R-mode Stability of GW190814’s Secondary Component as a Supermassive and Superfast Pulsar

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Abstract

The nature of GW190814’s secondary component \( m_2 \) of mass 2.50–2.67 \( M_\odot \) in the mass gap between the currently known maximum mass of neutron stars and the minimum mass of black holes is currently under hot debate. Among the many possibilities proposed in the literature, \( m_2 \) was suggested to be a superfast pulsar, while its \( r \)-mode stability against runaway gravitational radiation through the Chandrasekhar–Friedman–Schutz mechanism is still unknown. Previously, Fortin et al. constructed a sample of 33 unified equations of state using the same nuclear interactions from the crust to the core consistently; from that sample we use those equations that fulfill all currently known astrophysical and nuclear physics constraints to compare the minimum frequency required for \( m_2 \) to rotationally sustain a mass greater than 2.50 \( M_\odot \) with the critical frequency above which the \( r \)-mode instability occurs. We use two extreme damping models assuming that the crust is either perfectly rigid or elastic. Using the stability of 19 observed low-mass X-ray binaries as an indication that the rigid crust damping of the \( r \)-mode dominates within the models studied, we find that \( m_2 \) is \( r \)-mode-stable while rotating with a frequency higher than 870.2 Hz (0.744 times its Kepler frequency of 1169.6 Hz) as long as its temperature is lower than about 3.9 \times 10^7 \text{K}, further supporting the proposal that GW190814’s secondary component is a supermassive and superfast pulsar.

Unified Astronomy Thesaurus concepts: Pulsars (1306); Neutron stars (1108)

1. Introduction

The recent discovery by the LIGO/Virgo Collaborations that the compact binary merger GW190814 has a secondary component \( m_2 \) with mass (2.50–2.67) \( M_\odot \) (Abbott et al. 2020) at 90% credible level has generated much interest in the astrophysics community. As \( m_2 \) is in the mass gap between the currently known maximum mass of neutron stars and the minimum mass of black holes, its nature has significant ramifications for many interesting issues in astrophysics and cosmology. Many possibilities regarding its nature and formation path have been proposed very recently in the literature; see, e.g., Roupas et al. (2020), Biswas et al. (2020), and Bombaci et al. (2020) among the latest reports and references therein.

Since the maximum mass \( M_{\text{TOV}} \) of non-rotating neutron stars is predicted to be about 2.4 \( M_\odot \) on the causality surface with the equation of state (EOS) satisfying all known constraints (e.g., Zhang & Li 2019; Li et al. 2020), and it is well known that the centrifugal force in neutron stars rotating at Kepler frequencies can increase their maximum masses by about 20% with respect to \( M_{\text{TOV}} \), the mass of \( m_2 \) is well within reach with rotational support. Indeed, this possibility is among the first considered. However, the conclusions have been diverse mainly because of the different nuclear EOSs used (see, e.g., Abbott et al. 2020; Biswas et al. 2020; Dexheimer et al. 2021; Godzieba et al. 2021; Huang et al. 2020; Most et al. 2020; Tews et al. 2021; Zhang & Li 2020; Zhang & Mann 2020). Among the conclusions supporting \( m_2 \) as a superfast pulsar, Most et al. (2020) found that \( m_2 \) has a rotation frequency of 1210 Hz, assuming that it has a typical neutron star radius of 12.5 km and \( M_{\text{TOV}} = 2.08 M_\odot \). In a study by Zhang & Li (2020), \( m_2 \) was found to have a rotation frequency of 971 Hz using an EOS leading to an equatorial radius of 11.9 km for \( m_2 \) and \( M_{\text{TOV}} = 2.39 M_\odot \). More recently, Biswas et al. (2020) derived a minimum frequency of \( 1143^{+194}_{-155} \) Hz and an equatorial radius \( R_c = 15.7^{+1.0}_{-1.7} \text{km} \) for \( m_2 \) at 90% confidence level assuming \( M_{\text{TOV}} = 2.14 M_\odot \), which is the mass of MSR J0740+6620 (Cromartie et al. 2020). The minimum frequencies found for \( m_2 \) in these studies are significantly higher than the frequency of 716 Hz found in the fastest known pulsar, PSR J1748-2446ad (Hessels et al. 2006), thus making GW190814’s secondary the most massive and fastest known pulsar if confirmed.

