ISNN:2181-1296



SHAROF RASHIDOV NOMIDAGI SAMARQAND DAVLAT UNIVERSITETI

САМАРКАНДСКИЙ ГОСУДАРСТВЕННЫЙ УНИВЕРСИТЕТ ИМЕНИ ШАРОФА РАШИДОВА

SAMARKAND STATE UNIVERSITY NAMED AFTER SHAROF RASHIDOV

ILMIY AXBOROTNOMA

НАУЧНЫЙ ВЕСТНИК SCIENTIFIC JOURNAL

ANIQ VA TABIIY FANLAR SERIYASI

Matematika, Mexanika, Informatika
Fizika, Kimyo, Biologiya, Geografiya

№ 3/1 (139)
2023

ISSN 2181-1296

ILMIY AXBOROTNOMA

НАУЧНЫЙ ВЕСТНИК — SCIENTIFIC JOURNAL

2023-yil, 3-son 1-seriya (139) **ANIQ VA TABIY FANLAR SERIYASI**

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Samarqand viloyat matbuot boshqarmasida ro‘yxatdan o‘tish tartibi 09-25.
Jurnal 1999-yildan chop qilina boshlagan va OAK ro‘yxatiga kiritilgan.

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tashkilot, korxonalar uchun **- 5584**

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UDK:53(47) **DOI: https://doi.org/10.59251/2181-1296.2023.v4.139.1.2063**

WORMHOLE AND BLACK HOLE SOLUTIONS IN EINSTEIN-SCALAR-GAUSS-BONNET THEORIES

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Abstract. We consider wormholes and black holes in Einstein-scalar-Gauss-Bonnet theories. By varying the Gauss-Bonnet coupling constant we delimit the domain of existence of wormholes and black holes in these theories. There arise wormholes with a single throat and wormholes with an equator and a double throat. We determine the physical properties of these wormholes and black holes.

Keywords: wormholes; black holes; scalar field; Gauss-Bonnet term; Einstein-scalar-Gauss-Bonnet theories.

Eynshteyn-skalar-gauss-bonnet nazariyalaridagi yumronqoziq ini va qora tuynuk yechimlari

Annotatsiya. Biz Eynshteyn-skalar-Gauss-Bonnet nazariyalarida yumronqoziq inlari va qora tuynuklarni ko‘rib chiqamiz. Gauss-Bonnet bog‘lanish doimiysini o‘zgartirish orqali biz ushbu nazariyalarda yumronqoziq inlari va qora tuynuklarning mavjudligini chegaralaymiz. Bunda bir bo‘g‘izli yumronqoziq inlari va ekvatorga ega qo‘sh bo‘g‘izli yumronqoziq inlari paydo bo‘ladi. Biz bu yumronqoziq inlari va qora tuynuklarning fizik xususiyatlarini aniqlaymiz.

Kalit so‘zlar: yumronqoziq inlari; qora tuynuklar; skalyar maydon; Gauss-Bonnet atamasi; Eynshteyn-skalar-Gauss-Bonnet nazariyalari.

Решения коротных норов и черных дыр в теориях эйнштейна-скальяра-гаусса-бонне

Аннотация. Мы рассматриваем кротовые норы и чёрные дыры в теориях Эйнштейна-скаляра-Гаусса-Бонне. Варьируя константу связи Гаусса-Бонне, мы разграничиваем область существования кротовых нор и черных дыр в этих теориях. Кротовые норы появляются с одинарным горлом и двойным горлом с экватором. Мы определяем физические свойства этих кротовых нор и черных дыр.

Ключевые слова: кротовые норы; черные дыры; скалярное поле; термин Гаусса-Бонне; Теории Эйнштейна-скаляра-Гаусса-Бонне.

Wormholes and black holes are fascinating objects that have captured the attention of scientists and the public alike. They are both predicted by Einstein's theory of general relativity, which describes the fundamental nature of gravity and the structure of spacetime. However, recent developments in theoretical physics have led to the study of these objects in the context of Einstein-scalar-Gauss-Bonnet (ESGB) theories.

