A&A 403, 173–178 (2003)
DOI: 10.1051/0004-6361:20030374

Astronomy & Astrophysics

High-density QCD pairing in compact star structure

G. Lugones and J. E. Horvath

Instituto de Astronomia, Geofísica e Ciências Atmosféricas, Universidade de São Paulo Rua do Matão 1226, (05508-900) São Paulo SP, Brazil
e-mail: foton@astro.iag.usp.br

Received 2 December 2002 / Accepted 14 February 2003

Abstract. Strange quark matter in a color flavor locked (CFL) state can be the true ground state of hadronic matter for a much wider range of the parameters of the model (the gap of the QCD Cooper pairs Δ, the strange quark mass m_s and the Bag Constant B) than the state without any pairing. We review the equation of state (EOS) of CFL strange matter and study the structure of stellar objects made up of this phase, highlighting the novel features of the latter. Although the effects of pairing on the equation of state are thought to be small, we find that CFL stars may be in fact much more compact than strange stars (SS). This feature may be relevant in view of some recent observations claiming the existence of exotic and/or deconfined phases in some nearby neutron stars (NS).

Key words. stars: neutron – equation of state

1. Introduction

The study of a hypothetical stability of strange quark matter (SQM), put forward in Witten's (1984) seminal paper and a few important precursors (Bodmer 1971; Terazawa 1979; Chin & Kerman 1979) has entered its third decade. Nothing less than the nature of the true ground state of hadronic matter is being questioned and in fact, within simple models, the hypothesis of a stable form of cold catalyzed plasma was shown to be tenable. Following the pioneering works, a general calculation of strange matter by Farhi & Jaffe (1984) in the framework of the MIT Bag model of confinement (Degrand et al. 1975; Cleymans et al. 1986) identified the so-called "windows of stability", or regions in the plane $m_s - B$ inside which the stability of SQM can be realized. Other models of confinement have been worked out to find a quite ample range of conditions for SQM to be absolutely bound (Zhang & Ru-Ken Su 2002 and references therein; Hanauske et al. 2001). However, there is a consensus that the issue of the availability of a ∼1% binding energy difference for SQM to be bound is ultimately an experimental matter.

While the search for SQM in laboratory and astrophysical environments beyond their present limits continues, important theoretical developments have taken place. The most sound is probably the revival of interest in pairing interactions in dense matter, a subject already addressed in the early 1980s (Bailin & Love 1984) and revived a few years ago with new calculations of the pairing energy and related physics. It is now generally agreed (Alford et al. 1999b; Rapp et al. 2000; Rajagopal & Wilczeck 2000) that (at least for very high densities) the color-flavor locked (CFL) state, with equal numbers of u, d and s quarks is likely to be the ground state of strong interactions, even if the quark masses are unequal (Alford et al. 1999a; Schäfer & Wilczek 1999). The equal number of flavors is enforced by the symmetry of the state, and thus electrons are absent because the mixture is automatically neutral (Rajagopal & Wilczeck 2001; Steiner et al. 2002).

Long awaited by theoretical physicists, the high-performance of the space X-ray missions Chandra and XMM (Weisskopf 2002; Becker & Aschenbach 2002) enabled unprecedented studies of imaging and spectra of selected neutron stars with the aim of determining the masses and radii, perhaps the most simple forms of (indirectly) investigating the nature of high density matter. Adopting General Relativity as a framework, a comparison of the static models generated by integration of the Tolman-Oppenheimer-Volkof equations with observed data is expected to give information about the equation of state, and possibly other effects such as rotation, magnetic atmospheres and so on. A wonderful example of the pre-space determinations is the mass of the binary pulsar PSR 1913+16, accurate to several decimal places (van Kerkwijk 2001). Other methods based on combinations of spectroscopic and photometric techniques have been recently proposed. At least one X-ray source is significantly above the centroid of the binary distribution ∼1.4 $M_\odot$; namely Vela X-1 for which a value of $1.87^{+0.23}_{-0.17}\,M_\odot$ has been obtained (van Kerkwijk 2001). Recently, not only the masses have been determined, but also indications of the radii became available, suggesting a very compact structure. For instance, claims of high compactness have been made from the analysis

