Gravitational waves from the axial perturbations of hyperon stars*

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The eigen-frequencies of the axial w-mode oscillations of hyperon stars are examined. It is shown that as the appearance of hyperons softens the equation of state of the super-density matter, the frequency of gravitational waves from the axial w-mode of hyperon star becomes smaller than that of a traditional neutron star at the same stellar mass. Moreover, the eigenfrequencies of hyperon stars also have scaling universality. It is shown that the EURO third-generation gravitational-wave detector has the potential to detect the gravitational-wave signal emitted from the axial w-mode oscillations of a hyperon star.

Keywords: hyperon star, oscillation, gravitational wave

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1. Introduction

It is well known that the equation of state (EOS) of dense matter plays an important role in nuclear astrophysics. But the EOS of matter beyond the saturation density is still rather uncertain. Gravitational waves from neutron stars contain information about neutron star matter, which will help us understand super-density matter in the future. Gravitational-wave detectors (e.g., LIGO,[1] VIRGO,[2] and GEO[3]) regard neutron stars as ideal candidates for emitting gravitational waves. In spite of the great challenges encountered in detecting gravitational waves, the great efforts involved are worthwhile because a direct detection would have profound consequences for our basic understanding of high density matter, as well as the gravitational theory. Once gravitational waves from neutron stars are directly detected, they will become a powerful tool for probing super-dense matter. Non-radial oscillations of neutron stars, which can be aroused by gravitational collapse, glitch or phase transitions, are looked on as one of the most important potential candidates for producing detectable gravitational waves.[4−7] The axial w-mode is a type of space–time associated oscillation and is crucial for astrophysical applications. In terms of the work of Chandrasekhar & Ferrari,[8,9] the axial w-mode is described by a unique second-order differential equation. The necessary input in solving this equation is the EOS of nuclear matter. According to the characteristic of the frequency and damping time, the axial w-mode is categorized as $w_{\rm I}$ (standard) and $w_{\rm II}$ (additional) modes.[6]

Most previous works on the axial w-mode of neutron stars mainly focus on dealing with uniform-energy-density matter[10] or nucleon npe matter (composed of neutrons (n), protons (p), and electrons (e) with a possible admixture of muons (μ)).[6,11−14] It has long been recognized that hyperons will be present in the dense cores of neutron stars.[15−20] The properties of this kind of neutron star, commonly called a hyperon star, have been studied by many authors during the past decade.[21−25] It is well known that hyperons may appear around twice the normal nuclear matter density and can soften the EOS of neutron star matter, so we expect that there may exist a clear imprint of the hyperons on the gravitational waves from the axial w-mode oscillation. In this work, two types of super-dense EOSs are considered. The EOS of hyperon star matter will be mainly focused on, while the EOS of APR,[26] composed of traditional neutron star matter, is used for comparison.

This paper is organized as follows. We outline the EOS of hyperon star matter in Section 2. In Section 3 we present our numerical results and discussions. We

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give a brief discussion of the detection of the gravitational waves from axial w-modes of hyperon stars and neutron stars in Section 4. In Section 5 we conclude with a short summary. Geometrized units in which $G = c = 1$ are adopted in the following sections.

2. The equation of state of the hyperon star matter

The conversion of some nucleons to hyperons will occur through the weak interaction, and is active in dense matter because the Fermi energy of the highest-lying nucleons will exceed the mass of hyperons. The relativistic mean field (RMF) theory is one of the successfully constructed models used to describe nuclear matter and is widely adopted. Here we will employ this model to describe hyperon star matter. The typical form of the Lagrangian density including hyperons is given by[21,27−29]

$$\begin{aligned} L = & \sum_B \bar{\psi}_B (\mathrm{i}\gamma_\mu \partial^\mu + m_B - g_{\sigma B}\sigma - g_{\omega B}\gamma_\mu \omega^\mu \\ & - \frac{1}{2} g_{\rho B}\gamma_\mu \boldsymbol{\tau}\cdot\boldsymbol{\rho}^\mu)\psi_B + \frac{1}{2}(\partial\sigma)^2 \\ & - \frac{1}{2}m_\sigma^2\sigma^2 - \frac{1}{4}F_{\mu\nu}F^{\mu\nu} + \frac{1}{2}m_\omega^2\omega_\mu\omega^\mu - U(\sigma) \\ & - \frac{1}{4}\boldsymbol{\rho}_{\mu\nu}\cdot\boldsymbol{\rho}^{\mu\nu} + \frac{1}{2}m_\rho^2\boldsymbol{\rho}_\mu\cdot\boldsymbol{\rho}^\mu \\ & + \sum_l \bar{\psi}_l(\mathrm{i}\gamma_\mu\partial^\mu - m_l)\psi_l, \end{aligned} \tag{1}$$

