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What do the rapidly rotating pulsars signal?

Xiao-Ping Zheng ⋆, Na-Na Pan, Shu-Hua Yang and Miao Kang

The Institute of Astrophysics, Huazhong Normal University, Wuhan 430079, China

Abstract The rapidly spinning pulsars could be regarded as the consequence of a competition between gravitational wave emission and viscous dissipation. All cases, neutron stars, strange stars and hybrid stars, are discussed here. Viscosity due to strangeness-changing weak interactions in dense nuclear matter fixes the fastest spinning frequency. This only implies the existence of strangeness in the interior of the stars, and does not distinguish among hyperon matter, strange quark matter or a mixture of the two. We conclude that the cluster of rapidly spinning pulsars, containing two fastest millisecond pulsars and low-mass X-ray binaries, is possibly signalling strangeness.

Key words: dense matter — stars: neutron — stars: rotation — gravitation

1 INTRODUCTION

Since the idea of neutron stars was proposed, many investigators have been fascinated with constructing their models. The discovery of pulsars leads to a general acceptance that pulsars are rotating neutron stars. It is, however, very difficult to recognize the composition of nuclear matter in the interior of neutron stars (NSs) due to theoretical uncertainties in nuclear physics which lead to uncertainties in our understanding of observed pulsar data.

The discovery by Andersson, Friedman and Morsink of r-mode instabilities in rotating compact stars put rather severe limits on the highest rotation frequency of pulsars (Andersson 1998; Friedman and Morsink 1998). A pioneer investigation suggested that the millisecond pulsars data may signal the existence of strange stars (SSs) (Madsen 2000), made up of roughly equal numbers of up, down and strange quarks. The reason is that non-leptonic quark-process can produce very large bulk viscosity (Madsen 1992; Sawyer 1989). Actually, NSs may be constituted by a large variety of particles rather than just neutrons and protons. One possibility is that hyperons form at the center of the star, but we seem unable to settle this matter very simply. In this case, non-leptonic reactions for hadrons can be triggered and the bulk viscosity for hyperon matter is also considerable large relative to semi-leptonic weak reactions.

In the present paper, we are interested in probing the constituents inside compact stars by r-mode instability, in other words, in uncovering the implications of rapidly spinning pulsars. We will discuss the bulk viscosity in strange matter including strange hadron matter, strange quark matter and their mixed phase. We will also make a thorough investigation on stabilities of SSs, hyperon stars (HpSs) and hybrid stars (HbSs) in order to determine the critical rotation.

2 EQUATION OF STATE

We consider two kinds of compact stars: in one, the hyperons form at the center of the star, in the other, deconfinement transition occurs at places of high density in the star interior. We construct the equation of state of matter by modelling the hadronic phase by a relativistic mean field that includes the hyperons and quark phase by the MIT-bag model. We describe the composition of the mixed hadron-quark phase (MP) assuming a first-order phase transition. The relative concentrations of the various species are determined at

⋆ E-mail: zhxp@phy.ccnu.edu.cn

each density by imposing charge neutrality and β-equilibrium. At the high density of interest to us, these constraints are, for the first scenario,

$$\begin{aligned} n_p &= n_e + n_\mu + n_{\Sigma^-}, \\ \mu_p &= \mu_n - \mu_e, \\ \mu_\mu &= \mu_e, \\ \mu_{\Sigma^-} &= \mu_n + \mu_e, \\ \mu_\Lambda &= \mu_n \ , \end{aligned} \tag{1}$$

and for the second scenario,

$$\begin{aligned} n_p \ + \ & \frac{2}{3} n_u = \frac{1}{3} n_d + \frac{1}{3} n_s + n_e, \\ \mu_s \ &= \ \mu_d, \\ \mu_u \ &= \ \mu_d - \mu_e, \\ \mu_n \ &= \ \mu_u + 2\mu_d, \\ \mu_p \ &= \ \mu_u + \mu_d \ . \end{aligned} \tag{2}$$

Figure 1 shows the equilibrium composition in a hyperon star (HpS) (upper panel) and in a hybrid star (HbS) (lower panel). Both contain a significant number of hyperons or strange quarks in the highest density portions of their cores.