While the LIGO/Virgo Collaborations tightly constrained the primary spin of GW190814, the spin of its secondary \( m_2 \) remains unconstrained (Abbott et al. 2020). Thus, the possibility that \( m_2 \) might be a superfast pulsar is neither confirmed nor ruled out observationally. However, an outstanding question critical for \( m_2 \) to be a superfast pulsar remains to be answered. Namely, it is unknown whether \( m_2 \) with the required minimum frequency is stable against the well-known \( r \)-mode instability that leads to the exponential growth of gravitational radiation. As was pointed out already in Zhang & Li (2020) and Biswas et al. (2020), \( m_2 \)’s rotational instabilities would have to be suppressed for it to be a supermassive and superfast pulsar, otherwise it is more likely to be a black hole instead.

In this work, we examine the \( r \)-mode instability of \( m_2 \) using well established EOSs satisfying all currently known constraints within the \( r \)-mode formalisms established by Lindblom et al. (1998, 2000). While a multitude of damping mechanisms exist, an instability can develop only if its growth is faster than its strongest damping mechanism (Biswas et al. 2020). It is known that a rigid crust provides the strongest \( r \)-mode damping, and it can well explain the stability of all observed low-mass X-ray binaries (LMXBs) (e.g., Ho et al. 2011;
Haskell et al. 2012). Using this damping mechanism, we found that \( m_2 \) can be \( r \)-mode-stable as long as its temperature is sufficiently low, e.g., lower than about \( 3.9 \times 10^{17} \) K for \( m_2 \) rotating at \( 870.2 \) Hz (0.744 times its Kepler frequency). Since this temperature is about an order of magnitude higher than that of some known old neutron stars (see, e.g., WijnAarden et al. 2019), the \( r \)-mode instability should not be a concern for \( m_2 \) as a supermassive and superfast pulsar within the theoretical framework and models considered.

The \( r \)-mode instability (Andersson 1998; Andersson & Kokkotas 1998; Friedman & Morsink 1998; Ho & Lai 2000) can trigger the exponential growth of gravitational wave (GW) emission in rapidly rotating neutron stars through the Chandrasekhar–Friedman–Schutz mechanism (Chandrasekhar 1970; Friedman & Schutz 1978) if the GW growth rate is faster than its damping rate. Over the past two decades, significant efforts have been devoted to better understanding the \( r \)-mode instability and its damping mechanisms with many interesting findings (see, e.g., Madsen 2000; Sã 2004; Sã & Tomé 2005; Andersson et al. 2010; Haskell & Andersson 2010; Yang et al. 2011; Haskell et al. 2012; Vidaña 2012; Wen et al. 2012; Alford & Schwenzer 2014a, 2014b; Idrisy et al. 2015; Moustakidis 2015; Dai et al. 2016; Papazoglou & Moustakis 2016; Ofengeim et al. 2019; Wang et al. 2019; Krüger & Kokkotas 2020). In particular, it was found that the \( r \)-mode instability window (a region in the spin frequency versus temperature plane) in which the \( r \)-mode is unstable depends sensitively on the EOS of neutron-rich matter, especially its symmetry energy term, which encodes the information about the energy cost to make nuclear matter more neutron-rich. It depends even more sensitively on the poorly known properties of neutron star crust, especially whether it is rigid or elastic (see more discussions in recent reviews, e.g., Andersson & Kokkotas 2001; Haskell 2015; Andersson 2017; Kokkotas & Schwenzer 2016). To realize the goal of this work, it is thus critical to use unified EOSs for neutron stars not only satisfying all currently known constraints from both nuclear physics and astrophysics but also describing the crust, crust–core transition, and the core consistently based on the same nuclear interactions within the same nuclear many-body theories. Moreover, it is important to limit the uncertain \( r \)-mode damping mechanisms as much as possible and to identify the strongest one using existing astrophysical observations.