where

$$U(\sigma) = a\sigma + \frac{1}{3!}c\sigma^3 + \frac{1}{4!}d\sigma^4, \tag{2}$$

$$F_{\mu\nu} = \partial_\mu\omega_\nu - \partial_\nu\omega_\mu, \tag{3}$$

$$\boldsymbol{\rho}_{\mu\nu} = \partial_\mu\boldsymbol{\rho}_\nu - \partial_\nu\boldsymbol{\rho}_\mu, \tag{4}$$

ψ_B is the field operator of baryon B (B =n, p, Λ, Σ, Ξ, Δ); ψ_l is the field operator of lepton l (l =e, μ); σ, ω^μ, $\boldsymbol{\rho}^\mu$ are the field operators of σ, ω, and ρ mesons, respectively; $g_{\sigma B}$, $g_{\omega B}$, $g_{\rho B}$ are the coupling constants between σ, ω, ρ mesons and baryons, respectively; m_B, m_l, m_i, ($i = \sigma, \omega, \rho$) are the mass of baryon, lepton, and meson, respectively; and $\boldsymbol{\tau}$ is the isospin operator. In general, the coupling constants between σ (ω or ρ) meson and nucleon (neutron and proton) are equal ($g_{\sigma n} = g_{\sigma p}$, $g_{\omega n} = g_{\omega p}$) and are determined by the saturated property and the symmetry energy of nuclear matter. As to leptons, we assume that they are free Fermi gas. From the Lagrangian density described by Eq. (1), the EOS of the hyperon star matter can be obtained. In the numerical calculation, the following parameters are adopted:[29] $a = -2.1 \times 10^7$ MeV^3, $c = 0.97M_\mathrm{n}$, $d = 1277$, $g_s = 6.73$, $g_v = 8.59$, $M_\mathrm{n} = 938$ MeV, $m_\omega = 783$ MeV, $m_\sigma = 550$ MeV, $m_\rho = 770$ MeV, and $K = 224$ MeV. The parameters adopted here are obtained by fitting and reproducing the saturated properties and the symmetric energy of the nuclear matter. For the density below about 0.07 fm^{-3} (1 fm = 10^{-15} m), the results of Refs. [30] and [31] are employed. The EOSs considered in this work are displayed in Fig. 1, where the EOS of hyperon star matter is denoted as HS. The corresponding mass–radius relations are shown in Fig. 2.

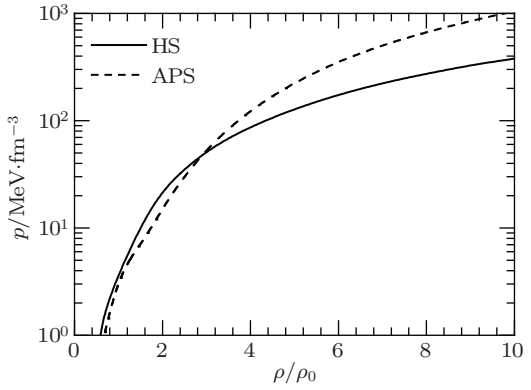


Fig. 1. Equation of state, where the energy density ρ is in units of saturation nuclear density ρ_0.

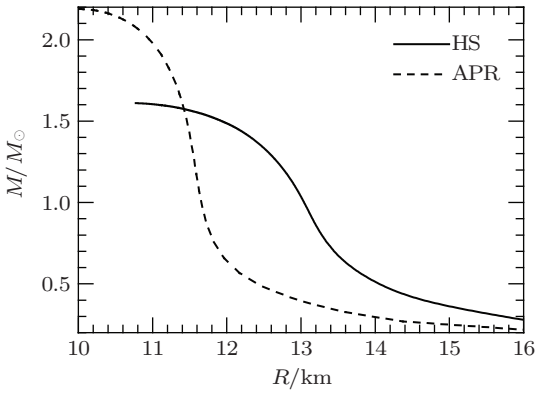


Fig. 2. The mass–radius relation for static hyperon stars and neutron stars.

