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<td>SERGEY PAVLUCHENKO</td>
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FONDO NACIONAL DE DESARROLLO CIENTIFICO Y TECNOLOGICO (FONDECYT)
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**OBJETIVOS**

Cumplimiento de los Objetivos planteados en la etapa final, o pendientes de cumplir. Recuerde que en esta sección debe referirse a objetivos desarrollados, NO listar actividades desarrolladas.

<table>
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<tr>
<th>Nº</th>
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<tr>
<td>1</td>
<td>Investigation of the anisotropic exact cosmological solutions in the Gauss-Bonnet gravity</td>
<td>TOTAL</td>
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<tr>
<td>2</td>
<td>Study dynamical compactification in the Einstein-Gauss-Bonnet gravity in the cosmological model with (3+D) space splitting</td>
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<td>3</td>
<td>Investigating spherically-symmetric solutions in the ( f(R,G) ) modified gravity theories</td>
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<td>4</td>
<td>Investigation of the exact exponential solutions in the Einstein-Gauss-Bonnet gravity and generalizing some of them onto more general case of Lovelock gravity</td>
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<tr>
<td>5</td>
<td>Consideration of the Einstein-Skyrme cosmological system as a `toy-model` for further work on multidimensional analogues</td>
<td>TOTAL</td>
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<tr>
<td>6</td>
<td>Constructing a scheme which allow to build an exponential solution in Lovelock gravity of any order and in arbitrary dimensions</td>
<td>TOTAL</td>
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<tr>
<td>7</td>
<td>Investigating the stability of the exponential solutions found</td>
<td>TOTAL</td>
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Otro(s) aspecto(s) que Ud. considere importante(s) en la evaluación del cumplimiento de objetivos planteados en la propuesta original o en las modificaciones autorizadas por los Consejos.
RESUL TS OBT AINED:
For each specific goal, describe or summarize the results obtained. Relate each one to work already published and/or manuscripts submitted. In the Annex section include additional information deemed pertinent and relevant to the evaluation process.
The maximum length for this section is 5 pages. (Arial or Verdana, font size 10).

1) Since works by N. Deruelle in end of 80s – beginning of 90s it was widely believed that for spatially flat (Bianchi-I-type) multidimensional metric there are two branches of power-law solutions in the Gauss-Bonnet gravity (which is the second Lovelock contribution, and first is just Einstein-Hilbert term). One of these two branches is generalized Kasner solution and it is widely known and studied for a number of properties. On the other hand the second solution, which we refer as generalized Milne, remained relatively unstudied for a while. Close consideration of generalized Milne solution revealed that it is unphysical – there is no equivalence between resulting system of equations in power-law ansatz and system of general equations. We believe that this solution is just an artifact originating from the fact that in pure Gauss-Bonnet gravity there is no Einstein-Hilbert contribution and so this solutions cannot be realized in general Einstein-Gauss-Bonnet system. Additionally, the differences in appearance of power-law and exponential solutions is addressed – there are no exponential solutions in General Relativity but there are power-law while in general Lovelock gravity there are solutions of both kinds. As exponent could be considered as power-law with infinite power, existence of exponential solutions could be linked with noncompactness of Kasner exponents space in Gauss-Bonnet and higher Lovelock theories. In contrary, in General Relativity the space of Kasner exponents is compact which results in impossibility of construction of exponential solutions.

(Published in S. A. Pavluchenko and A. V. Toporensky, Note on the properties of exact solutions in Lovelock gravity, Gravitation & Cosmology 20, 127 (2014))

2) Previous work finalized our study of power-law solutions and started study of exponential ones. In this work we proceeded with study of exponential solutions properties. To begin, we started with solutions in low number of dimensions in Einstein-Gauss-Bonnet gravity. Unlike power-law solution, which could be found only when single Lovelock term is considered (as different terms have different power of curvature, they scale differently with time and so construction of solution in form with single power of time is possible only with single Lovelock term in consideration), exponential solutions could be found with a mixture of Lovelock terms, which makes them more “correct” to consider. So we have considered exponential solutions in
(4+1)- and (5+1)-dimensional flat metric to find all possible solutions for all possible spatial splittings. Our approach unveiled that there are three classes of solutions – vacuum (with no source of any kind), Λ-term solutions (with cosmological constant as a source) and solutions with arbitrary equation of state (for stress-energy tensor in form of perfect fluid). For first two kinds of solutions there are no additional requirements but for the last of them – with arbitrary equation of state – there is requirement that the volume should be conserved. In the considered work we obtained all possible vacuum and Λ-term solutions in (4+1)- and (5+1)-dimensional Einstein-Gauss-Bonnet gravity. One of the (5+1)-dimensional solutions, namely, one with (3+2) spatial splitting (meaning that five spatial dimensions are split into 3 and 2, like, \((H, H, H, h, h)\)) potentially allows compactification as it could be that for \(H > 0\) calculated \(h\) allows \(h < 0\).


3) As it was mentioned in the previous section, three classes of solutions exist for exponential ansatz in flat anisotropic cosmological model in Einstein-Gauss-Bonnet gravity – vacuum, Λ-term, and solution with arbitrary equation of state. With first two classes were considered in the previous paper, last one – solutions with arbitrary equation of state (for the source in form of prefect fluid) is considered here. It appears that for continuity equation to be satisfied for arbitrary equation of state it is necessary that the comoving volume is preserved – in other words, the expansion of the universe in some directions should be compensated by contraction of other directions in a way that the volume is conserved. We have found the criteria for such solutions to exist; among them the constraint on the equation of state \(\omega < 1/3\) and density should exceed some critical value.