For the purposes outlined above, we describe in the next section how we selected the unified EOSs satisfying the conditions mentioned above. In Section 3, we compare 19 observed LMXBs with known frequencies and temperatures with the \( r \)-mode instability boundaries calculated with the selected unified EOSs assuming that the crust is either perfectly rigid or elastic. As expected, the stability of the 19 LMXBs prefers the perfectly rigid crust. Assuming that the same damping mechanism is at work in other neutron stars, we infer in Section 4 the maximum temperature of \( m_2 \) by comparing the minimum frequency it must have to sustain rotationally a mass of \( 2.50 \) \( M_\odot \) with the maximum frequency it can have before the \( r \)-mode instability occurs. We then summarize our work in Section 5.

2. Unified EOSs for Neutron Stars

Various EOSs for neutron stars have been used in the literature. Often, they are constructed by combining the EOSs for the core and crust calculated using different models and/or interactions. For most purposes, these EOSs are perfectly fine. As we discussed above, for the purpose of this work, it is advantageous to use the EOSs with the crust, crust–core transition, and core all calculated using the same nuclear interaction. We thus adopt the 33 unified EOSs derived by Fortin et al. (2016) within the Skyrme Hartree–Fock and the relativistic mean-field models for the core and the Thomas–Fermi model for the crust using the same interactions. Because new progress has been made in constraining the EOS since these 33 EOSs were derived, we shall first filter them through the following three tests: (1) satisfying new constraints on the density dependence of nuclear symmetry energy from analyzing both nuclear experiments and astrophysical observations, especially the radii and tidal deformability of neutron stars (Newton & Crocombe 2020; Xie & Li 2020), (2) being stiff enough to support the currently known maximum mass of neutron stars, i.e., the mass \( M = 2.14^{+0.09}_{-0.09} M_\odot \) (68% confidence level) of MSP J0740+6620 (Cromartie et al. 2020), and (3) being consistent with the simultaneous measurements of mass and radius by the Neutron Star Interior Composition Explorer (NICER) for PSR J0030+0451 (Miller et al. 2019; Raaijmakers et al. 2019; Riley et al. 2019).

The nuclear symmetry energy is well known to have significant effects on the structure of neutron stars (Lattimer & Prakash 2000; Steiner et al. 2005; Li et al. 2019), including the crust–core transition, the crust thickness, as well as the composition of the star. For a comprehensive review on nuclear symmetry energy and its astrophysical effects, we refer the reader to Li et al. (2014). It is defined as

\[
E_{\text{sym}}(n) = \frac{1}{2} \left( \frac{\partial^2 E(n, \beta)}{\partial \beta^2} \right)_{\beta=0},
\]

where \( E(n, \beta) \) is the binding energy of neutron-rich matter as a function of density \( n \) and isospin asymmetry \( \beta = (n_\uparrow - n_\downarrow)/n \). \( E_{\text{sym}}(n) \) can be characterized by using its slope \( L \) and curvature \( K_{\text{sym}} \) at the nuclear saturation density \( n_0 \), which are defined as

\[
L = 3n_0[\partial E_{\text{sym}}(n)/\partial n]_{n=n_0},
\]

\[
K_{\text{sym}} = 9n_0^2[\partial^2 E_{\text{sym}}(n)/\partial n^2]_{n=n_0}.
\]