3. Numerical results and discussion

In this section, we first briefly review the equation of axial w-mode perturbation.

The axial w-mode oscillation for a static neutron star can be described by a second-order differential

equation as[8,9]

$$\frac{\mathrm{d}^2 Z}{\mathrm{d}r_*^2} + [\omega^2 - V(r)]Z = 0, \tag{5}$$

where $\omega(=\omega_r + \mathrm{i}\omega_i)$ is the complex eigenfrequency of the axial w-mode, the real part of the complex eigenfrequency represents the actual frequency of the gravitational waves from the oscillation and the imaginary part represents the energy loss of the oscillation. Inside the star, the tortoise coordinate r_* and the potential function V are defined by

$$\frac{\mathrm{d}}{\mathrm{d}r_*} = \mathrm{e}^{\lambda-\nu}\frac{\mathrm{d}}{\mathrm{d}r} \tag{6}$$

and

$$V = \frac{\mathrm{e}^{2\nu}}{r^3}[l(l+1)r + 4\pi r^3(\rho - p) - 6m], \tag{7}$$

where l is the spherical harmonics index (here we let $l = 2$ only),[8] ρ and p are the density and pressure, respectively; and m is the mass inside radius r. The functions e^{ν} and e^{λ} are given by the line element

$$-\mathrm{d}s^2 = -\mathrm{e}^{2\nu}\mathrm{d}t^2 + \mathrm{e}^{2\lambda}\mathrm{d}r^2 + r^2(\mathrm{d}\theta^2 + \sin^2\theta\mathrm{d}\phi^2). \tag{8}$$

Outside the neutron star, Eqs. (6) and (7) reduce to

$$\frac{\mathrm{d}}{\mathrm{d}r_*} = \frac{r-2M}{r}\frac{\mathrm{d}}{\mathrm{d}r} \tag{9}$$

and

$$V = \frac{r-2M}{r^4}[l(l+1)r - 6M], \tag{10}$$

where M is the total mass of the star.

The solutions to this problem are subject to a set of boundary conditions constructed by Chandrasekhar & Ferrari[8] — regular at the neutron star center, continuous at the surface and behaving as a purely outgoing wave at infinity.

The practical way to calculate the eigenfrequency of axial w-mode is the ***continued fraction method***.[6] The details of the continued fraction method can be found in Refs. [6] and [13]. In this work, we will employ this method to investigate the effect of the crust on the eigenfrequency of the gravitational waves from the standard axial w-mode (categorized as w_{I}) and the additional interesting family of axial w-mode (categorized as w_{II}).[6]

The numerical results for the axial w-modes of hyperon stars (with HS EOS) and traditional neutron stars (with APR EOS) are presented in the following.

Figures 3, 6, and 9 display the frequency (a) and damping time (b) of the w_{I}-mode, w_{I2}-mode, and w_{II}-mode as a function of the stellar mass, respectively. These figures directly present the detectable values in gravitational wave detection and neutron star observation. According to these figures, it is shown that to a hyperon star with its mass in the region of $M < 0.95\ M_{\max}$ its frequencies of gravitational waves are always smaller than those of the traditional neutron star (with APR EOS) at a fixed mass.

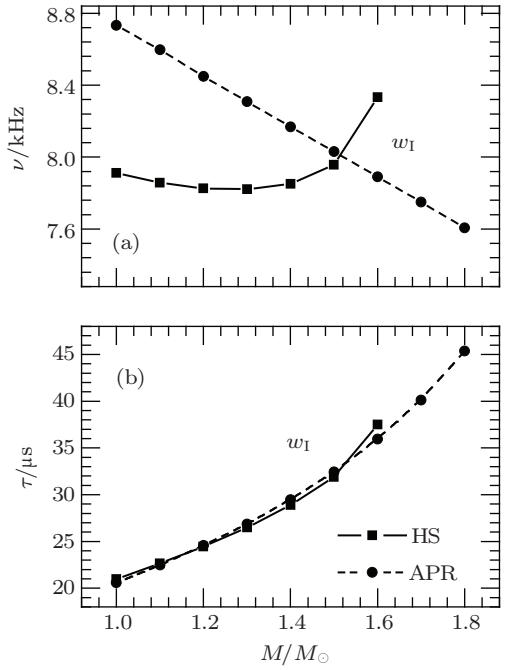


Fig. 3. The frequency (a) and damping time (b) of w_{I}-mode as a function of the stellar mass M.

