GW190814’s Secondary Component with Mass 2.50–2.67 $M_\odot$ as a Superfast Pulsar

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Abstract

We use Stergioulas’s RNS code for investigating fast pulsars with equations of state (EOSs) on the causality surface (where the speed of sound is equal to that of light) of the high-density EOS parameter space satisfying all known constraints from both nuclear physics and astrophysics. We show that one possible explanation for GW190814’s secondary component, which has mass 2.50–2.67 $M_\odot$, is that it is a superfast pulsar spinning faster than 971 Hz, about 42% below its Kepler frequency. If confirmed, it would be the fastest pulsar with the highest mass yet observed. There is a large and physically allowed EOS parameter space below the causality surface where pulsars heavier than 2.50 $M_\odot$ are supported if they can rotate even faster with critical frequencies that depend strongly on the high-density behavior of nuclear symmetry energy.

Unified Astronomy Thesaurus concepts: Pulsars (1306)

1. Introduction

The recent LIGO/Virgo observation of GW190814 from the merger of a black hole (BH) of mass (22.2–24.3) $M_\odot$ and a secondary compact object $m_2$ with mass 2.50–2.67 $M_\odot$ provided an exciting new stimulus to the ongoing debate on whether or not a gap exists between the maximum mass of neutron stars (NSs) and the minimum mass of BHs (Abbott et al. 2020). The highly unequal masses of the two objects involved and the unusually small secondary mass make the source of GW190814 unlike any other compact binary coalescence observed so far. As discussed in detail in the LIGO/Virgo discovery paper (Abbott et al. 2020), the nature of GW190814’s secondary component is largely unknown because of the lack of evidence of measurable tidal effects in the signal and no electromagnetic counterpart to the gravitational waves was identified. It is thus not clear whether $m_2$ is a BH, an NS, or another exotic object.

Several interesting proposals have already been made (e.g., Zevin et al. 2019; Abbott et al. 2020; Essick & Landry 2020; Fishbach et al. 2020; Lehmann et al. 2020; Most et al. 2020; Safarzadeh & Loeb 2020; Sedrakian et al. 2020; Tan et al. 2020; Vattis et al. 2020). It is well known that rotation provides additional support to the pressure balancing the gravity, leading to an NS maximum mass at the Kepler frequency, which is about 20% higher than that of the static NS for a given nuclear equation of state (EOS) (see, e.g., Cook et al. 1994; Lasota et al. 1996; Lattimer & Prakash 2004; Haensel et al. 2008, 2009; Krastev et al. 2008a; Breu & Rezzolla 2016; Wei et al. 2017). Therefore, the possibility that GW190814’s secondary is a rapidly rotating NS was first studied by the LIGO/Virgo Collaboration (Abbott et al. 2020). Since the spin parameter of the secondary was not observationally constrained and the calculation of the NS maximum mass depends on the unknown EOS of superdense neutron-rich nuclear matter, conclusions regarding rotational effects on GW190814’s secondary mass are not clear. Abbott et al. (2020) took 2.3 $M_\odot$ as the maximum mass $M_{\text{TOV}}$ of nonrotating NSs based on estimates from studying the merger remnant of GW170817 and found that, although the degree of EOS uncertainty is difficult to quantify precisely, if we take the more conservative 2.3 $M_\odot$ bound at face value, then $m_2$ is almost certainly not an NS. In contrast, Most et al. (2020) also adopted $M_{\text{TOV}} = 2.3 M_\odot$ in a more detailed study using universal relations connecting the masses and spins of uniformly rotating neutron stars (Breu & Rezzolla 2016). It was found that the secondary $m_2$ does not need to be an ab initio BH nor an exotic object; rather, it can be a rapidly rotating neutron star that collapsed to a rotating BH at some point before the merger. Moreover, a new bound of $M_{\text{TOV}} \geq 2.08 \pm 0.04 M_\odot$ was obtained even in the less likely scenario in which the secondary never collapsed to a BH.

While it is probably more interesting to study all other more exotic possibilities, the existing controversy calls for further studies about GW190814’s secondary simply as a rapidly rotating NS and about how fast it really has to rotate with respect to its Kepler frequency. In this work, we use Stergioulas’s RNS code for investigating rapidly rotating compact stars (Stergioulas 1995) to study the minimum frequency $f_{2.5}$ that can rotationally support an NS of mass 2.50 $M_\odot$ (and the corresponding spin parameter $\chi_{2.5}$) within the high-density EOS parameter space bounded by the NS tidal deformability from GW170817 and radii of canonical NSs from X-ray observations using Chandra, XMM-Newton, and NICER as well as nuclear theories and experiments. On the causality surface where the EOSs are the stiffest physically possible, the minimum value of $f_{2.5}$ is 971 Hz, while the ratio of $f_{2.5}$ to Kepler frequency $f_K$, i.e., $f_{2.5}/f_K$, is between 0.578 and 0.876 (the corresponding $\chi_{2.5}$ is between 0.375 and 0.550) depending on the high-density behavior of nuclear symmetry energy. Below the causality surface, there is a large and physically allowed EOS parameter space where the secondary of GW190814 can sustain masses above 2.50 $M_\odot$ if they rotate even faster than those on the causality surface. Thus, within the existing bounds on the EOS from both astrophysics and nuclear physics, GW190814’s secondary component can be a superfast pulsar spinning faster than the currently known fastest pulsar PSR J1748-2446ad of frequency 716 Hz (Hessels et al. 2006), which supports the findings of Most et al. (2020).
2. An Explicitly Isospin-dependent EOS Generator for Neutron Stars at $\beta$ Equilibrium

