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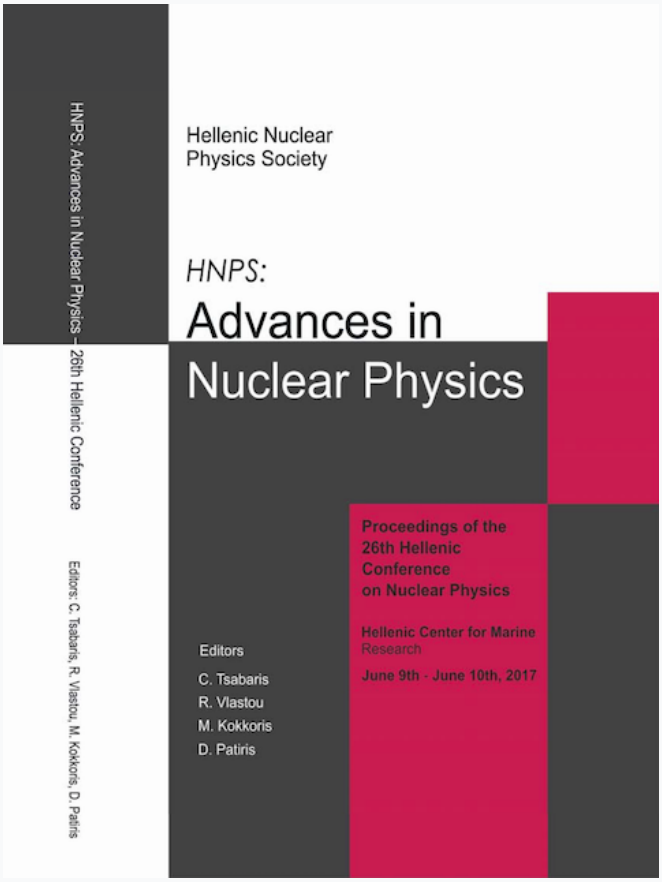

Speed of sound bounds, tidal polarizibility and gravitational waves from neutron stars

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Speed of sound bounds, tidal polarizability and gravitational waves from neutron stars

Ch. Margaritis[1], Ch.C. Moustakidis[1,*], T. Gaitanos[1], G.A. Lalazissis[1]

[1]Department of Theoretical Physics, Aristotle University of Thessaloniki, 54124 Thessaloniki, Greece

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Abstract We study possible effects of the upper bound of the speed of sound on the upper bound of the mass and the tidal polarizability. We conclude that this kind of measurements, combined with recent observations of neutron stars with masses close to 2 M_S (where M_S is the solar mass), will provide robust constraints on the equation of state of hadronic matter at high densities. Finally, we explore the possibility to constrain the equation of state from the detection of a signal of gravitational waves from black hole-neutron star and neutron star-neutron star binary systems.

Keywords Neutron star structure, Equation of state, Gravitational waves

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INTRODUCTION

The determination of the maximum mass of a neutron star (NS) (rotating and nonrotating) is one of the long-standing subjects in astrophysics [1]. Moreover, the experimental observations of neutron star masses have imposed strong constraints on the hadronic equation of state (EoS) of superdense matter. The most famous examples are the recent discoveries of massive neutron stars with gravitational masses of $M = 1.97 \pm 0.04$ M_S (PRS J1614- 2230 [2]) and $M = 2.01 \pm 0.04$ M_S (PSR J0348+0432 [3]). From a theoretical point of view, it is well known that the exact value of the maximum mass M_{max} of a NS depends strongly on the EoS of β-stable nuclear matter. One possibility of proceeding with an estimate of M_{max} is based on the pioneering idea of Rhoades and Ruffini [4], where an optimum upper bound of mass of non-rotating neutron stars was derived using a variational technique. An issue was raised recently concerning the high-density upper bound of the speed of sound. Because of the causality, it should not exceed that of light. Recently, Bedaque and Steiner [5] have provided simple arguments that support the limit $c/\sqrt{3}$ in non-relativistic and/or weakly coupled theories. The authors pointed out that the existence of neutron stars with masses about two solar masses combined with the knowledge of the EoS of hadronic matter at low densities is not consistent with this bound. The main motivation of the present paper is to study in detail the limiting cases of the upper bound of the speed of sound and their effects on the bulk neutron star properties. We use a class of equation of states, which have been extensively employed in the literature and mainly have the advantage to predict neutron star masses close or higher to the experimentally observed value of $2M_s$ [2, 3].

NUCLEAR EQUATION OF STATE AND THE MAXIMUM MASS CONFIGURATION

It is known that no bounds can be determined for the mass of non-rotating neutron stars without some assumptions concerning the properties of neutron star matter [1]. In this study, following the work of Sabbadini and Hartle [6] we consider the following four assumptions: (i) the matter of the neutron star is a perfect fluid described by a one-parameter equation of state between the pressure P and the energy density E, (ii) the energy density E is non-negative, (iii) the matter is microscopically stable, which is ensured by the conditions $\mathrm{P} \geq 0$ and $dP/dE \geq 0$ and (iv) below a critical baryon density n_0 the equation of state is well known. Furthermore, we introduce two regions for specifying more precisely the EoS. The radius R_0, at which the pressure is $P_0 = P(n_0)$, divides the neutron star into two regions. The core, where $r \leq R_0$ and $n \geq n_0$ and the envelope where $r \geq R_0$ and $n \leq n_0$ [13]. The adiabatic speed of sound is defined as $\frac{v_s}{c} = \sqrt{\left(\frac{dP}{dE}\right)_S}$, where S is the entropy per baryon.