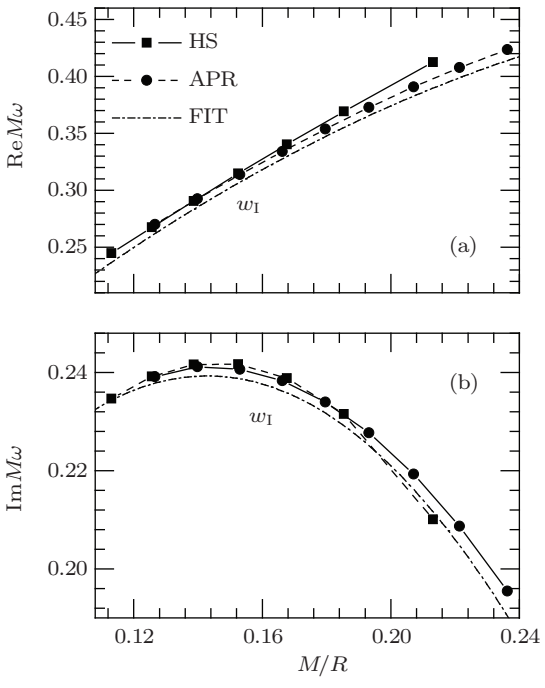


Fig. 4. The eigenfrequency of the w_{I}-mode scaled by the stellar mass M as a function of compactness M/R. The fit is performed by employing the parameters of Tsui *et al.*[11]

In Fig. 3, we notice that for a neutron star composed of traditional neutron star matter — neutrons, protons, electrons, and muons (APR EOS), its frequency of the $w_{\rm I}$-mode is linear decreasing as the stellar mass increases; but for a hyperon star its frequency has a totally different change along the stellar mass. This point could be explained by combining with Figs. 2 and 4. According to Fig. 4, the scaled frequency $\mathrm{Re}(M\omega)$ has an approximate linear relation to the compactness M/R, that is, $\mathrm{Re}(M\omega) = M\omega_0 \approx k(M/R) + c$, which can be simplified as

$$\omega_0 \approx \frac{k}{R} + \frac{c}{M}, \tag{11}$$

where k and c are positive constants, which can be obtained by fitting the lines in Fig. 4(a). This relation shows that the frequency of the axial $w_{\rm I}$-mode could be approximately decided by the mass and radius of the neutron star in a simple way described by Eq. (11). As we know, a stable neutron star's radius will decrease as its mass increases. To a traditional neutron star (with the APR EOS), the radius decreases very slowly as its mass increases in the region $1.0\ M_\odot \sim 1.8\ M_\odot$, as showing in Fig. 2. In this case, according to Eq. (11), the change of the stellar mass will dominate the change of frequency, that is, the frequency decreases as its mass increasing, as the line of APR in Fig. 3(a) shows. It is shown in Fig. 2 that for HS EOS the radius changes very quickly as its mass increasing in the region $M > 1.3\ M_\odot$, so in Eq. (11), the change of the radius will dominate the change of the frequency, that is, the frequency increases as the stellar mass increasing in the mass region $M > 1.3\ M_\odot$, as showing in Fig. 3(a). In Fig. 3(b), it is shown that at a fixed mass the hyperon star and neutron star have the similar damping time. This means that the decaying of the $w_{\rm I}$-mode oscillation is mainly determined by the stellar mass.

It has long been recognized that the eigenfrequency scaled by the stellar mass as a function of the neutron star compactness has a universal behavior independent of the EOS.[11−13,32,33] As it was pointed out in the above references, if both the frequency and damping time for a given neutron star are known, this could provide an efficacious way to determine the neutron star mass and radius. On the other hand, provided that the masses and radii of neutron stars are known, the universal scaling behaviors allows an accurate determination of the w-mode frequency and damping time of gravitational waves. This is very important for guiding the gravitational wave detection. In Figs. 4, 7, and 10, the real (a) and imaginary (b) parts of the eigenfrequency of $w_{\rm I}$-, $w_{\rm I2}$-, and $w_{\rm II}$-modes scaled by the mass M as a function of the neutron star compactness M/R are plotted, respectively. It is shown that the scaled eigenfrequency of a hyperon star has similar behavior to that of a traditional neutron star. Unlike that of $w_{\rm I}$- and $w_{\rm II}$-modes, the eigenfrequency of the $w_{\rm I2}$-mode scaled by the mass is still dependent on the EOS, as is shown in Fig. 7. According to Ref. [13], scaling the eigenfrequency of the $w_{\rm I2}$-mode by the total gravitational energy has a much better universal, here hyperon stars have the similar result, see Fig. 8.

