A&A 422, L1–L4 (2004)
DOI: 10.1051/0004-6361:20040180

Astronomy & Astrophysics

Letter to the Editor

Self-bound CFL stars in binary systems: Are they "hidden" among the black hole candidates?

J. E. Horvath[1] and G. Lugones[2]

[1] Instituto de Astronomia, Geofísica e Ciencias Atmosféricas Rua do Matão 1226, 05508-900 São Paulo SP, Brazil
e-mail: foton@astro.iag.usp.br

[2] Dipartimento di Fisica "Enrico Fermi", Università di Pisa via Buonarroti 2, 56127 Pisa, Italy
e-mail: lugones@df.unipi.it

Received 16 February 2004 / Accepted 22 May 2004

Abstract. The identification of black holes is one of the most important tasks of modern astrophysics. Candidates have been selected among binary stars based on a high mass function, and seriously considered when the lower mass limit exceeds $\sim 3\ M_{\odot}$. More recently the absence of (type I) thermonuclear bursts has been advanced as an additional criterion in favor of the black hole interpretation, since the absence of a solid surface naturally precludes the accumulation and ignition of accreting material. We discuss in this Letter the possibility that self-bound stars made of CFL-paired quarks mimic the behavior of at least the low-mass end black holes as a result of: a) higher maximum masses than ordinary neutron stars, b) low steady luminosities due to the bare surface properties, and c) impossibility of generating type I bursts because of the complete absence of normal matter crusts at their surfaces. These features caution against a positive identification of event horizons based on the lack of bursts.

Key words. X-ray binary systems – black holes – thermonuclear bursts – CFL stars

1. Introduction

The strong gravitational field regime of General Relativity is widely believed to be physically realized in black holes, uniquely possessing event horizons. The positive identification of black holes among existing astrophysical objects has the potential of providing a glimpse into that regime which captures the imagination of scientists and public alike. This is why the study of black hole candidates has consumed so much time of research efforts since the early days of X-ray astronomy, when the first strong sources were identified and some of them tentatively associated with astrophysical black holes.

Unfortunately, the task of a positive identification is still plagued with caveats, and even though the advances in the last decade or so have been quite impressive (Orosz 2002), the burden of proof is still with observational astrophysicists. Meanwhile, the discussion continues and new proposals arise as potential unique signatures of event horizons possessed by black holes only. In a recent series of papers (Narayan et al. 2001; Narayan 2003, and references therein), Narayan and coworkers have proposed a class of X-ray binaries (the soft-X transients, or SXT) as attractive candidates to black holes. The argument is that those sources show, in addition to a mass function $f(M)$ larger than the expected $\sim 3\ M_{\odot}$ maximum limit for NS models (the mass function is an absolute lower limit to the mass of the compact object in the SXT), an absence of type I bursts tentatively interpreted as evidence for an event horizon. In fact, a systematic study undertaken (Narayan 2003) to pin down the physical condition for type I thermonuclear bursts has shown that SXT sources should burst if they possess a normal matter crust, therefore the absence of bursts could be interpreted as indicating the presence of event horizons. In a recent paper, Yuan et al. (2004) made a general attempt to show that *any* neutron star (composed by matter described by a more or less general equation of state) should experience thermonuclear type I bursts at appropriate mass accretion rates. The question is whether an "abnormal" surface also allows such physical behavior. We shall argue below that general models do not necessarily possess the anomalous high-density surface properties of self-bound quark stars, which is one of the key ingredients that entangle their discrimination within the black hole candidates.

Since the proof of the existence of event horizons is so important for modern astrophysics, careful examinations of the possible loopholes and alternatives to the signatures are needed. As an example of the latter, a critical analysis by Abramowicz et al. (2003) concluded, based on a series of persuasive arguments, that a positive proof of the event horizon will be impossible in principle. Specifically, they argue that the case of SXTs as black holes based on the absence of type I bursts would be weakened by the finding of any kind of exotic star without a "normal" crust. We have reexamined this

Send offprint requests to: G. Lugones,
e-mail: lugones@df.unipi.it

objection with the aim of addressing the recently proposed models of self-bound CFL stars and report our findings below.

2. Stability of color flavor locked (CFL) quark matter and stellar sequences

It is widely accepted that at high temperatures and/or high baryon number densities confinement of quarks will be lost. The phase diagram of QCD seems to be very rich and lattice simulations (Fodor 2003; Kanaya 2003) are attempting to address this point in full detail. However, it is still not very clear whether the transition points are of actual interest in the low temperature/high density regime reached inside existing compact stars. Different compositions of deconfined matter have been analyzed in the literature, and it seems that at high densities a color-flavor locked state of u, d and s quarks is favored over other forms of paired and unpaired matter on general grounds (Alford et al. 1999; Alford & Rajagopal 2002).

