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INVESTIGATION OF THE INTERNAL STRUCTURE OF NEUTRON STARS IN MODIFIED GRAVITY THEORY

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Abstract. Neutron stars are among the densest compact objects in the universe and provide a unique astrophysical laboratory for testing gravity under extreme conditions. Their internal structure is mainly determined by the equation of state of ultra-dense matter and by the gravitational theory used to describe hydrostatic equilibrium. In General Relativity, the structure of neutron stars is commonly studied through the Tolman–Oppenheimer–Volkoff equations. However, recent developments in astrophysical observations and gravitational-wave astronomy have motivated the study of neutron stars within modified gravity theories. In such theories, additional geometric or scalar degrees of freedom may affect the mass-radius relation, central density, pressure distribution, tidal deformability and stability of neutron stars. This article discusses the theoretical basis for investigating neutron star interiors in modified gravity, focusing especially on f(R) gravity, scalar-tensor theories and matter-curvature coupling models. The study emphasizes that neutron stars can serve as powerful tools for testing gravitational theories beyond General Relativity.

Keywords: neutron star, modified gravity, f(R) gravity, equation of state, mass-radius relation, compact stars.

Annotatsiya. Neytron yulduzlar Koinotdagi eng zich kompakt obyektlardan biri bo‘lib, gravitatsiyani ekstremal sharoitlarda sinovdan o‘tkazish uchun noyob astrofizik laboratoriya vazifasini bajaradi. Ularning ichki tuzilishi asosan o‘ta zich moddaning holat tenglamasi hamda gidrostatik muvozanatni tavsiflovchi gravitatsiya nazariyasi bilan belgilanadi. Umumiy nisbiylik nazariyasida neytron yulduzlarning tuzilishi odatda Tolman–Oppengeymer–Volkov tenglamalari yordamida o‘rganiladi. Biroq, astrofizik kuzatuvlar va gravitatsion to‘lqinlar astronomiyasidagi so‘nggi yutuqlar neytron yulduzlarni modifikatsiyalangan gravitatsiya nazariyalari doirasida tadqiq etishga katta qiziqish uyg‘otdi. Bunday nazariyalarda qo‘shimcha geometrik yoki skalyar erkinlik darajalari neytron yulduzlarning massa-radius bog‘lanishi, markaziy zichligi, bosim taqsimoti, tidal deformatsiyasi va barqarorligiga sezilarli ta’sir ko‘rsatishi mumkin. Ushbu maqolada neytron yulduzlarning ichki tuzilishini modifikatsiyalangan gravitatsiya nazariyalari asosida o‘rganishning nazariy asoslari muhokama qilinadi. Ayniqsa, f(R) gravitatsiya nazariyasi, skalyar-tenzor nazariyalar hamda modda-egrilik o‘zaro ta’siriga asoslangan modellarga alohida e’tibor qaratiladi. Tadqiqot natijalari neytron yulduzlar Umumiy nisbiylik nazariyasidan

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tashqaridagi gravitatsiya nazariyalarini sinovdan o‘tkazishda samarali vosita bo‘lib xizmat qilishi mumkinligini ko‘rsatadi.

Kalit so‘zlar: neytron yulduz, modifikatsiyalangan gravitatsiya, f(R) gravitatsiya, holat tenglamasi, massa-radius bog‘lanishi, kompakt yulduzlar.

Аннотация. Нейтронные звёзды являются одними из самых плотных компактных объектов во Вселенной и представляют собой уникальную астрофизическую лабораторию для проверки гравитации в экстремальных условиях. Их внутренняя структура в основном определяется уравнением состояния сверхплотного вещества и гравитационной теорией, используемой для описания гидростатического равновесия. В рамках общей теории относительности структура нейтронных звёзд обычно изучается с помощью уравнений Толмана–Оппенгеймера–Волкова. Однако последние достижения в области астрофизических наблюдений и астрономии гравитационных волн стимулировали исследования нейтронных звёзд в рамках теорий модифицированной гравитации. В таких теориях дополнительные геометрические или скалярные степени свободы могут оказывать существенное влияние на соотношение массы и радиуса, центральную плотность, распределение давления, приливную деформируемость и устойчивость нейтронных звёзд. В данной статье рассматриваются теоретические основы исследования внутреннего строения нейтронных звёзд в теориях модифицированной гравитации. Особое внимание уделяется теории гравитации f(R), скалярно-тензорным теориям и моделям с взаимодействием между материей и кривизной пространства-времени. Подчёркивается, что нейтронные звёзды могут служить эффективным инструментом для проверки гравитационных теорий, выходящих за рамки общей теории относительности.

