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Nuclear Physics A 790 (2007) 558c–561c

The QCD phase diagram and the gamma-ray bursts

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Phase transitions which can take place in matter at different temperatures and densities are seen in the quantum chromodynamics diagram. The possibility that gamma-ray bursts might result from a phase change in the interior of a pulsar is discussed in the present work. The energy released in the conversion of a metastable star into a stable star is calculated and shown to be of the order of 10^{50}–10^{53} erg, accounting for both long and short gamma ray bursts.

1. INTRODUCTION

The relevant conditions for quark-gluon plasma (QGP) formation occur $10\,\mu$s after the Big-Bang. The QGP diagram shows all possible phase transitions which can take place in matter at different temperatures. The phase transition from hadronic matter to a deconfined quark matter is expected to take place at around a few times the nuclear saturation density (at zero temperature), and this could occur in the interiors of neutron stars, also identified as pulsars. The constituents of pulsars can be pure hadronic matter (hadronic stars) with or without hyperons; a mixed phase of hadrons and quarks (hybrid stars); a mixed phase of hadrons and pion or kaon condensates (also hybrid stars); and deconfined quarks (strange or quark stars) [1]. According to [2], one possibility does not exclude the others since the analysis of different astrophysical phenomena associated with compact X-ray sources show that there are stars with radii in the range of 10–12 km and also stars with smaller radii, around 6–9 km. At temperatures of the order of $\simeq$ 0–40 MeV, which are the relevant temperatures in compact stars [3], there are two possibilities for phase transitions, as can be seen from the QGP diagram. As the density increases, hadron matter first converts into QGP or into either a crystalline quark matter, or a two-flavor superconducting phase, and subsequently into a color-flavor locked superconducting phase.

In this paper we investigate the possibility that gamma-ray bursts (GRBs) might be a

doi:10.1016/j.nuclphysa.2007.03.094

result of a phase change in the interior of a neutron star. Two classes of GRBs have been identified [4]: the short and the long bursts. They are distinguished by their duration and the energies released [5]. The soft gamma ray bursts are believed to occur in star-forming galaxies at cosmological distances (red-shif of $z = 1$) and they produce X-ray and optical afterglows. They are associated with the explosion of massive stars [6]. Only recently accurate results have been obtained for two short bursts: GRB 050509B at $z = 0.225$ [7], and GRB 050709, located at $z = 0.16$ [8]. They are supposed to be caused by stellar merging into final compact binary. The total isotropic energy released in the first few hundred seconds is of the order of 10^{50} erg, which is two or three orders of magnitude smaller than seen in long GRBs.

In the present work we generalize the approach of [9] assuming that most of the released energy was due to a stellar conversion mechanism and considering the stellar conversions in which baryon number is conserved. We calculate the energy released in various possible conversions from a metastable to a stable star and check whether they can account for long or soft GRBs.

2. RESULTS, DISCUSSION AND CONCLUSIONS

Following [9], we assume that the energy released is determined by the change in the gravitational energy. In ergs it is given by $\Delta E = [M_G(MS) - M_G(SS)] \times 17.88 \times 10^{53}$, where $M_G(MS)$ is the gravitational mass of the metastable star and $M_G(SS)$ is the gravitational mass of the stable star, both given in solar masses.

In table I we present a series of hadronic, hybrid and quark stars and calculate all possible released energies in the conversion mechanism. The models used for the hadron matter are the non-linear Walecka model (NLWM) and the quark-meson coupling model (QMC) with the parametrizations discussed in [1]. For the quark matter we have used the MIT bag model, the bag model with paired quarks to which we refer as the CFL phase model and the Nambu-Jona- Lasinio (NJL) model. Only bare quark stars are considered in this paper. The value of the bag parameter is given beside the quark model, for instance, MIT 160 stands for the MIT bag model with a bag parameter $Bag^{1/4} = 160\,\text{MeV}$. (p,n) means that only protons and neutrons are considered in the EOS and (8b) means that the eight lightest baryons are taken into account. In all calculations with the CFL phase model, the Δ parameter was taken equal to 100 MeV.

If the metastable star is hadronic and the stable star is a quark star, the results depend a lot on the models chosen for each kind of star, but they are generally of the order of 10^{53} erg. However, for quark matter described within the NJL model, Δ is negative, and hence conversion is not possible. This is probably due to the large constituent quark masses which only approach the current quark masses at high densities and generate a lower binding energy than in the hadronic star. Within NJL the quark matter is only more stable than the hadronic matter at quite high densities. When a hadronic star composed only of protons and neutrons in the NLWM converts to a quark star, the energy released is always larger than in the conversion of a hadronic star with all eight lightest baryons. If the star is described by the QMC model, stars with proton and neutrons only and stars with eight baryons yield very similar results. The influence of the delta meson in this calculation is negligible since results with the NLWMδ and NLWM are practically