Here we summarize the main features of an EOS generator for NSs consisting of neutrons, protons, electrons, and muons (the $npem_\mu$ model). More details of our approach and its applications can be found in Zhang et al. (2018), Xie & Li (2019, 2020), and Zhang & Li (2019a, 2019b, 2019c, 2020). Unlike the widely used spectral EOS and other similar piecewise parameterizations that directly parameterize the pressure as a function of energy or baryon density, we start from parameterizing the energy per nucleon in symmetric nuclear matter (SNM), $E_0(\rho)$, and the nuclear symmetry energy $E_{\text{sym}}(\rho)$ according to

$$E_0(\rho) = E_0(\rho_0) + \frac{K_0}{2} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_0}{6} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^3,$$

$$E_{\text{sym}}(\rho) = E_{\text{sym}}(\rho_0) + \frac{K_{\text{sym}}}{2} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^2 + \frac{J_{\text{sym}}}{6} \left( \frac{\rho - \rho_0}{3\rho_0} \right)^3$$

where $E_0(\rho_0) = -15.9 \pm 0.4$ MeV (Brown & Schwenk 2014) is the binding energy and $K_0 \approx 240 \pm 20$ MeV (Shlomo et al. 2006; Piekarewicz 2010; Garg & Colò 2018) is the incompressibility at the saturation density $\rho_0$ of SNM, while $E_{\text{sym}}(\rho_0) = 31.7 \pm 3.2$ MeV is the magnitude and $L \approx 58.7 \pm 28.1$ MeV is the slope of symmetry energy at $\rho_0$ (Li & Han 2013; Oertel et al. 2017). $K_{\text{sym}}$, $J_{\text{sym}}$, and $J_0$ are parameters characterizing the EOS of superdense neutron-rich nuclear matter. In particular, $J_0$ and $J_{\text{sym}}$ reflect respectively the stiffness of the SNM EOS and the nuclear symmetry energy at densities above twice the saturation density of nuclear matter. They are parameters to be inferred from astrophysical observables and/or terrestrial experiments using either the direct inversion technique (Zhang et al. 2018; Zhang & Li 2019a, 2019b, 2019c) or the Bayesian statistical approach (Xie & Li 2019, 2020). $E_0(\rho)$ and $E_{\text{sym}}(\rho)$ are then used to first construct the average nucleon energy $E(\rho, \delta)$ in nuclear matter at nucleon density $\rho = \rho_n + \rho_p$ and isospin asymmetry $\delta = (\rho_n - \rho_p)/\rho$ according to the isospin-parabolic approximation for the EOS of neutron-rich nuclear matter (Bombaci & Lombardo 1991):

$$E(\rho, \delta) = E_0(\rho) + E_{\text{sym}}(\rho)\delta^2 + O(\delta^4).$$

The pressure in the $npem_\mu$ matter core of NSs is then calculated from

$$P(\rho, \delta) = \rho^2 \frac{dE(\rho, \delta)}{d\rho},$$

where $E(\rho, \delta) = E_n(\rho, \delta) + E_p(\rho, \delta)$ denotes the energy density, $E_n(\rho, \delta)$ and $E_p(\rho, \delta)$ are the energy densities of nucleons and leptons, respectively. The core EOS is connected to the LV EOS (Ngele & Vautherin 1973) for the inner crust and the BPS EOS (Baym et al. 1971) for the outer crust. The crust–core transition density and pressure are determined consistently from the same parametric EOS for the core. In particular, the density dependence of nuclear symmetry energy pays a very important role in determining the crust–core transition (see, e.g., Li et al. 2019 for a recent review).

As discussed in detail in Zhang et al. (2018), Zhang & Li (2019a), and Xie & Li (2020), the parameterizations of both the SNM EOS $E_0(\rho)$ and nuclear symmetry energy $E_{\text{sym}}(\rho)$ were chosen purposely as if they are Taylor expansions of some known energy density functions, while really they are just parameterizations and the parameters are not derivatives of some known functions but are to be inferred from data. Since the parameterizations become Taylor expansions of some functions asymptotically as the density approaches $\rho_0$, this choice allows us to use predictions of nuclear theory and terrestrial nuclear experiments for the EOS parameters around $\rho_0$ as guidance in setting the prior ranges and probability distribution functions (PDFs) when inferring their posterior PDFs from the observed data. Compared to directly parameterizing the normally composition-blind pressure in NSs as a function of energy or baryon density, the EOS generator described above has the advantage of tracking explicitly the composition of the $npem_\mu$ matter in NSs. For instance, with the information about the symmetry energy, one can find easily the density profile of isospin asymmetry $\delta(\rho)$ (or the corresponding proton fraction $x_p(\rho)$ at density $\rho$ through the $\beta$ equilibrium condition $\mu_n - \mu_p = \mu_e = \mu_\mu$) and the charge neutrality condition $\rho_e = \rho_n + \rho_p$, for the proton density $\rho_p$, electron density $\rho_e$, and muon density $\rho_\mu$. The chemical potential of particle $i$ can be calculated from $\mu_i = \partial E(\rho, \delta)/\partial \rho_i$.

