

Rotating compact star with superconducting quark matter

P. K. Panda and H. S. Nataraj

Indian Institute of Astrophysics, Koramangala, Bangalore-560034, India

(Dated: January 19, 2006)

A compact star with superconducting quark core, the hadron crust and the mixed phase between the two is considered. The quark meson coupling model for hadron matter and the color flavor locked quark model for quark matter is used in order to construct the equation of state for the compact star. The effect of pairing of quarks in the color flavor locked phase and the mixed phase on the mass, radius, and period of the rotating star is studied.

PACS number(s): 95.30.Tg, 21.65.+f, 12.39.Ba, 25.75.Nq, 21.80.+a

I. INTRODUCTION

Neutron/quark stars are the stellar objects produced as a result of supernova explosions. These objects are highly compact as their masses may, generally, be one or two times the solar mass and radii of only about 10 – 15 km. The neutron stars are normally treated as zero temperature stellar objects because their temperatures, although high, are still very low compared to their characteristic energies of excitation. Their outer crust is normally believed to be composed, mainly, of nuclei and electrons. Their interior, however, where density is of the order of five to ten times the nuclear saturation density, remains to be properly understood whether the central part of the star is either composed of quark matter alone, or of mixed matter, or of paired quark matter is one of the subjects of the present work.

Recently, Alford and Rajagopal [1] discussed the difficulty of the 2-flavor superconducting (2SC) phase to achieve charge neutrality and therefore they claimed that this phase would not be realised in compact stars. Without solving the gap equation, they considered strange quark mass as a parameter in their calculations and concluded that the color flavor locked (CFL) phase would be favourable against 2SC. In Ref. [2], Steiner, Reddy and Prakash investigated the color superconducting phase of quark matter by utilizing the Nambu-Jona-Lasinio (NJL) model supplemented by diquark and the t'Hooft six fermion interactions. They found that in the NJL model, a small 2SC window does exist at very small baryon densities which eventually would be shut by the hadronic phase. Again, the 2SC phase is less likely to occur in compact stars because the charge neutrality condition imposes a strong constraint to the quark chemical potential. Further, in a recent work [3] suggests that when the density drops low enough so that the mass of the strange quark can no longer be neglected, there is a continuous phase transition from the CFL phase to a new gapless CFL (gCFL) phase, which could lead observable consequences if it occurred in the cores of neutron star [4]. However, it now appears that some of the gluons in the gCFL phase have imaginary Meissner masses indicating towards an unknown lower energy phase [5, 6].

The observations of the fastest pulsars with high degree of compactness and the better theoretical understandings of the matter at high densities like that of a compact star with superconducting quark core in a color flavor locked phase are compelling theoreticians to come up with different models for the equation of state (EOS) of neutron stars and their interiors.

In the present paper, we are interested in building the EOS for mixed matter of quark and hadron phases. We employ the quark-meson coupling model (QMC) [7, 8] including hyperons in order to describe the hadron phase. In the QMC model, baryons are described as a system of non-overlapping MIT bags which interact through the effective scalar and vector mean fields, very much in the same way as in the Walecka model (QHD) [9]. Many applications and extensions of the model have been made in the last few years [10].

While the QMC model shares many similarities with QHD-type models, it however offers new opportunities for studying nuclear matter properties. One of the most attractive aspects of the model is that different phases of hadronic matter from very low to very high baryon densities and temperatures can be described within the same underlying model. This model describes nuclear matter with nucleons as nonoverlapping MIT bags and the quarks inside them couple to scalar and vector mesons. For matter at very high density and/or temperature, one expects that baryons and mesons dissolve and the entire system of quarks and gluons becomes confined within a single, big MIT bag. Another important aspect of the QMC is that the internal structure of the nucleon is introduced explicitly. It is found that the EOS for infinite nuclear matter at zero temperature derived from the QMC model is much softer than the one obtained in the Walecka model [9]. Also, the QMC model nucleon effective mass lies in the range 0.7 to 0.8 of the free nucleon mass, which agrees with results derived from non-relativistic analysis of scattering of neutrons from

lead nuclei [11] and is larger in comparison with Walecka model effective mass.