Send offprint requests to: G. Lugones,
e-mail: glugones@astro.iag.usp.br

of the binary Her X-1 (Li et al. 1995; Dey et al. 1998) with $M = 0.98 \pm 0.12\ M_\odot$ and $R = 6.7 \pm 1.2$ km, and of the isolated nearby RX J185635-3754 (Pons et al. 2002) with $M \approx 0.9\ M_\odot$ and $R \approx 6$ km. In both cases, the results have been revisited and challenged by other groups (Reynolds et al. 1997; Kaplan et al. 2001) who in turn found figures around the expected for conventional neutron star models. This stresses the cautionary remarks made by several researchers about the high-compactness objects and guarantees further studies, already undertaken in most cases. Li et al. (1999b) have also added the source 4U 1728-34 to the candidate list, showing that conventional accretion models indicate a very compact source in the mass-radius plane. As always, the actual distance to the source is a matter of concern. Needless to say, these results have yet to be confirmed carefully. Nonetheless, it is worthwhile to consider the possibility that at least some compact stars are extremely compact, or in other words, that their radii are ~30–40% less than the "canonical" 10 km favored by neutron matter models for $M \sim 1\ M_\odot$.

If actually present in these sources, compactness would be extremely difficult (perhaps impossible) to model using underlying equations of state based on ordinary hadrons alone, and a natural alternative would be to consider deconfined matter (or other exotic components, like kaon matter or hyperons). Stars suspected to be made of deconfined matter also include the X-ray bursters GRO J1744-28 (Cheng et al. 1998) and SAX J1808.4-3658 (Li et al. 1999a). This increasing availability of data on compact neutron star structure coupled with the new developments on the QCD ground sate leads to investigate the properties of compact stars in the light of the CFL state[1].

2. Color flavor locked strange matter

2.1. The equation of state

The very complex structure of the QCD phase diagram emerging from detailed calculations by several groups is still being explored. Therefore, only schematic models are available to explore stellar structure questions. It is, however, widely agreed that if the quark mass m_s is small enough (possibly the actual case in nature), the CFL state would be the minimum energy configuration at high densities. To proceed we need the thermodynamical potential $\Omega_{\rm CFL}$ to derive the relevant quantities. Fortunately, this potential can be found quite simply (Alford et al. 2001) to the lowest order in the gap Δ^2. The procedure is to start with the $\Omega_{\rm free}$ of a fictional state of unpaired quark matter in which all quarks which are "going to pair" have a common Fermi momentum ν, with ν chosen to minimize $\Omega_{\rm free}$. The binding energy of the diquark condensate is included by subtracting the condensation term $3\Delta^2\mu^2/\pi^2$ while the vacuum energy is introduced by means of the phenomenological bag constant B allowing the mixture to confine. In this work we assume that the CFL state has been reached by deconfined matter, although the precise way in which this is done (involving weak decays, etc.) merits a closer look. The thermodynamic potential $\Omega_{\rm CFL}$ of this model reads (Alford et al. 2001)

$$\begin{aligned}\Omega_{\rm CFL} &= \Omega_{\rm free} - \frac{3}{\pi^2}\Delta^2\mu^2 + B \\ &= \sum_{i=u,d,s} \frac{1}{4\pi^2}\left[\mu_i\nu(\mu_i^2 - \frac{5}{2}m_i^2) + \frac{3}{2}m_i^4 \log\left(\frac{\mu_i+\nu}{m_i}\right)\right] \\ &\quad - \frac{3}{\pi^2}\Delta^2\mu^2 + B, \end{aligned} \tag{1}$$

where $3\mu = \mu_u + \mu_d + \mu_s$, μ_i being the chemical potential of the i-species. The common Fermi momentum $\nu = (\mu_i^2 - m_i^2)^{1/2}$ is given by

$$\nu = 2\mu - \left(\mu^2 + \frac{m_s^2}{3}\right)^{1/2}. \tag{2}$$

The thermodynamic quantities, such as the pressure P, the baryon number density n_B, the particle number densities n_i, and the energy density ε can be easily derived at $T = 0$ and read (Lugones & Horvath 2002)