As an example, Figure 1 shows the high-density symmetry energy $E_{\text{sym}}(\rho)$ (top panel) and the corresponding isospin asymmetry profile $\delta(\rho)$ in NSs at $\beta$ equilibrium (bottom panel) as functions of the reduced baryon density $\rho/\rho_0$ by varying the $J_{\text{sym}}$ parameter within its broad range predicted by nuclear
theories while all other EOS parameters are fixed. It is seen that the effects of varying $J_{\text{sym}}$ only become important above about twice the saturation density. As $J_{\text{sym}}$ changes from $-200$ MeV to $+800$ MeV, the symmetry energy changes from being supersoft to superstiff. The corresponding isospin profile $\delta(\rho)$ goes from very neutron-rich or $\delta = 1$ (pure neutron matter) with the supersoft $E_{\text{sym}}(\rho)$ to almost zero (symmetric nuclear matter) with the stiffest $E_{\text{sym}}(\rho)$ at superhigh densities. This is well understood from minimizing the term $E_{\text{sym}}(\rho)\delta^2$ in the average nucleon energy of Equation (3). To aid our subsequent discussions, it is useful to emphasize that the symmetry energy term may contribute significantly to the total pressure. It is known that the total pressure around $2\rho_0$ has strong or even dominant contributions from the symmetry energy (Lattimer & Prakash 2000; Li & Steiner 2006; Li et al. 2008), making the radii of canonical NSs depend strongly on $E_{\text{sym}}(\rho)$ around $2\rho_0$. At even higher densities, when $E_{\text{sym}}(\rho)$ is supersoft, $\delta$ is close to 1 as shown in Figure 1, making the contribution of the $J_{\text{sym}}$ term to the total pressure as strong as the $J_0$ term in the SNM EOS $E_0(\rho)$ (Xie & Li 2019). Consequently, the mass–radius curve and the maximum mass of NSs are very sensitive to the high-density behavior of the nuclear symmetry energy (Li et al. 2019). This also explains the findings that the radii and/or tidal deformability of canonical NSs only constrain the parameters $L$ and $K_{\text{sym}}$ characterizing $E_{\text{sym}}(\rho)$ around $(1-2)\rho_0$ and not the parameter $J_{\text{sym}}$ (Zhang et al. 2018; Xie & Li 2019). To constrain the latter, one has to study the mass–radius correlations of NSs as massive as possible (Xie & Li 2020). Moreover, even for rapidly rotating NSs, it has been shown earlier using the RNS code that the mass–radius sequence, the moment of inertia, and the ellipticity all depend strongly on the high-density behavior of nuclear symmetry energy (Krastev et al. 2008a, 2008b; Worley et al. 2008). It is thus more useful to construct the EOS of NS matter by explicitly considering the isospin asymmetry at the nucleon energy level instead of directly parameterizing the pressure as a function of energy/baryon density.

The explicitly isospin-dependent NS EOS generator described above has been used successfully in solving the NS inverse-structure problems both in the direct inversions of NS observables in the three-dimensional (3D) high-density EOS parameter space (Zhang et al. 2018; Zhang & Li 2019a, 2019b, 2019c, 2020) and in Bayesian statistical inferences of multiple EOS parameters from observational data (Xie & Li 2019, 2020). It is very efficient in generating millions of EOSs in the allowed EOS parameter space as inputs for solving the Tolman–Oppenheimer–Volkov (TOV) NS structure equations (Tolman 1934; Oppenheimer & Volkoff 1939) in the inversion processes.

The NS EOS generator is a numerical realization of the EOS meta-model defined by the equations given above. The parameters are randomly generated in the inversion processes in large ranges covering most if not all known predictions based on extensive surveys of nuclear many-body theories (Tews et al. 2017; Zhang et al. 2017). This class of EOSs is thus very general. It is also most conservative and has broad applications especially for the purpose of constraining the high-density behavior of nuclear symmetry energy described by the parameter $J_{\text{sym}}$. The latter has been broadly recognized as among the most important but undetermined quantities affecting the properties of dense neutron-rich nuclear matter (Lattimer & Prakash 2004; Baran et al. 2005; Steiner et al. 2005; Li et al. 2008; Trautmann & Wolter 2012; Tsang et al. 2012; Horowitz et al. 2014; Baldo & Burgio 2016; Li 2017).

The origin of the uncertain high-density symmetry energy can be traced back to our poor knowledge of the spin–isospin dependence of the many-body (three or more nucleon interactions) nuclear forces and the isospin dependence of short-range nucleon–nucleon correlations induced by the tensor force or repulsive core in dense neutron-rich matter (see, e.g., Li et al. 2018 for a recent review).

