degenerate Fermi gas of electron neutrinos. In order to assess whether such a transition is possible or not, we apply our results to actual astrophysical scenarios, as given by detailed PNS evolutionary calculations. In closing, we comment on the consequences and observable signals of the transition.

2 THE TRANSITION FROM NUCLEAR MATTER TO QUARK MATTER

2.1 The equation of state for nuclear matter

In a recent paper, we have studied the conditions for the transition from nuclear matter to quark matter in the presence of a gas of degenerate electron neutrinos (Lugones & Benvenuto 1998, hereafter LB98). In that work we employed the hyperonic mean field model EOS presented by Glendenning (1985), which incorporates the particles n, p, Λ, Σ^+, Σ^0, Σ^-, Ξ^-, Ξ^0, μ and e. In the context of this EOS, baryons interact by means of the exchange of an attractive scalar field σ, a repulsive vector field $\boldsymbol{\omega}$, and an isovector ρ-meson field. The system is treated in the relativistic mean field approximation.

It is well known that, at birth, PNSs have a large electron neutrino content. Thus, in order to adapt the EOS to the actual conditions prevailing in PNSs, we also include a Fermi gas of electron neutrinos ν_e (for consistency, muon and tau neutrinos have not been included: see below). We assume β-equilibrium amongst the above-mentioned particles, and we consider the mixture at finite temperature. We refer the interested reader to LB98 for further details.

2.2 The equation of state for quark matter

The quark phase is composed of u, d and s quarks and gluons, electrons, muons and electron neutrinos. We describe this phase by means of the MIT 'bag model' at finite temperature with zero strong coupling constant, zero u and d quark masses and strange quark mass $m_s = 150$ MeV. Unfortunately, there exists a large uncertainty in the actual value of the bag constant B. For this reason we consider the following B-values: 60, 80, 100 and 120 MeV fm^{-3}. Finally, we neglect any dependence of B on density and temperature.

2.3 The transition to quark matter

The transition from nuclear matter to quark matter in chemical equilibrium (under weak interactions) occurs necessarily through an intermediate step of quark deconfinement driven by strong interactions.

Strong interactions operate on time-scales ($\approx 10^{-23}$ s) several orders of magnitude shorter than those of weak interactions ($\approx 10^{-8}$ s), so the latter cannot operate within a deconfinement time-scale. In view of that, in a deconfinement transition the abundance per baryon of each quark and lepton flavour is the same in both the hadron and quark phases. We should remark here that the actual conditions for the transition are different from those first discussed by Glendenning (1992), who proposed the existence of a mixed phase. In such a phase, mixed hadron and quark matter might co-exist over a wide range of densities if electric charge conservation is applied to both phases simultaneously. This is in contrast to the standard treatment in which each phase is treated separately.

In order to compute the transition conditions, we apply the standard Gibbs criteria, i.e. equality of pressure P, temperature T and Gibbs energy per baryon g in both phases:

$$P_q = P_h, \qquad T_q = T_h, \qquad g_q = g_h, \tag{1}$$

together with flavour per baryon conservation equations. The calculations show that neutrino degeneracy pushes the deconfinement transition densities significantly upwards as compared with the case in which neutrinos are absent. An extensive treatment of this problem for densities above the nuclear saturation density ρ_0 ($\rho_0 = 2.7 \times 10^{14}\,\mathrm{g\,cm^{-3}}$) and temperatures up to 100 MeV, and including the presence of a muon neutrino gas, has been presented by LB98, and we refer the reader to that paper for more details.

3 THE TRANSITION TO QUARK MATTER IN PROTO-NEUTRON STARS

3.1 The evolution of proto-neutron stars

The evolution of PNSs is essentially a process of deleptonization and cooling in which the newly born collapsed object radiates its leptonic and thermal excess, settling down to its asymptotic structure as a cool NS. In order to apply our results to actual astrophysical conditions, we consider the first stages of the evolution of a 1.6-$\mathrm{M}_\odot$ PNS computed by KJ95.

KJ95 calculated the first stages (few tens of seconds) of evolution of a 1.6-$\mathrm{M}_\odot$ PNS just after core bounce. They incorporated different EOSs in their study. In particular, they employed the same hyperonic EOS as we described above in our study of the phase transition to quark matter (for consistency, we employ here the hyperonic coupling constants used by KJ95 in their EOS B). They assumed a correction to the zero-temperature EOS that is typical of fermionic systems ($\propto T^2$). In this regard, their treatment at finite temperature is not a fully self-consistent one. Because we have made no approximation in incorporating thermal effects in our EOS, the two descriptions are not exactly equivalent. However, we assume that this inconsistency produces a negligible effect on the results that we present here. It is also worth mentioning that KJ95 neglected muon and tau neutrinos in their computations.