For the quark phase, we consider pairing of quarks described by the color-flavor locked (CFL) phase. Recently many authors [12] have discussed the possibility of quark matter in a color-superconducting phase, wherein quarks near the Fermi surface are paired and these Cooper pairs condense and break the color gauge symmetry [13]. At sufficiently high density the favored phase is called CFL, in which quarks of all three colors and all three flavors are allowed to pair.

We organize the paper as follows: In section 2, we briefly discuss the construction of the equation of state for a compact star. The mixed EOS would be built by enforcing appropriate Gibbs criteria and chemical equilibrium conditions. In section 3, we present our numerical results and discuss the properties like the maximum mass, radius and the period of the compact star, etc. under the influence of the pairing gap, Δ and the bag pressure, B .

II. EQUATION OF STATE

We now discuss the EOS for a compact star with a minimal mathematical details. The details of the QMC model can be found in [7, 8] and the details of CFL model can be found in [12].

In QMC model, the nucleon in nuclear medium is assumed to be a static spherical MIT bag in which quarks interact through the scalar and vector, σ , ω and ρ mesons. And these fields are treated as classical fields in the mean field approximation. The quark field, $\psi_q(x)$, inside the bag then satisfies the equation of motion:

$$\left[i \not{\partial} - (m_q^0 - g_\sigma^q \sigma) - g_\omega^q \omega \gamma^0 + \frac{1}{2} g_\rho^q \tau_z \rho_{03} \right] \psi_q(x) = 0, \quad q = u, d, s, \quad (1)$$

where m_q^0 is the current quark mass and g_σ^q , g_ω^q and g_ρ^q are the quark-meson coupling constants. After enforcing the boundary condition at the bag surface, the transcendental equation for the ground state solution of the quark (in s -state) is $j_0(x_q) = \beta_q j_1(x_q)$, which determines the bag eigenfrequency x_q , where $\beta_q = \sqrt{(\Omega_q - R_B m_q^*) / (\Omega_q + R_B m_q^*)}$, with $\Omega_q = (x_q^2 + R^2 m_q^{*2})^{1/2}$; $m_q^* = m_q^0 - g_\sigma^q \sigma_0$, is the effective quark mass. The energy of a static bag describing baryon B consisting of three ground state quarks can be expressed as

$$M_B^* = \sum_q n_q \frac{\Omega_q}{R_B} - \frac{Z_B}{R_B} + \frac{4}{3} \pi R_B^3 B_B, \quad (2)$$

where B_B is the bag constant and Z_B parameterizes the sum of the center-of-mass motion and the gluonic corrections. The medium dependent bag radius, R_B is then obtained through the stability condition for the bag.

The total energy density, ε , and the pressure, p , including the leptons can be obtained from the grand canonical potential and they read

$$\begin{aligned} \varepsilon = & \frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\rho^2 \rho_{03}^2 \\ & + \sum_B \frac{\gamma}{2\pi^2} \int_0^{k_B} k^2 dk [k^2 + M_B^{*2}(\sigma)]^{1/2} + \sum_l \frac{1}{\pi^2} \int_0^{k_l} k^2 dk [k^2 + m_l^2]^{1/2}, \end{aligned} \quad (3)$$

$$\begin{aligned} p = & -\frac{1}{2} m_\sigma^2 \sigma^2 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{1}{2} m_\rho^2 \rho_{03}^2 \\ & + \frac{1}{3} \sum_B \frac{\gamma}{2\pi^2} \int_0^{k_B} \frac{k^4 dk}{[k^2 + M_B^{*2}(\sigma)]^{1/2}} + \frac{1}{3} \sum_l \frac{1}{\pi^2} \int_0^{k_l} \frac{k^4 dk}{[k^2 + m_l^2]^{1/2}}. \end{aligned} \quad (4)$$