$$P = -\Omega_{\rm CFL}, \tag{3}$$

$$n_B = n_u = n_d = n_s = \frac{(\nu^3 + 2\Delta^2\mu)}{\pi^2}, \tag{4}$$

$$\varepsilon = \sum_i \mu_i n_i + \Omega_{\rm CFL} = 3\mu n_B - P. \tag{5}$$

In this approach we shall treat the values of B, m_s and Δ (possibly as high as ~100 MeV) as free constant parameters. The full dependence of $\Omega_{\rm CFL}$ on m_s has been known for years and certainly complicates the evaluation of the equation of state, which must be treated numerically. However, we have recently worked out an approximation to the order m_s^2 which has the main advantage of keeping the equation of state very simple, yet useful for most calculations, while at the same time highlights the effect of each parameter of the model (see Lugones & Horvath 2002 for details).

The stiffness of the EOS is relevant for stellar models since it has a direct impact on the compactness of the stellar configurations. As discussed by Lugones & Horvath (2002), whenever Δ is higher than $m_s/2$, the EOS is stiffer than the unpaired SQM (that is, produces more pressure for a given energy density). Since the actual value of Δ is not well known, we may expect either case, a stiffer or a softer EOS (for a given B).

2.2. Stability of the CFL phase

Self-bound matter, in which strong forces produce a zero-pressure point at finite density, is potentially interesting for astrophysics because it produces stellar sequences having $M \propto R^3$ in the Newtonian limit. For a given EOS the energy per baryon ε/n_B of the deconfined phase (at $P = 0$ and $T = 0$) must be lower than the neutron mass m_n if matter is to be absolutely

[1] Alford & Reddy (2002) have also independently analyzed the role of CFL quark matter in compact stars in a very recent work. Their work is rather general and focused on stars with a normal matter envelope, while our work deals with *absolutely stable* CFL stars only. However, it is worth noting that Alford & Reddy (2002) also include some results on pure CFL stars in their Figs. 5 and 6, which are in quantitative agreement with ours (see Sect. 3).

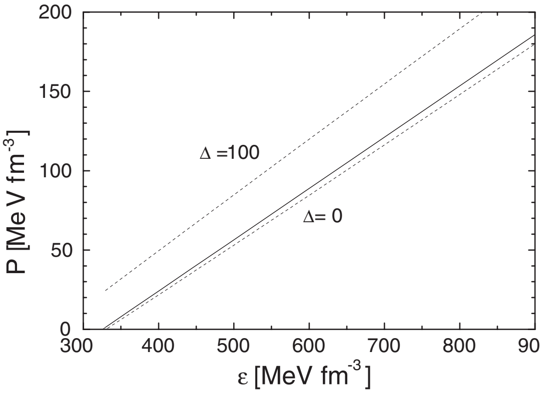

Fig. 1. The dashed lines show the equation of state for CFL strange matter for $B = 75$ MeV fm^{-3}, $m_s = 150$ MeV, and two different values of the gap Δ as indicated in the figure. The solid line corresponds to SQM without pairing. Note the change of stiffness according to the value of Δ, as discussed in the text.

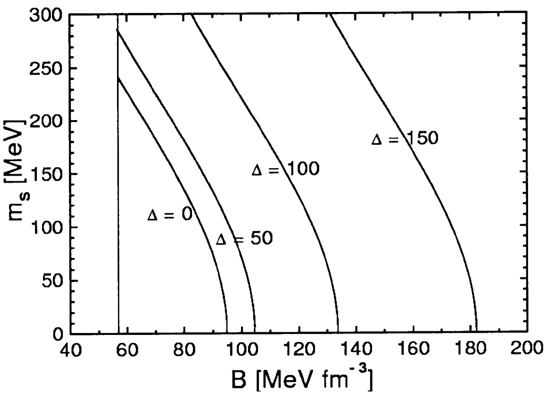

Fig. 2. The stability windows for CFL strange matter. If the strange quark mass m_s and the bag constant B lie inside the bounded region the CFL state is absolutely stable. Each window corresponds to a given value of the gap Δ as indicated by the label. The vertical solid line is the limit imposed by requiring instability of two-flavor quark matter. Note the enlargement of the window with increasing Δ.

