QCD phase transition in neutron stars and gamma-ray bursts

Wu, K.[1], Menezes, D. P.[2,3], Melrose, D. B.[3] and Providencia, C.[4]

1 Mullard Space Science Laboratory, University College London, UK
2 Departmento de Fisica, CFM, Universidade Federal de Santa Catarina, Brazil
3 School of Physics, University of Sydney, Australia
4 Centro de Fisica Teorica, Departmento de Fisica, Universidade de Coimbra, Portugal

UCL

A. Introduction

The possibility of formation of quark-gluon plasmas (QGP) in heavy-ion collisions leads to a suggestion that phase transition might occur in the dense interiors of neutron stars [1,2]. At temperatures T ~ 0 - 40 MeV, there are two possibilities for phase transitions (see the QGP diagram showing quantum chromodynamics (QCD) phases in Figure 1). As density increases, hadronic matter first converts into QGP, or into either a crystalline quark matter or a two-flavour superconducting phase, and subsequently to a colour-flavour-locked superconducting (CFL) phase.

The current models for the interior composition of neutron stars are
(i) pure hadronic matter with or without hyperons (hadronic stars) [1,3]
(ii) a mixed phase of hadrons and quarks (hybrid stars) [1,4]
(iii) a mixed phase of hadrons and pion or kaon condensates (hybrid stars) [5,6,7], and
(iv) deconfined quarks (strange quark stars) [6,8].
According to Bodmer-Witten hypothesis, strange matter is the true-ground state of all matter. Thus, a neutron star may decay to become a strange quark star [9]. A seed of strange quark matter in the neutron star interior would trigger a quark matter front, which propagates rapidly and converts the whole star into a strange quark star in only ~ 10^{-3} - 1 s [10]. It has been proposed that certain gamma-ray bursts (GRB) are manifestations of a phase transition in the interior of neutron stars. Based on the burst duration, GRB can be roughly divided into two classes (see e.g. [11,12]). They are also distinguishable by their energy released. The short bursts (SGRB) tend to have hard spectra than the long bursts (LGRB). The total isotropic energy released in a SGRB in the first hundred seconds is ~ 10^{50} erg. LGRB are a few hundreds to a few thousand times more energetic. Now there are evidences that LGRB are associated with violent explosions of massive stars [13,14], while SGRB are believed to be caused by compact-star merging.

Here, we consider various phase transitions in neutron stars and calculate the amount of energy released in conversions of meta-stable neutron stars to their corresponding stable counterparts. We will verify whether or not the QCD phase transition can power SGRB.

B. Phase transition and models for the dense matter phases

In this work, equations of state (EOS) based on the following models (see [15] for details) are used to determine the properties of the neutron stars.
(1) hadronic phase:
- -- non-linear Walecka model (NLWM)
- -- non-linear Walecka model with δ mesons (NLWM δ)
- -- quark-meson coupling model (QMC)

(2) quark phase:
- -- Nambu-Jona-Lasinio model (NJL)
- -- MIT bag model (MIT)
- -- colour-flavour-locked quark phase (CFL)

Two cases for the NLWM and NLWM δ models are considered. The first assumes only protons and neutrons (p,n) in the derivations of the EOS; the second includes the eight lightest baryons (8b). Several values are used for the bag parameters in the MIT and CFL models. Typically, the bag parameter $\mathrm{Bag}^{1/4}$ ~ 160 MeV (e.g. in the MIT 160 and CFL 160 models), where a quark star is allowed. Unless otherwise stated, the baryonic mass is set to be 1.56 $M_\odot$, approximately corresponding to neutron stars with gravitational mass of 1.4 $M_\odot$. The mass-radius relation and the gravitational mass vs baryonic mass plot of some hadronic, hybrid and quark stars are shown in Figure 2.

For the phase transition, charge conservation is restricted to the neutral case. Strangeness conservation is not required, but β equilibrium is enforced. The conservation of baryon number is approximated, assuming the conservation of the baryonic mass of the star. The Gibbs conditions remain the same, and the EOS is determined by the two chemical potentials μ_n and μ_e. The Tolman-Oppenheimer-Volkoff equations are solved to obtain the baryonic mass, gravitational mass, stellar radius and central energy density. The energy released is identified as the change in the gravitational energy in the conversion of a meta-stable star to a stable star, i.e.

$$\Delta E = [\,M_G(MS) - M_G(SS)]/M_\odot \times (17.88 \times 10^{53}\ \mathrm{erg})\,.$$

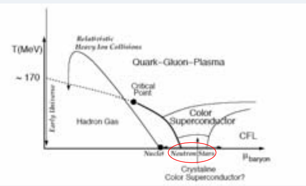

Figure 1. QGP diagram showing different phases and some possible QCD phase transitions.