In fact, the determination of the high-density behavior of nuclear symmetry energy was identified as a major scientific thrust for nuclear astrophysics in both the U.S. 2015 Long Range Plan for Nuclear Sciences (U.S. LRP 2015) and the Nuclear Physics European Collaboration Committee (NuPECC) 2017 Long Range Plan (NuPECC LRP 2017). In particular, several dedicated experiments (see, e.g., Russotto et al. 2011; Hong et al. 2014; Tamii et al. 2014; Xiao et al. 2014; FRIB User Committee 2019; Trautmann 2019; Tsang 2020) have been planned to pin down the high-density nuclear symmetry energy at the Facility for Antiproton and Ion Research (FAIR) in Europe, the Facility of Rare Isotope Beams (FRIB) in the USA, the Rare Isotope Beam (RIB) facility at RIKEN in Japan, the High-Intensity Heavy Ion Accelerator Facility in China, and the Rare Isotope Science Project in Korea. The EOS of Equation (3) is a basic input for transport model simulations of these experiments. It is thus critically important for the nuclear physics community.

Determining the EOS of superdense neutron-rich matter is a longstanding and shared goal of both astrophysics and nuclear physics (Danielewicz et al. 2002; Lattimer & Prakash 2004; Özel & Freire 2016; Watts et al. 2016; Oertel et al. 2017; Li et al. 2019). As we shall illustrate with an example in the next section, the constraints on the symmetry energy around $(1-2)\rho_0$ from analyzing properties of canonical NSs using the EOS outlined above can already help rule out many predictions based on several other classes of EOS models. We thus expect that the class of EOSs studied in this work is of significant general interest to both the astrophysics and nuclear physics communities.

The EOS generator described above also has its limitations and drawbacks. By assuming that the cores of NSs are made of only $npe\overline{\mu}$ matter even in the possibly most massive NSs, it lacks the physics associated with the possible phase transitions to exotic states of matter and/or productions of new particles, such as hyperons, mesons, and $\Delta(1232)$ resonances, proposed in the literature. The appearance of new phases and particles is known to generally soften the EOS. Nevertheless, the EOS of $npe\overline{\mu}$ matter serves as a useful baseline for future studies incorporating the possible new phases and particles. The necessary rotational frequency calculated within the $npe\overline{\mu}$ model can be generally considered as the minimum value because a softer EOS will require a higher frequency to support a given pulsar.

We note here that the class of NS EOSs outlined above can be extended to include both new particles and the quark phase at high densities. In fact, recent work connecting this class of NS EOSs with a quark phase described by an EOS with a constant speed of sound within a Bayesian framework will be reported elsewhere (W. J. Xie & B. A. Li 2020, in preparation). However, it is well known that the critical densities for forming hyperons (Sumiyoshi & Toki 1994; Lee 1996; Kubis & Kutschera 2003; Providência et al. 2019), $\Delta(1232)$ resonances...
3. The Constrained High-density EOS Parameter Space for Massive Neutron Stars

Here we illustrate the high-density EOS parameter space \( K_{\text{sym}}-J_{\text{sym}}-J_0 \) constrained by existing astrophysical observables and the causality condition. Much effort has been devoted in recent years to constraining the high-density EOS parameters \( K_{\text{sym}} \), \( J_{\text{sym}} \), and \( J_0 \) using both terrestrial experiments and astrophysical observations (see, e.g., Li et al. 2014 for a comprehensive review). Unfortunately, they are still not well determined. As we shall illustrate, the high-density SNM EOS parameter \( J_0 \) has the strongest control over the maximum mass of NSs. While the high-density symmetry energy parameters \( K_{\text{sym}} \) and \( J_{\text{sym}} \) mostly control the radii, tidal deformabilities, and proton fractions of massive NSs, they also have some significant influences on the maximum mass of NSs. On the other hand, while \( L \) and \( K_{\text{sym}} \) both play significant roles in determining the radii of especially canonical NSs, they have little effect on the maximum mass of NSs. These features have been well demonstrated by many calculations using various nuclear theories and used in extracting these parameters from astrophysical observations. However, due to the limited data available, large uncertainties still exist especially for the three high-density EOS parameters \( K_{\text{sym}} \), \( J_{\text{sym}} \), and \( J_0 \). For instance, using the combined data on NS tidal deformability from GW170817 and the simultaneous measurement of mass and radius of PSR J0030+0451 by the NICER Collaboration, a very recent Bayesian analysis inferred the most probable value of \( K_{\text{sym}} \) as \(-120^{+80}_{-100} \) MeV at 68\% confidence level (Xie & Li 2020). Obviously, its uncertainty is still very large. Since the available data from canonical NSs with masses around 1.4 \( M_\odot \) reflect mostly the EOS around \( 2 \rho_0 \) while \( J_{\text{sym}} \) characterizes the symmetry energy at higher densities, they do not provide much constraint on \( J_{\text{sym}} \) (Xie & Li 2019, 2020). As a result, the symmetry energy at twice the saturation density is only loosely constrained to \( E_{\text{sym}}(2\rho_0) = 54.8_{-19}^{+15} \) MeV at 68\% confidence level, while its behavior at higher densities is currently completely unconstrained as shown in Figure 1. This is well understood as we explained earlier. In the following studies, we will just use the full range of \(-200 \leq J_{\text{sym}} \leq 800 \) MeV predicted by many kinds of nuclear many-body theories (see, e.g., Tews et al. 2017; Zhang et al. 2017) for surveys of model predictions for \( J_{\text{sym}} \).