stable. Another condition to be considered results from the empirically known stability of normal nuclear matter against deconfinement at $P = 0$ and $T = 0$ (Farhi & Jaffe 1984), which means that the energy per baryon of deconfined matter (a pure gas of quarks u and d) at zero pressure and temperature must be higher than m_n (neglecting refinements of order ~1 MeV to the latter statement). Work using the MIT-based EOS has shown that the latter condition imposes that the MIT bag constant B must be larger than 57 MeV fm^{-3} (Farhi & Jaffe 1984).

Since all three flavors have the same common Fermi momentum, the absolute stability condition takes a very simple form

$$\left.\frac{\varepsilon}{n_B}\right|_{P=0} = 3\mu \leq m_n = 939\ \text{MeV}. \tag{6}$$

Therefore, at the zero pressure point we have (without any approximation)

$$B = -\Omega_{\rm free}(m_s, \mu_0) + \frac{3}{\pi^2}\Delta^2\mu_0^2, \tag{7}$$

where $\mu_0 = m_n/3 = 313$ MeV. A family of curves in the $m_s - B$ plane follow, and on each one the energy per baryon is exactly $\varepsilon/n_B = m_n$ for a given Δ (Lugones & Horvath 2002).

Figure 2 displays the stability window for the CFL phase (i.e. the region in the m_s versus B plane where E/n_B is lower than 939 MeV at zero pressure. Equation (7) sets the right side boundary of the window while the left side boundary is imposed by the minimum value $B = 57$ MeV. The window is greatly enlarged for increasing values of Δ with respect to the original SQM calculations which do not include any pairing (see for example, Fig. 1 of Farhi & Jaffe 1984). We have emphasized elsewhere that the pairing gap Δ may be important for a "CFL strange matter" state (Lugones & Horvath 2002; see also Madsen 2001 for a similar view).

3. Structure of color flavor locked stars

The study of the mass-radius relation for compact stars is a widely known tool for testing the existence of different phases of matter inside NSs. It is also well-known that simultaneous observational data on masses and radii can impose important constraints on the high density equations of state. Up to now, almost all of the measured masses of "neutron stars" clustered within a narrow range around 1.4 $M_\odot$. It has been conjectured that this mass scale may be due to the fact that neutron stars are formed in the gravitational collapse of supernovae and come just from the iron cores of the pre-supernovae. However, nothing fundamental precludes smaller neutron stars from existing provided some mechanism capable of creating them operates. Because small masses are not expected in core collapse models, they hold the potential for discriminating among possible equations of state. This is particularly significant given the recent claims of very low-mass/low-radii objects. As already mentioned, at least two sources, Her X-1 and RX J1856-37, are candidates for high compactness. They have been claimed to have radii ~7 km and masses around 1 $M_\odot$ (Li et al. 1995; Pons et al. 2002). Fragmentation of a larger star (perhaps due to high rotation) may be a possible way to produce sub-solar mass compact objects (Nakamura 2002). Nevertheless, it is clear that models and data are still subject to detailed analysis.

CFL strange matter offers the double bonus of enhancing the odds for a self-bound state, and also of allowing the existence of stable stars made up *entirely* of this phase. To pinpoint the effects of such a composition we have solved the Tolman-Oppenheimer-Volkoff equations of stellar structure, assuming a parameter set inside the windows of absolute stability discussed above (Lugones & Horvath 2002). Figure 3 shows sequences of compact star models thus calculated for particular values of the parameters Δ, m_s and B (see caption). These values of the latter quantities have been selected to highlight a potentially important feature of pairing in dense quark matter, namely the possibility of obtaining very compact stellar models. As expected, the mass-radius relation of stars made up of CFL strange matter presents the same qualitative shape as the curves found for strange stars . This is a direct consequence of the existence of a zero pressure point at finite density (of the order of the nuclear saturation density).

