

From Microscopic to Macroscopic: The Effect of Relativistic Mean Field Parameter Sets on Neutron Star Structure

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Abstract

Neutron stars, as extremely compact astrophysical objects, provide a unique natural laboratory for investigating the physics of compact matter. Neutron stars can be described from two complementary perspectives, namely microscopic and macroscopic states. The microscopic state is characterized through the relativistic mean-field (RMF) equation of state, which describes the dynamics of dense matter inside the star. The macroscopic state, on the other hand, is described by the Tolman–Oppenheimer–Volkoff (TOV) equations, which determine the global stellar structure. This study aims to examine how the microscopic properties of neutron stars influence their macroscopic behavior by varying the microscopic coupling constants encoded in different RMF parameter sets. The parameter sets employed in this work are taken from well-established and widely validated RMF models in the literature, including NL3, FSUGold, S271, and Z271. Through numerical modeling, the effects of variations in these parameter sets on the maximum mass, radius, energy density, and pressure of neutron stars are systematically investigated. The results demonstrate that the choice of parameter set has a significant impact on the maximum mass that a neutron star can support. In particular, stiffer parameter sets lead to larger maximum masses, whereas softer parameter sets result in smaller maximum masses.

Keywords: Neutron Star, Tolman–Oppenheimer–Volkoff, Equation of State, Relativistic Mean Field.

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INTRODUCTION

Neutron stars are among the densest objects in the universe. These stars are formed from the remnants of massive stars that undergo supernova explosions (Carroll & Ostlie, 2019). A neutron star can have a mass exceeding 1.5 times the mass of the Sun ($M_{\odot}$) while having a radius of only about 12 km, thus making neutron stars very compact objects (Lattimer & Prakash, 2004). Neutron stars exhibit extremely high density, reaching 2-3 times the normal nuclear density (ρ_0) on average. At their core, the density can increase up to 10-20 times the normal nuclear density (Alrizal & Sulaksono, 2016). Neutron stars can be classified as exotic objects due to their unique properties, which distinguish them from normal stars (main-sequence stars). Main-sequence stars remain stable due to the equilibrium between gravitational forces and thermal pressure generated from nuclear fusion, whereas neutron stars are supported by neutron degeneracy pressure (Pols, 2011). This degeneracy pressure arises because a large number of neutrons are confined within a limited volume, forcing them to occupy higher energy states. According to Pauli's exclusion principle, identical fermions cannot occupy the same quantum state, leading to the buildup of pressure that counteracts gravitational collapse (Fowler, 2024). In order to model neutron stars, both the equation of state and the structure equations are required. The structural equations describe neutron stars from a macroscopic perspective, particularly through differential equations that govern the radial gradient of pressure. The structure of neutron stars can be analyzed using the Tolman–Oppenheimer–Volkoff (TOV) equation, as shown in equation (1) below (Llamas & Dove, 2024):

$$\frac{dP}{dr} = -\frac{G\epsilon M}{r^2} \left(1 + \frac{P}{\epsilon}\right) \left(1 + \frac{4\pi Pr^3}{M}\right) \left(1 - \frac{2GM}{r^2}\right)^{-1} \quad (1)$$

Which equation for the distribution of mass:

$$\frac{dM}{dr} = 4\pi\epsilon r^2 \quad (2)$$

The equation above represents the relativistic structure equation for neutron stars, as their extremely high density requires the inclusion of relativistic effects. Here, G is the gravitational constant expressed in fm/MeV , P denotes the pressure in fm/MeV , ϵ represents the energy density in MeV/fm^3 , and M is the stellar mass expressed in units of solar mass MeV/fm^3 .

Modeling neutron stars also required an equation that governs their microscopic properties, namely the equation of state. The equation of state describes the relationship between pressure and energy density. Various models of equations of state have been proposed, ranging from simple formulations to more complex ones. Some of these models include the relativistic effect, while others do not. For example, (Suleiman et al., 2022) employed a polytropic equation of state, which has a relatively simple form, characterized by a power law relation, as shown in equation 3 below

$$P = K\rho^{\Gamma} \quad (3)$$

This simple polytropic equation, where P represents the pressure, K is a constant parameter, ρ denotes the energy density, and Γ the relativistic adiabatic constant has several limitations. In particular, it does not ensure continuity of higher-order derivatives, making it unsuitable for describing dynamic microscopic behavior. In addition, it is highly sensitive to the consistency of the crust-core transition, which limits its applicability primarily to the crust region. In contrast, (Wang et al., 2024), employed a more sophisticated equation of state, namely Skyrme. This equation of state incorporates more complex quantum physics terms to describe nuclear interactions. However, this equation of state still does not apply relativistic effects, making it less realistic for massive neutron stars (with mass above 2 times mass of the sun). Therefore, an equation of state that can combine the quantum physics and relativistic effects is required. In this study, an equation of state will be used based on the

relativistic mean field (RMF) approach. This model provides a relativistic theoretical framework to describe neutron star matter, in which the interaction between nucleons (proton and neutron) inside neutron stars is mediated by the exchange of meson fields (Alrizal, 2016). The RMF model is constructed through a Lagrangian density that describes the dynamics of matter inside neutron stars (Alrizal, 2017). The total lagrangian of the RMF model is given as follows:

$$\mathcal{L} = \mathcal{L}_{B,L} + \mathcal{L}_M + \mathcal{L}_{int}$$

From the most left to the right, lagrangian describe total barion and lepton contributions, the meson field terms, and the interaction terms. In this study, the RMF model is constructed based on three meson fields, namely the meson σ , meson ω and meson ρ , each of which represents a different type of interaction. The meson σ describes attractive interactions between nucleons, the meson ω describes repulsive interactions between nucleon and the meson ρ describes the isospin interaction (Alrizal, 2016). All meson fields can be described as lagrangian term as shown below:

$$\begin{aligned} \mathcal{L}_{RMF} = & \bar{\psi}(x) \left[\gamma^\mu (i\partial_\mu - g_\omega \omega_\mu(x)) - \frac{g_\rho}{2} \tau_3 \rho - (M - g_\sigma \sigma) \right] \psi - \frac{1}{2} m_\sigma^2 \sigma^2(x) - \frac{k}{3!} (g_\sigma \sigma(x))^3 \\ & - \frac{\lambda}{4!} (g_\sigma \sigma(x))^4 + \frac{1}{2} m_\omega^2 \omega^\mu(x) \omega_\mu(x) + \frac{\zeta}{4!} (g_\omega^2 \omega_0)^2 + \frac{1}{2} m_\rho^2 \rho_0^2 \\ & + \Lambda_v (g_\omega \omega_0)^2 (g_\rho \rho_0)^2 \end{aligned} \quad (5)$$

With the expectation value of equation 5:

$$\begin{aligned} \langle \mathcal{L} \rangle = & -\frac{1}{2} m_\sigma^2 \sigma^2(x) - \frac{k}{3!} (g_\sigma \sigma(x))^3 - \frac{\lambda}{4!} (g_\sigma \sigma(x))^4 + \frac{1}{2} m_\omega^2 \omega(x) \omega_\mu(x) + \frac{\zeta}{4!} (g_\omega^2 \omega_0)^2 + \\ & \frac{1}{2} m_\rho^2 \rho_0^2 + \Lambda_v (g_\omega \omega_0)^2 (g_\rho \rho_0)^2 \end{aligned} \quad (6)$$

Using the relationship between energy density and pressure as shown:

$$\begin{aligned} \epsilon &= \langle i\bar{\psi} \gamma_0 \partial_0 \psi \rangle - \langle \mathcal{L} \rangle \\ P &= \frac{1}{3} \langle i\bar{\psi} \gamma^i \partial_i \psi \rangle - \langle \mathcal{L} \rangle \end{aligned} \quad (7)$$

The study conducted by (Diener, 2008) derived the solutions for the expectation values of the operators in equations 7 and 8. Consequently, the corresponding expressions for the energy density and pressure are given as follows:

$$\begin{aligned} \epsilon = & \frac{1}{2} m_\sigma^2 \sigma_0^2 + \frac{k}{3!} (g_\sigma \sigma_0)^3 + \frac{\lambda}{4!} (g_\sigma \sigma_0)^4 - \frac{1}{2} m_\omega^2 \omega_0^2 - \frac{\zeta}{4!} (g_\omega \omega_0)^4 - \frac{1}{2} m_\rho^2 \rho_0^2 \\ & - \Lambda_v (g_\omega \omega_0)^2 (g_\rho \rho_0)^2 + g_\omega \omega_0 (\rho_n + \rho_p) - \frac{1}{2} g_\rho \rho_0 (\rho_p - \rho_n) + \frac{1}{\pi^2} \int_0^{k_p} dk \sqrt{k^2 + m^{*2}} \\ & + \frac{1}{\pi^2} \int_0^{k_n} dk \sqrt{k^2 + m^{*2}} \end{aligned} \quad (8)$$

$$\begin{aligned} p = & -\frac{1}{2} m_\sigma^2 \sigma_0^2 - \frac{k}{3!} (g_\sigma \sigma_0)^3 - \frac{\lambda}{4!} (g_\sigma \sigma_0)^4 + \frac{1}{2} m_\omega^2 \omega_0^2 + \frac{\zeta}{4!} (g_\omega \omega_0)^4 + \frac{1}{2} m_\rho^2 \rho_0^2 \\ & + \Lambda_v (g_\omega \omega_0)^2 (g_\rho \rho_0)^2 + \frac{1}{\pi^3} \int_0^{k_p} dk \frac{k^2}{\sqrt{k^2 + m^{*2}}} + \frac{1}{\pi^3} \int_0^{k_p} dk \frac{k^2}{\sqrt{k^2 + m^{*2}}} \end{aligned} \quad (9)$$

Where ρ_p and ρ_n are proton and neutron number density, respectively. The sigma term in the equation represents the sum of integrals over proton and neutron, where k denotes the Fermi momentum, while m^* corresponds to the effective mass, which is defined as follows:

$$m^* = m_n - g_\sigma \sigma_0 \quad (10)$$

Based on Equations (8) and (9), the behavior of neutron stars within the RMF framework is highly determined by the choice of parameter sets, such as coupling constants and interaction parameters. In these equations, m_n represents the neutron mass measured in MeV, while g_0 and σ_0 denote the sigma meson coupling constant and the expectation value of the sigma meson field, respectively. Therefore, this study employs several RMF parameter sets that are commonly used in the literature. The effects of the parameter sets are then analyzed in terms of the macroscopic properties of neutron stars, including maximum mass, radius, energy density, and pressure distribution.