It was shown previously that both \( L \) and especially \( K_{\text{sym}} \) as well as their correlation, affect the crust–core transition density and pressure significantly (e.g., Vidaña et al. 2009; Xu et al. 2009; Zhang et al. 2018; Providência et al. 2019; Li & Magno 2020). They also affect the EOS and especially the composition of the core (Lattimer et al. 1991). Fortunately, some significant progress has been made recently in experimentally constraining the slope parameter \( L \) (Li & Han 2013; Baldo & Burgio 2016; Oertel et al. 2017), while the curvature \( K_{\text{sym}} \) is still much less constrained. In particular, a recent Bayesian analysis of the radii and tidal deformations of canonical neutron stars (Xie & Li 2020) inferred the most probable values of \( L = 66^{+42}_{-26} \) MeV and \( K_{\text{sym}} = -120^{+190}_{-100} \) MeV at 68% confidence level. In another Bayesian analysis by Newton & Crocombe (2020) using combined data of neutron skin in \(^{40}\text{Ca}, ^{208}\text{Pb}, \) and tin isotopes as well as the best theoretical information about the EOS of pure neutron matter from ab initio microscopic nuclear many-body theories, the most probable values of \( L \) and \( K_{\text{sym}} \) were found to be \( L = 40^{+34}_{-26} \) MeV and \( K_{\text{sym}} = -209^{+170}_{-182} \) MeV at 95% confidence level.
Shown in Figure 1 are the two constraints on $L$ and $K_{\text{sym}}$ in comparison with predictions of the 33 unified EOSs from Fortin et al. (2016). It is seen that only seven of them fall into the overlapping area of the two latest constraints (Newton & Crocombe 2020; Xie & Li 2020). We further test them against the latest astrophysical observations in Figure 2. It is seen that the KDE0v1 EOS is further excluded by the mass measurement of MSP J0740+6620, to the 68.3% credibility interval, while the remaining six EOSs can support a maximum mass of about $2.14M_\odot$ (Cromartie et al. 2020) and satisfy the mass–radius constraints from NICER (Miller et al. 2019; Riley et al. 2019). We further test them against two recent constraints, to the 68% confidence level, on the slope $L$ and curvature $K_{\text{sym}}$ of the symmetry energy at saturation (Newton & Crocombe 2020; Xie & Li 2020). Note that the 95% confidence boundaries shown in Newton & Crocombe (2020) are rescaled to the 68% credible ranges here for a comparison. Only seven EOSs—DD2, DDME2, KDE0v1, SKb, SkI6, SLy2, and SLy9—fulfill both constraints.

3. R-mode Instability in Neutron Stars

All rotating neutron stars are generically r-mode-unstable due to the emission of gravitational waves. However, there are several possible damping mechanisms preventing the r-mode oscillation from growing exponentially. Here we adopt two extreme damping models assuming the crust is either rigid or elastic. For ease of discussion later, we first recall briefly some of the basic definitions and formulae most relevant for our study about the r-mode instability of $m_2$. We refer the reader to the original papers for more details.

3.1. Timescales of R-mode Growth and Damping

Whether the r-mode oscillation can grow exponentially or not depends on the competition between the growth rate of gravitational wave emission and the r-mode damping rate (mainly due to viscosity). Thus, the r-mode instability boundary is determined by setting the damping timescale $\tau_{\text{diss}}$ and driving timescale $\tau_{\text{gw}}$ equal to each other (Andersson & Kokkotas 2001), i.e., by solving for the zeros of

$$-\frac{1}{2\dot{E}} \left( \frac{d\dot{E}}{dt} \right) = \frac{1}{\tau_{\text{gw}}(\nu)} + \sum \frac{1}{\tau_{\text{diss}}(\nu, T)} = 0, \quad (4)$$

where $\dot{E}$ is the total energy of an r-mode oscillation. It is known that the shear viscosity dominates the energy dissipation for temperatures around $10^6$ K, while at higher temperatures (of the order of $10^{10}$ K) the bulk viscosity becomes important (Andersson & Kokkotas 2001). Since all the observed LMXBs have temperatures around $10^8$ K and the old neutron stars are cooler, in the present study we consider only the shear viscosity resulting from both neutron–neutron (nn) and electron–electron (ee) scatterings. We adopt the following parameterizations for the two viscosities as functions of temperature $T$ (Flowers & Itoh 1979; Cutler & Lindblom 1987; Shenmin & Yakovlev 2008):

$$\eta_{\text{nn}}(r) = 347[\rho(r)]^{3/4}T^{-2} \text{ (g cm}^{-1}\text{s}^{-1}), \quad (5)$$
$$\eta_{\text{ee}}(r) = 6 \times 10^6[\rho(r)]^2T^{-2} \text{ (g cm}^{-1}\text{s}^{-1}), \quad (6)$$

where $\rho(r)$ is the mass density profile of the star.