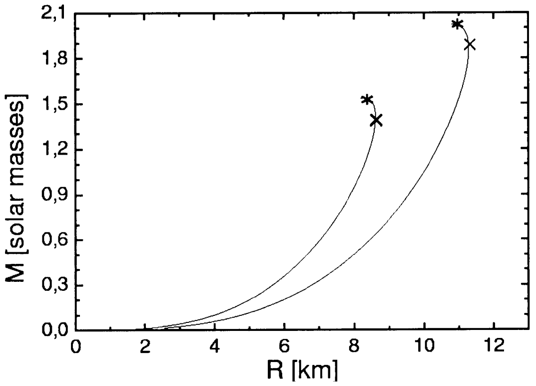

Fig. 3. The mass-radius relation for CFL strange stars for $B = 115\ \mathrm{MeV\,fm^{-3}}$, $m_s = 150$ MeV, $\Delta = 100$ MeV on the left, and for $B = 70\ \mathrm{MeV\,fm^{-3}}$, $m_s = 150$ MeV, $\Delta = 100$ MeV on the right. The crosses indicate the models of maximum radius for each set of parameters, while the asterisks indicate the models with the maximum mass (see Figs. 4–7 for more details).

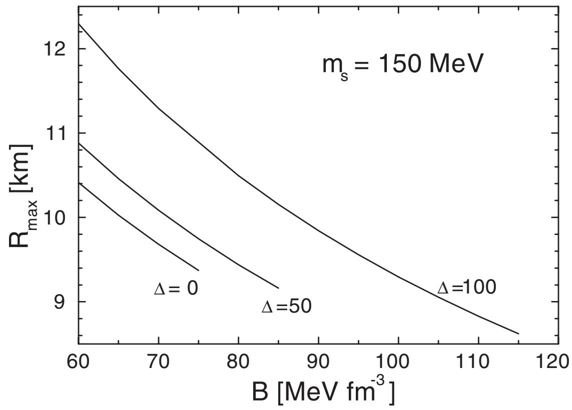

Fig. 4. The maximum radius indicated with crosses in Fig. 3 is shown here as a function of B, for $m_s = 150$ MeV and different values of Δ.

To assess the robustness of the results, and to understand the outcome of masses and radii for a given set of parameters, we have explored the effect of each parameters of the EOS on the static structure of the stellar models. As shown in Figs. 4–7, and quite analogously to the case of strange stars, the effect of increasing B while holding Δ and m_s fixed is to lower both the maximum radius $R_{\max}$ and the maximum mass $M_{\max}$ of the stellar configurations. The mass of the strange quark m_s works in the same direction although the effect is much smaller. The effect of the pairing gap Δ is qualitatively different and much more interesting. An increase of Δ increases the value of both $M_{\max}$ and $R_{\max}$. However, since the increase of Δ strongly enlarges the stability window, the combination of a large Δ with a large B allows the construction of very compact models made up of absolutely stable CFL strange matter. This is particularly illustrative when we set $\Delta = m_s/2$. In this case the EOS adopts, to order μ^2, the same simple form $\varepsilon = 3P + 4B$ as unpaired SQM. However, since the stability window is considerably enlarged, large values of B are allowed and very compact stars are found. This shows how, although the effects in the EOS are only a few percent ($O\,(\Delta/\mu)^2$), the enlargement of the stability window allows a very rich set of stellar configurations, ranging from very compact to quite extended objects. As is seen from the figures, for the smallest values of B the models tend to be less compact and show radii up to 13 km and masses as high as 2.4 $M_{\odot}$. The most extended configurations are obtained for a combination of small B and high Δ^2. It is not possible to select the most likely range of the parameters, which should be limited by observational arguments much in the same way as done for strange matter models.