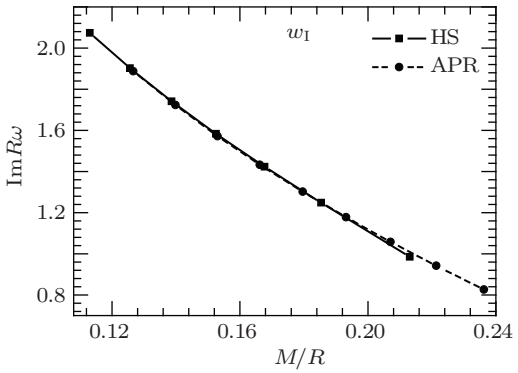


Fig. 5. The imaginary part of eigenfrequency of the $w_{\rm I}$-mode scaled by the stellar radius R as a function of compactness M/R.

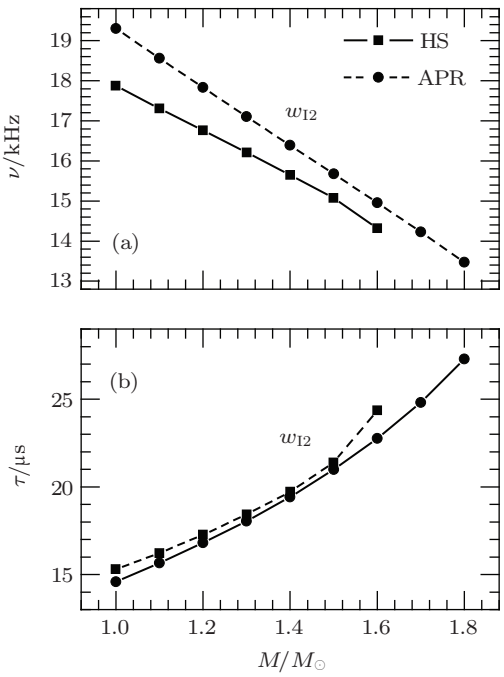


Fig. 6. The frequency (a) and damping time (b) of $w_{\rm I2}$-mode as a function of the stellar mass M.

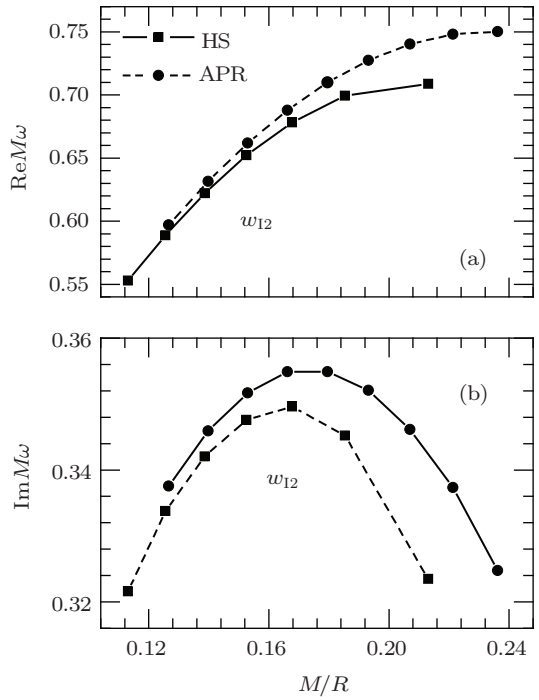


Fig. 7. The eigenfrequency of the $w_{\rm I2}$-mode scaled by the stellar mass M as a function of compactness M/R.