The main results of KJ95 are summarized in Fig. 1, where we show the profiles of the baryon rest mass density ρ_*, the temperature T and the electronic neutrino chemical potential μ_ν for PNS ages of 0.6, 1.6, 5.6, 10.6 and 18.6 s after core bounce. As far as the evolution of the density profile is concerned, during the first 5 s the PNS interior suffers a slight decompression followed by a slow compression to its asymptotic shape. The internal temperature of the PNS decreases in the outer regions, whereas in the innermost 0.5 $\mathrm{M}_\odot$ it increases to ~55 MeV. Needless to say, the most dramatic evolution is related to the neutrino content. It falls almost to zero throughout the entire PNS interior in ~10 s. Such neutrino losses have a key effect on the transition epoch.

3.2 The evolutionary state of proto-neutron stars at quark deconfinement

In order to study whether the conditions for the transition to quark matter are indeed attained during PNS evolution, we employ the

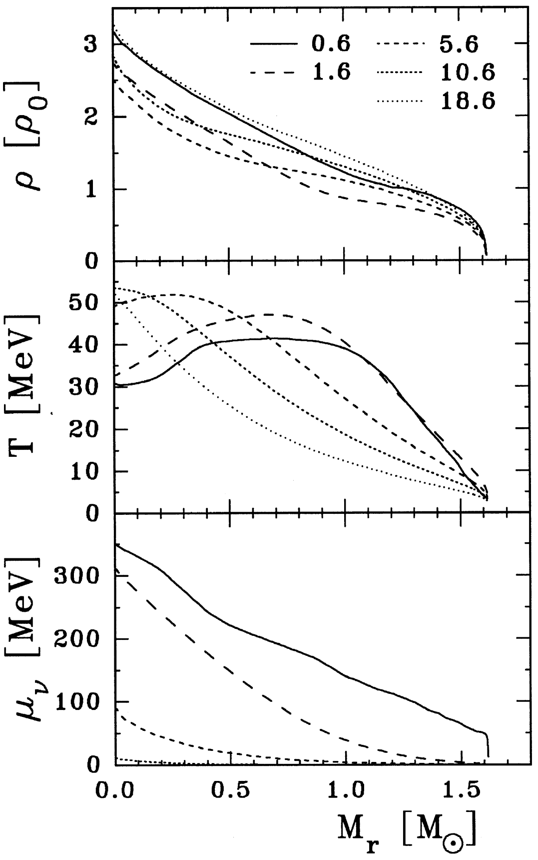

Figure 1. The evolution of a PNS of 1.6 $M_\odot$ computed by KJ95. In the first, second and third panels, we show the evolution of the profiles of density, temperature and neutrino chemical potential respectively, for ages of 0.6, 1.6, 5.6, 10.6 and 18.6 s after core bounce.

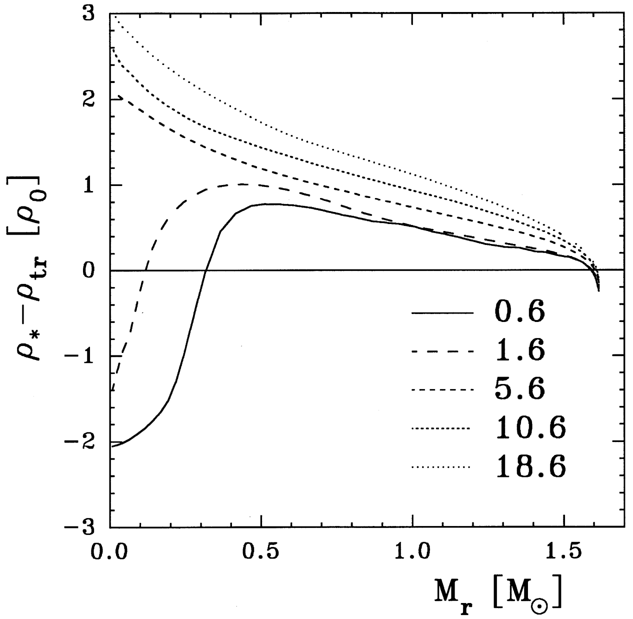

Figure 2. The profile of $\rho_* - \rho_{\rm tr}$ versus mass for different stages of evolution of a 1.6-$M_\odot$ PNS assuming a bag constant $B = 60\,{\rm MeV\,fm^{-3}}$. Here, ρ is the baryon rest mass density, i.e. $\rho = m_{\rm u} n_{\rm B}$ with the mass unit $m_{\rm u} = 1.66 \times 10^{-24}$ g and $n_{\rm B}$ the baryon number density. If $\rho_* - \rho_{\rm tr}$, then the star has reached a state that should undergo the phase transition to quark matter. Note that, in this case, even the first model considered here should have suffered the transition.