METHOD

In order to solve the governing equations, the Python programming language is employed. In general, the computational procedure used in this study can be divided into two main parts, namely the algorithm for solving the equation of state and the algorithm for determining the structure of neutron stars. The algorithm for solving the equation of state is illustrated in Figure 1:

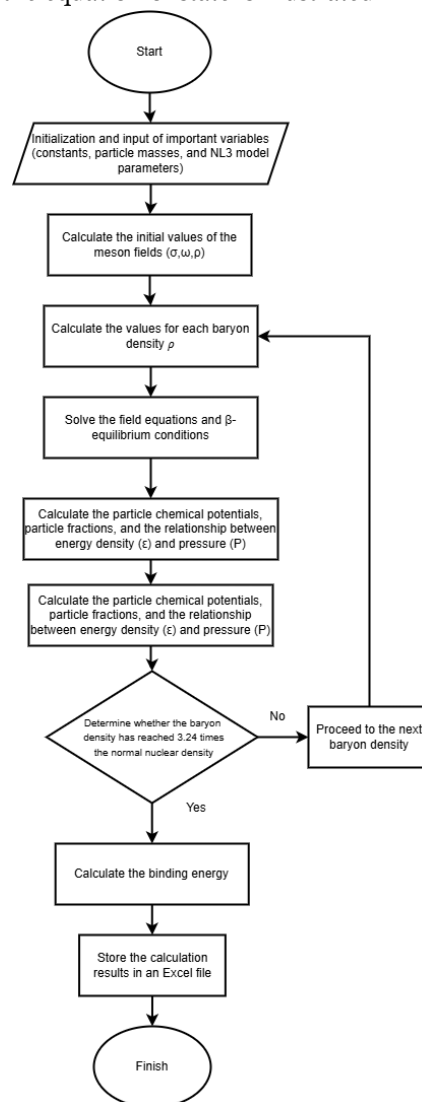


Figure 1. Algorithm for solving the equation of state

Based on Figure 1, the modeling of neutron stars starts with the definition of important variables, including conversion factors, the mass of neutron, the mass of proton, the mass of electron

as well as other relevant quantities. Next, define a function to calculate the initial condition of neutron star, which is used to determine the initial values of the meson fields (σ, ω, ρ). Subsequently, a root-finding function is defined to solve the β -equilibrium condition, allowing the determination of equilibrium number density of protons, neutrons, electrons and muons inside neutron stars. These results are then used to establish a relationship between energy density and pressure based on equations 8 and 9. Finally, the solver function is defined to systematically execute all preceding steps. The output of this algorithm is a table describing the relationship between energy density and pressure. Next, the algorithm for determining the structure of neutron stars is illustrated in Figure 2:

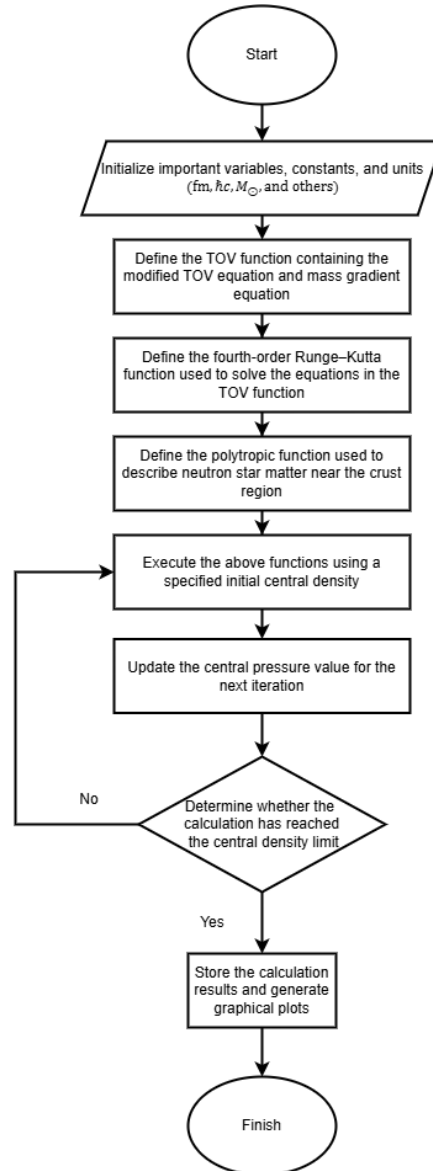


Figure 2. Algorithm to determine the structure of neutron stars

This algorithm begins with the definition of important variables. Next, a function representing the TOV equation is defined; this function consists of two differential equations, namely the TOV equation and mass distribution equation, based on equations 1 and 2 respectively. The fourth-order Runge-Kutta method is then implemented to solve these differential equations. Finally, a solver function is defined to systematically execute all preceding steps, starting from initial conditions and integrating up to certain boundary conditions.