Figure 2 shows the tightest constraints on the 3D high-density EOS parameter space from inverting the indicated radii and tidal deformability of canonical NSs (Zhang & Li 2020) as well as the causality condition and NSs’ minimum maximum mass of \( M = 2.14 \ M_\odot \). The latter is the mass of PSR J0740+6620 (Cromartie et al. 2019). It is the most massive confirmed NS observed so far. So all acceptable EOSs have to be stiff enough to predict a mass–radius curve with a maximum at least as high as 2.14 \( M_\odot \). Considering all possibly more massive NSs in the universe, 2.14 \( M_\odot \) is the minimum maximum mass of acceptable EOSs. The surface labeled as \( M = 2.14 \ M_\odot \) in Figure 2 collects all EOSs that predict an NS maximum mass of 2.14 \( M_\odot \). It limits the EOS space from below, while the upper bound is from the causality surface (blue) on which the speed of sound equals the speed of light (\( c = dP/d\varepsilon = c^2 \)) at the central density of the most massive
NS supported by the nuclear pressure at each point with the specific EOS there (Zhang & Li 2019a). Both surfaces are strongly controlled by the SNM EOS parameter $J_0$. As expected, these two surfaces are also significantly influenced by the high-density symmetry energy, especially when $E_{\text{sym}}(\rho)$ becomes supersoft with negative values of $K_{\text{sym}}$ and/or $J_{\text{sym}}$.

For example, with the supersoft $E_{\text{sym}}(\rho)$, the value of $J_0$ necessary to support the same NS maximum mass of $M = 2.14 M_\odot$ has to become higher, as one expects.

We considered several reported measurements of radius and tidal deformability, such as $10.62 \text{ km} < R_{1.4} < 12.83 \text{ km}$ from analyzing quiescent low-mass X-ray binaries (Lattimer & Steiner 2014), the dimensionless tidal deformability $70 < \Lambda_{1.4} < 580$ from the refined analysis of GW170817 data (Abbott et al. 2018), the mass and radius of PSR J0030+0451 $M = 1.44^{+0.15}_{-0.14} M_\odot$ and $R = 13.02^{+1.24}_{-1.06}$ km (Miller et al. 2019) or $M = 1.34^{+0.15}_{-0.16} M_\odot$ and $R = 12.71^{+1.19}_{-1.14}$ km (Riley et al. 2019) from NICER. Both the upper and lower limits of radii from these measurements of canonical NSs are consistent. The ones shown in Figure 2 provide the strongest constraint on the $K_{\text{sym}} - J_{\text{sym}}$ correlation. We notice that the lower radius boundary $R_{1.28} = 11.52$ km for $M = 1.28 M_\odot$ from NICER is just outside the line of intersection between the causality surface and the surface of constant maximum mass of $M = 2.14 M_\odot$. It is known that the extraction of the lower limit of $\Lambda_{1.4}$ from GW170817 suffers from large uncertainties and is largely model-dependent. The constant surface of $\Lambda_{1.4} = 70$ is actually on the right of the $R_{1.28} = 11.52$ km surface, and the upper limit for the radius $R < 13.85$ km from NICER is on the left of the constant surface with $R_{1.4} = 12.83$ km; they are thus not shown here. The almost vertical surfaces of the radius and tidal deformability indicate that they are not much affected by the high-density SNM EOS parameter $J_0$ but depend strongly on the high-density symmetry energy parameters $K_{\text{sym}}$ and $J_{\text{sym}}$.

The constraints of $M = 2.14 M_\odot$ (green surface), $R_{1.4} = 12.83$ km (yellow surface), and the causality condition (blue surface) together enclose the allowed high-density EOS parameter space in $K_{\text{sym}} - J_{\text{sym}} - J_0$. In particular, the causality surface determines the absolutely maximum mass $M_{\text{TOV}}$ of nonrotating NSs. To find the minimum rotational frequency of GW190814’s secondary if it is a pulsar, we focus on the constrained causality surface in the following discussions. Its left boundary is determined by its intersection with the $R_{1.4} = 12.83$ km (or the very nearby $\Lambda_{1.4} = 580$) surface, while its right boundary is determined by its intersection with the $M = 2.14 M_\odot$ surface. To make this clear, these intersections are projected to the $K_{\text{sym}} - J_{\text{sym}}$ plane in Figure 3. The shaded region corresponds to the parameters allowed.

The astrophysical constraining boundaries on the high-density symmetry energy parameters shown in Figure 3 have significant impacts on both nuclear theories and experiments. As an illustration, we examine their impacts on theoretical predictions of nuclear symmetry energy at suprasaturation densities in Figure 4. In fact, essentially all two-body and/or three-body nuclear forces available in the literature have been used in one way or another in all available nuclear many-body theories to predict the density dependence of nuclear symmetry energy (Li et al. 2014). The left panel shows 60 representatives selected from six classes out of a total of over 520 energy density functional theories including the relativistic mean field (RMF) using three different kinds of coupling schemes (NL-
properties for GW190814’s secondary component to be an NS. For technical and numerical details of the RNS code, we refer the reader to Stergioulas (1995), and for its underlying physics to Komatsu et al. (1989), Cook et al. (1994), Stergioulas & Friedman (1995), and Nozawa et al. (1998).

