Constraint on the equation of state from the quasi-periodic oscillations in ginat flare

Hajime Sotani[1,*], Kei Iida[2], and Kazuhiro Oyamatsu[3]

[1] *National Astronomical Observatory of Japan, 2-21-1 Osawa, Mitaka, Tokyo 181-8588, Japan*
[2] *Kochi University, 2-5-1 Akebono-cho, Kochi 780-8520, Japan*
[3] *Aichi Shukutoku University, 2-9 Katahira, Nagakute, Aichi 480-1197, Japan*
[*] *E-mail: sotani@yukawa.kyoto-u.ac.jp*

We examine crustal torsional oscillations, newly taking into account the effect of the pasta structure. We find from eigenmode analyses for various models of the equation of state of uniform nuclear matter that the fundamental frequencies of such oscillations are almost independent of the incompressibility of symmetric nuclear matter K_0, but strongly depend on the slope parameter of the nuclear symmetry energy L. On the other hand, we also find that the frequencies of the 1st overtones depend strongly on not only L but also K_0. By comparing the resultant frequencies to the quasi-periodic oscillations observed in the giant flares, we can constrain the values of L and K_0. Furthermore, considering the constraints on K_0 obtained from the terrestrial nuclear experiments, we can successfully make a more severe constant on L.

Keywords: equation of state, neutron star crust, shear oscillations

1. Introduction

Neutron stars would be produced via supernova explosions at the last moment of massive stars. The density inside the star significantly exceed the normal nuclear density, the magnetic field inside/around the star can become very strong, and the gravitational field is also so strong. The neutron stars, thus, are good candidate to probe physics under such extreme conditions. In order to extract the interior information of stars, the asteroseismology is very powerful technique. In practice, it would be possible to probe the stellar mass, radius, equation of state (EOS) of dense matter, and theory of gravity in the strong-field regime via future observations of gravitational waves[1–3].

The possible oscillations of neutron stars are observed as quasi-periodic oscillations (QPOs) in the giant flares from the soft-gamma repeaters[4]. In order to theoretically explain these observed QPOs, several studies have been done in terms of crustal torsional oscillations[5–9] or magnetic oscillations[10,11]. The magnetic oscillations strongly depend on uncertain magnetic field structure, field strength inside the star, and uncertain EOS in core region if magnetic fields penetrate the core. On the other hand, the crustal torsional oscillations are confined into the crust region because the shear modulus inside the core should be zero. With such reasons, we focus on the crustal torsional oscillations in the present study by especially taking into account the effect of presence of cylindrical nuclei as well as the phase of spherical nuclei. Then, comparing the observed QPO frequencies to the frequencies of crustal torsional oscillations, we can constrain the nuclear saturation parameters, which are important parameters for describing the neutron star crust. More details of this study can be seen in Ref. 9.

2. Crust in equilibrium

To avoid the uncertainties in the EOS of core region, we construct the crust in equilibrium by integrating Tolman-Oppenheimer-Volkoff equations from the stellar surface inward to the bottom of the curst, assuming the stellar mass M and radius R. The bulk energy per baryon of uniform nuclear matter at zero temperature for any EOS can be expanded as a function of baryon number density and neutron excess with five expansion parameters, i.e., the saturation density n_0, the saturation energy, incompressibility K_0 of symmetric nuclear matter, symmetry energy at n_0, and the slope parameter L. Among five parameters, K_0 and L are more difficult to be constrained by terrestrial nuclear experiments, because such parameters are higher order coefficients with respect to the change in density from n_0. In the present study, we adopt the phenomenological EOS, where K_0 and L are considered as free parameters and the other parameters are determined in such a way as to reproduce the empirical nuclear data[12,13]. The shear modulus is another important property describing the shear oscillations. Here, we adopt the standard shear modulus in the phase of spherical nuclei[14] together with that in the phase of cylindrical nuclei[15], where we also adopt the results by Ref. 16 as the effect of neutron superfluidity inside the phase of spherical nuclei, while the effect of it inside the phase of cylindrical nuclei is considered by introducing a parameter of N_s/N_d with the superfluid neutron density N_s and the dripped neutron density N_d. At last, to construct the crust in equilibrium, one has to choose M, R, K_0, L, and N_s/N_d in the phase of cylindrical nuclei.