Table 1
Metastable, stable stars and released energy

model(MS)	model(SS)	ΔE (10^{53} erg)
hadronic/NLWMδ(p,n)	quark/MIT 160	1.91
hadronic/NLWMδ(8b)	quark/MIT 160	0.94
hadronic/NLWMδ(p,n)	quark/CFL 160	3.73
hadronic/NLWMδ(8b)	quark/CFL 160	2.84
hadronic/NLWM(8b)	quark/MIT 160	0.95
hadronic/NLWM(8b)	quark/MIT 160	1.34
hadronic/NLWM(8b)	quark/CFL 160	2.84
hadronic/NLWM(8b)	quark/CFL 160	3.95
hadronic/NLWMδ(p,n)	quark/NJL	< 0
hadronic/NLWMδ(8b)	quark/NJL	< 0
hadronic/QMC(p,n)	quark/MIT 160	1.15
hadronic/QMC(8b)	quark/MIT 160	1.20
hadronic/QMC(p,n)	quark/CFL 160	2.97
hadronic/QMC(8b)	quark/CFL 160	3.01
hadronic/QMC(p,n)	hybrid/QMC+kaons	0.088
hadronic/QMC(8b)	hybrid/QMC+kaons	0.0
hadronic/NLWMδ(8b)	hybrid/NLWMδ(8b)+MIT 180	0.071
hadronic/NLWM(8b)	hybrid/NLWM(8b)+MIT 170	0.42
hadronic/NLWM(8b)	hybrid/NLWM(8b)+MIT 160	0.58
hadronic/NLWM(8b)	hybrid/NLWM(8b)+CFL 200	0.008
hadronic/NLWM(8b)	hybrid/NLWM(8b)+NJL	0.027
hybrid/NLWMδ(8b)+MIT 180	quark/MIT 160	0.92
hybrid/NLWMδ(8b)+MIT 180	quark/CFL 160	2.75
hybrid/NLWM(8b) +MIT 170	quark/MIT 170	< 0
hybrid/NLWM(8b) +MIT 160	quark/MIT 160	0.46
hybrid/QMC(8b)+CFL 200	quark/CFL 160	2.89
hybrid/QMC(8b)+CFL 200	quark/CFL 160	3.31
hybrid/NLWM(8b)+NJL	quark/NJL	< 0
hybrid/NLWM(8b)+CFL 200	quark/CFL160	2.90
quark/MIT 160	quark/CFL 160	1.82

identical within the precision of our calculations.

When conversions from hadronic to hybrid stars are analysed, we have found much lower released energies, of the order of 10^{50} to 10^{52} erg. A conversion from a hadronic to a hybrid star with kaons is possible, but the released energy is only measurable for the case without hyperons. The choice of the parameters affects the size of the core of quarks in a hybrid star. In particular, the smaller the bag parameter, the larger the energy which is released in the conversion of hadronic to hybrid stars.

In conversions from a hybrid star to a quark star, the released energy depends on the quark matter. When the star is described by matter in the CFL phase, the released energy is two to three times larger than if a conversion takes place to a star with unpaired quarks.

Finally, the conversion from a quark star with unpaired quarks to another one with a paired phase seems also to be possible, as a phase transition from a QGP to a color superconducting phase is possible in a QCD phase diagram.

Based on the results shown, it is possible to say that this kind of conversion mechanism from a metastable to a stable star releases energies of the order of 10^{50}–10^{53} erg, accounting for GRBs in general.

According to [7,8], the origin of short GRBs is certainly different from the origin of long GRBs. Notice, however, that the conclusions drawn in [8] are based on a small number of bursts and associated galaxy redshift measurements. Bursts coming from a source with a larger redshift would have a correspondingly larger intrinsic energy.

ACKNOWLEDGEMENTS

This work was partially supported by CNPq (Brazil), CAPES (Brazil), GRICES (Portugal) under project 100/03 and FEDER/FCT (Portugal) under the projects POCI/FP/63918/2005 and POCI/FP/63419/2005.

REFERENCES

1. D.P. Menezes, D.B. Melrose, C. Providência and K. Wu, Phys. Rev. C 73 (2006) 025806 and references therein.
2. I. Bombaci, I. Parenti and I. Vidaña, Astrophys. J. 614 (2004) 314.
3. D.P. Menezes and C. Providência, Phys. Rev.C 69 (2004) 045801.
4. Y. Qin *et al.*, Publ. Astr. Soc. Japan 52 (2000) 759.
5. T. Piran, Rev. Mod. Phys. 76 (2004) 1143.
6. E. Costa *et al.*, Nature 387 (1997) 783; J. van Paradijs *et al.*, Nature 386 (1997) 686; M.T. Metzger *et al.*, Nature 387 (1997) 878; F. Castander and D.Q Lamb, Astrophys. J. 523 (1999) 593; S.E. Woosley, Astrophys. J. 405 (1993) 273; C. Stanek *et al.*, Astrophys. J. 591 (2003) L17.
7. N. Gehrels *et al.*, Nature 437 (2005) 851.
8. D.B. Fox *et al.*, Nature 437 (2005) 845; J.S. Villasenor *et al.*, Nature 437 (2005) 855; J. Hjorth *et al.*; Nature 437 (2005) 859.
9. I. Bombaci and B. Datta, Ap. J. Lett. 530 (2000) L69.