For the purposes of this work, we examine the following NS rotational properties:

1. the mass–radius relations of fast pulsars with respect to those of nonrotating NSs, including the maximum mass $M_{\text{TOV}}$ of nonrotating NSs and the pulsar maximum mass $M_{\text{RNS}}$ at the Kepler frequency $f_K$, which is the maximum frequency at which the gravitational attraction is still sufficient to keep matter bound to the pulsar surface;
2. the minimum frequency $f_{2.5}$ (and the ratio $f_{2.5}/f_K$) necessary to rotationally support a pulsar with mass 2.50 $M_\odot$ for a given EOS;
3. the equatorial radius $R_{\text{RNS}}$ of the pulsar with mass $M_{\text{RNS}}$, and the equatorial radius $R_{2.5}$ of the pulsar with mass 2.50 $M_\odot$ and frequency $f_{2.5}$;
4. the dimensionless spin parameter $\chi = J/M^2$, where $J$ is the angular momentum of the pulsar, and its minimum value $\chi_{2.5}$ necessary to support the pulsar with mass 2.50 $M_\odot$.

Figure 5 shows the mass (top) and equatorial radius (bottom) of static (solid lines) and rapidly rotating neutron stars as functions of their central energy density for the EOS parameter sets marked in Figure 3 and listed in Table 1. The neutron stars rotating at their respective Kepler frequencies and at the minimum frequency $f_{2.5}$ that can rotationally support a neutron star with mass 2.50 $M_\odot$ are shown as dashed lines and dotted lines, respectively. The reported mass 2.50–2.67 $M_\odot$ of GW190814’s secondary component is shown as a gray band. The corresponding mass–radius relations are shown in Figure 6 and the resulting values of $M_{\text{TOV}}$, $M_{\text{RNS}}$, $R_{\text{RNS}}$, $R_{2.5}$, $f_{2.5}$, the ratio $f_{2.5}/f_K$, and $\chi_{2.5}$ are summarized in Table 1. Several interesting observations can be made from these results. We discuss the most important physics points in the following.

1. The rotational effects on the mass and radius as well as their correlations are consistent with previous findings in the literature. Most interestingly, while the maximum $M_{\text{TOV}}$ is 2.39 $M_\odot$ for the EOSs allowed by the existing astrophysical observations and terrestrial experiments as we discussed in the previous section, rotations at frequencies much below the Kepler frequencies can readily bring the NS maximum mass to be above 2.50 $M_\odot$. This seemingly trivial result obtained from the well established theory/code for pulsars using the most conservative EOSs without introducing any new physics is important for the current debate as to whether the secondary component of GW190814 is an NS, a BH, or a more exotic object. As we shall discuss in the following, all properties of GW190814’s secondary component as a superfast pulsar are consistent with expectations based on known physics. Thus, all together these lead firmly to our main conclusion that the secondary component of GW190814 is simply a superfast pulsar rather than a BH or an exotic object.

2. While $M_{\text{TOV}}$ of the 12 EOSs is between 2.14 and 2.39 $M_\odot$, pulsars at their respective Kepler frequencies can easily sustain masses greater than 2.50 $M_\odot$. Of course, the maximum pulsar mass $M_{\text{RNS}}$ depends sensitively on the EOS and the corresponding $M_{\text{TOV}}$. With the stiffest EOS possible, i.e., EOS1 with $M_{\text{TOV}} = 2.39 M_\odot$, $M_{\text{RNS}} = 2.87 M_\odot$, while with the soft EOSs including EOS3, EOS6, EOS9, and EOS12 on the right boundary of the allowed EOS space shown in Figure 3 that is determined by the causality condition and the $M = 2.14 M_\odot$ surface, $M_{\text{RNS}}$ is slightly larger than 2.50 $M_\odot$ but less than 2.67 $M_\odot$. Consequently, for these soft EOSs all with the same $M_{\text{TOV}} = 2.14 M_\odot$, the minimum frequency $f_{2.5}$ necessary to rotationally support a pulsar with mass 2.50 $M_\odot$ should be only slightly smaller than their $f_K$ values. For this reason, the RNS code does not give the $f_{2.5}$ pulsar sequences with EOS3, EOS6, EOS9, and EOS12.
3. The mass range on the mass–radius curve with a constant frequency becomes very narrow at higher frequencies (see, e.g., Haensel et al. 2008; Krastev et al. 2008a, for more detailed examples). Indeed, the pulsar sequences at $f_{2.5}$ shown with the dashed and dotted lines are very flat. As expected, the stiffest EOSs allow the lowest value of $f_{2.5}$. Thus, as the stiffest EOS allowed, EOS1 sets the lower limit of $f_{2.5}$ to $f_{2.5} > 971$ Hz. Since the frequency of XTE J1739-285 (Kaaret et al. 2007) at 1122 Hz was not confirmed, $f_{2.5}$ is higher than the confirmed highest frequency of 716 Hz of PSR J1748-2446ad (Hessels et al. 2006). But it is still much more than the corresponding Kepler frequency $f_K$ with $f_{2.5}/f_K = 0.578$. Obviously, the possibility for GW180814’s secondary to be a superfast pulsar or even the fastest one ever found (Most et al. 2020) cannot be excluded. The critical task is then to get more observational information about the secondary’s spin.