ESGB theories are extensions of general relativity that include an additional term known as the Gauss-Bonnet term. This term modifies the equations of general relativity by adding a term that is proportional to the curvature of spacetime. This modification leads to new and interesting solutions that are not predicted by general relativity alone, including the possibility of stable wormholes and black holes with exotic properties such as scalar hair [1].

The study of wormholes and black holes in the context of ESGB theories has gained considerable attention in recent years. In particular, the stability of wormholes and black holes in ESGB theories has been a topic of much interest. Several studies have shown that stable wormhole solutions can be obtained in ESGB theories under certain conditions [2, 3]. Additionally, scalarized black hole solutions have been predicted in ESGB theories, where the black hole is surrounded by a scalar field [4, 5].

The purpose of The paper is to provide an overview of the study of wormholes and black holes in the context of ESGB theories. We will begin by introducing ESGB theories and their modifications to general relativity, followed by a discussion of the role of the Gauss-Bonnet term in the study of wormholes and black holes. We will then explore the wormhole and black hole solutions predicted by ESGB theories, and their potential significance for our understanding of the universe. Finally, we will discuss the challenges and limitations of ESGB theories, and the potential future directions for research in this exciting field.

Einstein-Scalar-Gauss-Bonnet theories are an extension of general relativity that include an additional term known as the Gauss-Bonnet term. This term is a higher-order curvature term that becomes significant at high energies or in the presence of strong gravitational fields. The Gauss-Bonnet term is given by:

$$S_{GB} = \alpha \int d^4x\sqrt{-g}\left[R^2 + 4R_{\mu\nu}R^{\mu\nu} + R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma}\right] \quad (1)$$

where α is a constant with dimensions of length squared, g is the determinant of the metric tensor, R is the Ricci scalar, $R_{\mu\nu}$ is the Ricci tensor, and $R_{\mu\nu\rho\sigma}$ is the Riemann tensor.

ESGB theories modify the equations of general relativity by adding the Gauss-Bonnet term to the action. The resulting field equations are more complex than those of general relativity, but they offer new solutions and insights into the behavior of gravity in extreme conditions.

One important aspect of ESGB theories is that they introduce a length scale α, which can have important implications for the size and stability of objects such as black holes and wormholes. For example, the presence of the Gauss-Bonnet term can lead to the formation of black holes with a minimum size, below which they become unstable [6]. Similarly, the Gauss-Bonnet term can stabilize wormholes and prevent them from collapsing [2].

Wormholes are hypothetical objects that are predicted by the equations of general relativity. They are tunnels or shortcuts through space-time that could potentially allow for faster-than-light travel and time travel. Wormholes are formed by the curvature of space-time, which is created by the presence of matter and energy.

In ESGB theories, the Gauss-Bonnet term can have a significant impact on the formation and stability of wormholes. The addition of this term to the action can stabilize the throat of a wormhole and prevent it from collapsing, as shown in the work by Dzhunushaliev et al [2]. This stabilization occurs because the Gauss-Bonnet term contributes a repulsive force that balances the attractive force of gravity.

ESGB theories have also been used to study the properties of traversable wormholes, which are wormholes that can be traversed by matter and energy without being destroyed. Traversable wormholes require exotic matter, which has negative energy density, to keep the throat of the wormhole open. In ESGB theories, the presence of the Gauss-Bonnet term can reduce the amount of exotic matter required to keep a wormhole traversable [7-10].

We consider the effective action for ESGB theories,

$$S = \frac{1}{16\pi}\int d^4x\sqrt{-g}\left[R - \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - U(\phi) + F(\phi)R^2_{GB}\right], \quad (1)$$

where ϕ is the scalar field with the coupling function $F(\phi)$ and potential $U(\phi)$, and

$$R^2_{GB} = R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2, \quad (2)$$

is the quadratic Gauss-Bonnet term.