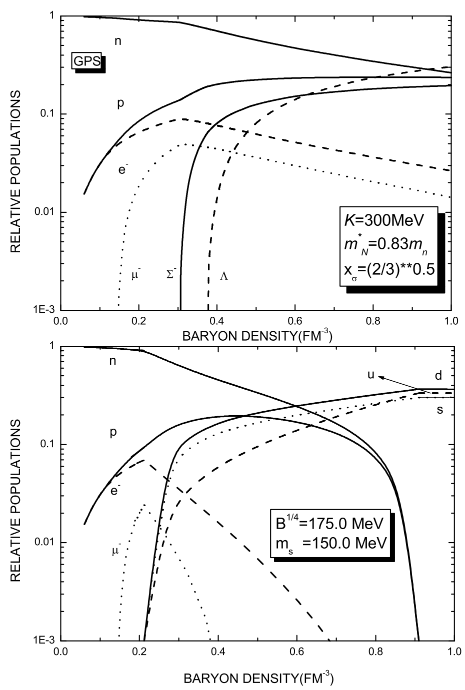

Fig. 1 Particle fractions as function of the total baryon density.

3 BULK VISCOSITY

Bulk viscosity is the dissipative process in which macroscopic compression-expansion of fluid element is converted to heat. The dissipation is due to microscopic reactions coming from the weak interaction in the compact-star matter. In general, there are two types of reactions, semi-leptonic and non-leptonic. The non-leptonic reaction is dominant when triggered. It is

$$d + u \longleftrightarrow u + s, \tag{3}$$

for strange quark matter. We should be interested in the following reactions for hyperon matter (Jones 2001),

$$n + n \longleftrightarrow p + \Sigma^-, \tag{4}$$

$$n + N \longleftrightarrow N + \Lambda, \tag{5}$$

where N denotes nucleons. Here we will treat the second process as the dominant channel for hyperons, which provide an upper limit on the bulk viscosity (Lindblom and Owen 2002). The bulk viscosity coefficient can be derived from kinetic theory in terms of the relaxation times of the microscopic processes. We adopt the formalism given by Lindblom and Owen (2002).

$$\zeta = \frac{p(\gamma_\infty - \gamma_0)\tau}{1 - i\omega\tau}, \tag{6}$$

with relaxation time $\frac{1}{\tau} = \frac{\Gamma_n}{\delta\mu}\frac{\delta\mu}{n_{\rm B}\delta x_n}$, where p is pressure of the fluid element, γ_∞, γ_0 are the "infinite" and the "zero" frequency adiabatic indices, Γ_n is the production rate of neutrons per unit volume, $\delta\mu$ is the overall chemical potential imbalance, $n_{\rm B}$ is baryon number density and x_n is the fraction of baryons that are neutrons in the given fluid element. In a mixed nucleon-hyperon and hadron-quark matter, we consider the relaxation times of the relevant reactions (3), (4) and (5); these are, for Λ hyperon non-leptonic process,

$$\frac{1}{\tau} = \frac{\Gamma_\Lambda}{\delta\mu}\frac{\delta\mu}{n_{\rm B}\delta x_n}, \tag{7}$$

for Σ^- hyperon non-leptonic process,

$$\frac{1}{\tau} = \frac{2\Gamma_\Sigma}{\delta\mu}\frac{\delta\mu}{n_{\rm B}\delta x_n}, \tag{8}$$

and for quark non-leptonic process,

$$\frac{1}{\tau} = \frac{\Gamma_{d\leftrightarrow s}}{2\delta\mu}\frac{\delta\mu}{n_{\rm B}\delta x_n}\,. \tag{9}$$