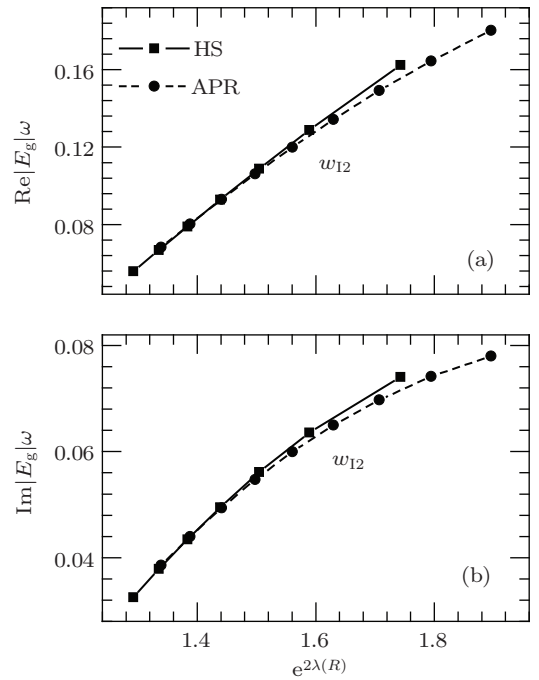


Fig. 8. The eigenfrequency of the $w_{\rm I2}$-mode scaled by the gravitational energy $|E_g|$ versus the metric function $e^{2\lambda}$ at the stellar surface.

In this work, we found another kind of scaling which can provide a more perfect universality, that is, scaling the eigenfrequency by the stellar radius. It is shown that only the imaginary parts of $w_{\rm I}$-modes and the real and imaginary parts of the $w_{\rm II}$-modes as a function of the compactness have this universality, as displayed in Figs. 5 and 11. Combining this universality scaled by the radius with that scaled by the mass, the properties of a hyperon star or a neutron star, especially to the radius, will be determined very accurately once the gravitational waves from the axial w-modes are detected in the future.

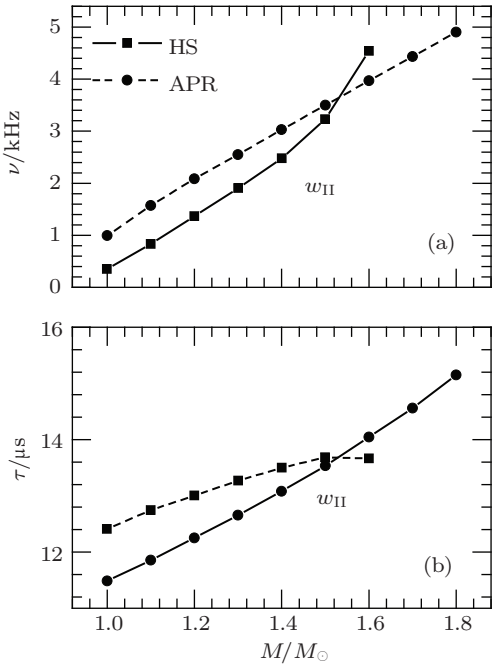


Fig. 9. The frequency (a) and damping time (b) of $w_{\rm II}$-mode as a function of the stellar mass M.

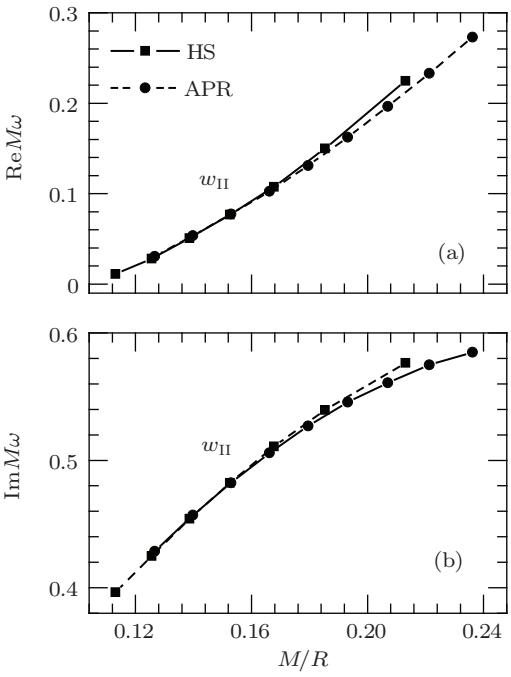


Fig. 10. The eigenfrequency of the $w_{\rm II}$-mode scaled by the stellar mass M as a function of compactness M/R.