To obtain static, spherically symmetric wormhole solutions we assume the line element in the form

$$ds^2 = -e^{f_0}dt^2 + e^{f_1}\left[d\eta^2 + h^2\left(d\theta^2 + \sin^2\theta d\varphi^2\right)\right], \quad (6)$$

with the auxiliary function $h^2 = \eta^2 + \eta_0^2$, where η_0 is a scaling parameter. The two metric functions f_0, and f_1 and the scalar field function ϕ are functions of the radial coordinate η only.

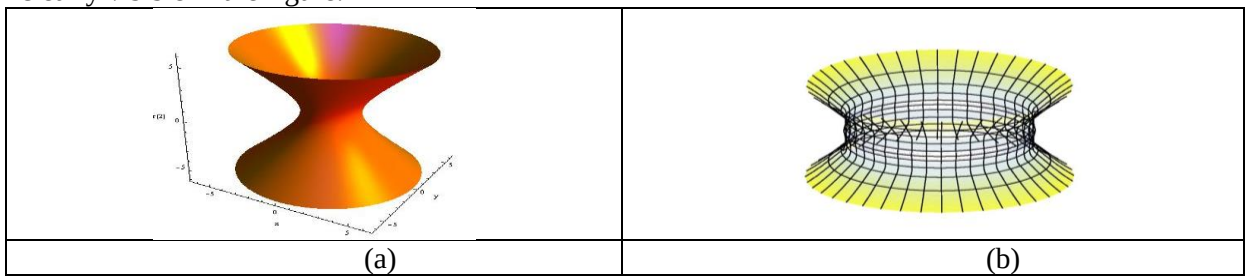
In the following we present our results, obtained with the coupling function $F(\phi)$ [11] and the potential $U(\phi)$ [12]:

$$F(\phi) = \frac{\alpha}{2\beta}\left(1 - e^{-\beta\phi^2}\right), \quad U(\phi) = \lambda\left(c_2\phi^2 + c_4\phi^4 + c_6\phi^6\right). \quad (14)$$

We fix the constant $\beta = 1.5$, but leave α as a free parameter. When employing the full potential we also set $\lambda = 0.06$, $c_2 = 1.1$, $c_4 = -2$, and $c_6 = 1$, whereas in the case of a mass term only, we retain $\lambda = 0.06$, $c_2 = 1.1$, but set $c_4 = c_6 = 0$. Furthermore, we set $\eta_0 = 1$.

We visualize the geometry of a typical single wormhole in Figure 1(a), where we have selected the coupling constant the quantity $\alpha = 1.7$ and for the scalar field at the center

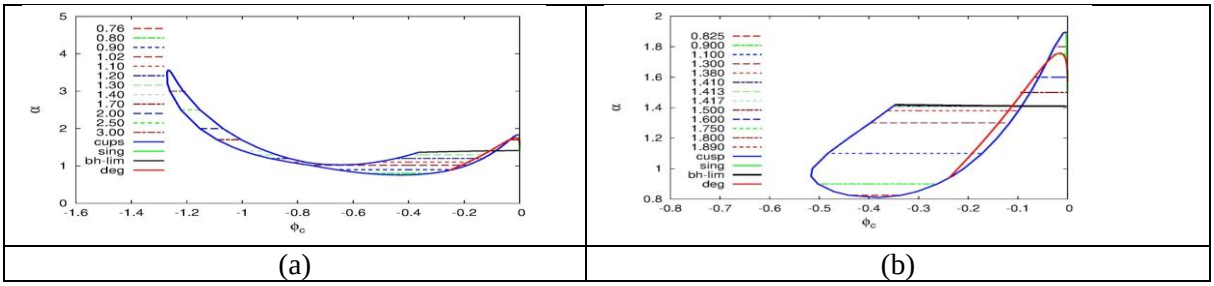
$\phi_c = -0.0121$. Figure 1(b) shows the geometry of a typical wormhole with an equator and a double throat, obtained with the parameter choice $\alpha = 1.7$ and $\phi_c = -0.03$. The equator and the throats are clearly visible in the figure.



(a) (b)

Figure 1. Embeddings of the equatorial plane (examples with self-interaction): (a) single throat wormhole with coupling constant $\alpha = 1.7$ and quantity of the scalar field at the center $\phi_c = -0.0121$; (b) double throat wormhole with $\alpha = 1.7$ and $\phi_c = -0.03$.