In the above equations γ and k_B are respectively the spin degeneracy and the Fermi momentum of the baryon species B . The hyperon couplings, $g_{\sigma B} = x_{\sigma B} g_{\sigma N}$, $g_{\omega B} = x_{\omega B} g_{\omega N}$, $g_{\rho B} = x_{\rho B} g_{\rho N}$ are not relevant to the ground state properties of nuclear matter, but information about them can be obtained from the levels in Λ hypernuclei [14]. The $x_{\sigma B}$, $x_{\omega B}$ and $x_{\rho B}$ are equal to 1 for nucleons and acquire different values in different parameterizations for the other baryons. Note that the s -quark is unaffected by the σ and ω -mesons i.e. $g_\sigma^s = g_\omega^s = 0$. The lepton Fermi momenta are the positive real solutions of $(k_e^2 + m_e^2)^{1/2} = \mu_e$ and $(k_\mu^2 + m_\mu^2)^{1/2} = \mu_\mu = \mu_e$. The equilibrium composition of the star is obtained with the charge neutrality condition at a given total baryonic density $\rho = \sum_B \gamma k_B^3 / (6\pi^2)$; the baryon effective masses are obtained self-consistently in the bag model. For stars in which the strongly interacting particles are baryons, the composition is determined by the requirements of charge neutrality and β -equilibrium conditions

under the weak processes $B_1 \rightarrow B_2 + l + \bar{\nu}_l$ and $B_2 + l \rightarrow B_1 + \nu_l$. After deleptonization, the charge neutrality condition yields $q_{\text{tot}} = \sum_B q_B \gamma k_B^3 / (6\pi^2) + \sum_{l=e,\mu} q_l k_l^3 / (3\pi^2) = 0$, where q_B corresponds to the electric charge of baryon species B and q_l corresponds to the electric charge of lepton species l . Since the time scale of a star is effectively infinite compared to the weak interaction time scale, weak interaction violates strangeness conservation. The strangeness quantum number is therefore not conserved in a star and the net strangeness is determined by the condition of β -equilibrium which for baryon B is, then, given by $\mu_B = b_B \mu_n - q_B \mu_e$, where μ_B is the chemical potential of baryon B and b_B is its baryon number. Thus the chemical potential of any baryon can be obtained from the two independent chemical potentials μ_n and μ_e of neutron and electron respectively.

We next study the equation of state of a compact star taking into consideration the CFL quark phase. We treat the quark matter as a Fermi sea of free quarks with an additional contribution to the pressure arising from the formation of CFL condensates.

The CFL phase can be described with the help of the thermodynamical potential which reads [15]:

$$\Omega_{CFL}(\mu_q, \mu_e) = \Omega_{quark}(\mu_q) + \Omega_{GB}(\mu_q, \mu_e) + \Omega_l(\mu_e), \quad (5)$$

where $\mu_q = \mu_n/3$ and

$$\Omega_{quark}(\mu_q) = \frac{6}{\pi^2} \int_0^\nu p^2 dp (p - \mu_q) + \frac{3}{\pi^2} \int_0^\nu p^2 dp (\sqrt{p^2 + m_s^2} - \mu_q) - \frac{3\Delta^2 \mu_q^2}{\pi^2} + B, \quad (6)$$

with $m_u = m_d$ set to zero,

$$\nu = 2\mu_q - \sqrt{\mu_q^2 + \frac{m_s^2}{3}}, \quad (7)$$

$\Omega_{GB}(\mu_q, \mu_e)$ is the contribution from the Goldstone bosons arising due to the chiral symmetry breaking in the CFL phase [15, 16]:

$$\Omega_{GB}(\mu_q, \mu_e) = -\frac{1}{2} f_\pi^2 \mu_e^2 \left(1 - \frac{m_\pi^2}{\mu_e^2}\right)^2, \quad (8)$$

where

$$f_\pi^2 = \frac{(21 - 8 \ln 2) \mu_q^2}{36\pi^2}, \quad m_\pi^2 = \frac{3\Delta^2}{\pi^2 f_\pi^2} m_s (m_u + m_d), \quad (9)$$

$\Omega_l(\mu_e) = -(\mu_e)^4 / 12\pi^2$, and the quark number densities are equal, i.e.,

$$\rho_u = \rho_d = \rho_s = \frac{\nu^3 + 2\Delta^2 \mu_q}{\pi^2}. \quad (10)$$

and in the above expressions Δ is the gap parameter [15].