[2] It can be checked that when the two particular values of B used by Alford & Reddy (2002) are selected ($B^{1/4} = 165$ MeV and $B^{1/4} = 185$ MeV; corresponding to $B = 97\ \mathrm{MeV\,fm^{-3}}$ and $B = 153\ \mathrm{MeV\,fm^{-3}}$ respectively) the values obtained for $M_{\max}$ and $R_{\max}$ from Figs. 4–7 are quantitatively in agreement (even if the latter value has to be extrapolated if needed in these figures). Moreover, a variety of CFL strange star models can be explored by varying the parameters, although, for example, a large variation in m_s does not result in substantial modifications of $M_{\max}$ and $R_{\max}$.

4. Discussion

We have addressed in this work stellar models constructed with the simplest version of a “CFL strange matter” phase. The CFL phase at zero temperature has been modelled as an electrically neutral and colorless gas of quark Cooper pairs, in which quarks are paired in such a way that all the flavors have the same Fermi momentum and hence the same number density (Rajagopal & Wilczeck 2001). Since the strange quark is massive, some energy must be spent in order to keep a common Fermi momentum for all three flavors. However, more than that is gained from the energy gap of the pairing. The model allows CFL strange matter to be the true ground state of strong interactions for a wide range of the parameters B, m_s and Δ. It is remarkable that the strange matter hypothesis may be quite *boosted* by pairing interactions. We have explored the mass-radius relation for all the values of the parameter space of the EOS that give absolutely stable CFL strange matter. Very compact configurations are found that could help to explain the recently claimed compactness of a few neutron stars. Also, for some parameter choices the models are massive and extended.

A feature that has been largely explored and debated in the context of strange star models is the existence of a normal matter crust (Zdunik 2002). Bare quark surfaces may alter drastically the ability of radiating photons, and thus they may produce interesting signatures for their identification (Page & Usov 2002). Conversely, a normal matter crust (held in mechanical equilibrium by the electrostatic potential at the surface) may hide most of the features of exotic matter. By its very construction, it is clear that (in striking contrast with the well-studied SS) no crust could be present in the case of CFL strange stars. This is directly related to the absence of electrons in the mixture (Rajagopal & Wilczek 2001), and thus to the absence of an electrostatic potential to prevent normal matter from being converted to the stable CFL state. CFL strange stars must have bare surfaces within these models. This in turn means that the transport properties of the state, which are still being explored (see, for example Shovkovy & Ellis 2002;

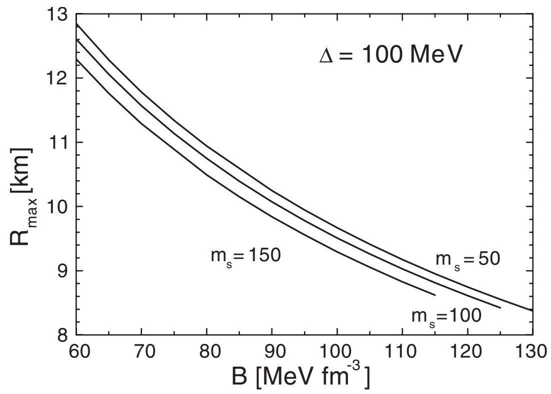

Fig. 5. The same as the previous figure but for fixed Δ and different values of m_s.

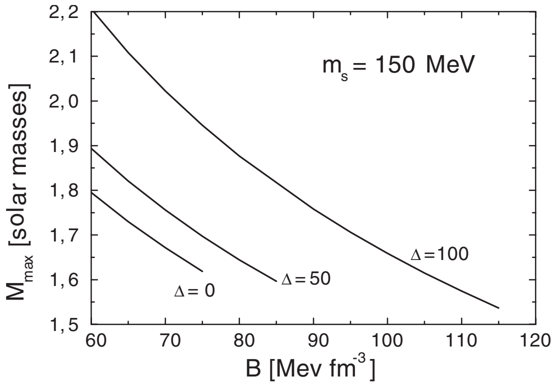

Fig. 6. The maximum mass indicated with asterisks in Fig. 3 is shown here as a function of B, for m_s = 150 MeV and different values of Δ.