Both solutions belong to the same family ($\alpha = 1.7$) of self-interacting wormholes. As ϕ_c is increased, the single throat (minimum) at the center first turns into a degenerate throat (saddle point) at a critical quantity of ϕ_c, and then becomes an equator (maximum), concealed by a throat (minimum) on each side.



(a) (b)

Figure 2. The domain of the existence of wormhole solutions for a set of fixed quantities of the coupling constant α. Coupling constant α is shown vs the quantity of the scalar field at the center ϕ_c. Also shown are the limiting solutions, scalarized ESGB black holes (black), singular solutions (green), cusp singularities (blue), and degenerate wormhole solutions (red).

Wormhole solutions exist for a limited range of parameter values. The domain of existence of wormhole solutions is illustrated in Figure 2 for wormholes with mass and self-interaction (left column) and wormholes with a mass term only (right column). As seen in Figure 2(a), where the coupling constant α is shown versus the quantity of the scalar field at the center ϕ_c, wormhole solutions arise for a minimal quantity of the coupling constant α, $\alpha_{\min} \approx 0.76$. As α increases, the corresponding families of solutions expand, until a critical value of α, $\alpha_{\rm cr} \approx 1.02$, is reached.

Further increase of α then leads to two disconnected branches of wormhole solutions. The branches with the smaller values of ϕ_c can be continued up to $\alpha_{\max} \approx 3.56$. The branches with the larger values of ϕ_c, on the other hand, cannot be continued that far. They end at a limiting value of $\alpha_{\lim} \approx 1.83$. The domain of existence is delimited by solutions with cusp singularities (blue), solutions with singularities at the center (green), and scalarized ESGB black hole solutions (black), reaching all the way up to their bifurcation point from the Schwarzschild black hole.

For wormholes with a mass term only, the coupling constant α is shown versus the quantity of the scalar field at the center ϕ_c in Figure 2(b). We immediately note, that the domain of existence basically only consists of one part of the domain of existence of wormholes with self-interaction.

This part more or less agrees with the right-hand side of the domain shown in Figure 2(a), and thus the larger values of ϕ_c. Thus the effect of the self-interaction is to allow for wormhole solutions with much smaller values of ϕ_c and much larger quantities of the coupling constant α.

Comparing ESGB wormholes with those predicted by general relativity, we can see that the addition of the Gauss-Bonnet term in ESGB theories allows for the formation of stable wormholes with less exotic matter. This is an important result, as it could potentially make interstellar travel and exploration more feasible in the future.

ESGB theories also offer new insights into the properties of black holes, which are some of the most mysterious objects in the universe. Black holes are formed by the collapse of massive objects, and they are characterized by an event horizon, which is a boundary beyond which nothing, not even light, can escape.

The Gauss-Bonnet term in ESGB theories modifies the equations of general relativity, which can lead to new black hole solutions with unique properties. One such solution is the black hole with a minimum size, known as the "minimal" black hole [3]. This black hole is stabilized by the Gauss-Bonnet term and has a minimum radius that depends on the value of α.

ESGB theories also offer new insights into the behavior of black holes in the presence of matter and energy. For example, the presence of a scalar field can affect the formation and stability of black holes [13]. In ESGB theories, the scalar field can interact with the Gauss-Bonnet term to create new types of black hole solutions with unique properties.

In addition, ESGB theories have been used to study the thermodynamics of black holes, which is an important area of research in physics. The thermodynamics of black holes describes the behavior of black holes in terms of temperature, entropy, and other thermodynamic quantities. ESGB theories have been used to study the thermodynamics of black holes with scalar hair, which are black holes that are surrounded by a scalar field [14].

Overall, the study of black hole solutions in ESGB theories offers new insights into the properties of black holes and the behavior of gravity in extreme conditions. These insights could have important implications for our understanding of the universe and the development of new technologies.