We next consider the scenario of a mixed phase of hadronic and quark matter where the hadron phase is described by the QMC model and the quark phase is described by the CFL model. In the mixed phase charge neutrality is imposed globally i.e. the quark and hadron phases are not neutral separately but rather, the system prefers to rearrange itself so that

$$\chi \rho_c^{QP} + (1 - \chi) \rho_c^{HP} + \rho_c^l = 0 \quad (11)$$

where ρ_c^{QP} and ρ_c^{HP} are the charge densities of quark and hadron phases, respectively. χ is the volume fraction occupied by the quark phase, $(1 - \chi)$ is the volume fraction occupied by the hadron phase and ρ_c^l is the lepton charge density. As usual, the phase boundary of the coexistence region between the hadron and quark phase is determined by the Gibbs criteria. The critical neutron and electron chemical potentials and the critical pressure are determined by the conditions, $\mu_i^{HP} = \mu_i^{QP} = \mu_i$, $i = n, e$, $T^{HP} = T^{QP}$, $P^{HP}(\mu^{HP}, T) = P^{QP}(\mu^{QP}, T)$ reflecting the need of chemical, thermal and mechanical equilibrium, respectively. The energy density and the total baryon density in the mixed phase read:

$$\varepsilon = \chi \varepsilon^{QP} + (1 - \chi) \varepsilon^{HP} + \varepsilon^l, \quad \rho = \chi \rho^{QP} + (1 - \chi) \rho^{HP}. \quad (12)$$

III. RESULTS AND DISCUSSION

We start by fixing the free-space bag properties for the QMC model. In the present calculation, we have used the current quark masses, $m_u = m_d = 0$ MeV and $m_s = 150$ MeV and $R_0 = 0.6$ fm for the bag radius. There are two unknowns, Z_B and the bag constant B_B . These are obtained as usual by fitting the nucleon mass, $M = 939$ MeV and enforcing the stability condition for the bag. The values obtained for Z_B and B_B are given in [17]. Next we fit the quark-meson coupling constants $g_\sigma = g_\sigma^q$, $g_\omega = 3g_\omega^q$ and $g_\rho = g_\rho^q$ for the nucleon to obtain the correct saturation properties of the nuclear matter, $E_B \equiv \varepsilon/\rho - M = -15.75$ MeV at $\rho = \rho_0 = 0.15$ fm $^{-3}$, $a_{sym} = 32.5$ MeV, $K = 257$ MeV and $M^* = 0.774M$. We have taken $g_\sigma^q = 5.957$, $g_\omega^q = 8.981$ and $g_\rho^q = 8.651$. We take the standard values for the meson masses, $m_\sigma = 550$ MeV, $m_\omega = 783$ MeV and $m_\rho = 770$ MeV. The meson-hyperon coupling constants used in our calculations are $x_{\sigma B} = x_{\omega B} = x_{\rho B} = \sqrt{2/3}$ and are obtained based on quark counting arguments [18].

We first plot the pressure as a function of energy density in Figure 1 for different values of gap parameter, Δ , keeping the bag pressure, $B^{1/4} = 210$ MeV constant. We see that for lower the pairing gap the higher would be the energy density and the pressure of both the transition points between the hadron crust and quark core. And the EOS of mixed phase is wider for lower Δ . Also the EOS for lower Δ in the mixed region is stiffer but it becomes softer in the CFL region.

We next proceed to calculate the properties of the compact star using the above EOS. The star is assumed to be rapidly rotating, relativistic and compact. The details of the model are given by Kamatsu *et. al* [19] [known as Komatsu, Eriguchi-Hachisu (KEH) method] and Cook *et. al* [20]. The star is assumed to be stationarily rotating and hence have axially, equatorially symmetric structures. The metric in spherical coordinates (t, r, θ, ϕ) can be written as,

$$ds^2 = -e^{2\nu} dt^2 + e^{2\alpha}(dr^2 + r^2 d\theta^2) + e^{2\beta} r^2 \sin^2 \theta (d\phi - \omega dt)^2 \quad (13)$$

where the metric potentials, α , β , ν and ω are functions of r and θ only (geometrized units, $c = G = 1$). The matter is assumed to be a perfect fluid so that the energy-momentum tensor T^{ab} is given by

$$T^{ab} = (\varepsilon + p)U^a U^b + pg^{ab}, \quad (14)$$

where ε , p , U , and g^{ab} are the energy density, pressure, four velocity and metric tensor respectively. It is further assumed that the four velocity U^a is simply a linear combination of time and angular Killing vectors. The details of the calculations for solving the field equations are given in Ref. [19].

