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Electron screening effects on crustal torsional oscillations

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ABSTRACT

We systematically examine the crustal torsional oscillations as varying the stellar mass and radius, where we take into account the effect of electron screening due to the inhomogeneity of electron distribution. In the examinations, we adopt two different equations of state (EOSs) for the inner crust region of neutron stars. As a result, we find that the frequencies depend obviously on the EOS, even if the neutron star models are almost independent of the EOS. That is, one could solve the degeneracy of the stellar models with different EOS via the observations of shear oscillations frequencies. Additionally, we find that the fundamental frequencies of the ℓ-th order torsional oscillations can reduce 6% due to the effect of electron screening, which is independent of the adopted EOS and stellar models. This reduction of frequencies can be crucial to make constraints on the density dependence of the nuclear symmetry energy, L, i.e., the constraint on L can reduce ∼15% by the electron screening effect.

1. Introduction

The structure of neutron stars is still not fixed exactly due to the uncertainty of the equation of state (EOS) for neutron star matter. This is because the density inside the neutron star can reach up to $\sim 10^{15}$ g/cm^3 and the examinations of such properties are quite difficult on the Earth. So, neutron stars may be considered as a suitable laboratory to examine the physics in high density region. In practice, it is suggested that the interior properties of neutron stars can be understood through the observations of oscillations and/or the emitted gravitational waves [1–7]. This is a unique technique known as (gravitational wave) asteroseismology, which is similar to helioseismology for the Sun. Although we still have no direct observations of gravitational waves, we have observational evidences of neutron star oscillations. That is quasi-periodic oscillations (QPOs) in the giant flares from the soft-gamma repeaters (SGRs). SGR is considered as one of the promising candidates of magnetar, which is a neutron star with the magnetic fields stronger than $\sim 10^{14}$ gauss [8]. The extremely strong flare phenomena rarely happen from the SGRs, which are called as the giant flares and different from the usual flare activities. Three giant flares have been detected so far and the QPOs are found in the afterglow of such flare activities. The frequencies of the QPOs in giant flares are in the range from tens of hertz up to a few kilo-hertz [9].

The discovery of the QPOs in giant flares triggers many theoretical attempts to explain such observations in terms of shear oscillations in the neutron star crust and/or magnetic oscillations (e.g., [10–18]). Through these attempts, it is found that either the crustal torsional oscillations or magnetic oscillations dominate the excited oscillations near the stellar surface, depending on the strength of stellar magnetic fields [19–22]. The magnetic field strength of the SGRs the giant flares arose, may not be so large that the magnetic oscillations become the dominating oscillations, considering the observations of spindown of central objects in the SGRs [23,24]. Then, assuming that the observed QPO frequencies would come from the crustal torsional oscillations, one can obtain the information about the neutron star matter in the crust region [25–30]. Furthermore, one might see the properties about the density region higher than the standard nuclear density through the torsional oscillations [31].

To calculate the torsional oscillations, one needs to prepare the shear modulus describing the properties of elasticity, because the restoring force of such oscillations is shear stress due to the elasticity. The principal contribution in the shear modulus must come from the Coulomb energy of the lattice structure composed of nuclei in the crust region. In this context, the shear modulus for bcc lattice in the neutron star crust is derived by Ogata and Ichimaru [32]. With this formula, many calculations of torsional oscillations have been done as mentioned above. However, as the secondary contribution in the shear modulus, one should also take into account the inhomogeneous electron distribution in the crust region, i.e., effect of electron screening. In fact, such effects can reduce the shear modulus around 10% compared to that without such an effect [33,34]. In contrast to this simple estimation, the shear modulus strongly depends on the nuclear properties in realistic stellar models, such as the distributions of charge number and

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Wigner–Seitz radius, and the frequencies of crustal oscillations can be determined by solving the eigenvalue problem in the crust region with the appropriate boundary conditions at the crust basis and stellar surface. This means, it is still uncertain how the frequencies of crustal torsional oscillations depend on the effect of electron screening.

In this article, we examine the frequencies of torsional oscillations with and without the effect of electron screening, as varying the stellar models systematically. Then, we quantitatively evaluate the reduction of frequencies due to such effect, and discuss the possibility how the previous results should be modified. Probably, these are the first calculations of the frequencies of torsional oscillations in the crust region with the effect of electron screening and we will show the importance of such effect. In particular, we adopt two different EOSs for the inner crust region to see the dependence of EOS [34,35], where the difference in the adopted EOSs is whether the neutron skin is taken into account or not to produce the crust properties. Identifying the observed QPO frequencies with the crustal torsional oscillations, one may be able to get the insight about the neutron skin, which is one of the important properties describing the structure of nucleus in the crust region. We remark that, according to the macroscopic neutron-star crust models, the non-uniform nuclear structures, the so-called pasta structures, could exist between the crustal region composed of the spherical nuclei and the core region [36,37], which may play an important role in the crustal torsional oscillations [26,27], although the adopted EOSs in this article are not taken into account such properties.