Scalarized black holes have been studied extensively in ESGB theories. The presence of the scalar field modifies the properties of the black hole, including its mass, angular momentum, and horizon radius. The modifications to black hole properties in ESGB theories can be expressed mathematically by the Einstein-scalar-Gauss-Bonnet equations with a non-minimal coupling between the scalar field and the Gauss-Bonnet term R^2_{GB}, which can be written as:

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi T^{(m)}_{\mu\nu} + 8\pi T^{(\phi)}_{\mu\nu} + \alpha R^2_{GB} + 8\pi\beta\left(\nabla_\mu\phi\right)\left(\nabla_\nu\phi\right) \qquad (3)$$

where $G_{\mu\nu}$ is the Einstein tensor, Λ is the cosmological constant, $g_{\mu\nu}$ is the metric tensor, $T^{(m)}_{\mu\nu}$ is the stress-energy tensor of matter fields, $T^{(\phi)}_{\mu\nu}$ is the stress-energy tensor of the scalar field, α is the Gauss-Bonnet coupling constant, ϕ is the scalar field, and β is the non-minimal coupling constant [15].

Scalarized black holes have important implications for astrophysics, as they could potentially explain the properties of certain observed black hole candidates, such as X-ray binaries and ultraluminous X-ray sources. The presence of scalar hair in these black holes could potentially affect their observable properties, such as their gravitational waves signature, which could be detected by future gravitational wave observatories [16].

The study of black hole solutions in ESGB theories is an active area of research, with potential implications for both fundamental physics and astrophysics.

Despite the promise of ESGB theories in providing new insights into the behavior of black holes and wormholes, there are significant challenges and limitations associated with these theories.

One major challenge is the complexity of the mathematical formalism involved in ESGB theories. The inclusion of additional terms beyond those present in general relativity makes the equations more complicated and difficult to solve, particularly for more complex spacetimes such as those associated with rotating black holes or traversable wormholes.

Another challenge is the difficulty in testing the predictions of ESGB theories with current technology. While the existence of black holes has been inferred through observational evidence, detecting the modifications predicted by ESGB theories is much more challenging. Additionally, the theoretical predictions of these theories may be difficult to distinguish from those of other alternative gravity theories or modified theories of general relativity.

Despite these challenges, there are potential avenues for further research in ESGB theories. One promising direction is the study of the behavior of scalarized black holes in the presence of matter, which could shed light on their properties and potential observational signatures. Additionally, the study of the

formation and evolution of black holes and wormholes in the context of ESGB theories could provide new insights into the nature of spacetime and the behavior of gravity at a fundamental level.

In conclusion, the study of wormhole and black hole solutions in ESGB theories has provided new insights into the behavior of gravity in extreme conditions. The Gauss-Bonnet term in ESGB theories modifies the equations of general relativity, leading to the formation of new types of solutions with unique properties.

Wormholes, which are hypothetical objects that could potentially allow for faster-than-light travel and time travel, are stabilized by the Gauss-Bonnet term, which can prevent them from collapsing. The presence of the Gauss-Bonnet term in ESGB theories can reduce the amount of exotic matter required to keep a wormhole traversable.

Black holes, which are some of the most mysterious objects in the universe, are also affected by the Gauss-Bonnet term in ESGB theories. The addition of this term can lead to the formation of new types of black hole solutions with unique properties, such as the “minimal” black hole. ESGB theories have also been used to study the thermodynamics of black holes with scalar hair, which are black holes that are surrounded by a scalar field.

Overall, the study of wormhole and black hole solutions in ESGB theories offers new insights into the behavior of gravity in extreme conditions, and could potentially lead to the development of new technologies for space travel and exploration. Further research in this area could help us to better understand the universe and its fundamental laws.

Authors gratefully acknowledge the support from Ministry of Innovative Development of the Republic of Uzbekistan, Project no. FZ20200929385.

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SamDU «Ilmiy axborotnoma» jurnali tahririyati kompyuterida terildi. Bosishga 30.06.2023-yilda ruxsat etildi. Qog'oz o'lchami A-4. Nashriyot hisob tabog'i 10,00.
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ISSN 2181-1296