Ключевые слова: нейтронная звезда, модифицированная гравитация, гравитация f(R), уравнение состояния, соотношение масса–радиус, компактные звёзды.

INTRODUCTION.

Neutron stars are among the most compact and fascinating astrophysical objects in the universe. They are formed as the final evolutionary stage of massive stars after supernova explosions, when the stellar core undergoes gravitational collapse. Despite having radii of only about 10–14 kilometers, neutron stars may contain masses comparable to or greater than the mass of the Sun. This means that matter inside these objects is compressed to extremely high densities, often exceeding nuclear saturation density. Under such conditions, the behavior of matter, gravity, pressure, and energy cannot be fully understood by ordinary laboratory experiments. Therefore, neutron stars are considered natural

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laboratories for investigating fundamental physics under extreme conditions [1]. The internal structure of neutron stars is determined by the balance between gravitational attraction and the pressure of ultra-dense matter. Gravity tends to compress the star inward, while internal pressure resists collapse and maintains hydrostatic equilibrium. In the framework of General Relativity, this equilibrium is usually described by the Tolman–Oppenheimer–Volkoff equations. These equations make it possible to calculate the variation of pressure, density, enclosed mass, and radius from the center of the star to its surface. However, the results obtained from these equations strongly depend on the equation of state of dense matter. The equation of state describes the relationship between pressure and energy density inside the neutron star and plays a central role in determining its mass-radius relation and stability [2].

One of the most important unresolved problems in neutron star physics is the true nature of matter at extremely high densities. At densities higher than those found in atomic nuclei, matter may not consist only of neutrons, protons, and electrons. It may also contain exotic components such as hyperons, meson condensates, deconfined quark matter, or other possible phases of dense nuclear matter. Since the equation of state at such extreme densities is still uncertain, different theoretical models may lead to different predictions for the maximum mass, radius, compactness, and internal composition of neutron stars. This uncertainty makes neutron stars highly valuable objects for testing both nuclear physics and gravitational theory. Although General Relativity has been very successful in explaining many gravitational phenomena, it may not represent the final and complete theory of gravity. In particular, at very strong gravitational fields, very high densities, or cosmological scales, possible deviations from General Relativity may appear. For this reason, modified gravity theories have attracted considerable attention in modern theoretical physics and astrophysics. These theories extend or modify Einstein's theory by introducing additional geometric terms, scalar fields, higher-order curvature corrections, or couplings between matter and curvature. Such modifications may affect the structure and evolution of compact stars, including neutron stars. In modified gravity theories, the equations governing the internal structure of neutron stars are generally different from those in General Relativity. The standard Tolman–Oppenheimer–Volkoff equations may be modified by additional terms related to curvature, scalar fields, or matter-geometry interactions. As a result, the pressure profile, density distribution, gravitational mass, radius, and stability conditions of neutron stars may change. In some cases, modified gravity can allow neutron stars to support larger maximum masses or produce different mass-radius relations compared with the predictions of General Relativity. Therefore, studying neutron

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stars in modified gravity provides an important opportunity to distinguish between different gravitational models [3].