We have previously addressed the issue of CFL matter absolute stability. The idea is an extension of the celebrated "strange matter" case, and in fact, we found (Lugones & Horvath 2002) that pairing *enhances* the possibility of absolute stability. 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 & Wilczek 2001). 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, and this is why we have called this state "CFL strange matter" (Lugones & Horvath 2002). The exploration of the stellar sequences (see also Lugones & Horvath 2003; Alford & Reddy 2003, for a discussion of the physics and stellar models) constructed with the values of the parameter space of the EOS that give absolutely stable CFL strange matter, yielded very compact configurations (which could help explain the recently claimed compactness of a few neutron stars). In addition, for some parameter choices the models are quite massive and extended (see Lugones & Horvath 2003).

With the aim of addressing the SXT systems we have explored the parameter space to check whether self-bound CFL stars sequences end with very massive stars. Actually, the basics of $M_{\rm max}$ for any fluid configuration has been discussed by Haensel (2003) in a pedagogical form. That work highlighted the value of scaling laws for gaining insight of the problem, particularly for the case of linear equations of state that allow simple solutions of the stellar structure. In the case of strange quark matter, if quark-quark interactions are ignored and the mass of the s quark is small enough, the maximum mass of a stellar sequence would be just (Haensel 2003)

$$M_{\rm max} = \frac{1.96\,M_\odot}{\sqrt{B_{60}}} \qquad (1)$$

(being $B_{60} \equiv B/[60\,{\rm MeV fm^{-3}}]$) as already discussed by Witten (1984).

We note that the case of a CFL equation of state in fact closely resembles the well-known theory of strange quark matter, having an equation of state of the form $P = \kappa(\rho - 4B_{\rm eff})$, with $B_{\rm eff} = B - 3\mu^2\Delta^2/\pi^2$ (Lugones & Horvath 2002, 2003). This parametrization, however, yields a $B_{\rm eff}$ which is dependent on density through the chemical potential μ, and therefore a simple scaling of the maximum mass of the star is not possible as in the case of strange matter. However, and in order to gain a qualitative insight of the structural properties, we can approximate the chemical potential in $B_{\rm eff}$ by a characteristic mean value $\mu_* \sim 200$ MeV for CFL strange matter. In this simplified case $B_{\rm eff}$ is a constant that depends just on B and Δ and allows a very simple scaling

$$M_{\rm max} \approx \frac{1.96\,M_\odot}{\sqrt{B_{60}}}\,(1+\delta) \qquad (2)$$

valid for $B > 3\mu_*^2\Delta^2/(2\pi^2)$, where

$$\delta = 0.15\left(\frac{\Delta}{100\,{\rm MeV}}\right)^2\left(\frac{60\,{\rm MeV fm^{-3}}}{B}\right). \qquad (3)$$

Therefore, and ignoring for the moment the entanglement between the quark masses and the density dependence of the condensation term, we may state that CFL matter can produce high mass compact stars because the existence of pairing reduces the effective value of the vacuum energy density parametrized by B by adding a term with opposite sign. It is this condensation energy Δ that causes an increase of the maximum mass from $\sim 2\,M_\odot$ to $\sim 4\,M_\odot$ for the range considered in the present paper.

Figures 1–3 show the results of the full calculations, which have taken into account all the important ingredients such as quark masses and the correct density dependence of the condensation term. As discussed above, the value of the pairing gap Δ is the key ingredient of the equation of state. Lacking of a definitive indication of the latter we conclude that very massive models ($M_{\rm max} \sim 4\,M_\odot$) are possible if Δ is high enough ($\geq$250 MeV). Only refined calculations will confirm or rule out this range, which is entirely possible according to the present research.

3. Absence of normal matter crusts in self-bound CFL stars

A crucial feature for a wide set of observations (largely explored and debated in the context of strange star (SS) models) is the existence of a normal matter crust (see Zdunik 2002, and references therein). It has been realized that bare quark surfaces may alter drastically the ability of radiating photons (see e.g. Alcock et al. 1986; Page & Usov 2002; Xu 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. It has been recently shown that CFL states force an equal number of u, d and s quarks. As a consequence, this phase is electrically neutral and at the same time it does *not* allow electrons in beta-equilibrium (Rajagopal & Wilczek 2001). Therefore, it is clear that (in striking contrast with the well-studied SS) no crust could be present in the case of CFL strange stars. CFL strange stars must have bare surfaces within these models. Particularly, photon radiation from a bare CFL surface is vanishingly small