4. The minimum value of $\chi_{2.5}$ corresponding to the minimum $f_{2.5}$ is 0.375 with the stiffest EOS, namely EOS1. Since the fixed-frequency pulsar sequences cannot be calculated with the RNS code when $f_{2.5}$ approaches the Kepler frequency as we discussed above, the upper boundary of $\chi_{2.5}$ is not determined here. However, it should be smaller than the maximum spin parameter $\chi_{\text{max}}$, which is around 0.6–0.7 and model-independent (Friedman & Ipser 1992; Lo & Lin 2011). As shown in Figure 2, the causality surface goes downward toward its intersection with the 2.14 $M_\odot$ surface, that is, the EOS becomes softer with decreasing $K_{\text{sym}}$ when $J_{\text{sym}}$ is fixed. As a result, as shown in Table 1, $M_{\text{TOV}}, f_{2.5}$, and $\chi_{2.5}$ all decrease correspondingly. Thus, the left boundary of the projected EOS space shown in Figure 3 provides the lower boundary of $\chi_{2.5}$ and the upper boundary of $M_{\text{TOV}}$. As shown in Figure 2, this is the boundary set by the intersection between the causality surface and the surface with a constant radius of $R_{1.4} < 12.83$ km.

5. The maximum mass $M_{\text{TOV}}$ of nonrotating NSs (top panel) and the corresponding minimum spin parameter $\chi_{2.5}$ of pulsars with frequency $f_{2.5}$ (bottom panel) are shown in Figure 7 as functions of the parameter $J_{\text{sym}}$. As we discussed earlier, the latter controls the behavior of nuclear symmetry energy at densities above $2\rho_0$. It is currently considered to be the most uncertain parameter of the EOS of superdense neutron-rich nucleonic matter (Li 2017). For a comparison, the mass $M = 2.14 + 0.10$ $M_\odot$ (68% confidence level) of MSR J0740+6620 is also shown in the top panel. The arrows indicate the conditions for GW190814’s secondary component to be a superfast pulsar with its minimum spin parameter $\chi_{2.5}$. Combining the information from this plot and the constrained EOS parameter space shown in Figure 2, clearly all the EOSs in the whole space between the causality surface and the $M = 2.14$ $M_\odot$ surface can support pulsars as heavy as $2.50$ $M_\odot$, if they rotate with varying minimum frequencies higher than 971 Hz depending on the symmetry energy of superdense neutron-rich nuclear matter. This further illustrates the importance of better constraining the latter with terrestrial experiments and/or astrophysical observations.

6. The stiffest EOS, EOS1 ($K_{\text{sym}} = 33$ MeV, $J_{\text{sym}} = -200$ MeV, and $J_0 = 112.5$ MeV), requires the smallest spin parameter $\chi_{2.5} = 0.375$. The corresponding $M_{\text{TOV}} = 2.39 M_\odot$ is a little higher than $M_{\text{TOV}} = 2.3 M_\odot$ adopted by Most et al. (2020) from analyzing GW170817. Using the latter and assuming the radius of GW190814’s secondary is 13 km, they extracted a range of $0.49 < \chi < 0.68$ and $f > 1140$ Hz for the spin parameter based on the universal relations of masses and spin parameters (Breu & Rezzolla 2016). Our results are qualitatively consistent, and the quantitative difference can be well understood from the differences in $M_{\text{TOV}}$ and the pulsar radius used. In fact, as shown in Table 1, if we restrict the EOSs to those giving approximately $M_{\text{TOV}} = 2.30 M_\odot$ and $R_{2.5} = 13$ km, our numerical results are in even better agreement.

7. There are some longstanding and interesting issues regarding the stability of fast pulsars (see, e.g., Hessels et al. 2006; Haensel et al. 2008), such as the r-mode instability in their cores (see, e.g., Lindblom et al. 1998;
Owen et al. 1998; Andersson & Kokkotas 2001; Levin & Ushomirsky 2001) that may happen at frequencies much lower than the Kepler frequency. The r-mode instability window depends strongly on the core temperature and its transport properties as well as the coupling with and structure of the crust. Its calculation is still very model-dependent and relies on many poorly known properties of NS matter. For instance, it has been shown by Wen et al. (2012) and Vidaña (2012) that both the Kepler frequency \( f_K \) and the boundaries of the r-mode instability window in the frequency–temperature plane have significant dependences on nuclear symmetry energy. The separation between \( f_K \) and the critical frequency \( f_r \) above which the r-mode instability occurs is strongly temperature-dependent. How the minimum frequency \( f_{2.5} \) for GW190814’s secondary component to be a superfast pulsar compares with the critical r-mode instability frequency \( f_r \) is an interesting question for future studies.