Among the most widely studied modified gravity models are f(R) gravity, scalar-tensor theories, f(R,T) gravity, and other extensions involving curvature-matter coupling. In f(R) gravity, the gravitational action is generalized by replacing the Ricci scalar R with a function of R. This modification introduces higher-order curvature effects that may become significant in strong gravitational fields. Scalar-tensor theories introduce one or more scalar fields in addition to the metric tensor, which can influence the gravitational interaction inside compact objects. In matter-curvature coupling models, the interaction between matter and geometry may lead to additional forces or corrections to the standard equilibrium equations. These theoretical frameworks provide new ways to study the internal properties of neutron stars. The investigation of neutron stars in modified gravity is also important because of recent progress in astrophysical observations. Precise measurements of massive pulsars, X-ray observations of neutron star radii, and gravitational-wave detections from neutron star mergers have provided new constraints on the properties of compact stars. Observational data related to mass, radius, tidal deformability, and merger dynamics can be used to test the validity of different equations of state and gravitational theories. If the predictions of modified gravity are consistent with observational constraints, such theories may offer alternative explanations for the behavior of gravity under extreme conditions. The study of neutron star interiors in modified gravity theory is therefore a multidisciplinary research topic that connects astrophysics, nuclear physics, relativity, and cosmology. It allows researchers to examine how changes in gravitational theory affect the microscopic and macroscopic properties of compact stars. By comparing theoretical predictions with observational data, it is possible to evaluate whether General Relativity remains valid in the strong-field regime or whether modifications are required. In this context, neutron stars serve as powerful probes of fundamental physics and provide a unique testing ground for theories beyond General Relativity [4].

The main purpose of this article is to examine the internal structure of neutron stars within the framework of modified gravity theories. The study focuses on how modifications to the gravitational field equations influence the pressure distribution, density profile, mass-radius relation, and stability of neutron stars. Special attention is given to the role of the equation of state and to the possible differences between General Relativity and modified gravity predictions. Through this approach, the article aims to provide a theoretical understanding of neutron stars as compact objects and to highlight their significance in testing alternative theories of gravity.

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Theoretical background and research framework

The study of neutron star interiors in modified gravity requires a clear theoretical framework because the structure of such compact objects depends on both the properties of dense matter and the gravitational model used. In standard General Relativity, the internal equilibrium of a neutron star is described by the Tolman–Oppenheimer–Volkoff equations. These equations determine how pressure, density, mass, and radius change from the center of the star to its surface. However, in modified gravity theories, additional terms may appear in the gravitational field equations. These terms can change the balance between gravitational attraction and internal pressure, leading to different predictions for the structure and stability of neutron stars [5].

Modified gravity theories are especially important in the strong-field regime, where gravitational effects are extremely intense. Since neutron stars have very high density and strong curvature, they provide a suitable environment for testing possible deviations from General Relativity. In this context, theoretical models such as f(R) gravity, scalar-tensor gravity, and matter-curvature coupling theories can be used to examine whether alternative gravitational effects influence the maximum mass, radius, compactness, and pressure distribution of neutron stars [6]. The reliability of a theoretical study increases when the main physical parameters and research stages are clearly presented. For this reason, the present study focuses on the relationship between the gravitational model, equation of state, and internal stellar parameters. The basic structure of the research framework is shown in Table 1 and Figure 1.

Table 1.

Main physical parameters used in the study of neutron star interiors

Parameter	Scientific meaning	Role in neutron star structure
Central density	Density at the core of the neutron star	Determines the compactness and internal composition of the star
Pressure profile	Distribution of pressure from the center to the surface	Shows how matter resists gravitational collapse
Equation of state	Relationship between pressure and energy density	Defines the physical behavior of ultra-dense matter
Stellar mass	Total gravitational mass of the neutron star	Used to evaluate maximum mass and stability

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Stellar radius	Distance from the center to the surface	Important for determining the mass-radius relation
Compactness	Ratio between mass and radius	Indicates the strength of the gravitational field
Gravitational model	General Relativity or modified gravity theory	Determines the form of the equilibrium equations
Stability condition	Criterion showing whether the star remains stable	Helps identify physically acceptable stellar models

Modified Gravity Theory
↓
Modified Field Equations
↓
Modified Hydrostatic Equilibrium Equations
↓
Equation of State of Dense Matter
↓
Calculation of Internal Parameters
↓
Mass – Radius – Density – Pressure Relations
↓
Stability Analysis of Neutron Stars

