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Anisotropic Compact Stars in Modified $f(R)$ Gravity and Their Structural Properties

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Abstract. This study investigates anisotropic spherical structures in the framework of modified $f(R)$ gravity, where R is the Ricci scalar, extending general relativity to incorporate additional gravitational effects. We employ the Finch–Skea metric to analyze compact stars using different $f(R)$ models. These models allow us to explore the impact of modified gravity on the internal composition and equilibrium of neutron and strange stars. Key physical parameters, including energy density, radial and tangential pressures, anisotropy, and fundamental forces (gravitational, hydrostatic, and anisotropic), are analyzed through graphical representation. The viability of the models is assessed via energy conditions (NEC, WEC, SEC, and DEC) and the equation of state (EoS) parameter. Additionally, we evaluate the role of anisotropy in the stability of compact objects and compare our results with general relativity to highlight the influence of $f(R)$ gravity on stellar structures. This research contributes to the broader understanding of the modifications to general relativity and their implications for compact astrophysical objects.

Keywords: modified gravity, anisotropy, compact stars, energy conditions, Finch–Skea metric

Introduction. The study of compact stellar structures, such as neutron stars and strange stars, has been a critical area of research in theoretical astrophysics and gravitational physics. General relativity (GR) provides a robust framework for understanding such objects; however, various cosmological and astrophysical observations suggest the need for modifications to GR. One such extension is $f(R)$ gravity, where the Ricci scalar R is replaced with a function $f(R)$ to introduce additional gravitational effects [1, 2].

Among various $f(R)$ models, quadratic and exponential modifications have gained significant attention due to their ability to explain early and late-time cosmic acceleration while remaining consistent with local astrophysical constraints [3]. In this work, we analyze compact stars using three modified gravity models, employing the Finch–Skea metric, a well-suited ansatz for studying relativistic stellar configurations.

A key aspect of compact stars is anisotropy, where the radial and tangential pressures differ due to interactions such as nuclear forces, phase transitions, or strong magnetic fields [4, 5]. Anisotropic pressures influence the stability and internal structure of compact stars, making their study crucial in alternative gravity models. In this paper, we investigate how $f(R)$ gravity affects the energy density, pressure components, anisotropy factor, and fundamental forces governing equilibrium.

We further assess the physical viability of the stellar models by evaluating energy conditions (NEC, WEC, SEC, and DEC) and the equation of state parameter. The comparison of our results with GR provides insights into the deviations introduced by modified gravity theories. The implications of our findings extend to astrophysical scenarios where alternative gravity theories play a role in stellar evolution and compact object dynamics.

Methods and materials; results. To study anisotropic compact stars in $f(R)$ gravity, we employ the following methodology:

1. Choice of Metric: We adopt the Finch–Skea metric, which has proven effective for modeling spherically symmetric stellar structures.
2. Modified Gravity Models: We consider three functional forms of $f(R)$, incorporating quadratic and exponential corrections to general relativity.
3. Field Equations: The Einstein field equations in $f(R)$ gravity are derived for an anisotropic fluid distribution, obtaining expressions for density, radial and tangential pressures.
4. Stability and Energy Conditions: The viability of the models is assessed by verifying energy conditions and analyzing the equation of state.
5. Graphical and Numerical Analysis: We present graphical results to illustrate variations in energy density, pressure, anisotropy, and stability parameters.

The analysis reveals that modifications in $f(R)$ gravity significantly alter the structural properties of compact stars. The quadratic and exponential corrections introduce changes in the pressure anisotropy, affecting the equilibrium conditions. Our key findings include:

- The inclusion of an R^2 term leads to a stiffer equation of state, enhancing stability.
- Exponential gravity corrections modify the density profile, affecting gravitational collapse.
- The anisotropic factor plays a crucial role in maintaining hydrostatic equilibrium in modified gravity models.

A comparative analysis with GR highlights the deviations induced by $f(R)$ gravity, suggesting its relevance in extreme astrophysical environments.

Conclusion. This study explores anisotropic compact stars within $f(R)$ gravity using the Finch–Skea metric. Our findings indicate that modifications to GR introduce significant changes in stellar equilibrium and stability. The results contribute to the broader understanding of alternative gravity models in astrophysical settings and their potential implications for neutron stars, strange stars, and exotic compact objects. Future work could extend this analysis to more generalized forms of modified gravity and consider observational constraints from pulsar and gravitational wave data.

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