3. Torsional oscillations and comparison to the observations

In the left panel of Fig. 1, the calculated frequencies of fundamental torsional oscillations with various values of ℓ are shown as a function of L together with the QPO frequencies observed in SGR 1806–20 for the neutron star model with

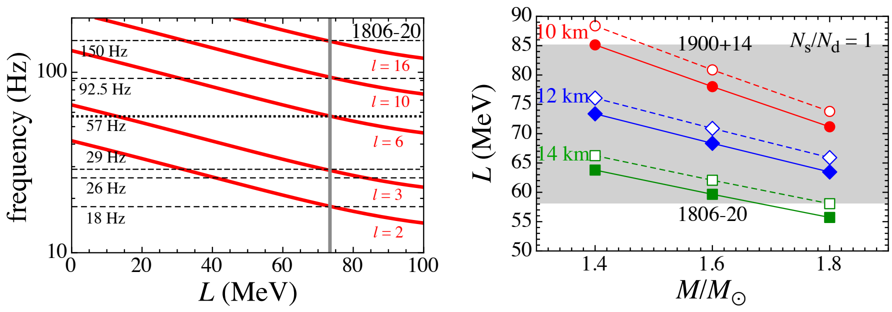

Fig. 1. Comparison of the low-laying QPOs observed in SGR 1806–20 with the fundamental frequencies of crustal torsional oscillations with various values of ℓ in the left panel[9]. For various stellar models, the optimal value of L obtained by the comparison of QPOs in SGR 1806–20 and in 1900+14 with the fundamental torsional oscillations in the right panel[9].

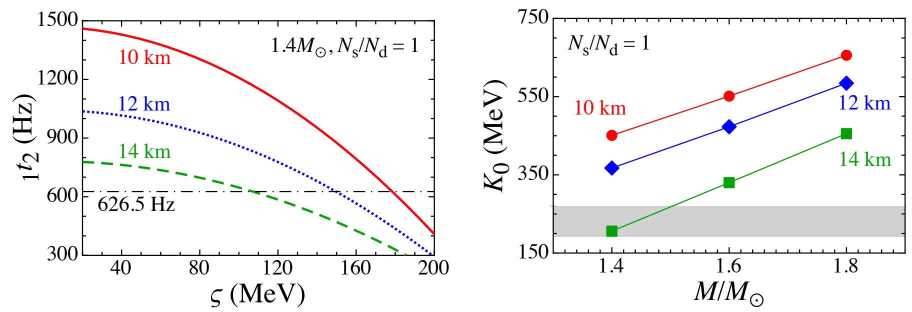

Fig. 2. The frequencies of 1st overtones for the $1.4M_\odot$ neutron star models with different stellar radii in the case of $N_s/N_d = 1$ in the phase of cylindrical nuclei are compared with the 626.5 Hz QPO in SGR 1806 (left panel), while the value of K_0 constrained by the combination of constraints on L from the fundamental torsional oscillations and those on ς from the 1st overtones for the various stellar models (right panel)[9].

$M = 1.4M_\odot$ and $R = 12$ km. From this figure, one can see that the QPO frequencies except for the 26 Hz can be identified by the crustal torsional oscillations with $L \simeq 73.4$ MeV. We remark that the 26 Hz QPO may be identified by the torsional oscillations confined in the phase of bubble structure[8]. In a similar way, the optima value of L for identifying the observed QPOs with the fundamental crustal torsional oscillations is shown in the right panel of Fig. 1 for various stellar models, where the filled and open marks denote the results for identifying the QPOs observed in SGR 1806–20 and 1900+14, respectively, and the painted region is allowed region of L.

On the other hand, the frequencies of overtones depend on the crust thickness, which depends on L and K_0[17]. As a result the frequencies of overtones depend on L and K_0. We successfully find that the frequencies of the 1st overtones can be expressed well with a combination of L and K_0[9] as

$$\varsigma \equiv \left(K_0^4 L^5\right)^{1/9}. \tag{1}$$

In the left panel of Fig. 2, we show the 1st overtone frequencies for the $1.4M_\odot$ stellar model with different radius as a function of ς. By identifying the QPO frequencies observed in SGR 1806–20 with the 1st overtones, one can determine the optimal value of ς, with which one can determined the value of K_0 by combining the results obtained from the identification of the QPO frequencies with the fundamental oscillations as shown in Fig. 1. Such a value of K_0 is shown in the right panel of Fig. 2, where the value of K_0 constrained from terrestrial nuclear experiments also denote by the painted region[18]. By considering the both constraints from the observations of QPOs and terrestrial nuclear experiments, the preferable stellar model as SGR 1806–20 is relatively low mass and larger radius neutron star, such as $M = 1.3 - 1.4M_\odot$ with $R = 13$ km or $M = 1.4 - 1.5M_\odot$ with $R = 14$ km. With this constraint on the stellar model for SGR 1806–20, we further constrain the value of L from the right panel of Fig. 1, i.e., $L \simeq 58 - 71$ MeV, which is consistent with the terrestrial nuclear experiments[19].

4. Conclusion

In this study, we successfully constrain the value of L and K_0 by identifying the low-laying QPOs and higher QPO observed in giant flares with the fundamental oscillations and 1st overtones of crustal torsional oscillations. The constraint on K_0 obtained from terrestrial nuclear experiments makes a constraint on the stellar model and further constraint on L.

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