In order to investigate the effect of parameter sets on the Relativistic mean field model and the resulting neutron star structure, several parameter sets are employed. These parameter sets, namely NL3, FSUGold, S271, and Z271, have been widely validated in the literature. The corresponding values of these parameter sets are presented in Table 1:

Table 1. Parameter Sets (Diener, 2008; Todd & Piekarewicz, 2003; Piekarewicz, 2006)

Model	g_σ^2	g_ω^2	g_ρ^2	κ (MeV)	λ	ζ	Λ_ν	m_σ (MeV)	m_ω (MeV)	m_ρ (MeV)
NL3	104.3871	165.5854	79.6	3.8599	-0.01591	0	0	508.194	782.5	763
FSUGold	112.1996	204.5469	138.4701	1.4203	0.0238	0.06	0.03	491.5	783	763
S271	81.1071	116.7655	85.4357	6.6834	-0.01580	0	0	505	783	763
Z271	49.4401	70.6689	90.2110	6.1696	0.15634	0.06	0	465	783	763

RESULTS AND DISCUSSION

In this section, the results of the study are discussed. The discussion begins with the equation of state, including the relationship between energy density and pressure, the characteristics of the RMF parameter sets used, and the relationship between pressure and baryon density. These results are essential because the equation of state provides the primary input for modeling the internal structure and macroscopic properties of neutron stars.

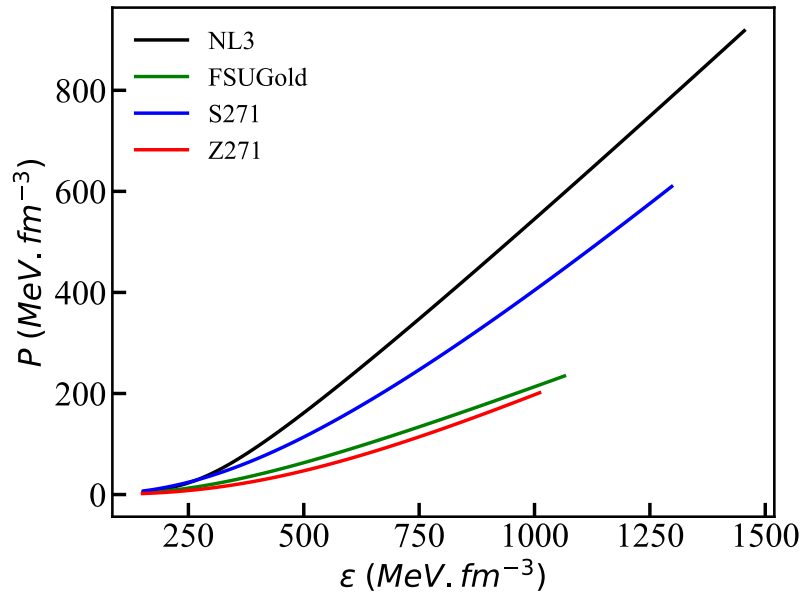


Figure 3. Relationship between energy density and pressure

Figure 3 shows the relationship between energy density and pressure. The results indicate that the NL3 parameter set exhibits the steepest increase in pressure with respect to energy density. In this case, the pressure reaches $555.78 \text{ MeV}/\text{fm}^3$ at an energy density of $1000 \text{ MeV}/\text{fm}^3$. In contrast, other parameter sets such as FSUGold, S271 and Z217 yield lower pressure at $213.89 \text{ MeV}/\text{fm}^3$, $407.66 \text{ MeV}/\text{fm}^3$ and $197.997 \text{ MeV}/\text{fm}^3$, respectively, at the same energy density. This indicates that the gradient of the equation of state for the NL3 parameter set is larger compared to the other

parameter sets. The stiffness of an equation of state characterizes how rapidly the pressure increases with respect to energy density. (Ecker & Rezzolla, 2023):

$$C_s^2 = \left(\frac{\partial P}{\partial \epsilon} \right)_s \quad (11)$$

Equation 11 determines the stiffness of an equation of state. Since stiffness is defined through the ratio between changes in pressure and energy density, it is dimensionless and has no associated unit. A stiffer equation of state implies that a neutron star can support a higher maximum mass. Therefore, the NL3 parameter set is expected to yield the highest maximum mass compared to other parameter sets. The stiffness values for all four parameter sets are represented in Table 2:

Table 2. The stiffness values for all parameter sets

Parameter Set	Stiffness
NL3	0.742
FSUGold	0.258
S271	0.526
Z271	0.173

Based on Table 2, the NL3 parameter set is identified as the stiffest, followed by S271, FSUGold and Z271. In several studies, a parameter set is classified as stiff if its stiffness value exceeds 0.5, while values below 0.5 are considered to correspond to soft parameter set. Next, relationship between baryon number density and proton fraction is examined.