Jaikumar et al. 2002; Reddy et al. 2003), hold the clue to the identification of these compact stars. We expect the photon emission properties of CFL strange stars to resemble those of bare SS. Briefly, pairing effects should affect the plasma frequency ω_p through the baryon number density as a small correction of order $\mu\Delta^2$ so that ω_p will not be very different from the ∼20 MeV expected for bare SS. The equilibrium photon radiation will show a very hard spectrum and a tiny luminosity, making CFL strange stars very difficult to detect. On the other hand, while the thermal emission of photons from the bare quark surface of a hot strange star (mainly by electron-positron pair production) has been shown to be much higher than the Eddington limit (Page & Usov 2002), this would not be the case for CFL SS since no electrons will be present at the surface.

As already mentioned, the fact of considering CFL SQM to be absolutely stable together with the absence of electrons in the mixture precludes the existence of a crust of normal matter, then CFL strange stars are bare by construction. In a more general approach, Alford & Reddy (2002b) found mass-radius relations with essentially the same shape as that for neutron stars made up of normal nuclear matter when considering a wider range of parameters in which "hybrid" stars are allowed. This corresponds to a large part of the parameter space and not only do they find a normal matter envelope for all these models, but also the composition of the less massive objects becomes

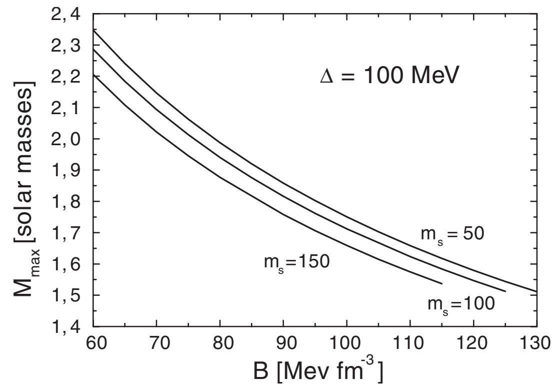

Fig. 7. The same as the previous figure but for fixed Δ and different values of m_s.

pure nuclear matter, as expected. In addition, as pointed out in Sect. 3, a subset of the models of Alford and Reddy (2002) correspond to our "CFL strange stars", and the full range of these self-bound models can be obtained with the aid of Figs. 4–7. The self-bound CFL state may be compared to stable diquark states, which have been found to produce very similar stellar structural properties than CFL strange matter within completely different models (Horvath 1993; Horvath & de Freitas Pacheco 1998; Lugones & Horvath 2003). We finally note that, due to the presence of m_s and Δ in the EOS, a linear form $P(\rho)$ is obtained in particular cases only, therefore the scaling behavior of the Tolman-Oppenheimer-Volkov equations that allows the construction of simple expressions for the maximum masses and radii is lost for these CFL stars. The relevance of this modelling to understand actual observed stars is not clear as yet, but certainly the latter will continue to advance to the point at which this and other questions will be answered with confidence.

Acknowledgements. G. Lugones acknowledges the Instituto de Astronomia, Geofísica e Ciências Atmosféricas de São Paulo and the financial support received from the Fundação de Amparo à Pesquisa do Estado de São Paulo. J.E. Horvath wishes to acknowledge the CNPq Agency (Brazil) for partial financial support.

References

Alford, M., Berges, J., & Rajagopal, K. 1999a, Nucl. Phys. B, 558, 219
Alford, M., Rajagopal, K., & Wilczek, F. 1999b, Nuc. Phys. B, 537, 433
Alford, M., Rajagopal, K., Reddy, S., & Wilczeck, F. 2001, Phys. Rev. D, 64, 074017
Alford, M., & Rajagopal, K. 2002a [hep-ph/0204001]
Alford, M., & Reddy, S. 2002b [nucl-th/0211046]
Bailin, D., & Love, A. 1984, Phys. Repts., 107, 325
Becker, W., & Aschenbach, B. 2002, in Proc. of the 270.WE-Heraeus Seminar on Neutron Stars, Pulsars and Supernova Remnants, Jan. 21–25, 2002, Physikzentrum Bad Honnef, ed. W. Becker, H. Lesch, & J. Truemper
Bodmer, A. 1971, Phys. Rev. D, 4, 1601
Cheng, K. S., Dai, Z. G., Wai, D. M., & Lu, T. 1998, Science, 280, 407
Chin, S., & Kerman, A. K. 1979, Phys. Rev. Lett., 43, 1292