The radius of the maximum mass star is sensitive to the low density EOS. We have used Baym, Pethick and Sutherland [21] values for pressure and energy at low baryonic densities. In Figure 2, we have shown the mass - radius relation for the hybrid star for different values of Δ in the range 0 – 150 MeV while keeping the bag pressure constant, $B^{1/4} = 210$ MeV fixed. The maximum mass, M_{max} , is higher for lower Δ and it shifts towards the low radius side as Δ decreases. The M_{max} for $\Delta = 150$ MeV is $1.61 M_\odot$ and the corresponding radius, R_{max} is 18.54 km, where as, for $\Delta = 0$ MeV M_{max} and R_{max} are $2.35 M_\odot$ and 16.47 km respectively. For an unpaired quark matter star [22], for the same bag pressure of 210 MeV, we obtained maximum mass and radius, are $2.36 M_\odot$ and 16.12 km respectively. To compare with, van Kerkwijk *et al.* have obtained the mass of 1.86 ± 0.32 for an X-ray pulsar Vela X-1 [23]. The compactness of a star, which is the ratio of M_{max} to R_{max} , therefore, decreases with increasing Δ . We observe from Figure 3 that, for $\Delta = 0$ MeV the ratio turns out to be $0.142 M_\odot/\text{km}$, where as, for $\Delta = 150$ MeV it is $0.086 M_\odot/\text{km}$. The general relativistic limit for the ratio is, $M/R < 4/9$ [24] (i.e. for a uniform density star with the causal equation of state $P = \varepsilon$) which is much above our range. The lower limit for the ratio found from observations of [25] is $0.115 M_\odot/\text{km}$. Hence the hybrid star prefers to have low pairing gap to be compact.

We observe that, as the bag pressure increases, keeping the pairing gap fixed, both the central energy density, ε_c and M_{max} increases but the radius, R_{max} of a star decreases. This is in consistent with [26]. For a fixed Δ of 100 MeV, $\varepsilon_c = 7.95 \times 10^{14}$ gcm $^{-3}$, $M_{max} = 1.32 M_\odot$, and $R_{max} = 18.8$ km for $B^{1/4} = 190$ MeV, where as, for $B^{1/4} = 210$ MeV, $\varepsilon_c = 1.29 \times 10^{15}$ gcm $^{-3}$, $M_{max} = 2.17 M_\odot$, and $R_{max} = 17.4$ km. But when the bag pressure is kept constant, the decrease in Δ increases ε_c . Our results thus reflect that the dense cores of the compact stars favor low pairing gap and high bag pressures.

We have also observed that, as Δ increases the M_{max} decreases unlike the plots in [27] where they have shown an opposite trend i.e., the increase in maximum mass with the pairing gap for pure CFL stars with a broader Δ range they have considered. We would like to mention that, our results are not contradicting theirs inasmuch as we also have checked for the pure CFL phase and have seen the same trend. From our results, we observe that the stability of the hybrid star will not favor the onset of pure CFL phase at its core, with the EOS we have used as the M_{max} lies in the mixed region as in [17] for all the values of Δ in the range from 0 – 150 MeV for a fixed bag pressure of 210 MeV. Thus, the CFL effect is reflected on to the stability of the hybrid star only through the mixed phase.

In Figure 4, we have plotted the angular velocity versus the mass of the rotating compact star. For a fixed value of Δ and the bag pressure of $B^{1/4} = 210$ MeV, the angular velocity increases with the mass. And we see that as Δ decreases both the angular velocity and the M_{max} increases. For $\Delta = 150$ MeV, the angular velocity at M_{max} is $5.5 \times 10^3 s^{-1}$, where as, for $\Delta = 0$ MeV it is $7.7 \times 10^3 s^{-1}$. For an unpaired quark matter star also the angular velocity obtained is $7.7 \times 10^3 s^{-1}$. The angular velocities for the fastest observed pulsars till date, PSR $B1937 + 21$ and PSR $B1957 + 20$, are $4033 s^{-1}$ and $3908 s^{-1}$ respectively [29]. We have also seen that the angular velocity increases with a decrease in the radius of the compact star. The effect of the pairing gap on the period, $P = 2\pi/\Omega$, of the rotating star, for a fixed bag pressure of $B^{1/4} = 210$ MeV, is shown in Figure 5. As the pairing gap increases the period increases. The limit imposed by general relativity on the period of a relativistic compact star should be, $P > 0.24$ ms [24]. The period for the said fastest pulsars till date is 1.55 ms and 1.6 ms respectively [28, 29]. The period in our case lies in the range of 0.8 to 1.2 milliseconds for the Δ range of 0 – 150 MeV. The periods predicted for strange stars are in submillisecond range [24]. Thus, the stars with low pairing energies are more compact and are the fast rotors.