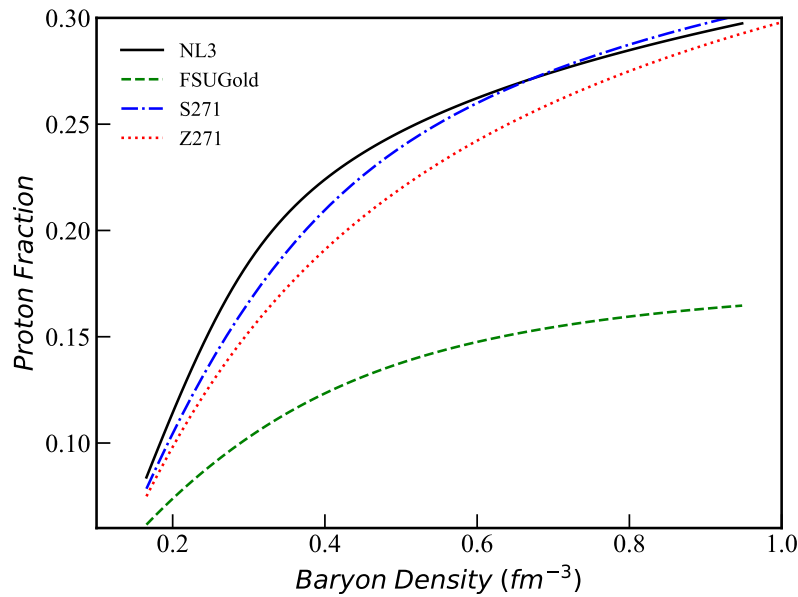


Figure 4. Relationship between baryon density and proton fraction

The proton fraction represents the relative concentration of neutrons at a given baryon density. Figure 4 shows that all parameter sets exhibit a similar trend, where the proton fraction increases with increasing baryon number density, forming an approximately logarithmic behavior. This behavior arises because, at low baryon density, the proton concentration is relatively small, while increasing baryon density leads to a higher proton fraction. At sufficiently high density, the composition tends to approach a more stable configuration between protons and neutrons. A similar

result has also been reported by (Wu et al., 2021). Next, the structure of neutron star is examined. First, the relationship between mass and central energy density is analyzed.

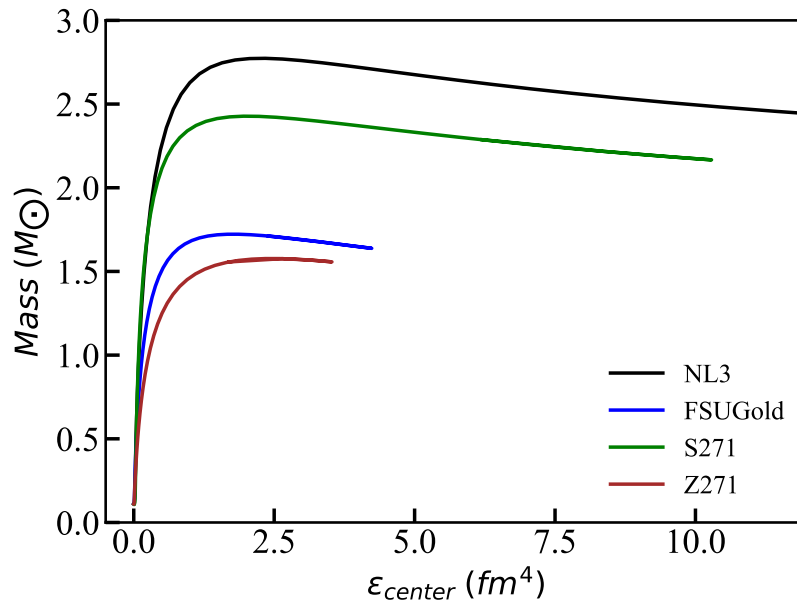


Figure 5. Relationship between mass and central energy density

Figure 5 shows mass in units of the solar mass. The results indicated that the NL3 parameter set can support the highest mass compared to other parameter sets, which is consistent with the fact NL3 parameter set is the stiffest parameter set.

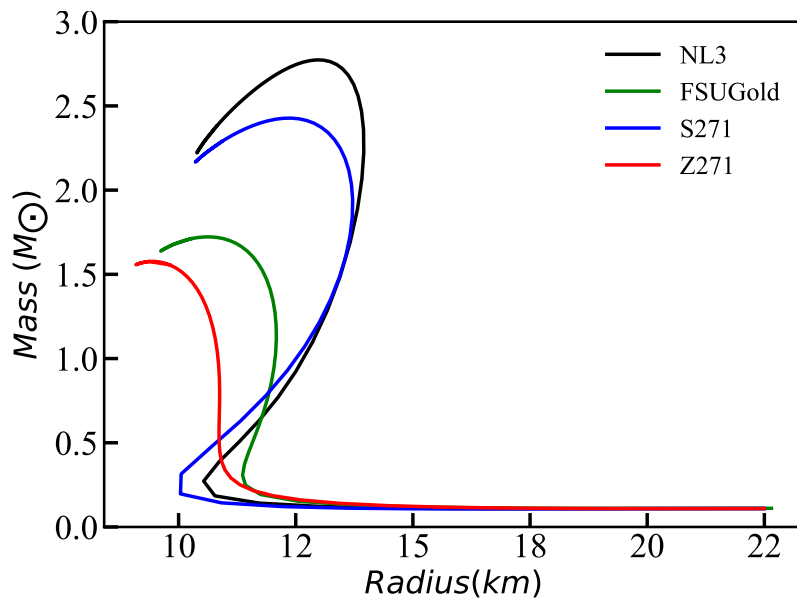


Figure 6. Relationship between mass and radius

Figure 6 shows the relationship between mass and radius of a neutron star. The curve exhibits a non-monotonic behavior, where a single radius can correspond to two different mass values.