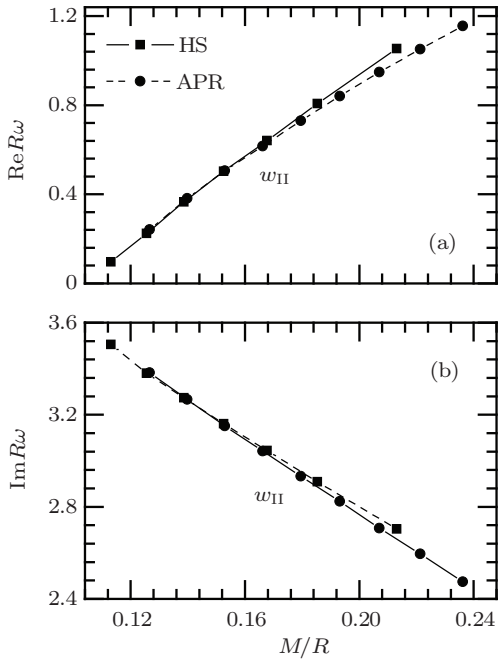


Fig. 11. The eigenfrequency of the $w_{\rm II}$-mode scaled by the stellar radius R as a function of compactness M/R.

4. Detection of the gravitational waves from axial perturbation

In this section, we discuss the possibility of detecting the gravitational waves from axial w-modes of neutron stars based on analysis outlined in Refs. [7] and [34].

The amplitude of gravitational wave signal emitted from oscillations of neutron star can be estimated by[7,34]

$$A \sim \frac{2.4}{10^{20}} \cdot \left(\frac{E_{\rm gw}}{10^{-6}\ M_\odot c^2}\right)^{1/2} \left(\frac{10\ \mathrm{kpc}}{d}\right) \times \left(\frac{1\ \mathrm{kHz}}{f}\right) \left(\frac{1\ \mathrm{ms}}{\tau}\right)^{1/2}, \tag{12}$$

where $E_{\rm gw}$ is the energy released through the mode and d is the distance between detector and source. The signal-to-noise ratio is given by[7,34]

$$\left(\frac{S}{N}\right)^2 = \frac{4Q^2}{1+4Q^2}\frac{A^2\tau}{2S_{\rm n}}, \tag{13}$$

where the quality factor $Q = \pi f\tau$, and $S_{\rm n}$ is the noise level of detector. The sensitivity of the current detector (LIGO and VIRGO) has the order of $S_{\rm n}^{1/2} \approx 10^{-23}\ \mathrm{Hz}^{-1/2}$ in the hundred-Hertz range. The second generation gravitational-wave detector, LIGO-II, has a noise level given approximately by[34]

$$\frac{S_{\rm n}(f)}{\mathrm{Hz}^{-1}} = 10^{-49}\left[x^{-4.14} - 5x^{-2} + \frac{111\cdot(2-2x^2+x^4)}{2+x^2}\right], \tag{14}$$

in which $x = f/(215\ \mathrm{Hz})$. As shown in Fig. 12 and Tabble 1, in the range of $f > 1$ kHz (the frequency range of the neutron star oscillation modes), LIGO II is not sensitive enough to detect the gravitational wave signal from axial w-modes even to the nearest neutron stars, with distance $d \sim 0.5$ kpc.

Table 1. The frequency f, the damping time τ, the noise amplitude spectral density $S_{\rm n}^{1/2}\ (\mathrm{Hz})^{-1/2}$, the signal to noise ration $(\mathrm{S/N})^2$, and the relative measurement error of the frequency and damping time σ_f/f, σ_τ/τ for axial w-mode of neutron star with mass of 1.4 $M_\odot$ to HS and APR EOS are tabulated for gravitational wave detectors: LIGO II and EURO. Here $E_{\rm gw} \sim 10^{-6}\ M_\odot c^2$ and $d \sim 0.5$ kpc are assumed.

	Detector	$w_{\rm I}$ (HS)	$w_{\rm II}$ (HS)	$w_{\rm I}$ (APR)	$w_{\rm II}$ (APR)
f/kHz		7.85	2.48	8.17	3.05
τ/μs		28.9	13.5	29.5	13.1
	LIGO II	1.21×10^{-22}	3.79×10^{-23}	1.26×10^{-22}	4.70×10^{-23}
$S_{\rm n}^{1/2}\ (\mathrm{Hz}^{-1/2})$	EURO	9.02×10^{-25}	3.05×10^{-25}	9.38×10^{-25}	3.66×10^{-25}
	LIGO II	84.8	553.2	75.1	335.2
$(\mathrm{S/N})^2$	EURO	1.54×10^{6}	8.51×10^{6}	1.36×10^{6}	5.48×10^{6}
	LIGO II	0.1243	2.6323	0.1237	2.3452
σ_f/f	EURO	0.0009	0.0212	0.0009	0.0184
	LIGO II	0.3262	0.1844	0.3387	0.2352
σ_τ/τ	EURO	0.0024	0.0015	0.0025	0.0018

