Color Superconductivity in Compact Stars and Gamma Ray Bursts

A. Drago[a], A. Lavagno[b], G. Pagliara[a]

[a]*Dipartimento di Fisica, Università di Ferrara and INFN, Sezione di Ferrara, 44100 Ferrara, Italy*

[b]*Dipartimento di Fisica, Politecnico di Torino and INFN, Sezione di Torino, 10129 Torino, Italy*

Abstract

We study the effects of color superconductivity on the structure and formation of compact stars. We show that it is possible to satisfy most of recent observational boundaries on masses and radii if a diquark condensate forms in a hybrid or a quark star. Moreover, we find that a huge amount of energy, of the order of 10^{53} erg, can be released in the conversion from a (metastable) hadronic star into a (stable) hybrid or quark star, if the presence of a color superconducting phase is taken into account. Accordingly to the scenario proposed in Astrophys.J.586(2003)1250, the energy released in this conversion can power a Gamma Ray Burst. This mechanism can explain the recent observations indicating a delay, of the order of days or years, between a few Supernova explosions and the subsequent Gamma Ray Burst.

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1 Introduction

The new accumulating data from X-ray satellites provide important information on the structure and formation of compact stellar objects. Concerning the structure, the new data fix rather stringent constraints on the mass and the radius of a compact star. These data are at first sight difficult to interpret in a unique and self-consistent theoretical scenario, since some of the observations are indicating rather small radii and other observations are indicating large values for the mass of the star.

Concerning the formation scenario, crucial information are provided by the very recent observations of Gamma-Ray Bursts (GRB), indicating the possibility that some of the GRBs are associated with a previous Supernova ex-

plosion, with a delay between the first and the second explosion of the order of days or years [1,2]. These observations could be explained associating the second explosion with the conversion of a (metastable) hadronic star (HS) into a more stable stellar object made at least in part of deconfined quark matter (QM). In the scenario proposed in Ref.[3] (see also references therein), the HS can be metastable due to the presence of a non-vanishing surface tension at the interface separating hadronic matter (HM) from QM. The nucleation time (i.e. the time to form a critical-size drop of quark matter) can be extremely long if the mass of the star is small. Via mass accretion the nucleation time can be dramatically reduced and the star is finally converted into the stable configuration.

In recent years, many theoretical works have investigated the possible formation of a diquark condensate in quark matter, at densities reachable in the core of a compact star [4,5,6]. The formation of this condensate can deeply modify the structure of the star [7,8,9].

In this Letter we show that it is possible to satisfy the existing boundaries on mass and radius of a compact stellar object if a diquark condensate forms in a Hybrid Star (HyS) or a Quark Star (QS). Moreover, the formation of diquark condensate can significantly increase the energy released in the conversion from a purely HS into a more stable star containing deconfined QM.

2 Equation of state of beta-stable matter

The EOS appropriate to the description of a compact star has to satisfy beta-stability conditions. Moreover two charges are conserved, the baryonic and the electric one. These conditions need to be satisfied in the hadronic, in the quark and in the mixed phase. Although electric charge neutrality and beta-stability are easy to impose for non-interacting quark matter, these conditions are highly non-trivial when a diquark condensate can develop.

Concerning the hadronic phase we use the relativistic non-linear Glendenning-Moszkowski model (GM1-GM3) [10]. At very low density we have used the Negele-Vautherin [11] and the Baym-Pethick-Sutherland [12] EOS. For the quark matter phase we adopt a MIT-bag like model in which the formation of a diquark condensate is taken into account in a simple and effective way which will be described below. To connect the two phases of our EOS, we impose Gibbs equilibrium conditions. When the Gibbs conditions are applied in presence of more than one conserved charge, the technique developed by Glendenning has to be adopted [13,14] and the pressure need not to be constant in the mixed phase. Therefore a finite volume of the star can be occupied by the mixed phase, what is crucial for the stability of the star.

It is widely accepted that the Color-Flavor Locking phase (CFL) is the real ground state of QCD at asymptoticly large densities but, at the scales which are involved in a compact star, there is yet uncertainty about the presence of this phase and in particular about the transition from superconducting QM to HM. There are different possible scenarios depending on the value of the strange quark mass. A direct transition from CFL to HM is possible for a small value of m_s. Alternatively, an intermediate window of Crystalline Color Superconductivity phase can develop [15,16] or a phase can be formed in which the Cooper pairing involves only quarks of the same flavor [17]. A pure two flavor color superconductivity (2SC) phase is ruled out due to the high free energy cost resulting from the requirement of color and electric neutrality [17,18]. A mixed 2SC-CFL phase could exist but it seems to be unstable due to Coulomb and surface effects [19]. In our model the CFL phase is connected directly to HM through a first order phase transition, what seems to be consistent with the use of a small value for m_s, of the order of 150 MeV.