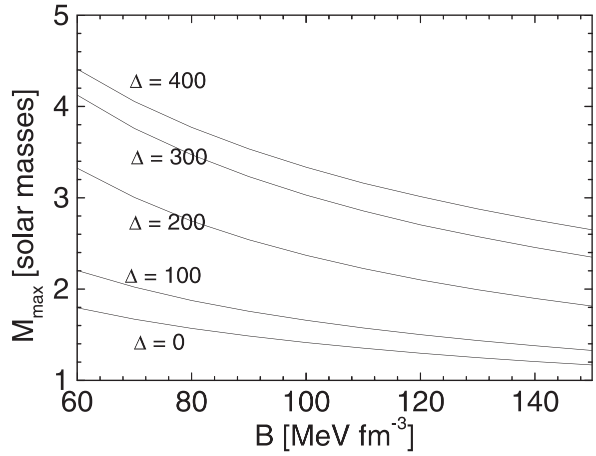

Fig. 1. The maximum masses of self-bound CFL stars as a function of the bag constant B, for different values of the pairing energy Δ. The strange quark mass is set to $m_s = 150$ MeV. In order to be absolutely stable the energy per baryon of the CFL phase must be lower than 939 MeV and the bag constant must be greater than 57 MeV fm^{-3}. The stellar models were constructed using the equations of state derived in Lugones & Horvath (2002). Large maximum masses are found for "standard" values of B and $\Delta \geq 250$ MeV.

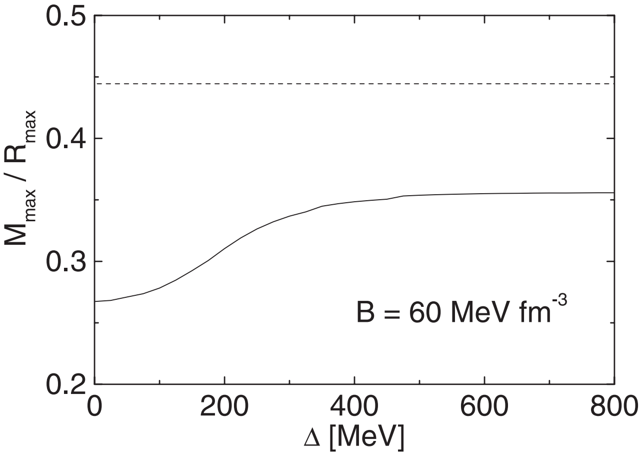

Fig. 3. The compactness $GM_{\rm max}/(c^2R_{\rm max})$ as a function of the pairing gap Δ for $B = 60$ MeV fm^{-3}. In dashed line it is shown the maximum limit $M/R = 4/9$ imposed by general relativity (i.e. for a uniform density star with the causal equation of state $P = \varepsilon$). Note that the gravitational redshift of the maximum mass configuration is $z_{\rm max} = [1 - 2GM_{\rm max}/(c^2R_{\rm max})]^{-1/2} - 1 \approx GM_{\rm max}/(c^2R_{\rm max})$ and has an asymptotic value $\sim$0.35.

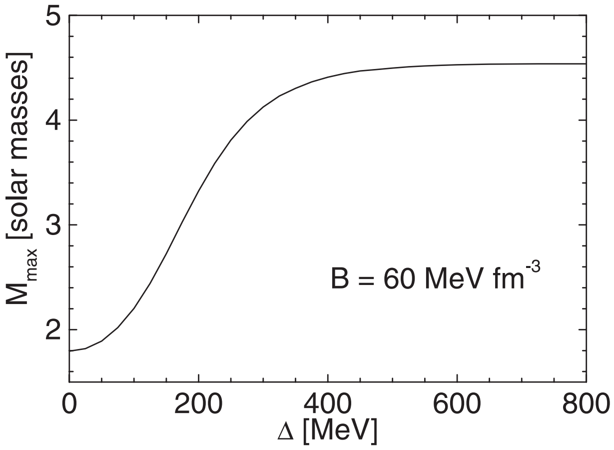

Fig. 2. The maximum masses of self-bound CFL stars as a function of the pairing gap Δ for $B = 60$ MeV fm^{-3}.

and the star is dark in optical frequencies (see Vogt et al. 2003, and references therein).

As discussed by Narayan (2003), the type I bursts observed from many X-ray sources require the presence of a normal matter crust. Abramowicz et al. (2003) correctly (and boldly) stated that "no nuclei, no burst". It is worth noting that, strictly speaking, the presence of a material surface only implies that energy can be radiated once matter lands on the surface. However, this evidence of the presence of a material surface can be seriously obscured if the energy is emitted in the form of weakly interacting particles. This is the case of the bare surface of a CFL star in which almost all energy is expected to be radiated in neutrinos. Thus, the absence of a crust is an important feature of self-bound CFL models, because normal matter would never accumulate at the surface (as discussed in the strange matter case). Instead, when matter is accreted onto a bare electrically neutral CFL surface, there will be in addition to the usual gravitational energy release $\sim GM\dot{M}/R$, an additional term related to the exothermic fusion of the incoming proton with the quark liquid. The latter is approximately given by $\sim \dot{M}\Delta/m_{\rm p}$, and for typical values it may amount to $\sim$30% of increase over the normal case.