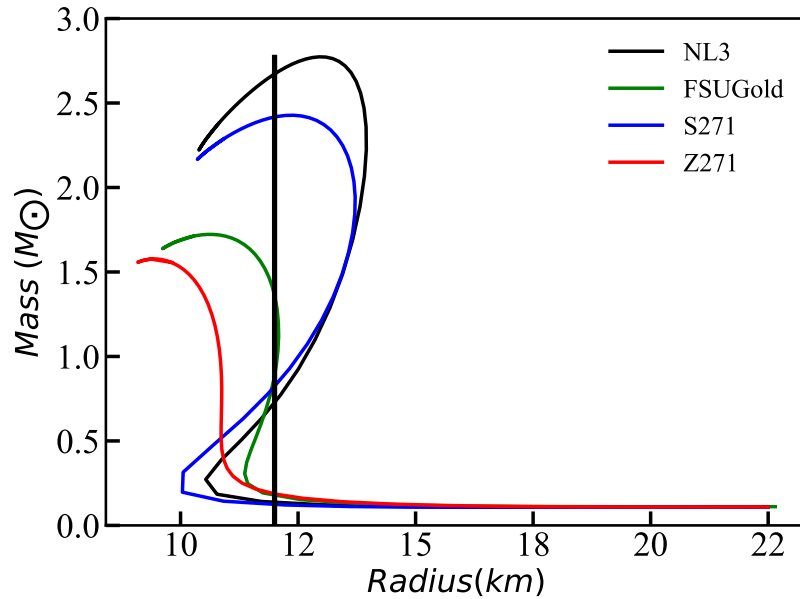


Figure 7. Hubungan massa dengan jari-jari bintang neutron

This behavior arises because Figures 6 and 7 are presented as a “scatter plot of the maximum mass obtained from each iteration. In modeling neutron star structure, each central pressure value is treated as an initial condition, and for each of these values, an iterative process generates the corresponding mass-radius relation for a given central pressure. The integration is terminated when the condition $P \leq 0$ is reached, which defines the surface of the star. The final values of mass and radius are then recorded and plotted in Figures 6 and 7. While Figure 8 illustrates the iteration process for a single central pressure.

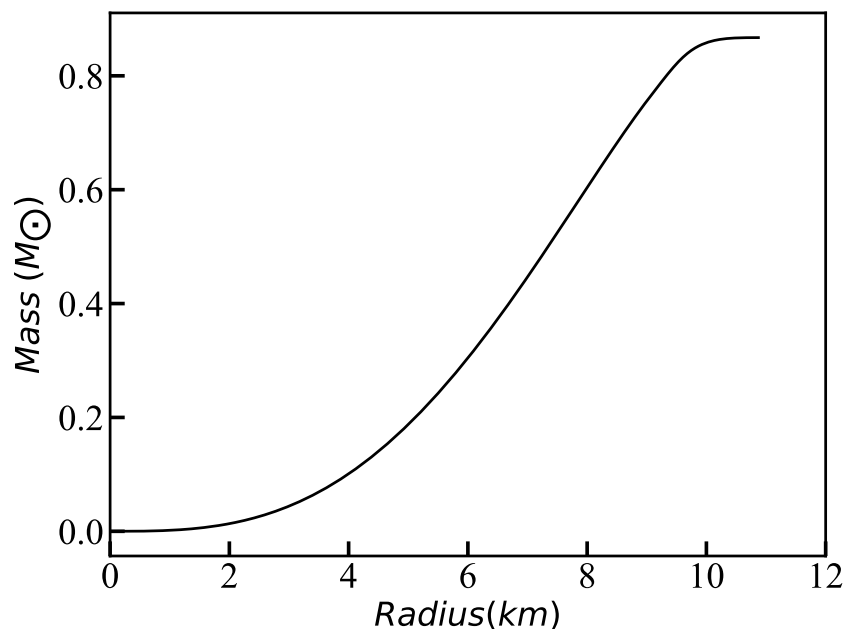


Figure 8. Relationship between mass and radius for a single central pressure

Iteration in figure 8 is conducted one hundred times, where for each final value being recorded and plotted to make figures 6 and 7. The mass-radius relations shown in Figures 6 and 7 may appear difficult to interpret directly, as the relationship between mass and radius is not strictly monotonic.