In this Letter we are interested in the bulk properties of a compact star. We use therefore a schematic model which takes into account in a simple and effective way the main characteristics of the EOS of quark matter in the presence of diquark condensation. The main aim of our work is to discuss the dependence of the structure of the star on the numerical value of three crucial parameters, namely the height and position of the maximum of the diquark gap and the value of the pressure of the vacuum B of the MIT bag model.

We adopt the scheme proposed in Refs.[7,20] where the thermodynamic potential is given by the sum of two contributions. The first term corresponds to a "fictional" state of unpaired quark matter in which all quarks have a common Fermi momentum chosen to minimize the thermodynamic potential. The other term is the binding energy of the diquark condensate expanded up to order $(\Delta/\mu)^2$. In Ref.[7] the gap is assumed to be constant, independent on the chemical potential. In the present calculation we consider a μ dependent gap resulting from the solution of the gap equation. We describe the superconducting phase using the first work of Alford, Rajagopal and Wilczek in which the Color-Flavor Locking phase was introduced [4] by considering three massless flavors. This approximation is a sensible one as long as m_s is small in comparison with the quark chemical potential [15]. The quark-quark interaction is described by a NJL-like Lagrangian with an effective coupling constant K and a form factor which mimics the asymptotic freedom of QCD. The form factor reads: $F(k) = \left(1 + \exp\left[\frac{k-\Lambda}{w}\right]\right)^{-1}$, where w and Λ are free parameters of this model.

The CFL phase is characterized by the existence of two order parameters Δ_s (singlet) and Δ_o (octet) which are the solutions of two coupled gap equations. The value of the coupling K is fixed, as in Ref.[4], by imposing that the NJL Lagrangian with the same K gives, through chiral symmetry breaking at zero

chemical potential, a reasonable value for the chiral gap Δ_χ. This procedure in turn fixes the maximum of the superconducting gap. In this work we use values for K giving a Δ_χ ranging from 300 to 600 MeV and a corresponding maximum of the "effective gap" $\Delta(\mu) = F^2(\mu)\sqrt{[8(\Delta_o(\mu))^2 + (\Delta_s(\mu))^2]/12}$ varying from 70 to 150 MeV. This definition of Δ corresponds to the gap used in Ref.[7] if $\Delta_s = 2|\Delta_o|$, as assumed in that work. In Fig.1 we display the "effective gap" as a function of the chemical potential. In our calculation we have not really solved self-consistently the coupled equations for the chiral and the superconducting gap. The result of microscopic calculations, like the ones of Refs.[18,19] indicates that the two gaps are mutually exclusive. In particular, the superconducting gap is suppressed at low μ. Therefore we do not consider realistic the parameters corresponding to gaps Δ_1 and Δ_2, and they are mainly introduced to illustrate the effects connected with the position μ_{max} of the maximum of the gap.

In our model, confinement is schematically described by introducing the MIT bag constant B. Moreover, the pressure and the energy density are modified by the contributions of the electrons, which are necessary in the mixed phase[1]:

$$P = -\Omega_{CFL}(\mu) - B - \Omega^{electrons}(\mu_e) \tag{1}$$

$$E/V = \Omega_{CFL}(\mu) + \mu\rho + B + \Omega^{electrons}(\mu_e) + \mu_e\rho_e, \tag{2}$$

where

$$\Omega_{CFL}(\mu) = \frac{6}{\pi^2}\int_0^\nu k^2(k-\mu)\,\mathrm{d}k + \frac{3}{\pi^2}\int_0^\nu k^2(\sqrt{k^2 + m_s^2} - \mu)\,\mathrm{d}k - \frac{3\Delta^2\mu^2}{\pi^2} \tag{3}$$

with

$$\nu = 2\mu - \sqrt{\mu^2 + \frac{m_s^2}{3}}, \tag{4}$$

and the quark density ρ is calculated numerically by deriving the thermodynamic potential respect to μ.

In Fig.2 we show the EOS with and without color superconductivity. The effect of the gap is to increase the pressure of paired QM respect to the unpaired QM at a fixed chemical potential. This extra pressure reduces the values of the critical densities. Comparing the curves for $\Delta = 0$ and $\Delta \neq 0$ we can see that the CFL EOS is softer than the unpaired QM EOS at low density and stiffer at high density. This will have important consequences in the M-R curves.