References:
[1] Glendenning, N. K., 2000, Compact Star, Springer-Verlag
[2] Pakash, M. et al., 1997, Phys. Rep., 280, 1
[3] Espindola, A. L., Menezes, D. P., 2002, Phys. Rev., C 65, 045803
[4] Menezes, D. P., Providencia, C., 2003, Phys. Rev., C 68, 035804
[5] Glendenning, N. K., Schaffner-Bielich, J., 1988, Phys. Rev. Lett., 81, 4564
[6] Glendenning, N. K., 2001, Phys. Rep., 342, 393
[7] Menezes, D. P., Panda, P. K., Providencia, C., 2005, Phys. Rev. C 72, 035802
[8] Menezes, D. P., Melrose, D. B., 2005, PASA, 22, 292
[9] Bombaci, I., Datta, B., 2000, ApJ, 530, L69
[10] Horvath, J. E., Benvenuto, O. G., 1988, Phys. Lett., B 213, 516
[11] Piran, T., 2004, Rev. Mod. Phys., 76, 1143
[12] Qin, J. et al., 2000, PASJ, 76, 1143
[13] Woosley, S. E., 1993, ApJ, 405, 273
[14] van Paradijs, J. et al., 1997, Nature, 386, 686
[15] Menezes, D. P., Melrose, D. B., Providencia, C., Wu, K., 2006, Phys. Rev., C 73, 025806

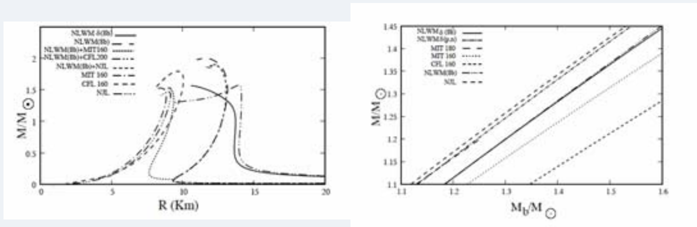

Figure 2. (Left) Mass-radius relation of some examples of hadronic, hybrid and quark stars considered in this work. (Right) Gravitational mass vs baryonic mass for some hadronic, hybrid and quark stars. (Adopted from [15].)

C. Results

Four types of conversion of metastable stars (MS) to stable stars (SS) may occur. The energy released in some cases are presented in Table 1.

(1) Hadronic star ---> quark star
- -- Conversion of a MS with NLWM(δ)/QMC to a SS with MIT/CFL generally yields ΔE ~ 10^{53} erg.
- -- Conversion of a MS with NJL to a SS with MIT/CFL is not allowed.
- -- ΔE depends on the bag parameter, and smaller bag parameters give larger ΔE.
- -- Negative ΔE will result if a too large bag parameter is assumed for the MIT/CFL matter.
- -- ΔE is larger for MS with NLWM(p,n) than MS with NLWM(8b), and similar results for QMC(p,n) and QMC(8b).
- -- ΔE is similar for cases of MS with NLWM δ and MS with NLWM .

(2) Hadronic star ---> hybrid star
- -- ΔE, ~ 10^{50} - 10^{52} erg, are smaller than those of conversions of hadronic stars to quark stars.
- -- Conversion of a hadronic star to a hybrid star with kaons is possible, but ΔE is measurable only for the cases without hyperons.
- -- Smaller bag parameters give larger core for the hybrid star, and hence also give larger ΔE.

(3) Hybrid star ---> quark star
- -- ΔE is 2 to 3 times larger for a conversion to a SS with CFL than to a SS with MIT.

(4) Quark star ---> quark star
- -- Conversion of a quark star with unpaired quarks (MIT) to a quark star with paired quark (CFL) is possible and could yield ΔE ~ 10^{53} erg.