5. Internal Properties of GW190814’s Secondary Component as a Superfast Pulsar

Besides the observational properties discussed above, it is also interesting to examine the corresponding internal
properties of GW190814’s secondary component because learning about them is the ultimate goal of all NS observations. We have studied the profiles of the energy density $\varepsilon$ and the proton fraction $x_p$ for all 12 EOSs considered. For comparison, we present and discuss results with EOS1 and EOS4. As listed in Table 1, EOS1 has the highest $M_{\text{TOV}}$ of 2.39 $M_\odot$ and thus the lowest $f_{2.5} = 971$ Hz necessary to rotationally support NSs with a mass of $M = 2.50 M_\odot$, while EOS4 has almost the lowest $M_{\text{TOV}}$ of 2.30 $M_\odot$ but the highest $f_{2.5} = 1217$ Hz along the mass and spin boundaries shown in Figure 7. Moreover, because EOS1 has $J_{\text{sym}} = -200$ MeV but EOS4 has $J_{\text{sym}} = +200$ MeV while they have approximately the same $K_{\text{sym}}$, they represent respectively the supersoft and stiff symmetry energy functionals at densities above $2 \rho_0$ as shown in Figure 1. As discussed in Section 2, one distinctive feature of our NS EOS generator is the explicit isospin dependence and the ability to keep tracking the composition of NSs. Here we shall examine the proton fraction and its potential impact on fast cooling through the direct URCA process (Lattimer et al. 1991) with EOS1 and EOS4.

Figure 8 shows the energy density contours on the equatorial ($r_p$)–polar ($r_p$) plane with EOS1 (top) and EOS4 (bottom) at the minimum frequency $f_{2.5}$ to rotationally support NSs with a mass of $M = 2.50 M_\odot$. EOS4 predicts an equatorial radius about 0.9 km larger than that with EOS1, as one expects since EOS4 has $f_{2.5} = 1217$ Hz. However, the ratio $R_{p}/R_{e}$ of polar to equatorial radius differs only slightly, about 4%, with the two EOSs. EOS1, having the highest $M_{\text{TOV}}$ of 2.39 $M_\odot$, also has the highest central energy density of about $2 \times 10^{15}$ g cm$^{-3}$. The energy density decreases gradually toward the surface. This feature is shown more quantitatively in the top panel of Figure 9. It is seen that the difference in energy
The density with the two EOSs occurs mostly in the central areas of NSs.

The bottom panel of Figure 9 shows the profiles of the proton fraction $x_p$. It is clearly seen that the NS with EOS1 is much more neutron-rich (proton-poor) than the one with EOS4. In fact, the core of the NS with EOS1 is almost purely made of neutrons ($x_p \approx 0.025$). This is what one expects based on the discussions about the density dependence of symmetry energy in Figure 1. Again, due to the $E_{\text{sym}}(\rho)\delta^2$ term in the average nucleon energy in neutron-rich matter in Equation (3), a supersoft (low value) symmetry energy with $J_{\text{sym}} = -200\,\text{MeV}$ in EOS1 makes the corresponding $\delta$ at $\beta$ equilibrium close to its maximum value of 1 at densities above about $3.5\rho_0$.

It is well known that the proton fraction is the most critical quantity determining the cooling mechanisms of proto-neutron stars and the related neutrino emissions (Lattimer et al. 1991). In $npe\mu$ matter, the threshold proton fraction $x_p^{\text{DU}}$ enabling fast cooling through the direct URCA process (DU) is

$$x_p^{\text{DU}} = 1/\left[1 + x_e^{1/3}\right]$$

with $x_e = \rho_e/\rho_0$ between 1 and 0.5 leading to $x_p^{\text{DU}}$ between 11.1% and 14.8% (Klähn et al. 2006). As indicated in the bottom panel of Figure 9, EOS4 allows the direct URCA process in a large region of the core but EOS1 completely forbids it. This has significant implications for some NS observables, such as the neutrino flux and surface temperature. In turn, observational data on these observables will allow us to probe the high-density behavior of the nuclear symmetry energy. It is hoped that future analyses of GW190814 or similar events will make this possible.

6. Summary and Conclusion

Using Stergioulas’s RNS code for investigating fast pulsars with EOSs on the causality surface and allowed by all known constraints from both nuclear physics and astrophysics, we found that GW190814’s secondary component can be a superfast pulsar as long as it rotates faster than 971 Hz, about 42% below its Kepler frequency. There is a large high-density EOS parameter space below the causality surface permitting pulsars heavier than $2.50\,M_\odot$ if they can rotate even faster with varying critical frequencies that depend strongly on the high-density behavior of the nuclear symmetry energy. Interestingly, it was suggested very recently that the secondary was born as an NS where a significant amount of the supernova ejecta mass from its formation remained bound.
to the binary due to the presence of the massive BH companion (Safarzadeh & Loeb 2020). In this model, very high spin angular momentum, such as we found necessary here to rotationally support GW190814’s secondary as a superfast pulsar, could be supplied through the circumbinary accretion disk (Safarzadeh & Loeb 2020, M. Safarzadeh 2020, private communication). To rule out completely the possibility for GW190814’s secondary component to be a superfast pulsar, it is critical to observationally constrain its spin properties. To better understand the properties of superfast pulsars it is important to further constrain the high-density behavior of nuclear symmetry energy with astrophysical observations and/or terrestrial nuclear experiments. In turn, if confirmed as the most massive and fastest pulsar observed so far, the cooling curve and/or the associated neutrino emission of GW190814’s secondary will provide a great opportunity to further probe the symmetry energy of superdense neutron-rich nuclear matter.

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