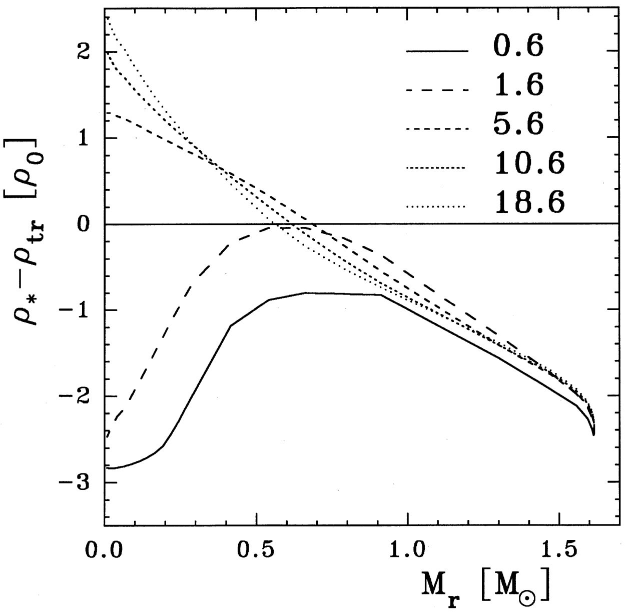

Figure 3. As Fig. 2, but for $B = 80\,{\rm MeV\,fm^{-3}}$. The transition conditions are reached off-centre, soon after 1.6 s after core bounce.

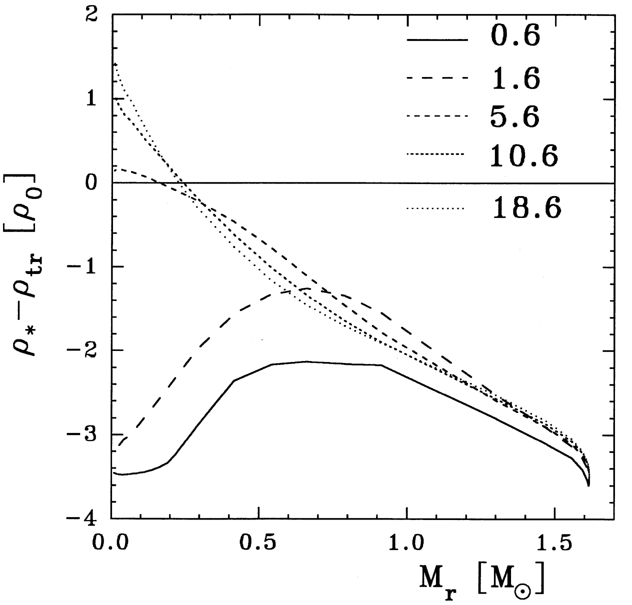

Figure 4. As Fig. 2, but for $B = 100\,{\rm MeV\,fm^{-3}}$. The transition conditions are reached at the centre of the PNS, just before 5.6 s after core bounce.

KJ95 results in the following way: at a given layer of the PNS we have values for T and μ_ν, then for these values we compute the density $\rho_{\rm tr}$ at which transition occurs, and compare such a density with the density ρ_* of the layer considered. Then, if $\rho_* - \rho_{\rm tr}$ is negative, the star is not compressed enough for the transition to occur (i.e. the preferred phase is the nuclear one). However, in contrast, if $\rho_* - \rho_{\rm tr}$ is positive, the star should undergo the phase transition to quark matter.

We have computed $\rho_* - \rho_{\rm tr}$ for the KJ95 PNS models included in Fig. 1 and the values of the bag constant quoted in Section 2.2. The main results of this work are presented in Figs 2–5.

In Fig. 2 we show $\rho_* - \rho_{\rm tr}$ versus $M_{\rm r}$ (the baryon rest mass enclosed in a radius r) for the case $B = 60\,{\rm MeV\,fm^{-3}}$. Here, the value of B is so low that the phase transition is expected to occur at

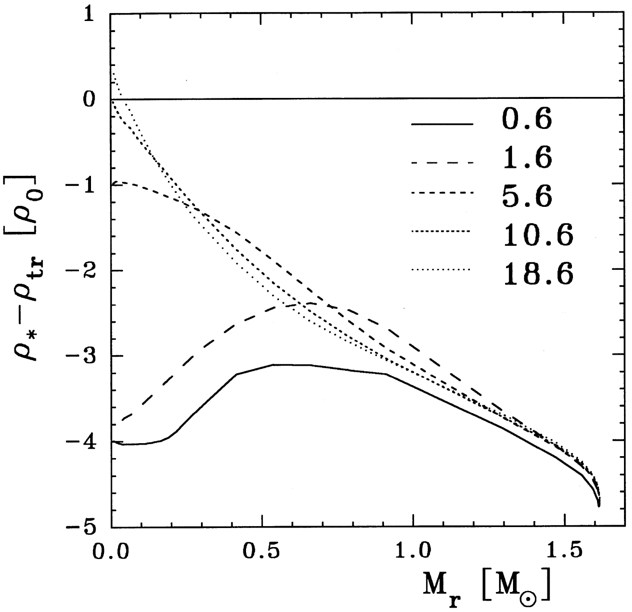

Figure 5. As Fig. 2, but for $B = 120\,\mathrm{MeV\,fm^{-3}}$. The transition conditions are reached at the centre of the PNS, just before 10.6 s after core bounce.