MS	model (MS)	SS	model (SS)	$M_b(M_\odot)$	$\Delta E(10^{53}$erg)
hadronic^a	NLWMδ(p,n)	quark^b	MIT 160	1.56	1.91
hadronic^a	NLWMδ(p,n)	quark^b	MIT 180	1.25	0.081
hadronic^a	NLWMδ(8b)	quark^b	MIT 160	1.56	0.94
hadronic^a	NLWMδ(8b)	quark^b	MIT 180	—	<0
hadronic^a	NLWMδ(p,n)	quark^b	CFL 160	1.56	3.73
hadronic^a	NLWMδ(8b)	quark^b	CFL 160	1.56	2.84
hadronic^c	NLWM(8b)	quark^b	MIT 160	1.56	0.95
hadronic^c	NLWM(8b)	quark^b	MIT 180	1.80	1.34
hadronic^c	NLWM(8b)	quark^b	CFL 160	1.56	2.84
hadronic^c	NLWM(8b)	quark^b	CFL 180	2.11	3.95
hadronic^a	NLWMδ(p,n)	quark^d	NJL	—	<0
hadronic^a	NLWMδ(8b)	quark^d	NJL	—	<0
hadronic^e	QMC(p,n)	quark^b	MIT 160	1.56	1.15
hadronic^e	QMC(8b)	quark^b	MIT 160	1.56	1.20
hadronic^e	QMC(p,n)	quark^b	CFL 160	1.56	2.97
hadronic^e	QMC(8b)	quark^b	CFL 160	1.56	3.01
hadronic^e	QMC(p,n)	hybrid^f	QMC+kaons	1.56	0.088
hadronic^e	QMC(8b)	hybrid^f	QMC+kaons	—	0.0
hadronic^a	NLWMδ(8b)	hybrid^a	NLWMδ(8b)+MIT 180	1.56	0.071
hadronic^c	NLWM(8b)	hybrid^g	NLWM(8b)+MIT 170	1.56	0.42
hadronic^c	NLWM(8b)	hybrid^g	NLWM(8b)+MIT 160	1.56	0.58
hadronic^c	NLWM(8b)	hybrid^g	NLWM(8b)+CFL 200	1.56	0.008
hadronic^c	NLWM(8b)	hybrid^{h,i}	NLWM(8b)+NJL	1.52	0.027
hybrid^a	NLWMδ(8b)+MIT 180	quark^b	MIT 160	1.56	0.92
hybrid^a	NLWMδ(8b)+MIT 180	quark^b	CFL 160	1.56	2.75
hybrid^h	NLWM(8b)+MIT 170	quark^b	MIT 170	—	<0
hybrid^h	NLWM(8b)+MIT 160	quark^b	MIT 160	1.56	0.46
hybrid^f	QMC(8b)+CFL 200	quark^b	CFL 160	1.56	2.89
hybrid^f	QMC(8b)+CFL 200	quark^b	CFL 160	1.80	3.31
hybrid^i	NLWM(8b)+NJL	quark^d	NJL	—	<0
hybrid^g	NLWM(8b)+CFL 200	quark^b	CFL 160	1.56	2.90
quark^b	MIT 160	quark^b	CFL 160	1.56	1.82

a. Menezes, D. P., Providencia, C., 2004, Phys. Rev., C 70, 058801
Menezes, D. P., Providencia, C., 2004, Braz. J. Phys., 34, 724
b. Menezes, D. P., Melrose, D. B., 2005, PASA, 22, 292
c. Espindola, A. L., Menezes, D. P., 2002, Phys. Rev., C 65, 045803
Santos, A. M. S., Menezes, D. P., 2004, Phys. Rev., C69, 045803
Carvangioli, R., Menezes, D. P., 2005, Braz. J. Phys., 35B, 869
d. Menezes, D. P., Providencia, C., Melrose, D. B., 2005, astro-ph/0507529
e. Panda, P. K., Menezes, D. P., Providencia, C., 2004, Phys. Rev., C69, 025207
f. Menezes, D. P., Panda, P. K., Providencia, C., 2005, Phys. Rev., C 72, 0305802
g. Menezes, D. P., Melrose, D. B., Providencia, C., Wu, K., 2006, Phys. Rev., C73, 025806
h. Menezes, D. P., Providencia, C., 2003, Phys. Rev., C 68, 035804
i . Menezes, D. P., Prolidencia, C., 2003, Phys. Rev., C 69, 045801

Table 1