The crust is expected to play an important role in determining the r-mode stability of neutron stars. Here we consider two extreme cases. Assuming the crust is perfectly rigid (i.e., the “slippage” factor $S = 1$), so the fluid motion associated with the r-mode would be significantly damped at the crust–core boundary, $\tau_{\text{gw}}$ is given by (Lindblom et al. 2000)

$$\frac{1}{\tau_{\text{gw}}} = \frac{32\pi G\Omega^2 \rho^2}{c^{2\nu+3}} \frac{(l - 1)^{2}I}{[(2l + 1)!!]^2} \frac{(l + 2)^{2l+2}}{I + 1} \times \int_{0}^{R_c} \rho(r)r^{2\nu+2}dr, \quad (7)$$

where $G$ is the gravitational constant, $\Omega = 2\pi\nu$ is the angular velocity of the star, $c$ is the speed of light, and $R_c$ is the stellar radius at the crust–core transition mass density $\rho_c$; $\tau_{\text{diss}}$ can be evaluated from (Lindblom et al. 2000)

$$\tau_{\eta} = \frac{1}{2\Omega} \frac{2^{l+3/2}(l + 1)!!}{G} \frac{\rho_c^2}{\eta_c} \frac{2\Omega R_c^2}{\rho_c} \frac{\eta_c}{\rho_c} \frac{r^{2l+2} dr}{R_c}, \quad (8)$$
where $\eta$ is the viscosity at the crust–core transition density. Following Lindblom et al. (1998), we only consider the lowest-order contribution of the multipole moment ($l = 2$), with $C_2 = 0.80411$ (Rietfeld 2001).

In the other extreme case of neglecting the crustal damping, or where the crust is regarded as extremely elastic (i.e., the “slippage” factor $S \to 0$; see, e.g., Glampedakis & Andersson 2006), the crust will also participate in the oscillation. In this case, $\tau_{gw}$ is given by (Lindblom et al. 1998)

$$\frac{1}{\tau_{gw}} = -\frac{32\pi G\Omega^{2l+2}}{c^{2l+3}} \frac{(l - 1)^{2l}}{(2l + 1)!} \frac{1}{\mathcal{F}(l + 1)} \int_0^R r^{2l+2} \rho(r) dr,$$

where $\eta$ is written as (e.g., Vidaña 2012)

$$\frac{1}{\tau_{\eta}} = (l - 1)(2l + 1) \left( \int_0^R \rho(r)r^{2l+2} dr \right)^{-1} \int_0^R \eta(r)r^{2l} dr.$$

The actual neutron star crust should have some elasticity; therefore, by calculating the $r$-mode boundary in the two extreme cases, i.e., Equations (7)–(8) (where a rigid crust is considered) and Equations (9)–(10) (where no crustal damping is included), we may estimate the uncertainty due to the crustal modeling. Moreover, confronting the theoretical results with observations of neutron stars’ frequency and temperatures in LMXBs, we may get some hints about which damping mechanism dominates.

### 3.2. Lower Boundaries of R-mode Instability Windows

For each star at a given temperature, one can find from Equation (4) its critical frequency $\nu_{crit}$ above which the star becomes unstable against runaway gravitational radiation, by setting $1/\tau_{gw}(\nu_{crit}) + 1/\tau_{\eta}(\nu_{crit}) = 0$. $\nu_{crit}$ serves as an upper limit of stable pulsars’ frequencies for a given temperature. The region above this boundary in the frequency–temperature plane is the so-called $r$-mode instability window. In the following, we examine the $r$-mode instability boundaries with the six selected EOSs with respect to the locations of the 19 LMXBs. Since the masses of the neutron stars in these LMXBs are not measured accurately, the calculations are done for both canonical ($M = 1.4M_\odot$) and massive ($M = 2.0M_\odot$) neutron stars.

Our results are shown in Figure 3 for both cases assuming a perfectly rigid crust (upper group of lines) or an elastic one (lower group of lines). Several interesting observations can be made.

1. The $r$-mode instability boundary depends most sensitively on the crust’s elasticity, while effects of the EOS and neutron star mass are appreciable. Most importantly, for the present study, the rigid crust provides the strongest damping.

2. The damping mechanism with a perfectly rigid crust can accommodate all neutron stars in the 19 LMXBs, while the one with an elastic crust can only accommodate a few slowly rotating neutron stars, such as NGC 6440 X-2, XTE J1807-294, and XTE J0929-314.

3. The $r$-mode instability boundaries are sensitive to the EOS, especially the $L$ parameter (see, e.g., Wen et al. 2012), but the effects shown here are much less than previously reported in the literature, mainly because the six unified EOSs used here are much more stringently constrained than those used before. Nevertheless, one can still clearly see that the $L$ parameter (shown in Figure 1) cannot be very large, e.g., smaller than $\sim 60$ MeV if LMXB neutron stars are massive (e.g., $M = 2.0M_\odot$), to ensure that the rapidly rotating neutron stars, such as 4U 1608-522 and SAX J1705.8-2900, stay $r$-mode-stable.