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[1] In the pure CFL phase the contribution of electrons vanishes due to the electrical neutrality enforced by the existence of the gap [21].
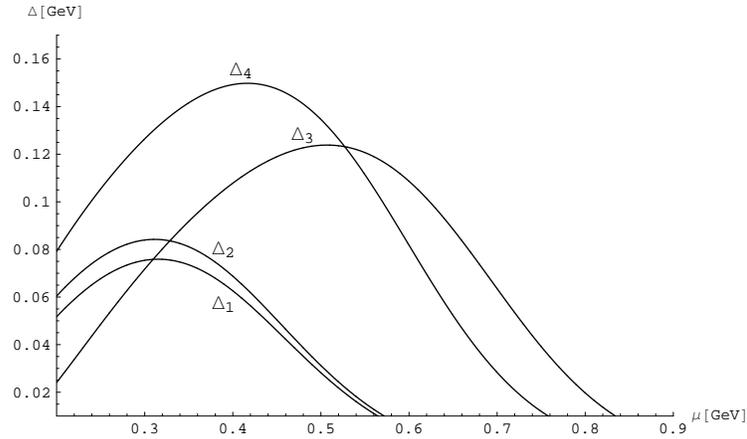
Fig. 1. Gap as function of the chemical potential, for four different parameter sets.
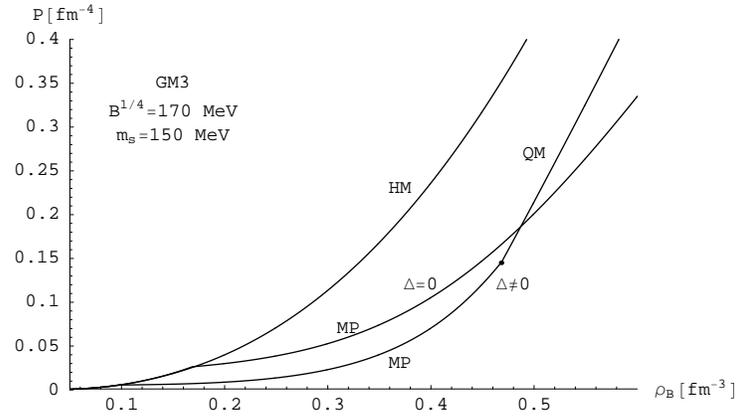
Fig. 2. Pressure versus baryonic density. HM indicates a purely hadronic EOS, MP a mixed-phase of hadrons and quarks and QM pure quark matter. The effect of a non-vanishing superconducting gap is displayed.

3 Masses and radii of compact stellar objects

In Fig.3 we have collected most of the analysis of data from X-ray satellites, concerning masses and radii of compact stellar objects [22,23,24,25,26,27,28]. Most of the data have been obtained very recently due to the technological progresses in the field of X-ray detectors. Although some (or all) of the data analysis are controversial, since they depend on specific assumptions on the structure of the X-ray source, we do think that these observational results deserve to be carefully discussed.
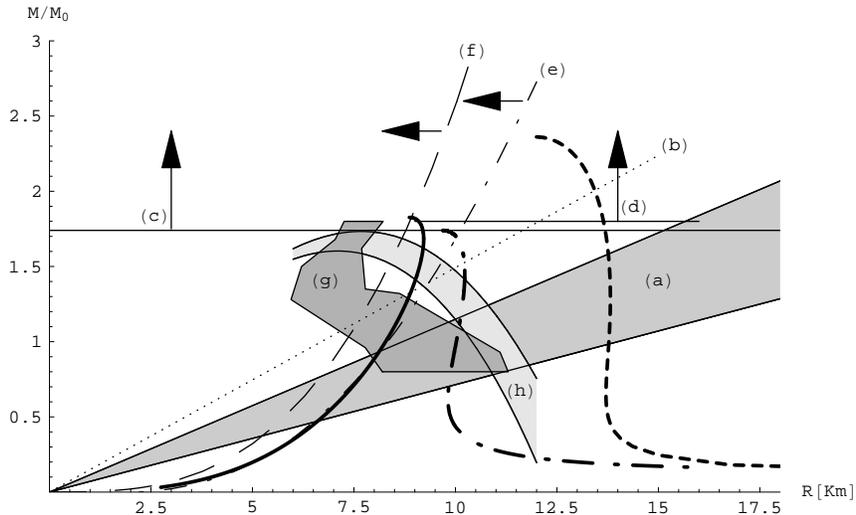
Fig. 3. Mass-radius plane with observational limits and a few representative theoretical curves: thick solid line indicates CFL quark stars, thick dot-dashed line CFL hybrid stars, thick-dashed line hadronic stars (see text). The observational limits come from: (a) Sanwal et al. 2002 [22], (b) Cottam et al. 2002 [23], (c) Quaintrell et al. 2003 [24], (d) Heinke et al. 2003 [25], (e),(g) Dey et al. 1998 [26], (f) Li et al. 1999 [27], (h) Burwitz et al. 2002 [28].