We construct the maximum mass configuration by considering the following structure for the neutron star EoS: Above the critical energy density E_0 the EoS is maximally stiff with the speed of sound $\sqrt{\left(\frac{dP}{dE}\right)_S}$ fixed in the interval $\left[\frac{c}{\sqrt{3}}, c\right]$. In the intermediate region $E_{c-edge} \leq E \leq E_0$ we employed a specific EoS which is used for various nuclear models (see below for more details), while for $E \leq E_{c-edge}$ we used the EoS given in Ref. [7]. The crust-core interface energy density E_{c-edge}, between the liquid core and the solid crust is determined by employing the thermodynamical method [8].

We use the following notations and specifications for the results of the theoretical calculations: a) the case where the critical (fiducial) density is $n_0 = 1.5n_s$ and for $n \geq n_0$ the speed of sound is fixed to the value $v_s = c$ (EoS/maxstiff), b) the case where the fiducial density is $n_0 = 1.5n_s$ and for $n \geq n_0$ the speed of sound is fixed to the value $v_s = c/\sqrt{3}$ (EoS/minstiff), and c) the case where the for $n \geq n_{c-crust}$ we simply employ the selected EoS without constraints (EoS/normal) [13].

THE NUCLEAR MODELS

In the present work we employed various relativistic and non-relativistic nuclear models, which are suitable to reproduce the bulk properties of nuclear matter at low densities, close to saturation density as well as the maximum observational neutron star mass (Refs. [2, 3]). The nuclear models that we use are the following: the momentum-dependent interaction model (MDI model), the momentum-dependent relativistic mean-field model (the so called NLD model), the HLPS model, the H-HJ model and the wellknown Skyrme parametrization.

TIDAL POLARIZABILITY

Gravitational waves from the final stages of inspiraling binary neutron stars are expected to be one of the most important sources for ground-based gravitational wave detectors. The tidal fields induce quadrupole moments on the neutron stars. The response of the neutron star is described by the dimensionless so-called Love number k_2, which depends on the neutron star structure and consequently on the mass and the EoS of the nuclear matter. The tidal Love number k_2 is related to the tidal polarizability λ by the expression $\lambda = 2R^5 k_2/3G$, where R is the NS radius. In addition, the combined tidal effects of two neutron stars in a circular orbits are given by a weighted average $\tilde{\lambda}$ of the quadrupole responses [9, 10]. The weighted average $\tilde{\lambda}$ is usually plotted as a function of chirp mass $\widetilde{M} = (m_1 m_2)^{3/5}/m^{1/5}$ for various values of the symmetric mass ratio $h = m_1 m_2/m^2$, where $m = m_1 + m_2$ the total mass of the 2 NSs.

RESULTS AND DISCUSSION

All the hadronic models that we use, without any restriction on the speed of sound (except the relativistic one) can reproduce the recent observation of two-solar massive neutron stars. In general, the stiffer EoS (at high densities) the higher the maximum neutron star mass. All the EoSs are causal even for high values of the pressure (the only exception is the case HLPS (stiff) where the v_s exceed the c for relative low pressure). However, it is worth mentioning that in all hadronic models, used in the present study, the speed of sound v_s reaches the bound limit $c/\sqrt{3}$ at relative low values of the pressure (for $P \leq 100 MeV \cdot fm^{-3}$). This feature has dramatic effect on the maximum mass configuration. By setting the upper limit to $v_s = c/\sqrt{3}$ the stiffness of the EoS weakens at higher densities and consequently the neutron star mass reduces to lower values.

To further clarify the critical density dependence on M_{max}, we display in Figure 1 the dependence of the maximum mass for the chosen EoS, on the fiducial density n_0.

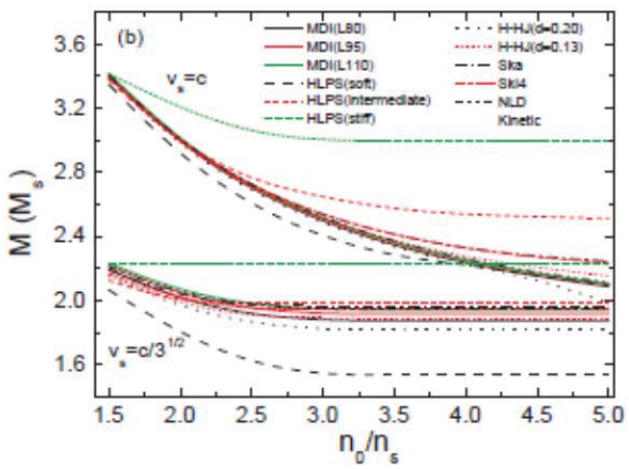

Fig. 1. The maximum mass of neutron stars as a function of the critical density n_0 for the two upper bounds for the speed of sound $v_s = c$ and $v_s = c/\sqrt{3}$.