As matter falls on the bare surface it is immediately converted to the CFL phase and the gravitational + pairing gap energy is (almost) instantaneously emitted mainly in ν's (due to the unavoidable β-decays in the quark phase) and a smaller fraction of (most probably) γ-rays. Because matter is being continuously converted at the surface, and cannot accumulate, sudden X-ray flashes are not expected.

4. Discussion

The photon emission properties of CFL strange stars are expected to resemble those of bare SS (Shovkovy & Ellis 2002). Since pairing effects should appear in the plasma frequency $\omega_{\rm p}$ through the baryon number density as a correction of order $\mu\Delta^2$, the plasma frequency $\omega_{\rm p}$ will not be very different from (typical) 20 MeV of unpaired quark matter, and thus the equilibrium photon radiation will be suppressed. A tiny luminosity makes CFL strange stars very difficult to detect directly. The thermal emission of photons from the bare quark surface of an (unpaired) strange star (due mainly by electron-positron pair production) shown to be much higher than the Eddington limit by Page & Usov (2002) may not operate for CFL strange stars since no electrons will be present at the surface and the emissivities due to other processes are negligible at low temperatures.

These features (high maximum masses, absence of normal matter crusts and lack of surface emission) show that "exotic" stellar models may be constructed in which type I thermonuclear bursts can not occur, but which are not black holes either. If physically realized in nature, some of the

SXT systems observed to possess a relatively low mass function (e.g. SXT A0620-00, with $f(M) \geq 3\ M_{\odot}$; Mc Clintock & Remillard 1986) may harbor self-bound CFL stars.

In these models, the lack of type I thermonuclear bursts is not interpreted as a signature of an event horizon, but rather as a consequence of the impossibility of a normal crust with $\rho \leq 10^6\ \mathrm{g\,cm^{-3}}$ where accreted matter could accumulate and eventually ignite. Further work is needed to elaborate or rule out this tentative association, but it is already clear that CFL stars provide a definite counterexample of the event horizon proof as a representative of a class of exotic alternatives not easily discarded.

Acknowledgements. We acknowledge E. M. de Gouveia Dal Pino for helpful discussions. J. E. Horvath wishes to acknowledge the CNPq Agency (Brazil) for partial financial support. G. Lugones acknowledges the Physics Department of the University of Pisa (Italy), and FAPESP (Brazil).

References

Abramowicz, M., Kluźniak, W., & Lasota, J.-P. 2003, A&A, 396, L31
Alford, M., & Rajagopal, K. 2002, JHEP, 06, 031
Alford, M., Rajagopal, K., & Wilczek, F. 1999, Nucl. Phys. B, 537, 443
Alford, M., & Reddy, S. 2003, Phys. Rev. D, 67, 074024
Alcock, C., Farhi, E., & Olinto, A. V. 1986, ApJ, 310, 261
Farhi, E., & Jaffe, R. L. 1984, Phys. Rev. D, 30, 2379
Fodor, Z. 2003, Nucl. Phys. A, 715, 319
Haensel, P. 2003, Final Stages of Stellar Evolution, Proc. of the conference held 16–21 September, 2001 in Aussois, France, ed. C. Motch, & J.-M. Hameury, EAS Publ. Ser., 7, 249
Kanaya, K. 2003, Nucl. Phys. A, 71, 233
Lugones, G., & Horvath, J. E. 2002, Phys. Rev. D, 66, 074017
Lugones, G., & Horvath, J. E. 2003, A&A, 403, 173
Mc Clintock, J. E., & Remillard, R. A. 1986, ApJ, 308, 110
Narayan, R., García, M. R., & Mc Clintock, J. E. 2001, in Proc. of the The Ninth Marcel Grossmann Meeting, ed. V. G. Gurzadyan, R. T. Jantzen, & R. Ruffini (World Scientific Publishing) [arXiv:astro-ph/0107387]
Narayan, R. 2003 [arXiv:astro-ph/0310692]
Orosz, J. A. 2002 [arXiv:astro-ph/0209041]
Page, D., & Usov, V. V. 2002, Phys. Rev. Lett., 89, 131101
Rajagopal, K., & Wilczek, F. 2001, Phys. Rev. Lett., 86, 3492
Shovkovy, I. A., & Ellis, P. J. 2002 [arXiv:hep-ph/0211049]
Vogt, C., Rapp, R., & Ouyed, R. 2003 [arXiv:hep-ph/0311342]
Xu, R. X. 2002, ApJ, 570, L65
Yuan, Ye-Fei, Narayan, R., & Rees, M. J. 2004, ApJ, 606, 1112
Witten, E. 1984, Phys. Rev. D, 30, 272
Zdunik, J. L. 2002, A&A, 394, 641