Observing Fig.3, we notice that the constraints coming from a few data sets (labeled "e", "f" [2] "g" and maybe also constraint "h" [3]) indicate rather unambiguously the existence of very compact stellar objects, having a radius smaller than ~ 10 km. At the contrary, at least in one case ("a" in the figure), the analysis of the data suggests the existence of stellar objects having radii of the order of 12 km or larger, if their mass is of the order of 1.4 $M_\odot$. In this analysis one has also to take into account that it is difficult from an astrophysical viewpoint to generate compact stellar objects having a mass of the order of one solar mass or smaller. Therefore the most likely interpretation of constraint "a" is that the corresponding stellar object does not belong to the

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[2] A very recent reanalysis of the data of the pulsar SAX J1808.4-3658, discussed in Ref. [27], seems to indicate slightly larger radii, of the order of 9-10 km for a star having a mass of 1.4-1.5 $M_\odot$ [29].

[3] The data at the origin of constraint "h" have been discussed in many recent papers. In Ref.[30] an indication for an even more compact stellar object can be found. Anyway, the so-called thermal radius obtained in these analysis could be significantly smaller than the total radius of the star.

same class of objects which have a radius smaller than ~ 10 km. Concerning constraint "b", its interpretation is less clear, since it can be satisfied both with a very compact star or with a star having a larger radius. The apparent contradiction between the constraints "e", "f", "g" and the constraint "a" can be easily accommodated in our scheme, since it can be the signal of the existence of metastable purely hadronic stars which can collapse into a stable configuration when deconfined quark matter forms inside the star. In the next Section we will discuss the possible relation between this transition and at least some GRBs.

Finally, constraints ("c" and "d") do not provide stringent limits on the radius of the star, but they put strong constraints on the lower value of its mass. Constraints "c" and "d" are very important, since it is in general not easy to obtain solutions of the Tolman-Oppenheimer-Volkoff equation having both large masses and very small radii. As we will see, the existence of an energy gap associated with the diquark condensate helps in circumventing this difficulty, since the effect of the gap is to increase the maximum mass of QSs or of HySs having a huge content of pure quark matter, as shown in Fig.4.

In the upper panel of Fig.4 we show that a CFL HyS has a smaller radius respect to an unpaired QM HyS, if the mass of the star is smaller than ~ 1.35 $M_{\odot}$. This can be explained observing the EOSs shown in Fig.2. For a low mass star, the central density lies in the region of the $P - \rho$ plane where the CFL EOS is softer than the unpaired QM EOS and therefore the radius of the star is smaller. For a large mass star, on the contrary, the central density is in the region where the CFL EOS is stiffer than unpaired QM EOS and therefore the radius of the star is larger. It is also worth remarking that if the value of the gap is increased the amount of QM in the star also increases. Therefore, for large values of the gap, heavy HySs have a shape more and more similar to the shape of pure QSs, which are finally obtained by a further increase of the value of the gap[4] (see also the lower panel of Fig.4). All these results are totally consistent with the ones obtained in Ref.[7].

Concerning the value of the chemical potential μ_{max}, which corresponds to the maximum of the gap, we get relevant modifications to the mass-radius relation if 0.3 GeV $\lesssim \mu_{max} \lesssim 0.6$ GeV. For larger values of μ_{max} the effect of the gap is negligible. Low values of μ_{max}, of the order of 0.3 GeV, correspond to interesting stellar configurations, but are difficult to justify at the light of results like the ones presented in Ref.[19] (see discussion at the end of Sec.2). In the upper panel of Fig.4 we display results for three values of μ_{max}, whose corresponding gaps are shown in Fig.1. We also show that, using $B^{1/4} = 170$ MeV, only a big value of the gap, located at a not too large density (Δ_4)

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[4] Notice that the existence of a large CFL gap is not constrained by the traditional argument concerning the stability of Fe against decay into two-flavor QM.

allows the formation of a QS, while for the other gaps HySs are obtained.