First, one sees an overall reduction of the neutron star mass with increasing critical density. Using the density behavior of the $v_s = c/\sqrt{3}$ constraint, in all cases the neutron star mass drops below the experimental value of two solar masses (the only exception is the stiff case of the HLPS model). Therefore, this upper limit for the speed of sound in compressed matter would exclude particular EoSs which contradict with recent astrophysical observation of massive neutron stars. Our results are similar to those of Bedaque and Steiner [5]. On the other hand, when the causality limit $v_s = c$ is imposed, the upper bound on the maximum mass significantly increases as is well known from previous studies and the relevant predictions (see Refs. [11] and references therein).

We propose now an additional approach to investigate the upper bound of v_s. The influence of the star's internal structure on the waveform is characterized by the value of the tidal polarizability λ. It was found that λ exhibits very strong dependence on the radius R and consequently on the details of the EoS at low and high values of the baryons density. The effects are more pronounced for low values of n_0 and for high values of neutron star mass. Furthermore, the measure of the difference of phase ΔΦ of a gravitational wave, between a spinless black hole-black hole and black hole-neutron star binary system [12] will provide robust constraints on the EoS.

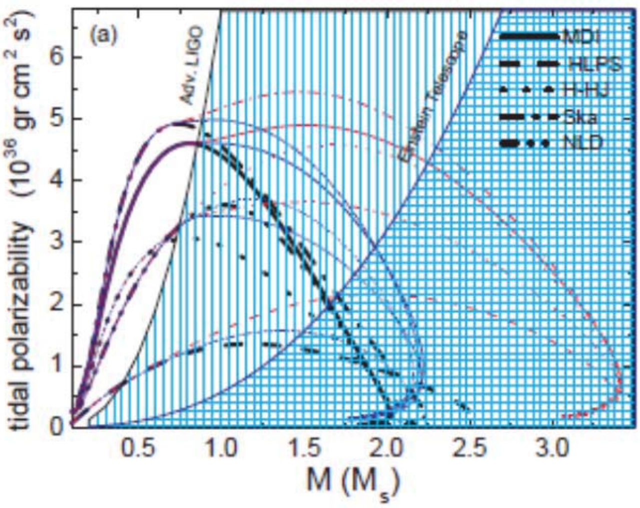

Fig. 2. The tidal polarizability λ of a single neutron star as a function of the mass for the five selected EoSs (EoS/normal case) in comparison with the corresponding maximum mass configurations results (EoS/minstiff and EoS/maxstiff cases).

The tidal polarizability can be deduced from observations on neutron star binary systems. This is shown in Figure 2. We found that λ takes a wide range of values ($\lambda \sim (1 - 5) \times 10^{36} gr \cdot cm^2 \cdot s^2$) for the employed EoS (EoS/normal case). Because λ is sensitive to the neutron star radius, an EoS leading to large neutron star radii will also give high values for the tidal polarizability λ (and vice versa). The constraints of the upper bound on the speed of sound (EoS/minstiff) lead to a non-negligible increase of λ for high values of neutron star mass. However, in the EoS/maxstiff case the corresponding increase of λ is substantial, compared to the EoS/normal case. The increase of the upper bound on the speed of sound influences significantly the maximum mass configuration in two ways. First, a dramatic increase of the upper bound of M_{max}. Second, the neutron star radius is significantly increased. A radius increase by 10% leads already to a rise of the tidal polarizability λ by 60%. In the same figure, the ability to measure the tidal polarizability from the Advanced LIGO and the Einstein Telescope is indicated (see also Ref. [10]).

Note that the Einstein Telescope will be able to measure λ even for neutron stars with a masses up to $2.5M_S$ and consequently to constrain the stiffness of the EoS. To be more precise, from these observations one will be able to test the upper bound $v_s = c/\sqrt{3}$, which seems to be violated for intermediate mass neutron stars (1 - $2M_S$) with large values for the tidal polarizability λ.

Finally, we discuss the weighted tidal polarizability $\tilde{\lambda}$ as a function of the chirp mass $\widetilde{M}$ varying the symmetric ratio h. It is concluded that the upper bound of the speed of sound and consequently the maximum mass configuration affects appreciable the chirp mass-weighted tidal polarizability dependence (for chirp masses $\widetilde{M} > 0.5M_S$). In particular, for high values of $\widetilde{M}$, the Einstein telescope has the sensibility to distinguish the mentioned dependence.

We believe that the simultaneous measure of M and λ will help to better understand the stiffness limit of the EoS, in particular observations with third-generation detectors. This is expected to provide more information related to the upper bound of the speed of sound in hadronic matter which is greatly important for a consistent prediction of the maximum mass of a neutron star. The future detection and analysis of gravitational waves in binary neutron star systems is expected to shed light on this problem.

Acknowledgements

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