4. Comparing the results for $1.4M_\odot$ and $2.0M_\odot$ neutron stars, we see that the $r$-mode instability window is generally broader for the latter in agreement with earlier findings (e.g., Vidaña 2012), especially in the case with the rigid crust. Moreover, the uncertainty band due to the EOS is wider for neutron stars of mass $2.0M_\odot$, due to the

![Figure 3](image_url)
more significant diversity of the EOS at the higher densities reached.

Since the Kepler frequency \( \nu_K \) is the absolute upper limit of spin frequencies of all stars with a given mass, it is interesting and informative to examine the reduced critical frequency \( \nu_{\text{crit}}/\nu_K \) as a function of the temperature \( T \) for both 1.4 \( M_\odot \) and 2.0 \( M_\odot \) neutron stars. Our results for \( \nu_{\text{crit}}/\nu_K \) are shown in Figure 4. Compared to the unscaled results shown in Figure 3, it is seen that the \( r \)-mode instability boundaries of the reduced frequency are more sensitive to the neutron star mass with both rigid and elastic crusts. This is because \( \nu_K \) is proportional to the square root of the average density of neutron stars (Andersson & Kokkotas 2001). The average density depends on the mass; thus, the reduced frequency becomes more sensitive to the neutron star mass. The lighter neutron stars have a lower average density and a lower \( \nu_K \), giving them higher reduced frequencies than the massive ones.

Since the Kepler frequency is EOS-dependent (see, e.g., Li et al. 2016, 2017), the reduced frequencies thus obtain a more complicated EOS dependence. With the rigid crust, as shown in Equations (7)–(8), the location \( R_c \) of the crust–core transition plays an important role. In this case, the strong EOS dependence of \( R_c \) makes the reduced frequency more strongly EOS-dependent than in the case with an elastic crust. In the latter case, both \( \nu_{\text{crit}} \) and \( \nu_K \) are calculated by integrating from the center to the surface. The reduced frequency obtained appears rather insensitive to the EOS due to some canceling effects in taking the ratio. Finally, the difference in the reduced frequency between the two cases at the same temperature is very large. More quantitatively, for a typical temperature \( T = 10^8 \) K relevant for the LMXBs, \( \nu_{\text{crit}} \) is lifted from \( \sim 0.16 \nu_K \) (\( \sim 0.13 \nu_K \)) to \( \sim 0.79 \nu_K \) (\( \sim 0.48 \nu_K \)) for \( M = 1.4 M_\odot \) (\( M = 2.0 M_\odot \)) neutron stars when assuming a rigid crust as opposed to an elastic one.

In short, the main lessons we learned from this section that are most important for our following study about the \( r \)-mode stability of \( m_2 \) are (1) the rigid crust provides the strongest damping, (2) the stability of the 19 neutron stars in LMXBs favors the rigid crust damping, and (3) the reduced critical frequency \( \nu_{\text{crit}}/\nu_K \) with the rigid crust is sensitive to both the neutron star mass and the EOS used.

### 4. \( r \)-mode Stability of GW190814’s Secondary Component of Mass 2.50 \( M_\odot \)

We now examine the \( r \)-mode stability of GW190814’s secondary component \( m_2 \) as a supermassive and superfast pulsar. For this purpose, we first find the minimum frequency \( \nu_{\text{min}} \) to support GW190814’s secondary component with a minimum mass of 2.50 \( M_\odot \) (Abbott et al. 2020) using the well-tested RNS code (Stergioulas 1995) for a given EOS. Among the six EOSs used above, we found that the SLY2 EOS cannot rotationally support a 2.50 \( M_\odot \) star even at the Kepler frequency. Thus, only the remaining five EOSs are used. As discussed in the previous section, only the damping with the rigid crust is necessary for this discussion because it provides the strongest/quickest damping.