In Fig.3 we show a few theoretical M-R relations which correspond to the scenario we are proposing. More precisely, we show a thick-dashed line corresponding to HSs (GM1), a thick dot-dashed line corresponding to HySs (GM1, $B^{1/4} = 170$ MeV, Δ_2) and a thick solid line corresponding to QSs (GM1, $B^{1/4} = 170$ MeV, Δ_4). Both the HyS and the QS lines can satisfy essentially all the constrains derived from observations (concerning the constraint "f" see footnote (2)). Concerning the constraint "a", it is probably better satisfied by the HS line than by the HyS or QS lines, which would give stars having a mass smaller than $\sim 1.2 M_\odot$. In conclusion, in our scheme most of the compact stars are either HySs or QSs having a mass in the range $1.2 - 1.8 M_\odot$ and a radius $\sim 8.5 - 10$ km. Metastable HS can exist. As we will see in the next section their mass is probably smaller than $\sim 1.3 M_\odot$.

4 Nucleation time and energy released

In the model we are discussing the formation of QSs or HySs is due to the conversion of a purely HS into a more compact star in which deconfined QM is present. An HS can be metastable if a non-vanishing surface tension is present at the interface between HM and QM. The process of quark deconfinement can be a powerful source for GRBs and it can also explain the delay between a supernova explosion and the subsequent GRB observed in a few cases [1,2] [5]. In the scenario proposed in Ref.[3], the central density of a pure HS increases, due to spin down or mass accretion, until its value approaches the deconfinement critical density. At this point a spherical virtual drop of QM can form. The potential energy for fluctuations of the drop radius R has the form [33]:

$$U(R) = \frac{4}{3}\pi R^3 n_q (\mu_q - \mu_h) + 4\pi\sigma R^2 + 8\pi\gamma R \tag{5}$$

where n_q is the quark baryon density, μ_h and μ_q are the hadronic and quark chemical potentials, all computed at a fixed pressure P, and σ is the surface

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[5] A possible mechanism explaining these GRBs is the supranova model [31]. In this model, the GRB is the result of the collapse to a black hole of a supramassive fast rotating NS, as it loses angular momentum. According to this model NS is produced in the Supernova explosion preceding the GRB event. The initial baryonic mass of the NS is assumed to be above the maximum baryonic mass for non-rotating configurations. As noticed in Ref. [32] in these collapse too much baryonic material is ejected and thus the energy output is expected to be too small to produce GRBs. Moreover, the supranova model seems to produce GRBs which are too short compared with the observed durations.
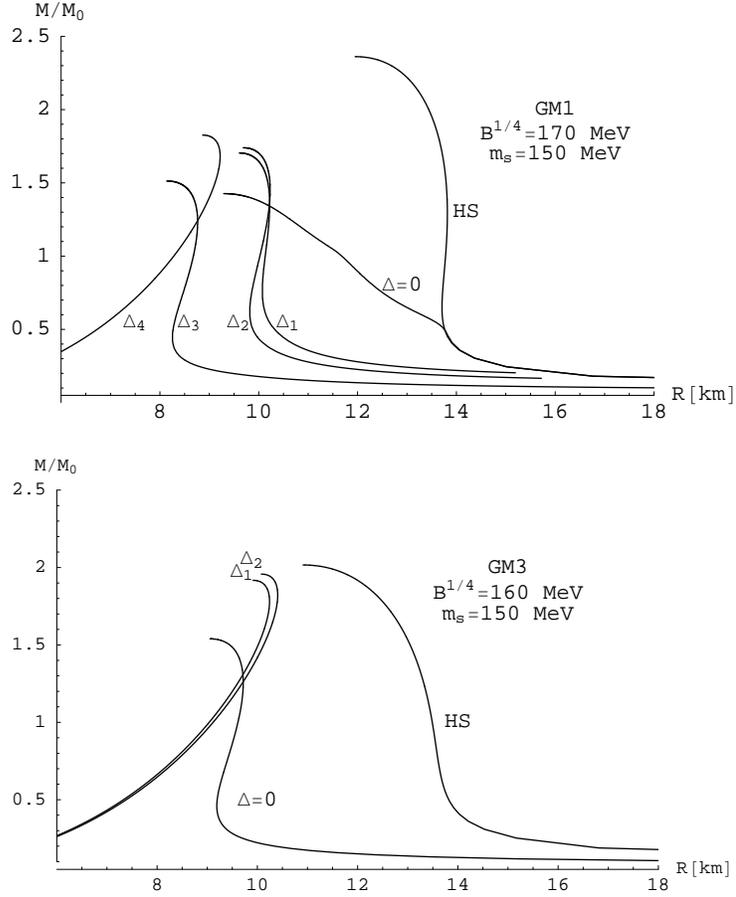
Fig. 4. A few theoretical mass-radius relations are shown. HS indicates purely hadronic stars. The other lines correspond either to hybrid or quark stars, depending on the value of the gap for a given value of B.

tension for the interface separating quarks from hadrons. Finally, the term containing γ is the so called curvature energy. For σ we use standard values from 10 to 40 MeV/fm^2 and we assume that it takes into account, in a effective way, also the curvature energy. The value of σ was estimated in Ref.[34] to be ~ 10 MeV/fm^2. Values for σ larger than ~ 30 MeV/fm^2 are probably not useful at the light of the result of Refs.[35,36].