This article is organized as follows. In the next section, we describe the equilibrium configuration of neutron star crust together with the adopted EOSs. In Section 3, we show the equation governing the torsional oscillations and the boundary conditions to determine the eigenfrequencies. Additionally, we also show the obtained spectra of such oscillations. Before concluding, we briefly discuss the importance on the crustal torsional oscillations due to the pasta structures in Section 4. At the end, we make a conclusion in Section 5. We adopt the geometric unit of $c = G = 1$ in this article, where c and G denote the speed of light and the gravitational constant, respectively, and the metric signature is $(-, +, +, +)$.

2. Crust equilibrium models

We can neglect the magnetic and rotational effects to construct the equilibrium stellar models, because the magnetic energy is much smaller than the gravitational binding energy and the observed magnetars rotate quite slowly. So, we consider spherically symmetric neutron stars in this article, which are given by the solution of the Tolman–Oppenheimer–Volkoff (TOV) equations. The metric of the spherically symmetric spacetime can be written as

$$ds^2 = -e^{2\Phi}\,dt^2 + e^{2\Lambda}\,dr^2 + r^2\,d\theta^2 + r^2\sin^2\theta\,d\phi^2, \qquad (1)$$

where Φ and Λ are functions of r. The function $\Lambda(r)$ is associated with the mass function $m(r)$, such as $e^{-2\Lambda} = 1 - 2m(r)/r$. In order to close the equation system, one needs to prepare the relation between the pressure p and the energy density ρ, i.e., EOS, in addition to the TOV equations. In this article, we adopt the EOS derived by Haensel and Pichon [38] for the outer crust region. For the inner crust region, we adopt two different EOSs; one is the EOS derived by Kobyakov and Pethick [34], which is based on Lattimer and Swesty's microscopic calculations [39], and the other is the EOS derived by Douchin and Haensel [35]. Both EOSs for the inner crust region are derived with the compressible liquid drop model (CLDM) based on the Skyrme-type effective nuclear interaction, but the EOS by Douchin and Haensel also takes into account the effect of thickness of neutron skin [35]. Due to the different treatment of the neutron skin, the density at the basis of crust is different from each other. Hereafter, these two EOSs for the inner crust region are referred to as KP2013 and DH2001, and the comparison of two EOSs is shown in Table 1. We remark again that the adopted EOSs, KP2013 and DH2001, do not include the pasta structures at the basis of crust region.

Table 1
Comparison between the EOSs derived by Kobyakov and Pethick (2013) and by Douchin and Haensel (2001). n_{bc} and ρ_c denote the baryon number density and energy density at the basis of crust.

	KP2013	DH2001
model	CLDM	CLDM
neutron skin	×	◯
effective interaction	SI	SLy4
n_{bc} [1/fm^3]	8.913×10^{-2}	7.596×10^{-2}
ρ_c [g/cm^3]	1.504×10^{14}	1.285×10^{14}

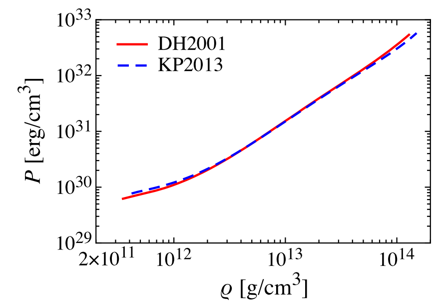

Fig. 1. EOS for the inner crust of neutron star, where the solid and broken lines correspond to the EOS derived by Douchin and Haensel (2001) and by Kobyakov and Pethick (2013), respectively.

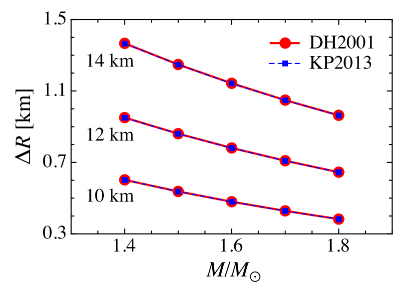

Fig. 2. Crust thickness, ΔR, with different stellar models as a function of the stellar mass, $M/M_\odot$, where the solid lines with circles correspond to the stellar models with DH2001, while the broken lines with squares correspond to those with KP2013. The labels denote the corresponding stellar radius.

Fig. 1 shows the pressure as a function of the density with two different EOSs for the inner crust region, where one can hardly observe a difference between KP2013 and DH2001. The stellar properties constructed with such EOSs are shown in Fig. 2. From this figure, one can see the degeneracy of stellar models with different EOSs, i.e., it may be impossible to distinguish the crust EOS by only using the direct observations of neutron star itself. However, one can see the difference in the microscopic properties of neutron star matter, such as the charge number, Z (left panel in Fig. 3), and in the radius of a Wigner–Seitz cell, a (right panel in Fig. 3), especially close to the basis of crust. These properties affect on the shear modulus μ, as will be shown later. Consequently, one expects the possibility to distinguish the crust EOS via the observations of the crustal torsional oscillations.

Furthermore, as mentioned before, we focus on how the effect of electron screening affects on the torsional oscillations in the crust region of neutron stars. Thus, we should remove an uncertainty coming from the other factors. In particular, to avoid