Cleymans, J., Gavai, R. V., & Suhonen, E. 1986, Phys. Rep., 4, 217
Degrand, T., Jaffe, R. L., Johnson, K., & Kiskis, J. 1975, Phys. Rev. D, 12, 2060
Dey, M., Bombaci, I., Dey, J., Ray, S., & Samanta, B. C. 1998, Phys. Lett. B, 438, 123; Addendum 1999, Phys. Lett. B, 447, 352; Erratum 1999, Phys. Lett. B, 467, 303
Farhi, E., & Jaffe R. L. 1984, Phys. Rev. D, 30, 2379
Hanauske, M., Satarov, L. M., Mishustin, I. N., Stoecker, H., & Greiner, W. 2001, Phys. Rev. D, 64, 043005
Hong, D. K., Hsu, S. D. H., & Sannino, F. 2001, Phys. Lett B, 516, 362
Horvath, J. E. 1993, Phys. Lett. B, 242, 419
Horvath, J. E., & de Freitas Pacheco, J. A. 1998, Int. J. of Mod. Phys. D, 7, 19
Jaikumar, P., Prakash, M., & Schafer, T. 2002, Phys. Rev. D, 66, 063003
Kaplan, D. L., van Kerkwijk, M. H., & Anderson, J. 2001 [astro-ph/0111174]
Li, X. -D., Lai, Z. -G., & Wang Z. -R. 1995, A&A, 303, L1
Li, X., Bombaci, I., Dey, M., Dey, J., & van den Heuvel, E. P. J. 1999a, Phys. Rev. Lett., 83, 3776
Li, X., Ray, S., Dey, J., Dey, M., & Bombaci, I. 1999b, AJ, 527, L51
Lugones, G., & Horvath, J. E. 2002, Phys. Rev. D, 66, 074017
Lugones, G., & Horvath, J. E. 2003, Int. Jour. Mod. Phys. D, 12, to be published [astro-ph/0203069]
Madsen, J. 2001, Phys. Rev. Lett., 87, 172003
Nakamura, T. 2002 [astro-ph/0205526]
Page, D., & Usov, V. V. 2002, Phys. Rev. Lett., 89, 131101
Pons, J., Walter, F. M., Lattimer, J. M., et al. 2002, ApJ, 564, 981
Rajagopal, K., & Wilczeck, F. 2000 [hep-ph/0011333]
Rajagopal, K., & Wilczeck, F. 2001, Phys. Rev. Lett., 86, 3492
Rapp, R., Schäfer, T., Shuryak, E. V., & Velkovsky, M. 2000, Ann. Phys., 280, 35
Reddy, S., Sadzikowski, M., & Tachibana, M. 2003, Nucl. Phys. A, 714, 337
Reynolds, A. P., Quaintrell, H., Still, M. D., et al. 1997, MNRAS, 288, 43
Schäfer, T., & Wilczek, F. 1999, Phys. Rev. D, 60, 074014
Shovkovy, I. A., & Ellis, P. J. 2002 [hep-ph/0211049]
Steiner, A. W., Reddy, S., & Prakash, M. 2002, Phys. Rev. D, 66, 094007
Terazawa, H. 1979, INS-Report, 336
van Kerkwijk, M. H. 2001, in Proc. of the ESO Workshop on Black Holes in Binaries and Galactic Nuclei, ed. L. Kaper, E. M. van den Heuvel, & P. A. Woudt (Springer-Verlag)
Weisskopf, M. C. 2002, in Proceedings of the 270. WE-Heraeus Seminar on Neutron Stars, Pulsars and Supernova Remnants, Jan. 21-25, 2002, Physikzentrum Bad Honnef, ed. W. Becker, H. Lesch, & J. Truemper
Witten, E. 1984, Phys. Rev. D, 30, 272
Zdunik, J. L. 2002, A&A, 394, 641
Zhang, Y., & Ru-Ken Su 2002, Phys. Rev. C, 65, 035202