To compute the time needed to form a bubble of quarks having a radius larger than the critical one, we use the technique of quantum tunneling nucleation. We can assume that the temperature has no effect in our scheme: for values of $B^{1/4} \sim 160 - 180$ MeV, which we use in this Letter, the critical density ρ_1 separating pure HM from mixed phase is larger than $4\rho_0$ for $Z/A \sim 0.3$, i.e. for an isospin fraction typical of a newly formed and hot proto-neutron star [37]. This critical density typically exceeds the central density of hot and not too massive stars. Therefore the mixed phase can form only when the star has deleptonized and its temperature has dropped down to a few MeV [38]. When the temperature is so low, only quantum tunneling is a practicable mechanism. The calculation proceed in the usual way: after the computation (in WKB approximation) of the ground state energy E_0 and of the oscillation frequency ν_0 of the virtual QM drop in the potential well $U(R)$, it is possible to calculate in a relativistic frame the probability of tunneling as [39]:

$$p_0 = \exp[-\frac{A(E_0)}{\hbar}] \tag{6}$$

where

$$A(E) = 2 \int_{R_-}^{R_+} dR \sqrt{[2M(R) + E - U(R)][U(R) - E]} \, . \tag{7}$$

Here $R_{\pm}$ are the classical turning points and

$$M(R) = 4\pi \rho_h \left(1 - \frac{n_q}{n_h}\right)^2 R^3 \quad , \tag{8}$$

ρ_h being the hadronic energy density and n_h, n_q are the baryonic densities at a same and given pressure in the hadronic and quark phase, respectively. The nucleation time is then equal to

$$\tau = (\nu_0 p_0 N_c)^{-1} \, , \tag{9}$$

where N_c is the number of centers of droplet formation in the star, and it is of the order of 10^{48} [39]. In the calculation of nucleation times we neglect the effects of color superconductivity. We assume that the CFL gap cannot form until the radius of the quark drop has increased enough and therefore the energy released in the pairing process has not to be taken into account when computing the nucleation time. A support to our assumption can be found in Ref.[40], where the authors have investigated finite size effects on the formation of a 2SC gap, projecting onto states of defined baryon number and onto color singlets. If the radius of the quark nugget is smaller than a

critical length (of the order of 1.5–2 fm in their case) the magnitude of gap is drastically reduced. A similar calculation for the CFL phase has not yet been done, but it is reasonable to assume that due to the "locking" between color and flavor in the CFL phase the color projection will yield even larger effects.

Let us recall once again the astrophysical scenario we have in mind. In a few cases a delay of the order of days or years between the Supernova explosion and the subsequent GRB have been postulated to explain the astrophysical data on the GRBs. In the scheme we are discussing, this delay is due to the formation of a metastable HS having a relatively small mass. The nucleation time, computed using Eq. (9), can be extremely long if the mass of the metastable star is small enough. Via mass accretion the nucleation time can be reduced from values of the order of the age of the universe down to a value of the order of days or years. We can therefore determine the critical mass M_{cr} of the metastable HS for which the nucleation time corresponds to a fixed small value (1 year in Table 1).

In Table 1 we show the value of M_{cr} for various sets of model parameters. In the conversion process from a metastable HS into an HyS or a QS a huge amount of energy ΔE is released. ΔE is the difference between the gravitational mass of the metastable HS and that of the final HyS or QS having the same baryonic mass. We see in the Table that the formation of a CFL phase allows to obtain values for ΔE which are one order of magnitude larger than the corresponding ΔE of the unpaired QM case ($\Delta = 0$). Moreover, we can observe that ΔE depends both on magnitude and position of the gap.

Finally let us comment on the dependence of the results of Table 1 on the value of B. As we can see, if $B^{1/4} < 160$ MeV the value of M_{cr} is very small and it is unlikely that a metastable HS having a mass $M \leq M_{cr}$ can be obtained from a Supernova explosion. In that case all compact stars would be either HySs or QSs. If, at the contrary, $B^{1/4} > 170$ MeV, the value of M_{cr} is so large that a compact star can be only a (metastable) HS since, after the conversion from HM into QM, the HS collapses into a Black Hole (BH). Therefore, only if 160 MeV $\lesssim B^{1/4} \lesssim 170$ MeV a GRB can be generated within the mechanism we are proposing.