Listed in Table 1 are the maximum mass of non-rotating neutron stars \( M_{\text{TOV}} \), Kepler frequency \( \nu_K \), and the minimum frequency \( \nu_{\text{min}} \) to support a neutron star of mass 2.50 \( M_\odot \) for the five EOSs used. \( \nu_{\text{min}} \) is then plotted as a horizontal line in Figure 5, where the \( r \)-mode stability boundary for each EOS is shown in the frequency–temperature plane. Their point of intersection is marked with a diamond, indicating the maximum temperatures \( T_{\text{max}} \) below which neutron stars remain

| Model    | \( M_{\text{TOV}} \) (\( M_\odot \)) | \( \nu_K \) (Hz) | \( \nu_{\text{min}} \) (\( \nu_K \)) | \( T_{\text{max}} \) (K) |
|----------|-------------------------------|----------------|--------------------------|------------------|
| DD2      | 2.42                          | 1196.6         | 0.755                    | \( 3.0 \times 10^7 \) |
| DDME2    | 2.48                          | 1169.6         | 0.744                    | \( 3.9 \times 10^7 \) |
| Skb      | 2.20                          | 1446.5         | 0.809                    | \( 1.3 \times 10^7 \) |
| Sk6      | 2.20                          | 1433.4         | 0.827                    | \( 1.1 \times 10^7 \) |
| SLY9     | 2.16                          | 1515.4         | 0.855                    | \( 7.5 \times 10^6 \) |

Note. \( M_{\text{TOV}} \) is the maximum mass of non-rotating neutron stars supported by the given EOS. \( \nu_{\text{min}} \) is the minimum frequency (in units of the Kepler frequency \( \nu_K \)) to support GW190814’s secondary component \( m_2 \) with a minimum mass of 2.50 \( M_\odot \). \( T_{\text{max}} \) is the maximum temperature for \( m_2 \) to remain \( r \)-mode-stable.

Figure 4. Temperature dependence of the reduced critical frequency \( \nu_{\text{crit}}/\nu_K \) for \( M = 1.4 M_\odot \) and \( M = 2.0 M_\odot \) neutron stars with rigid crusts (upper groups of lines) or elastic crusts (lower groups of lines).

Figure 5. Temperature dependence of the reduced critical frequency \( \nu_{\text{crit}}/\nu_K \) for neutron stars with rigid crusts. For each EOS, the \( \nu_{\text{crit}} \) is plotted as a horizontal line in Figure 4, where the \( r \)-mode instability boundary for each EOS is shown in the frequency–temperature plane. Their point of intersection is marked with a diamond, indicating the maximum temperatures \( T_{\text{max}} \) below which neutron stars remain \( r \)-mode-stable.
5. Conclusions

In conclusion, GW190814’s secondary component $m_2$ can be an $r$-mode-stable supermassive and superfast pulsar rotating with a frequency higher than 870.2 Hz (0.744 times its Kepler frequency of 1169.6 Hz) as long as its temperature is lower than about $3.9 \times 10^7$ K which is still about 10 times hotter than some of the known old neutron stars. Thus, the $r$-mode instability should not be a concern for $m_2$. The minimum frequency and limiting temperature found here may be useful for further understanding the formation mechanism of $m_2$ and the merger dynamics of GW190814.

Our study is carried out within the minimum model of neutron stars consisting of only nucleons and leptons. Moreover, fast rotation is probably the simplest mechanism to provide the additional support besides nuclear pressure against the strong gravity of massive neutron stars. Furthermore, we selected the EOSs satisfying all currently known astrophysical and nuclear physics constraints from a group of 33 unified EOSs constructed from the crust to the core consistently using the same nuclear interactions. Thus, our approach is probably among the most conservative ones used in the literature in investigating the nature of GW190814’s secondary component.

A major caveat of our work is the assumption that the rigid crust of neutron stars provides the strongest $r$-mode damping among a multitude of possible damping mechanisms. While both our current work and previous theoretical calculations by others as well as the stability of the 19 neutron stars in LMXBs favor the dominating rigid crust damping, there may be other even stronger damping mechanisms and/or model ingredients that significantly affect the location of the $r$-mode instability windows. Nevertheless, our current study can successfully describe all relevant observations of neutron stars. We are thus confident that our present conclusions are physically sound and useful for the community to finally solve the mystery regarding the nature of GW190814’s secondary component.

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