Here$\Gamma_\Lambda, \Gamma_\Sigma$ and $\Gamma_{d\leftrightarrow s}$ denote the rates of the weak reactions. By standard evaluation, we have the following formalism for the bulk viscosity,

$$\zeta_s = \frac{\alpha T^2}{\omega + \beta T^4}\,. \tag{10}$$

For all types of strange matter (strange quark matter, nucleon-quark matter, nucleon-hyperon matter and nucleon-hyperon-quark matter) reasonable parameter values are, $\alpha \sim 10^{20} - 10^{22} n_{\rm B}$ g cm^{-1} s^{-1} K^{-2} and $\beta \sim 10^{-29} - 10^{-27}$ s^{-2} K^{-4}, with $n_{\rm B}$ in units of fm^{-3}. For comparison, the npe Urca bulk viscosity calculated by Ipser and Lindblom (1991) is

$$\zeta_U = 1.6 \times 10^{-28}\frac{n_{\rm B}T^6}{\omega^2}. \tag{11}$$

We immediately find that there is quantitative and qualitative difference between ζ_s and ζ_U as functions of temperature: ζ_U decreases monotonically when the temperature falls at the birth of the compact star after the supernova explosion, while ζ_s initially increases, reaching a maximum at temperature about $10^9 \sim 10^8$ K, then decreases. Clearly, the essential distinction between the two kinds of process is whether or not strangeness quantum number changes before and after the process.

4 THE R-MODE INSTABILITY WINDOWS AND CRITICAL ROTATION OF COMPACT STARS

We can now address the problem of limiting rotation in compact stars. The limiting rotation arises out of viscous dissipation and r-mode increase due to gravitational wave emission. Competition between these two factors determines the stability status, ie, the r-mode instability window. Here we take a stellar mass $M = 1.4M_\odot$ and consider the two cases, HpS and HbS. The stellar structure can be solved by the Tolman-Oppenheimer-Volkov equation with the above relevant equation of state imposed. The stars are considered to have a solid BPS crust. Therefore, according to the standard formalism, the critical rotation is obtained by solving the equation

$$-\frac{1}{\tau_{\rm GR}}+\frac{1}{\tau_s}+\frac{1}{\tau_U}+\frac{1}{\tau_{\rm R}}=0\,. \qquad (12)$$

where $\tau_{\rm GR}$ is the time scale for gravitational wave emission and $\tau_{\rm R}$ is that for the rubbing between the solid crust and fluid core (Bildsten and Ushomirshy 2000; Andersson et al. 2000) that dominates the shear viscosity of fluid. The numerical results are shown in Figure 2. As comparison, we also plot the r-mode instability windows of neutron stars and strange stars (Madsen 2000).

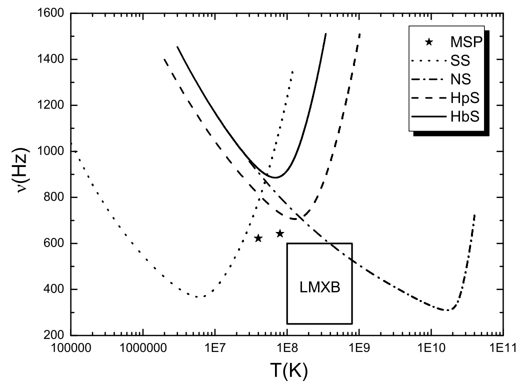

Fig. 2 The r-mode instability windows of compact stars.

It is surprising that there is evidence that the data of rapid pulsars seem to support the existence of strange stars (Madsen 1998, 2000; Zheng et al. 2003, 2005), in place of neutron stars. It looks as though we may have underestimated the complexity of the problem, considering the variety of all the works. We find that rapidly rotating pulsars indeed indicate the existence of strange matter in the interior of compact stars, without being able to distinguish strange quark matter from hyperon matter. We conclude the millisecond pulsars may be a signal of strange matter stars because of the response to strangeness-changing weak-interactions. Further work is necessary to distinguish quark stars from hyperon stars.

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