low densities (see fig. 2 of LB98). As a result, even the first PNS model considered here should have suffered the deconfinement transition to quark matter. If the actual value of B is $80\,\mathrm{MeV\,fm^{-3}}$, the transition is expected at higher densities. In particular, the PNS is expected to suffer the transition to quark matter off-centre, soon after 1.6 s of evolution (see Fig. 3). Higher B-values increase the densities expected for transition further: for $B = 100$ and $120\,\mathrm{MeV\,fm^{-3}}$, for instance, the transition conditions are reached at the centre of the PNS just before 5.6 and 10.6 s after core bounce, respectively (see Figs 4 and 5). Employing the latest KJ95 model, we have verified that B must have a value $B < 126\,\mathrm{MeV\,fm^{-3}}$ for the occurrence of the transition during PNS evolution.

4 DISCUSSION

The results presented here indicate that, if $B < 126\,\mathrm{MeV\,fm^{-3}}$, the conditions for transition to quark matter are indeed attained during proto-neutron star evolution. Regrettably, the uncertainty existing in the actual value of B makes the computation of the PNS stage at which transition is expected to occur almost impossible. However, it should be noted that, unless B is very low, the transition should occur after a fraction of the deleptonization time-scale ($\sim$10 s).

It is worth noting that the newly deconfined quark matter, which is far from chemical equilibrium, decays to a composition with a higher quantity of strange quarks by means of weak interactions. This decay releases a lot of heat and fresh neutrinos which should modify the PNS evolution in a non-trivial way. Comparing the conditions for the occurrence of the transition with the predictions of standard PNS evolutionary calculations, it is possible to estimate from our results the epoch of onset of the transition and the layers at which it should be expected. Nevertheless, further evolutionary stages, including the quark matter decay, should be calculated in a fully detailed way. We plan to study such a decay under the conditions found here in a future publication. For the decay of quark matter under other conditions, see Dai, Peng & Lu (1995); and Anand et al. (1997).

Once the first seed of quark matter has been produced, it should grow (probably by means of a detonation wave), thus turning part of the PNS into quark matter. The newly deconfined quark matter will decay on a time-scale of $\sim 10^{-8}$ s, radiating a large number of additional neutrinos. Under these circumstances, the temperature should increase appreciably, to such an extent that the three kinds of neutrinos and antineutrinos should be thermally generated. These additional neutrinos would be radiated away on a diffusion time-scale, and could be crucial for the success of the delayed explosion mechanism, since they could provide the necessary energy to revive the shock wave. In addition, if $B \gtrsim 100\,\mathrm{MeV\,fm^{-3}}$, the delay expected for the transition to quark matter could be so large that the neutrinos could be observed by terrestrial detectors as a second neutrino signal superimposed on the standard one. It is worth noting that the delay from the first neutrino peak, owing to core collapse and failed prompt shock, to the second quark matter decay driven neutrino peak should be given by the time that the PNS needs to evolve to deconfinement plus the time of neutrino diffusion from the deconfined interior up to the neutrinosphere.

It is well known that the Kamiokande Group detected two neutrino peaks in SN 1987A (Hirata et al. 1987). They observed 11 neutrinos associated with this historic explosion. Notably, the first eight were detected in a 2-s interval, whereas the three remaining were detected after a hiatus of 7 s. Many researchers have linked this rather unexpected time distribution of detections to an effect related to a few-event statistics in the framework of a standard supernova explosion and subsequent PNS evolution (see e.g. Bludman & Schinder 1988). Nevertheless, in the framework of the above results, and if $B \gtrsim 100\,\mathrm{MeV\,fm^{-3}}$, the abovementioned hiatus is naturally accounted for by the time that the PNS spent in reaching the deconfinement conditions plus the neutrino transport to the PNS neutrinosphere ($\sim$ a few seconds).

Of course, it would be very interesting to explore the conditions for the transition to quark matter in PNS models with different masses, and also employing other EOSs.

It is worth remarking that all of the phenomena described in this work may be correct, provided that strange quark matter is the ground state of matter at the high pressures and temperatures found in PNS interiors, even if it is not the ground state at zero pressure and temperature. This represents a much less restrictive constraint on the physical properties of quark matter.

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