However, these results remain highly valuable for examining neutron stars in realistic astrophysical contexts. Observationally, the mass of neutron stars can be determined through analysis of the gravitational effects they create. In contrast, the measurement of neutron star radii and internal structure remains challenging. This is where figures 6 and 7 become particularly useful. Once the mass of a neutron star is known from observations, it can be compared with the theoretical mass-radius relations presented in these figures. From this comparison, the corresponding radius of neutron star can be estimated. Furthermore, to investigate the internal structure of the neutron star, such as the relationship between mass and central density, Figure 5 can be utilized. Several observational results of neutron stars have been reported in the literature, as shown below:

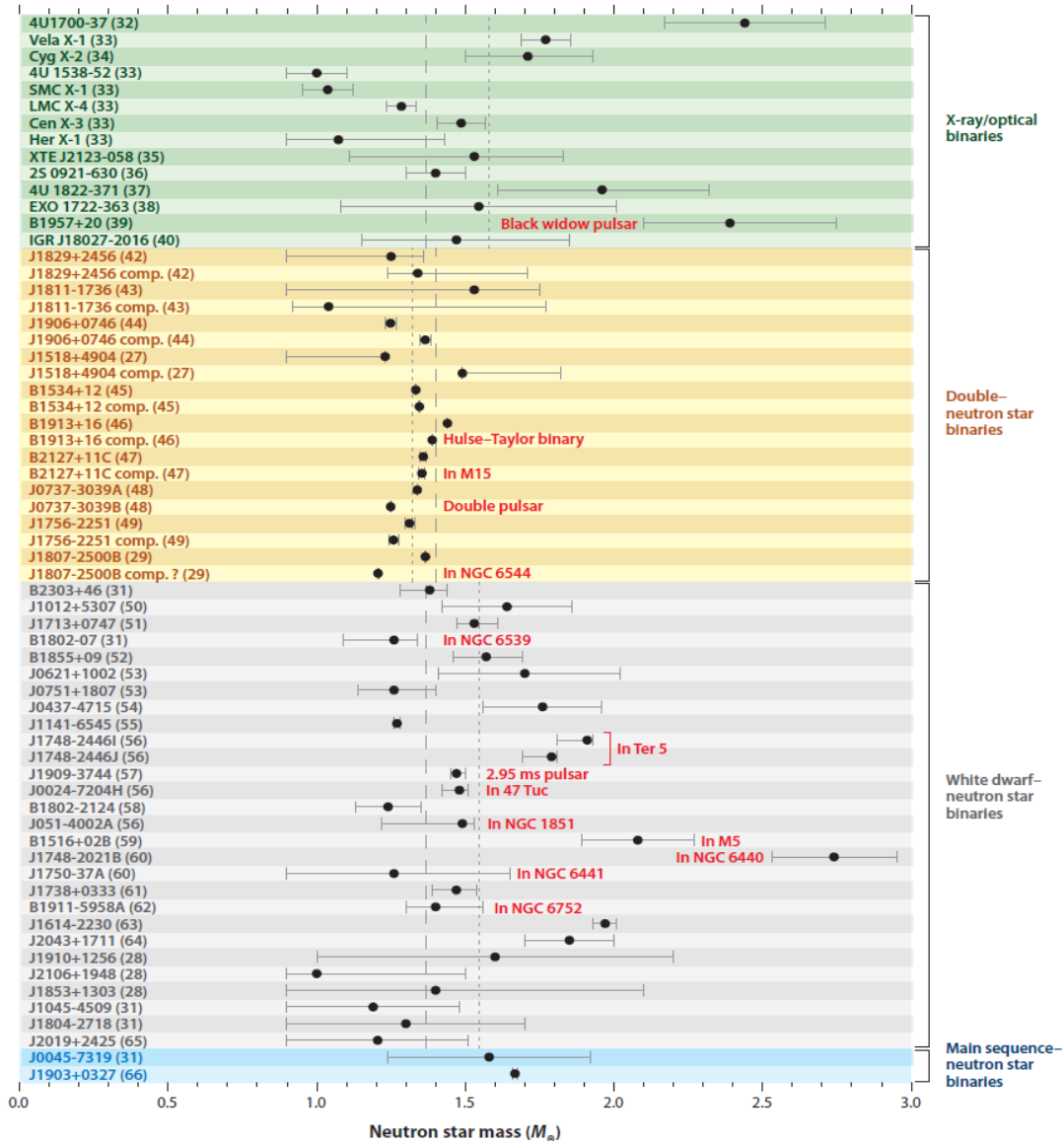


Figure 9. All observed neutron stars (Lattimer, 2012)

An example that can be used to test the model is the neutron star merger event GW170817, reported by the LIGO Scientific Collaboration and Virgo Collaboration (Abbott et al., 2018). This event corresponds to the merger of two neutron stars, with a total mass of approximately 2.7 solar masses. Observational analysis constrains the typical neutron star radius to be around 11.9 ± 1.4 Km. The results suggest that stiff equations of state are less suitable, as they predict radii inconsistent with

observational data. Therefore, the findings are more consistent, such as FSUGold or Z271. By comparing the mass-radius relations obtained from all parameter sets, the compatibility with observational constraints can be evaluated, as shown in Figure 10.

