Structure and astrophysics of self-gravitating objects in multiscalar theories

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Recent direct detections of gravitational waves from various binary sources have paved the way for gravitational-wave astronomy, which in turn, combined with electromagnetic observations, forms multimessenger astronomy. Multimessenger astronomy is a powerful tool for studying the universe, with great hopes for unraveling many mysteries in Nature, such as dark matter and dark energy, as well as searching for new fundamental fields and new exotic objects. Although general relativity is in brilliant agreement with all observations to date, there are reasons to go beyond the accepted model of gravity in search of new fundamental physics. It is scalar fields that are the simplest to consider, and they appear naturally in extensions of the Standard Model in particle physics and in alternative theories of gravity. In these theories, gravity is described both by the metric tensor and by one or more scalar fields. Of great interest to modern physics are theories with scalar fields coupled to the curvature of space-time, to which the multiscalar Gauss–Bonnet theories also belong. These theories predict the existence of new phenomena, such as spontaneous scalarization of black holes and neutron stars, as well as new types of objects such as space tunnels without the need for exotic matter. This in turn gives rise to new interesting astrophysics related to these objects.

The aim of the present thesis is to show the existence of scalarized self-gravitating compact objects supporting non-trivial scalar fields in multiscalar theories of gravity and especially in Einstein–Gauss–Bonnet gravity, where scalar fields interact with space-time curvature through the Gauss–Bonnet topological invariant. In particular, the present thesis numerically demonstrates the existence of scalarized black holes and neutron stars with a rapidly decreasing "scalar hair" in multiscalar Gauss– Bonnet theories, whose scalar space is a maximally symmetric three-dimensional Riemannian space. Constructing these solutions makes it possible to probe the astrophysics around them in order to search for astrophysical effects with a pronounced signature of the scalar fields that could be observed with the next generation of gravity detectors and/or electromagnetic telescopes. As a clear example, quasi-periodic oscillations from accretion disks around rotating space-tunnels have been studied, analyzing the differences with similar oscillations for Kerr black holes, which would help distinguish the two types of self-gravitating objects in future observational missions. Currently, a new generation of spectrometers is being prepared, such as the eXTP (China), STROBE-X (NASA) and LOFT (ESA) missions, which will have extremely high accuracy in measuring the frequencies of quasi-periodic oscillations and will be fully capable of detecting clear signs about the existence of fundamental scalar fields and new exotic objects.

In Chapter 1, the results of the study of the quasi-periodic oscillations of accretion disks around rotating space-time tunnels are presented. The stability of circular orbits in the equatorial plane is discussed and analytical formulas for the epicyclic frequencies are presented. A comparative analysis is made with the case of Kerr black holes.

Chapter 2 introduces multiscalar Einstein–Gauss–Bonnet gravity through its action. Then the dimensionally reduced field equations describing black holes in the theory under the relevant assumptions are presented. Numerically constructed solutions describing black holes as well as their physical characteristics such as horizon area, entropy and the radius of the photon sphere are also given.

Chapter 3 is devoted to neutron stars in multiscalar Einstein–Gauss–Bonnet gravity. The dimensionally reduced field equations describing the structure of neutron stars in the theory are presented. Numerical solutions for neutron stars and the basic dependences such as mass–central density, mass–radius of the star, and binding energy–baryon mass are also presented.
The main results and conclusions of our study can be summarized as follows [Deligianni et al. 2021, Doneva et al. 2020, Staykov & Zheleva,2022]:

1. The quasi-periodic oscillations of the accretion disk around rotating traversable space tunnels are investigated using the resonance models. The linear stability of circular geodesic orbits in the equatorial plane for a general class of space tunnel geometries is also investigated and analytical expressions for epicyclic frequencies are derived. Since space tunnels can often mimic black holes in astrophysical observations, we analyze the properties of quasi-circular oscillating motions compared to a Kerr black hole. We show that space tunnels possess distinctive features that may be important for observations. A characteristic of Kerr black holes is that the orbital and epicyclic frequencies obey a constant ordering over the entire range of the spin parameter. In contrast, in tunnels we can have different types of orderings between frequencies in different regions of the parameter space. This allows the excitation of many more diverse types of resonances, including lower-order parametric and forced resonances, which can lead to stronger visible signals. In addition, for uniformly rotating orbits, resonances can be excited in the very close vicinity of the tunnel throat for a wide range of angular momentum values, making tunnels a valuable laboratory for testing strong gravity.
2. The existence of black holes in multiscalar Gauss–Bonnet theories with a maximally symmetric scalar space for several coupling functions, including the case of spontaneous scalarization, is numerically proven. Various characteristics of black holes and the space-time around them, such as the horizon area, entropy and radius of the photon sphere, have also been systematically investigated. One of the most important properties of the resulting solutions is that the scalar charge is zero and thus the scalar dipole emission is suppressed, leading to much weaker observational constraints on the theory. For one of the coupling functions, we find branches of scalarized black holes that have a non-trivial structure – there is a nonuniqueness of the scalarized solutions.
3. Solutions describing spontaneously scalarized neutron stars in Gauss–Bonnet multiscalar theories with maximally symmetric scalar space are numerically constructed. The dependences $\mathrm{M}(\rho)$ and $\mathrm{M(R)}$ were constructed, as well as the dependence of the binding energy on the baryon mass, which also carry information about the stability of the neutron stars.

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References

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