4) Two previous results are analytical as they deal with exact solutions obtained in power-law and exponential ansatz. As the next step we decided to investigate more general model with topology to be a warped product of 4-dimensional Lorenzian space-time and constant curvature \(D\)-dimensional manifold. The gravity model is Einstein-Gauss-Bonnet with boundary (“cosmological”) term. With this topology 4-dimensional Lorenzian manifold could be treated as “our world while \(D\)-dimensional constant curvature manifold – as extra dimensions. 2 We report existence of a regime
where four-dimensional space-time approaches nearly-exponential expansion while extra dimensions approach regime with nearly constant size. This regime appears for open region of parameters and could be treated as successful and natural appearance of compactification. Indeed, since it appear for open region of couplings space, it is not suppressed by them and it represent one of the branches of the solution which always appears.


5) Apart from describing abovementioned regime we also numerically investigated entire area of initial conditions and parameters space to identify all possible regimes. It appears that the regime described in the previous section is the only one that could be called viable. Indeed, all other regimes are singular - they have either standard or nonstandard singularity in future. Here by “nonstandard singularity” we mean the situation when the highest (second) derivative of the scale factor diverges while all other variables (scale factors and theirs first derivatives) are regular. One can clearly see that this singularity is physical (as the scalar curvature diverge due to divergence of the second derivative), yet, it happens to the finite value of the scale factor. This kind of singularity is due to the nonlinearity of the equations of motion with respect to the highest derivative and is absent in General Relativity.

(Published in F. Canfora, A. Giacomini, and S.A. Pavluchenko, *Cosmological dynamics in higher-dimensional Einstein-Gauss-Bonnet gravity*, General Relativity and Gravitation 46, 1805 (2014))

6) Another interesting research I have conducted and which is also relate to the project’s main topic is study of the cosmological dynamics of (3+1)-dimensional Friedmann universe with Skyrme (low-energy QCD theory) as a source. The main reason to consider such model is to make use of the Skyrme’s anisotropic pressure. On the other hand, as Skyrme theory describe nucleons and pions, it is absolutely physical. This research will be used as a “startup” for the following research on non-linear sigma model in extra dimensions, where anisotropic pressure could lead to viable compactification schemes. Our study suggests that using just a requirement of nonsingular behavior of the scale factors could lead us to constraints on the Skyrme couplings.


3
7) Upon completing description of all possible exponential solutions in Einstein-Gauss-Bonnet gravity we decided to achieve even a greater goal – to do the same but in more general Lovelock gravity. So we considered exponential metric ansatz in the general Lovelock gravity of any order and with terms of all possible orders in given number of dimensions; the number of dimensions is also arbitrary. And we generalized the results of 2) in the sense that we developed a scheme which allows to find all solutions in Lovelock gravity of any order (and mixture of terms of any possible orders in given dimension) in any number of dimensions. The developed scheme is applied to Einstein-Gauss-Bonnet gravity in (6+1) and (7+1) dimensions as well as to cubic Einstein-Lovelock gravity in (6+1) and (7+1) dimensions. This allows us to build enough solutions in Einstein-Gauss-Bonnet gravity to find similarities through different number of spatial dimensions as well as to compare Einstein-Gauss-Bonnet with cubic Einstein-Lovelock solutions in (6+1) and (7+1) to investigate the effect of higher-order Lovelock terms on the abundance of the solutions.


8) Next obvious step after reporting a number of exact solution is to check their stability. This is exactly what was done in this paper – for all solutions from previous and 2) sections we preformed linear stability analysis. It appears that the majority of solutions are unstable; for others there exist stable branches. This research alone leave us with at most third of all solutions found as stable – and this is only linear stability analysis. This leads us to the conclusion that further investigation of the solutions could diminish number of viable solutions to almost zero, and that is what we going to do next.

ACHIEVEMENTS OF THE PROJECT:
- Research visit(s) to other institution(s).
- Outreach activities related to the project’s main topic.
- Any other contribution, not addressed elsewhere, that you consider important.
The maximum length for this section is 1 page. (Arial or Verdana, font size 10).

Research visits to Sternberg Astronomical Institute (Moscow Lomonosov State University, Moscow, Russia) to collaborate with Alexey Toporensky and Dmitri Chirkov in 2013, 2014 and 2015.

Research visits to Yerevan Physics Institute (Yerevan, Armenia) to collaborate with Arpine Piloyan and give seminars on the project’s main topic in 2014 and 2015.

Attendance of the long-term workshop on gravitation waves at the Yukawa Institute for Theoretical Physics, Kyoto, Japan in 2013 to create new directions with the project’s main topic.

Attendance of the 1st ICRAA Meeting on the black holes and compact objects in Yerevan, Armenia in 2014 to discuss current findings on the project’s main topic and create new directions.
I am pleased to report the successful completion of the FONDECYT postdoctoral project “Modified theories of gravity in various dimensions” carried out by Dr. Sergey Pavluchenko. The main objective of the project was to investigate various aspects of modified theories of gravity by studying the corresponding cosmological solutions. To that end, in the last three years Dr. Pavluchenko has made an extensive research on higher dimensional cosmological solutions in Lovelock gravity which has led to 8 articles in total, 6 of which has already been published in reputed journals and 2 articles are in the process of refereeing. He has also collaborated with members in our group at UACH and presented his findings in international conferences as well as in the group seminars in our institute. Overall I am very happy with the execution of the project and wish him success in future.

Sponsor signature

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OTRAS PUBLICACIONES / PRODUCTOS

Sin información ingresada.

CONGRESOS

Sin información ingresada.

ANEXOS

A continuación se detallan los anexos físicos/papel que no se incluyen en el informe en formato PDF.