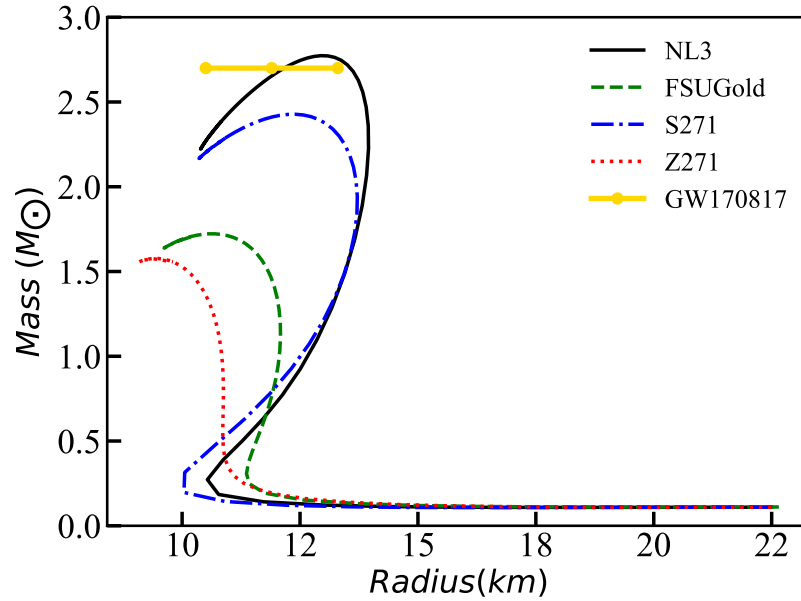


Figure 10. Mass-radius relations and GW170817 position

Figure 6 shows the position of GW170817 in the mass-radius diagram, corresponding to a total system mass of approximately $2.7 M_{\odot}$. This relatively high mass arises from the merger of two neutron stars in a binary system. The observational constraints derived from GW170817 provide limits on the neutron star equation of state, particularly through tidal deformation measurements. Figure 6 shows that stiff parameter sets, such as NL3, tend to predict large radii and higher maximum masses. In contrast, moderately soft parameter sets, such as FSUGold, and Z271, produce mass-radius relations within the observational constraints. Another observational test case is provided by (Riley et al., 2019), who analyzed the pulsar PSR J0030+0451. The observations constrain the neutron star mass to approximately $1.34 M_{\odot}$, with radius of $12.17^{+1.14}_{-1.19}$

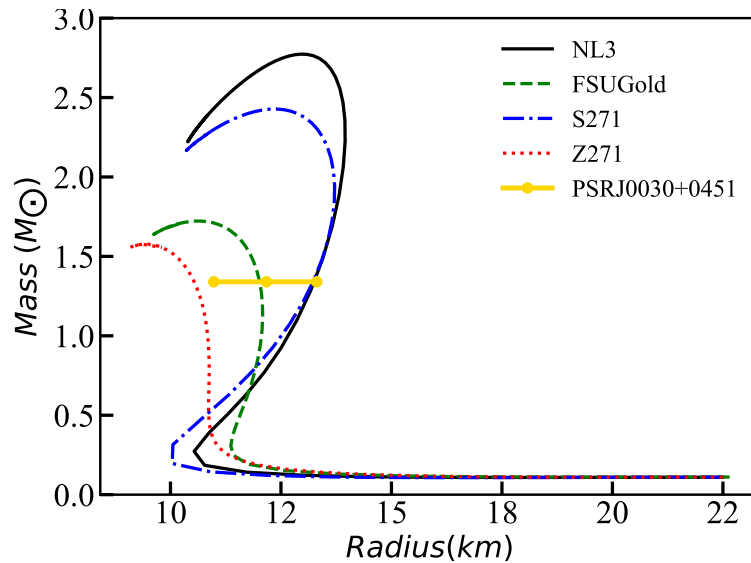


Figure 11. Mass-radius relations and PSR J0030+0451 position

By comparing this constraint with the mass-radius relations shown in Figure 6, the position of PSR J0030+0451 can be evaluated for each parameter set. The results indicate that parameter sets predicting extremely small radii tend to underestimate the observed radius, while overly stiff parameter sets predict radii that are slightly larger than the central observed value. Overall, the observational constraint lies within a region spanned by a moderately stiff equation of state, suggesting that neither extremely soft nor extremely stiff provided the best agreement. Instead, parameter sets such as S271 and FSUGold appear to be more consistent with the observed mass-radius range

CONSLUSION

The result of this study shows that variations in parameter sets significantly affect both microscopic and macroscopic properties of neutron stars. At the microscopic level, different parameter sets modify the equation of state, in particular, the pressure response to increasing energy density. As a consequence, stiffer equations of state, such as NL3, yield higher maximum masses and larger radii. In contrast, softer parameter sets, such as Z271, produce lower maximum masses and lower radii. While intermediate parameter sets provide a balance in mass-radius relations. Furthermore, comparisons with observational data, such as gravitational wave event GW170817 and measurement from PSR J0030+045, indicate the usefulness of various parameter sets, where GW170817 is suitable with a stiff parameter set, while PSR J0030+045 is suitable with a moderate-stiff parameter set.

DECLARATION OF GENERATIVE AI

The authors declare that no generative AI or AI-assisted technologies were used in the writing process of this manuscript.

CONFLICTING INTEREST STATEMENT

The authors states that there is no conflict of interest in the publication of this article.

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