5   Conclusions

We have studied the effect of color superconductivity on the EOS of quark matter and on the mass-radius relation for hybrid and quark stars. Comparing the theoretical curves with recent analysis of observational data, we find that color superconductivity is a crucial ingredient in order to satisfy all the constraints coming from observations. The most difficult problem posed by

the astrophysical data is the indication of the existence of stars which are both very compact (R $\lesssim$ 9–10 km) and rather massive ($M \gtrsim 1.7 M_\odot$). We can satisfy these constraints either with hybrid or quark stars. In particular, concerning hybrid stars, the gap increases significantly the maximum mass of the stable configuration, while keeping the corresponding radius $\lesssim$ 10 km. These findings are in agreement with the ones of Ref.[7], where a chemical potential independent gap was used. Anyway, we have shown in this Letter that, to obtain very large masses for hybrid stars, the maximum of the superconducting gap need to be located at a value of the chemical potential which is probably too small.

The superconducting gap affects also deeply the energy released in the conversion from hadronic star into hybrid or quark star. To explain recent observations indicating a delay between a Supernova explosion and the subsequent Gamma Ray Burst [1,2], in Ref.[3] it has been proposed to associate the second explosion with the transition from a metastable hadronic star to a stable star containing deconfined quark matter. In this Letter we have shown that the energy released, which will power the Gamma Ray Burst, is significantly increased by the effect of the superconducting gap and it can reach a value of the order of 10^{53} erg.

To satisfy the constraints on masses and radii of the compact stellar objects and to obtain a huge energy from the conversion of the metastable hadronic star into a quark or hybrid star, rather stringent limits on the parameter values have to be imposed. More explicitly, the pressure of the vacuum has to be in the range 160 MeV $\lesssim B^{1/4} \lesssim$ 170 MeV and the value of the gap has to have a maximum $\Delta \sim$ 0.15 GeV at a chemical potential 0.4 GeV $\lesssim \mu_{max} \lesssim$ 0.6 GeV. All these parameters are compatible with the results both of hadronic physics calculations and of microscopic studies of superconducting quark matter. Finally, let us remark that for values of B in the indicated range, hybrid stars are obtained for unpaired quark matter, while, in most cases, the formation of the superconducting gap yields quark star configurations.

Very recently, a new candidate for a delayed Supernova – Gamma Ray Burst association, with an estimated delay of the order of months, has been proposed in Ref.[41]. If confirmed, this observation would constitute an important support to models like the one we have suggested.

References

[1] L. Amati et al., Science 290 (2000) 953.

[2] J.N. Reeves et al., Nature 414 (2002) 512.

[3] Z. Berezhiani, I. Bombaci, A. Drago, F. Frontera, A. Lavagno, Astrophys. J. 586 (2003) 1250.

[4] M. G. Alford, K. Rajagopal and F. Wilczek, Nucl. Phys. B 537 (1999) 443.

[5] M. G. Alford, J. Berges and K. Rajagopal, Nucl. Phys. B 558 (1999) 219.

[6] T. Schafer and F. Wilczek, Phys. Rev. D 60 (1999) 074014.

[7] M. G. Alford and S. Reddy, arXiv:nucl-th/0211046.

[8] M. Baldo, M. Buballa, F. Burgio, F. Neumann, M. Oertel and H. J. Schulze, arXiv:nucl-th/0212096.

[9] D. Blaschke, H. Grigorian, D. N. Aguilera, S. Yasui and H. Toki, arXiv:hep-ph/0301087.

[10] N.K. Glendenning, S.A. Moszkowski, Phys. Rev. Lett. 67 (1991) 2414.

[11] J. Negele and D. Vautherin, Nucl. Phys. A 207 (1973) 298.

[12] G. Baym, C. Pethick, D. Sutherland, Astrophys. J. 170 (1971) 299.

[13] N. K. Glendenning, Phys. Rev. D 46 (1992) 1274.

[14] N.K. Glendenning, *Compact Stars*, 1997 Springer-Verlag, New York.

[15] J. Kundu and K. Rajagopal, Phys. Rev. D 65 (2002) 094022.

[16] J. A. Bowers and K. Rajagopal, Phys. Rev. D 66 (2002) 065002.

[17] M. G. Alford and K. Rajagopal, JHEP 0206 (2002) 031.

[18] A. W. Steiner, S. Reddy and M. Prakash, Phys. Rev. D 66 (2002) 094007.

[19] F. Neumann, M. Buballa and M. Oertel, Nucl. Phys. A 714 (2003) 481.

[20] G. Lugones and J. E. Horvath, Phys. Rev. D 66 (2002) 074017.