Let us now summarize our results. We have studied the compact stars with a mixed matter of hadrons and deconfined quarks using QMC model for hadron phase and CFL quark model for quark phase. We conclude here that the dense hybrid stars indeed favor low pairing energy and high bag pressures. And these stars are more massive, more compact, and are fast rotors with the periods of sub-milliseconds. Also our results clearly show that the hybrid stars, of the kind we have considered, possess a quark matter core only as a mixed phase of deconfined quark matter in a CFL phase and hadrons. And no pure CFL quark matter core can be possible on the stability grounds. These findings have to be deduced more carefully both from the astrophysical observations of compact stars and from laboratory measurements of high density matter to confirm or discard the ranges of the said parameters we have considered.

Acknowledgments

The authors acknowledge Professor B. P. Das, Professor C. Providência and Professor D. P. Menezes for their critical suggestions. PKP would like to thank the friendly atmosphere at Indian Institute of Astrophysics, Bangalore, where this work was partially done.

-
- [1] M. Alford, K. Rajagopal, JHEP **0206**, 031 (2002) S. Reddy, and F. Wilczek, Phys. Rev. D **64**, 074017 (2001).
 - [2] A. W. Steiner, S. Reddy and M. Prakash, Phys. Rev. C **66**, 094007 (2002).
 - [3] M. Alford, C. Kouvaris and K. Rajagopal, Phys. Rev. Lett. **92**, 222001 (2004); M. Alford, C. Kouvaris and K. Rajagopal, Phys. Rev. D **71**, 054009 (2005).
 - [4] M. Alford, P. Jotwani, C. Kouvaris, J. Kundu and K. Rajagopal, Phys. Rev. D **71**, 114011 (2005).
 - [5] M. Huang, I.A. Shovkovy, Phys. Rev. D **70**, 094030 (2005).
 - [6] R. Casalbuoni, R. gatto, M. Mannarelli, G. Nardulli and M. Ruggieri, Phys. Lett. B **605**, 362 (2005) [Erratum-ibid B **615**, 297 (2005)].
 - [7] P. A. M. Guichon, Phys. Lett. B **200**, 235 (1988).
 - [8] K. Saito and A. W. Thomas, Phys. Lett. B **327**, 9 (1994); **335**, 17 (1994); **363**, 157 (1995); Phys. Rev. C **52**, 2789 (1995); P. A. M. Guichon, K. Saito, E. Rodionov, and A. W. Thomas, Nucl. Phys. **A601** 349 (1996); K. Saito, K. Tsushima, and A. W. Thomas, Nucl. Phys. **A609**, 339 (1996); Phys. Rev. C **55**, 2637 (1997); Phys. Lett. B **406**, 287 (1997).
 - [9] J. D. Walecka, Ann. Phys. **83**, 491 (1974); B. D. Serot and J. D. Walecka, Adv. Nucl. Phys. **16**, 1 (1986).
 - [10] P. G. Blunden and G. A. Miller, Phys. Rev. C **54**, 359 (1996); P. K. Panda, R. Sahu, C. Das, Phys. Rev. C **60**, 38801 (1999); P. K. Panda, M. E. Bracco, M. Chiapparini, E. Conte, and G. Krein, Phys. Rev. C **65**, 065206 (2002); P. K. Panda, and F. L. Braghin, Phys. Rev. C **66**, 055207 (2002); D. P. Menezes, P. K. Panda, and C. Providência, Phys. Rev. C **72**, 035802 (2005); P. K. Panda, A. Mishra, J. M. Eisenberg, W. Greiner, Phys. Rev. C **56**, 3134 (1997); I. Zakout, H. R. Jaqaman, Phys. Rev. C **59**, 962 (1999); G. Krein, D. P. Menezes, M. Nielsen, and C. Providência, Nucl. Phys. **A674**, 125 (2000); P. K. Panda, G. Krein, D. P. Menezes and C. Providência, Phys. Rev. C **68**, 015201 (2003).
 - [11] C. H. Johnson, D. J. Horen and C. Mahaux, Phys. Rev. C **36**, 2252 (1987).
 - [12] M. Buballa and M. Oertel, Nucl. Phys. A **703**, 770 (2002); M. Alford, K. Rajagopal, S. Reddy, and F. Wilczek, Phys. Rev. D **64**, 074017 (2001); K. Rajagopal and F. Wilczek, Phys. Rev. Lett. **86**, 3492 (2001).
 - [13] M. G. Alford, Annu. Rev. Nucl. Part. Sci. **51** 131 (2001).
 - [14] R. E. Chrien and C. B. Dover, Annu. Rev. Nucl. Part. Sci. **39**, 113 (1989).
 - [15] M. Alford and S. Reddy, Phys. Rev. D **64**, 074024 (2003).
 - [16] D. Son and M. Stephanov, Phys. Rev. D **61**, 074012 (2000); **62**, 059902(E) (2000).
 - [17] P. K. Panda and D. P. Menezes, Phys. Rev. C **69**, 025207 (2004); P. K. Panda and D. P. Menezes, Phys. Rev. C **69**, 058801 (2004).
 - [18] S. A. Moszkowski, Phys. Rev. D **9**, 1613 (1974).
 - [19] H. Komatsu, Y. Eriguchi, and I. Hachisu, Mon. Not. R. Astron. Soc. **237**, 355 (1989).

