

Interior matter estimates of rapidly rotating compact stars

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1 Introduction

The components and properties of interiors in neutron stars have attracted much attention since the discovery of the first pulsar and then the confirmation of it to be a fast rotational neutron star. However, the composition of matter for neutron star at super-nuclear density is still an indeterminacy due to the uncertain nuclear physics. This is also the main central question for the astronomy and astrophysics decadal survey in the future [1]. Since the observational phenomena of pulsars and compact radioactive source with high energy are often related to the nuclear processes and the composition of dense matter in compact stars, it offers us an effective method to probe the signal of matter composition at super-nuclear density. On one hand, the equation of state (EOS) and dynamic properties would affect the structure and evolution behavior of compact stars, on the other hand, we may estimate the correlative information of nuclear matter according to the observational macroscopic compact star properties such as the structure and evolution behavior. Hence, many investigators spontaneously expect to probe the super-dense matter through astrophysical observations [2]. However, up to now, constraints of inferred masses and radii for pulsars on equations of state cannot uniquely examine and distinguish the compositions inside neutron stars. Along with the abundance of data about spin frequency for fast rotating pulsars, researchers begin to pay much attention to confirming limit spin of pulsars, which is another way to probe into the interior of compact stars.

2 Method and Result

For a uniform rigid compact star with mass M and radius R , there exist some limits on the attainable rotation frequency. The most obvious one is the Keplerian limit [3]

$$\nu_K = 1.042 \times 10^3 \times \frac{(M/M_\odot)^{1/2}}{(R/10km)^{3/2}} \text{Hz}, \quad (1)$$

Which is also called the mass-shedding limit. It is roughly independent of the equation of state. If we get the frequency of observed pulsar and assume it to be the Keplerian limit, we can obtain a critical mass-radius relation in the mass-radius plane to constrain various equations of state for compact stars. This is the universal treatments as rotation limit by many investigators which seems to have no help in distinguishing the composition of super-nuclear matter.

Actually, the emission of gravitational radiation following the excitation of non-radial oscillation modes may lead to the instability of rotating stars [4], which can be obtained via

$$\frac{1}{\tau_G} + \frac{1}{\tau_\nu} = 0. \quad (2)$$

Here τ_ν is the damping timescales due to shear, bulk viscosities and other rubblings, which relates to the viscosities of the matter inside neutron stars and their differences could result in diverse behaviors. Based on many works that a star may spend much more time at the lowest point of r-mode instability window, we can assume it to be another critical limit on the attainable rotation frequency. So the genuine limit rotation of compact stars should actually be decided by both Keplerian and r-mode constraints. Since we have synthesized both the equations of state, dynamic properties of matter, this could exert significantly more stringent constraints to estimate the matter composition of compact stars.

We have used our method shown in Fig 1 [5] to discuss two rapidly rotating compact stars. One is SAX J1808.4-3658 with millisecond rotation period, and the other is XTE J1739-285 with possible sub-millisecond. In the left panel of Fig 2, the light cyan district refers to our predicted compatible models that could satisfy the genuine rotation constraint together with the mass prediction analyzed by Leahy et al. [6] at 99.7% confidence lever. We find that the ordinary neutron star should be excluded. While hyperon star, hybrid star and strange star are supposed to be the best candidates for the millisecond pulsar in SAX J1808.4-3658. Therefore, the star could contain exotic matter either hyperon or strange quark matter at super-nuclear region, but we could not tell them from each other, which must depend on more observational information such as the thermal emission data. However, in the right panel of Fig 2, we find that only some parts of hybrid star sequences could spin above 1122Hz. Therefore, we could conclude that 1122Hz rotation is an obvious evidence for the existence of quark matter inside the neutron star of XTE J1739-285, or this

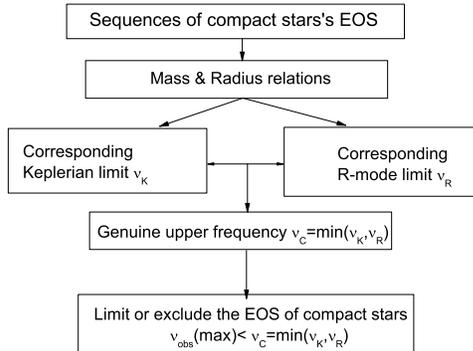


Figure 1: Schematic diagram of thought about our treatment.

possible sub-millisecond pulsar is a hybrid star. Meanwhile, compared with situation under SAX J1808.4-3658, the compatible district here is so small that it probably means that the possibility for the existence of compact stars with sub-millisecond period is small.

3 Conclusions

The composition of matter in the core of neutron stars has attracted much attention owing to its important significance. In our estimation, we try to probe the inner components of rapidly rotating compact stars such as the millisecond pulsar SAX J1808.4-3658 and the possible sub-millisecond pulsar XTE J1739-285 in our own way by comparing the genuine rotation frequencies under different theoretical models with the observational data, which may exert more stringent constraint on matter composition of compact stars. According to our treatment, the SAX J1808.4-3658 is a star with exotic matter and XTE J1739-285 a hybrid star.

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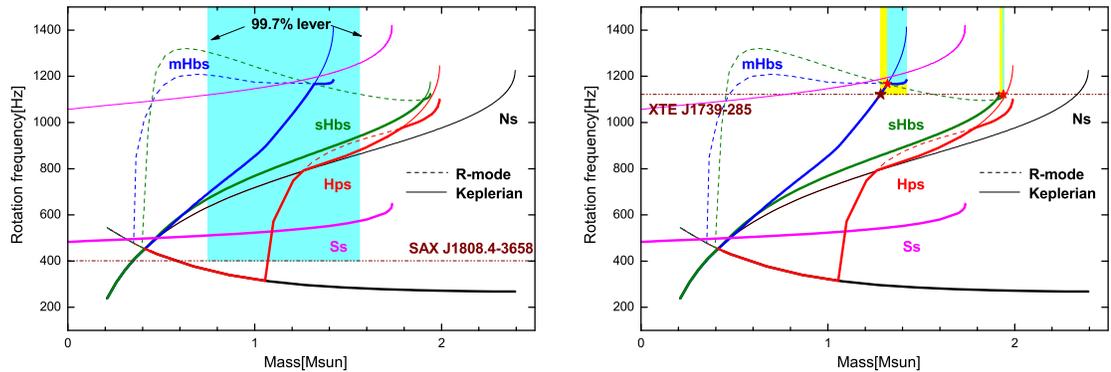


Figure 2: Limit rotation frequencies for various compact stars. Ns, Ss, Hps, mHbs and sHbs represent the normal neutron, strange, hyperon, hybrid star with mixed phase or not respectively. These corresponding thick solid lines are genuine upper frequencies. In the left panel, the wine dash-dot-dot horizontal line represents the 401Hz rotation frequency of the millisecond pulsar in the transient X-ray burster SAX J1808.4-3658 discovered by Wijnands and van der Klis [7]; while in the right panel, it represents the 1122 Hz of burst oscillation in the X-ray transient XTE J1739-285 that is interpreted as due to the rotation of the central neutron star by Kaaret et al. [8] .

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