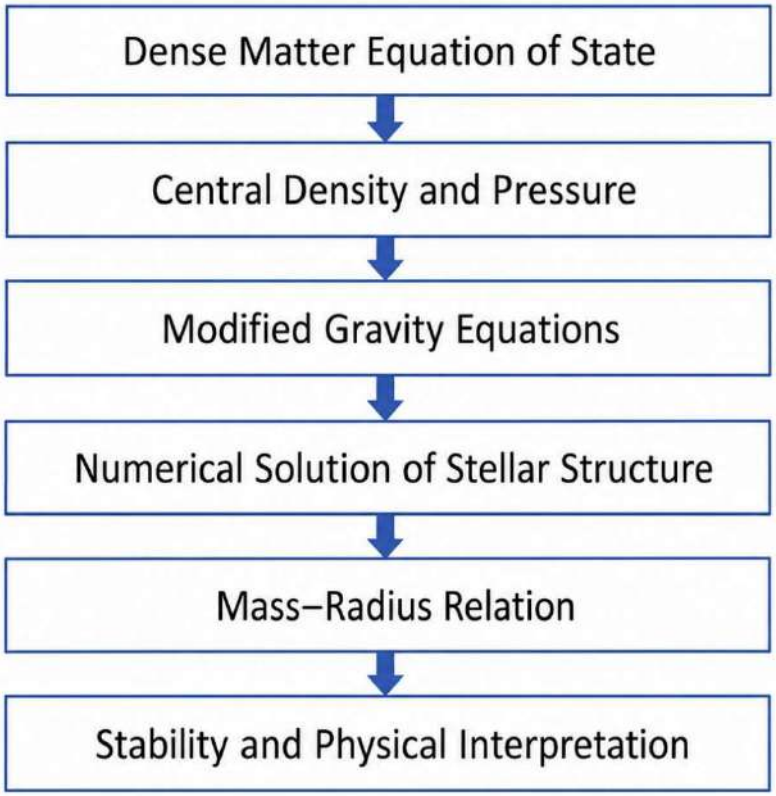
Figure 1. Conceptual framework for studying neutron star interiors in modified gravity

This framework shows that the internal structure of neutron stars cannot be explained only by the equation of state. The gravitational theory also plays a decisive role. If the gravitational field equations are modified, the resulting hydrostatic equilibrium equations may also change. As a result, the predicted mass-radius relation, central density, pressure profile, and stability limits may differ from those obtained in General Relativity. The inclusion of a table and a conceptual diagram helps to organize the theoretical basis of the article. Table 1 summarizes the main physical parameters that are commonly used in neutron star studies, while Figure 1 illustrates the logical sequence of the research process. Such a presentation makes the article more systematic and scientifically reliable, because it clearly shows which variables are considered and how they are connected to the main research problem. Therefore, the investigation of neutron stars in modified gravity should be carried out through a combined analysis of gravitational theory, dense matter physics, and stellar stability. This approach allows researchers to compare the predictions of General Relativity with those of

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modified gravity models and to evaluate whether alternative theories can provide a better explanation for compact star observations [7].

Figure 2. Research Model of Neutron Star Structure in Modified Gravity



This diagram illustrates the general research sequence used to investigate the internal structure of neutron stars within the framework of modified gravity theory. The process begins with the selection of an appropriate equation of state for dense matter, which defines the relationship between pressure and energy density inside the star. After determining the central density and pressure, the modified gravitational field equations are applied to describe the hydrostatic equilibrium of the neutron star. These equations are then solved numerically in order to obtain the main structural properties of the star. As a result, the mass-radius relation is derived and used to evaluate the physical behavior of the model. Finally, the stability and physical interpretation of the neutron star configuration are analyzed. This research model shows that the structure of neutron stars depends not only on the properties of dense matter, but also on the gravitational theory used in the calculation [8].

DISCUSSION.

The investigation of neutron star interiors in modified gravity theory provides an important opportunity to examine the behavior of gravity under extreme physical conditions. Neutron stars are characterized by very high densities, strong gravitational fields, and compact structures. Therefore, even

small modifications to the gravitational field equations may lead to significant changes in their internal properties. In this context, the study of neutron stars is not limited only to astrophysical modeling, but also contributes to the broader discussion about the validity of General Relativity in the strong-field regime. The results and theoretical considerations discussed in this study show that the internal structure of neutron stars depends on two main factors: the equation of state of dense matter and the gravitational model used in the calculation. In General Relativity, the equilibrium configuration of neutron stars is determined by the standard Tolman–Oppenheimer–Volkoff equations. However, in modified gravity theories, additional curvature terms, scalar fields, or matter-geometry couplings may appear in the field equations. These additional terms can alter the pressure gradient, density distribution, mass-radius relation, and stability conditions of the star.