- [20] G. B. Cook, S. L. Shapiro, and S. L. Teukolsky, *Astrophys. J.* **422**, 227 (1994), and references there in.
- [21] G. Baym, C. Pethick and P. Sutherland, *Astrophys. J.* **170**, 299 (1971).
- [22] B. Freedman and L. McLerran, *Phys. Rev. D* **17**, 1109 (1978); E. Farhi and R.L. Jaffe, *Phys. Rev. D* **30**, 2379 (1984).
- [23] O. Barziv, L. Kaper, M. H. van Kerkwijk, J. H. Telting, J. van Paradijs, *astro-ph/0108237* vol 14 (2001)
- [24] N. K. Glendenning, *Compact Stars: Nuclear Physics, Particle Physics, and General Relativity*, Springer Verlag, 2000.
- [25] D. Sanwal, G. G. Pavlov, V. E. Zolvin, and M.A.Teter, *Astrophys. J.* **574**, L61 (2002)
- [26] I. Shovkovy, M. Hanauske, M. Huang, *Phys. Rev. D* **67**, 103004 (2003).
- [27] G. Lugones, J. E. Horvath, *Astronomy and Astrophysics*, **403**, 173 (2003).
- [28] John. L. Friedman, ASP conference series, Vol. **72**, 177 (1995)
- [29] S. E. Thorseti and D. Chakrabarty, *Astrophys. J.* **512**, 288 (1999).

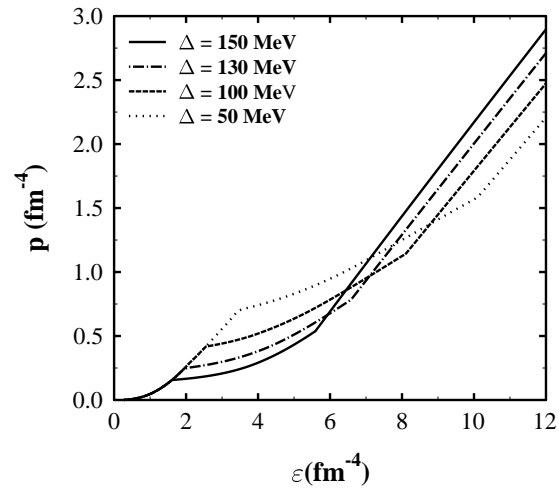


FIG. 1: Equation of state for different values of pairing gap and for a fixed bag pressure, $B^{1/4} = 210$ MeV. The stiffer(softer) EOS in mixed phase becomes softer(stiffer) in CFL phase.