[21] K. Rajagopal and F. Wilczek, Phys. Rev. Lett. 86 (2001) 3492.

[22] D. Sanwal, G. G. Pavlov, V. E. Zavlin and M. A. Teter, Astrophys. J. 574 (2002) L61.

[23] J. Cottam, F. Paerels and M. Mendez, Nature 420 (2002) 51.

[24] H. Quaintrell et al., arXiv:astro-ph/0301243.

[25] C. O. Heinke, J. E. Grindlay, D. A. Lloyd and P. D. Edmonds, arXiv:astro-ph/0301235.

[26] M. Dey, I. Bombaci, J. Dey, S. Ray and B. C. Samanta, Phys. Lett. B 438 (1998) 123 [Addendum-ibid. B 447 (1999) 352].

[27] X. D. Li, I. Bombaci, M. Dey, J. Dey and E. P. van den Heuvel, Phys. Rev. Lett. 83 (1999) 3776.

[28] V. Burwitz, F. Haberl, R. Neuhaeuser, P. Predehl, J. Truemper and V. E. Zavlin, Astron.Astrophys. 399 (2003) 1109.

[29] J. Poutanen and M. Gierlinski, arXiv:astro-ph/0303084.

[30] S. Zane, R. Turolla, J.J. Drake, astro-ph/0302197.

[31] M. Vietri, L. Stella, Astrophys. J. 45 (1998) L507.

[32] M. Bottcher, C.L. Fryer and C.D. Dermer, Astrophys. J. 441 (2002) 567.

[33] Lifshitz, I.M., & Kagan, Yu. 1972, Zh. Eksp. Teor. Fiz., 62, 385 [Sov. Phys. JETP, 35, 206].

[34] M.S. Berger and R.L. Jaffe, Phys. Rev. C 35 (1987) 213.

[35] D.N. Voskresensky, M. Yasuhira and T. Tatsumi, arXiv: nucl-th/0208067.

[36] M. G. Alford, K. Rajagopal, S. Reddy and F. Wilczek, Phys. Rev. D 64 (2001) 074017.

[37] M. Di Toro, A. Drago, V. Greco and A. Lavagno, arXiv:nucl-th/0210052.

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

[39] K. Iida and K. Sato, Phys. Rev. C 58 (1998) 2538.

[40] P. Amore, M. C. Birse, J. A. McGovern and N. R. Walet, Phys. Rev. D 65 (2002) 074005.

[41] N. R. Butler et al., arXiv:astro-ph/0303539.

Hadronic Model	$B^{1/4}$ [MeV]	σ [MeV/fm^2]	$M_{cr}/M_\odot$	ΔE $\Delta=0$	ΔE Δ_1	ΔE Δ_2	ΔE Δ_3	ΔE Δ_4
GM3	160	20	0.69	20	65•	69•	76•	148•
GM3	160	30	0.91	32	90•	95•	106•	196•
GM3	160	40	1.00	38	100•	105•	119•	216•
GM3	170	10	1.12	0	34	40	68	162•
GM3	170	20	1.26	4	44	50	86	185•
GM3	170	30	1.39	11	53	60	104	207•
GM3	170	40	1.49	BH	62	68	120	224•
GM3	180	10	1.55	BH	11	13	BH	–
GM3	180	20	1.61	BH	BH	22	BH	–
GM3	180	30	1.67	BH	BH	BH	BH	–
GM1	160	10	0.45	11	41•	44•	47•	96•
GM1	160	20	0.72	28	75•	79•	86•	160•
GM1	160	30	0.96	48	108•	114•	127•	220•
GM1	160	40	1.18	72	142•	148•	166•	276•
GM1	170	10	1.17	18	59	65	96	191•
GM1	170	20	1.33	33	79	85	124	226•
GM1	170	30	1.45	50	96	103	150	254•
GM1	170	40	1.60	BH	122	128	BH	290•
GM1	180	10	1.63	BH	BH	72	BH	–
GM1	180	20	1.72	BH	BH	BH	BH	–
GM1	180	30	1.79	BH	BH	BH	BH	–

Table 1

Energy released ΔE (measured in foe=10^{51} erg) in the conversion to hybrid or quark star (labeled with a •), for various sets of model parameters, assuming the hadronic star mean life-time $\tau = 1$ yr (see text). M_{cr} is the gravitational mass of the hadronic star at which the transition takes place, for fixed values of the surface tension σ and of the mean life-time τ. BH indicates that the hadronic star collapses to a Black Hole. We indicate with a dash (–) situations in which the Gibbs construction does not provide a mechanically stable EOS.