One of the most important aspects of modified gravity models is their possible effect on the maximum mass of neutron stars. Observations of massive pulsars indicate that neutron stars with masses around two solar masses exist. This observational fact creates strong constraints on both the equation of state and gravitational theory. Some equations of state may not be able to support such massive neutron stars within the framework of General Relativity. In this case, modified gravity theories may provide alternative explanations by allowing additional gravitational corrections that change the equilibrium structure of the star. Another important issue is the mass-radius relation. The radius of a neutron star is directly related to the stiffness of dense matter and to the strength of gravity inside the star. If gravity is modified, the same equation of state may produce a different radius and compactness compared with General Relativity. Therefore, comparing theoretical mass-radius curves with observational data is one of the most effective ways to test modified gravity models. In particular, X-ray observations and gravitational-wave measurements from neutron star mergers can provide important constraints on the allowed parameter space of such theories.

The equation of state remains one of the largest sources of uncertainty in neutron star studies. At extremely high densities, matter may include exotic components such as hyperons, meson condensates, or deconfined quark matter. These components may soften or stiffen the equation of state and change the predicted maximum mass and radius of the star. Modified gravity adds another layer of complexity to this problem because changes in the gravitational sector may produce effects similar to changes in the equation of state. For this reason, it is necessary to analyze the equation of state and the gravitational model together rather than separately. The stability of neutron stars is also strongly influenced by the chosen gravitational theory. A physically acceptable neutron star model must

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satisfy stability conditions, such as positive pressure and density, regular behavior at the center, decreasing pressure toward the surface, and a stable mass-central density relation. In modified gravity, these conditions may require additional constraints because new degrees of freedom can introduce new modes of instability. Therefore, stability analysis is essential for determining whether a theoretical neutron star configuration is physically realistic.

From a theoretical point of view, modified gravity models such as f(R) gravity, scalar-tensor gravity, and matter-curvature coupling theories provide useful frameworks for studying compact stars. These models can extend the standard description of gravity and may explain certain astrophysical or cosmological phenomena without introducing unknown forms of matter or energy. However, their predictions must be consistent with existing observational data. Therefore, neutron stars play a crucial role in testing the physical reliability of these theories. Overall, the discussion shows that neutron stars are powerful probes of gravitational physics. Their internal structure can reveal whether General Relativity remains valid in extremely strong gravitational fields or whether alternative theories are required. The study of neutron stars in modified gravity therefore represents an important bridge between theoretical physics, astrophysics, and observational astronomy.

CONCLUSION.

In this article, the internal structure of neutron stars was examined within the framework of modified gravity theory. Neutron stars were considered as compact astrophysical objects that provide a natural laboratory for testing gravity and dense matter under extreme conditions. The study emphasized that their structural properties are determined by the combined effects of the equation of state and the gravitational theory used to describe hydrostatic equilibrium. The analysis shows that modified gravity theories may lead to different predictions from General Relativity regarding the mass, radius, central density, pressure profile, compactness, and stability of neutron stars. In particular, additional curvature terms, scalar fields, or matter-geometry interactions can modify the standard equilibrium equations and influence the internal behavior of the star. These modifications may affect the maximum mass and mass-radius relation, which are among the most important observable properties of neutron stars.

It can be concluded that the study of neutron stars in modified gravity is scientifically significant for two main reasons. First, it helps to improve our understanding of ultra-dense matter and compact stellar objects. Second, it provides a strong-field test of gravitational theories beyond General Relativity. By comparing theoretical predictions with observational data from pulsars, X-ray measurements, and gravitational-wave events, it is possible to evaluate the

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validity of modified gravity models. The results of this theoretical discussion indicate that modified gravity should be considered as an important alternative framework in neutron star research. However, reliable conclusions require careful selection of the equation of state, precise numerical solutions, and detailed stability analysis. Future studies should focus on comparing different modified gravity models with updated observational constraints in order to determine which theoretical approaches are physically acceptable. In conclusion, neutron stars are not only important astrophysical objects but also key tools for testing the fundamental nature of gravity. Their internal structure may provide valuable information about both dense nuclear matter and possible deviations from General Relativity. Therefore, the investigation of neutron stars in modified gravity theory remains a promising and relevant direction in modern astrophysics.

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