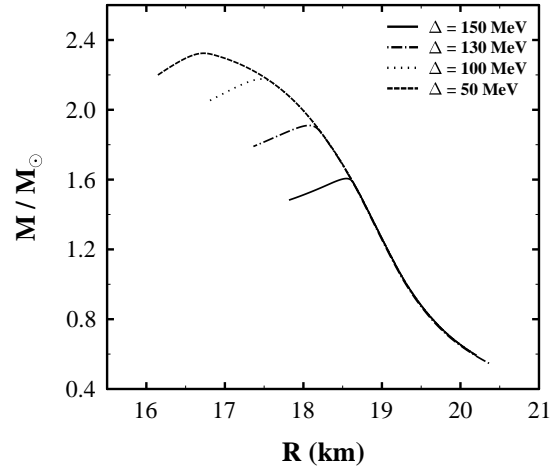


FIG. 2: The mass - radius relation for different values of pairing gap and for a fixed bag pressure, $B^{1/4} = 210$ MeV. As the pairing gap decreases the M_{max} increases and it shifts towards lower radius side.

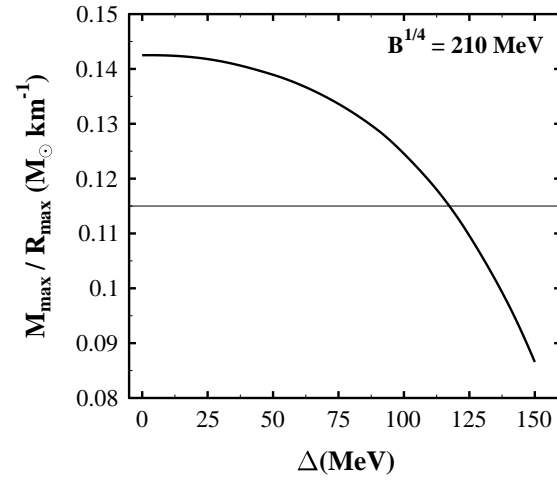


FIG. 3: The degree of compactness, which is the ratio of maximum mass to the corresponding radius of the compact star, decreases with an increasing pairing gap while keeping bag pressure, $B^{1/4} = 210 \text{ MeV}$, fixed.

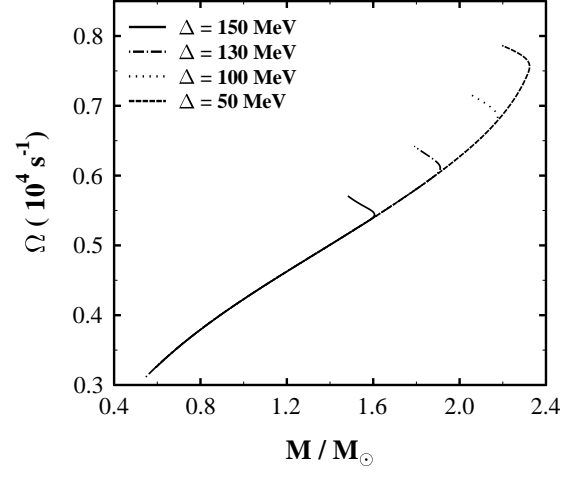


FIG. 4: Angular velocity versus the mass of the rotating compact star for different values of pairing gap and for a fixed bag pressure, $B^{1/4} = 210 \text{ MeV}$.

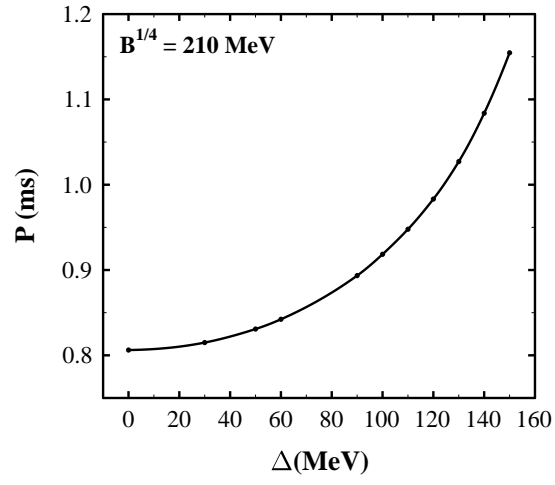


FIG. 5: The period of the rotating compact star as a function of the pairing gap for a fixed bag pressure, $B^{1/4} = 210$ MeV. The stars with low pairing gap seem to have sub-millisecond periods.