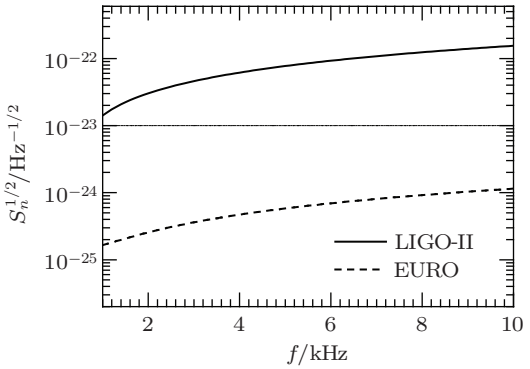


Fig. 12. The noise amplitude $S_{\rm n}^{1/2}$ ($\mathrm{Hz}^{-1/2}$) is plotted as a function of frequency f for LIGO II and EURO gravitational wave detectors, where the frequency is adopted in the region of 1 kHz $< f <$ 10 kHz.

EURO (European Gravitational Wave Observatory) is a third-generation gravitational-wave detector, proposed by a group of European scientists in 2000.[34,35] EURO aims to detect gravitational waves with frequencies from 1 Hz to tens of kHz.[35,36] Its noise level is given by[35]

$$\frac{S_{\rm n}(f)}{\mathrm{Hz}^{-1}} = 10^{-50}\left[\frac{3.6\times10^{9}}{f^4}+\frac{1.3\times10^{5}}{f^2} + \frac{1.3}{10^3}\cdot f_k\left(1+\frac{f^2}{f_k^2}\right)\right], \quad (15)$$

in which $f_k = 1000$ Hz. The noise level of EURO is much lower than that of LIGO II.

The relative errors in the measurement of the frequency and damping time are estimated, respectively, in the following form[7,34]

$$\frac{\sigma_f}{f} \approx 0.0042P^{-1}\sqrt{\frac{1-2Q^2+8Q^4}{4Q^4}}\left(\frac{\tau}{1\ \mathrm{ms}}\right)^{-1}, \quad (16)$$

$$\frac{\sigma_\tau}{\tau} \approx 0.013P^{-1}\sqrt{\frac{10+8Q^2}{Q^2}}\left(\frac{f}{1\ \mathrm{kHz}}\right), \quad (17)$$

where

$$P^{-1} = \left(\frac{E_{\rm gw}}{10^{-6}\ M_\odot c^2}\right)^{-1/2}\left(\frac{d}{10\ \mathrm{kpc}}\right) \times\left(\frac{S_{\rm n}^{1/2}}{10^{-23}\ \mathrm{Hz}^{-1/2}}\right). \quad (18)$$

In the calculation for the detecting parameters to the gravitational-wave signal from the axial w-mode of hyperon stars and neutron stars, here we assume that $E_{\rm gw} \sim 10^{-6}\ M_\odot c^2$ and $d \sim 0.5$ kpc, which is the nearest distance from the known neutron stars to the detector. The results are tabulated in Tabble 1. The results show that the future EURO detector has the potential to detect gravitational waves emitted from the axial w-modes of neutron stars. These results are in agreement with the discussion of Tsui *et al.*[34]

5. Conclusion

In this work, the frequencies and damping times of the gravitation waves from the axial w-modes of hyperon stars are examined. Our studies indicate that at a fixed mass the axial w-mode of a hyperon star has a lower frequency relative to a traditional neutron star. It is shown that the eigenfrequencies of a hyperon star also have scaling universality, although the EOS of hyperon star matter is very different from the EOS of traditional neutron star matter. A new kind of scaling to the axial w-mode, scaling by the stellar radius, is found. The detectable parameters of the gravitational-wave signal from axial w-mode of hyperon stars and neutron stars are calculated and discussed. It is shown that the EURO third-generation detector has the potential to detect the gravitational waves emitted from the axial w-modes of hyperon stars and neutron stars.

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