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Chinese Astronomy and Astrophysics 40 (2016) 220–227

CHINESE
ASTRONOMY
AND ASTROPHYSICS

R-mode Instability of Low-mass Bare Strange Stars† ⋆

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Abstract The r-mode instability window of low-mass strange stars is studied using the modified bag model of strange quark matter and reasonable sets of parameters. The results show that the ultimate spin frequency of strange stars increases with the decreasing stellar mass, and the highest spin frequency (716 Hz) of pulsars observed sofar can be explained by the bare strange stars with a mass lower than about 0.1∼0.2 $M_{\odot}$, depending on the selected parameters.

Key words stars: neutron—stars: oscillations—stars: rotation—stars: low-mass—stars: interiors

1. INTRODUCTION

Since it was proposed in 1998, the r-mode instability (one of the gravitational instabilities) that possibly exists in the evolutionary process of compact stars has been widely studied[1,2]. There are two aspects for the important significance of the study on the r-mode instability of compact starts: on the one hand, the periods of pulsars may be explained by the ultimate rotation limited by the r-mode instability[3−6]; on the other hand, the gravitational radiation when the r-mode instability occurred in compact stars is possibly observed by the new-generation of gravitational wave detectors[7]. In addition, when the r-mode instability occurs in compact stars, the viscous dissipation heating in the stellar interior may play an important role for the thermal evolution of stars. For instance, the cooling process of a star after the dissipative heating of r-mode instability is finished can well explain the fast cooling phenomenon of the neutron star observed in the Cas A supernova remnant[8,9].

† Supported by National Natural Science Foundation (11447012, 11203010)

Received 2015–01–12; revised version 2015–01–21

⋆ A translation of *Acta Astron. Sinica* Vol. 56, No. 4, pp. 335–341, 2015

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doi:10.1016/j.chinastron.2016.05.008

According to the Witten's assumption about the strange quark matter[10], compact stars may be the strange stars composed of three-flavor quark matter of u, d, and s, rather than the neutron stars composed of neutron matter. There were many studies on the r-mode instability of strange stars, and by comparing with the observations of pulsars, they tried to distinguish strange stars from neutron stars[3,11−16].

However, the previous studies relevant to the r-mode instability commonly refer to the strange stars of about $1.4M_{\odot}$, this paper plans to study the r-mode instability of low-mass bare strange stars. It is necessary to point out that the r-mode instability of low-mass bare strange stars was studied briefly in Reference [17], in which the conclusions similar to this paper were obtained by qualitative analysis, i.e., the smaller the stellar mass, the lower the emissivity of gravitational waves, and greater the ultimate rotation frequency limited by the r-mode instability. But in this paper, besides carefully calculating the relevant timescales of r-mode instability mechanism, the parameters in the equation of state of strange quark matter are also restricted by using the observed pulsars with a maximum mass, namely PSR J1614-2230 ($M = (1.97 \pm 0.04)M_{\odot}$)[18] and PSR J0348+0432 ($M = (2.01 \pm 0.04)M_{\odot}$)[19], and the observed highest spin frequency (716 Hz)[20] of pulsars can be explained by the r-mode instability window of low-mass bare strange stars.

Up to now, there have been already some astronomical observations to support the existence of low-mass strange stars[17,21−23], but it has not yet been finally confirmed. Furthermore, for the problem of origin, it is difficult to form the low-mass strange stars by the supernova explosion of massive stars, but some studies suggested that they may form by the accretion and collapse of white dwarfs[17,24].

This paper is limited to study the bare strange stars, it is more complicated to study the strange stars with shells, which will be done in our subsequent work. In addition, the quark cluster stars are not mentioned in our work[25,26], because the interior matter in the quark cluster stars is rigid, and the r-mode instability can not happen to them.

2. EQUATION OF STATE OF STRANGE QUARK MATTER AND STRANGE STARS

For the strange quark matter, we accept the phenomenologically modified bag model[27−29]. In this model, the coupling coefficient α_s is introduced to consider the first-order perturbation correction of strong interaction, the u and d quarks are the zero-mass particles, and the mass of s-quark is taken as a free parameter. The grand thermodynamic potentials of the u, d, and s quarks and electron are respectively written as:

$$\Omega_{\rm u} = -\frac{\mu_{\rm u}^4}{4\pi^2}(1 - \frac{2\alpha_{\rm S}}{\pi})\,, \tag{1}$$

$$\Omega_{\rm d} = -\frac{\mu_{\rm d}^4}{4\pi^2}(1 - \frac{2\alpha_{\rm S}}{\pi})\,, \tag{2}$$