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Magnetic brane solutions in Gauss–Bonnet–Maxwell massive gravity

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ABSTRACT

Magnetic branes of Gauss–Bonnet–Maxwell theory in the context of massive gravity is studied in detail. Exact solutions are obtained and their interesting geometrical properties are investigated. It is argued that although these horizonless solutions are free of curvature singularity, they enjoy a cone-like geometry with a conic singularity. In order to investigate the effects of various parameters on the geometry of conic singularity, its corresponding deficit angle is studied. It will be shown that despite the effects of Gauss–Bonnet gravity on the solutions, deficit angle is free of Gauss–Bonnet parameter. On the other hand, the effects of massive gravity, cosmological constant and electrical charge on the deficit angle will be explored. Also, a brief discussion related to possible geometrical phase transition of these topological objects is given.

1. Introduction

General relativity (GR) is one of the most successful theories in physics. Nonetheless, this theory could not predict precisely the fact that our universe has an accelerated expansion [1,2]. In order to interpret this expansion, some various candidates have been proposed, such as the cosmological constant idea [3], dark energy models [4,5] and modified gravities including Lovelock gravity [6], F(R) gravity models [7–9], scalar–tensor theories [10,11] and brane world cosmology [12,13]. The theory of Lovelock gravity is special between others, since this theory is ghost-free and also enjoys the principles of general relativity in higher dimensions.

On the other hand, GR includes the graviton as a massless particle, but the results of LIGO experiment, and also from theoretical point of view, it was shown that the graviton might be a massive particle with an upper limit on its mass [14–17]. Therefore, one may regard a generalization of Einstein's theory of gravity in the context of massive gravity. In addition, considering the massive gravitons improves our viewpoint about the cosmological constant problem [18]. Furthermore, the observational evidences suggest that about 95% energy of our universe is dark energy and dark matter [19] which is based on assumption that GR is equally valid at all length scales. So, the modifications of GR by massive gravitons could possibly change this scenario over large distances.

The first attempt regarding introduction of linear massive gravity was done by Fierz and Pauli [20,21]. Later, Boulware and Deser (BD) showed that this theory of massive gravity suffers the BD ghost instability at the nonlinear level [22]. The existence of ghost indicates that the theory under consideration is unstable. In order to avoid such instability, some other models of massive gravity were introduced. One of the ghost-free massive theories was introduced by Bergshoeff, Hohm and Townsend in which such theory was a three dimensional massive theory and is known as new massive gravity (see [23], for more details). However, this theory has some problems in four and higher dimensions. Recently, de Rham, Gabadadze and Tolley (dRGT) introduced another class of massive gravity [24] which is ghost-free

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in arbitrary dimensions. It is notable that, in this theory, the mass terms are produced by considering a reference metric. This reference metric plays a crucial role for constructing the massive theory of gravity [25]. Study of this theory showed that dRGT theory is stable [26,27], and it is free of BD ghost [26,27]. Black hole solutions and their thermodynamical properties, stability of various black holes and cosmological solutions of dRGT theory have been investigated in literature [28–34]. From astrophysical point of view, Katsuragawa et al., investigated the neutron stars in this gravity and found that the massive gravity leads to small deviation from the GR results [35].

Another massive gravity model with different reference metric was proposed by Vegh which is motivated by the applications of gauge/gravity duality [36]. Vegh showed that graviton may behave like a lattice and exhibits a Drude peak in this theory of massive gravity [36]. It is notable that, this theory is ghost-free and stable for arbitrary singular metric [37]. Charged black hole solutions and the existence of van der Waals like behavior in extended phase space have been studied in the context of this gravity [38,39]. Besides, the generalizations of such theory to include Born–Infeld electrodynamics [40], higher derivative gravity [41], and also gravity's rainbow [42] have been investigated. In addition, BTZ black hole solutions in massive gravity with linear and nonlinear electrodynamics have been studied in Ref. [43]. The hydrostatic equilibrium equation of neutron stars in the context of this massive gravity was extracted and it was found that the maximum mass of neutron stars can be more than $3.2M_{\odot}$ [44].

In summary, massive gravity have some interesting properties, such as (i) From cosmological point of view, massive gravity can be used to explain the cosmological constant problem [45], and also provides an interesting basis for self-acceleration of our universe without introducing the cosmological constant [46]. In other words, some of the massive terms of cosmological solutions can be regarded as an effective cosmological constant [47,48]. (ii) Graviton is one of the best candidates for dark matter [49]. (iii) The existence of massive gravitons provides extra polarization for the gravitational waves and also affects their propagation's speed [50]. Massive gravitons had considerable effect on the production of gravitational waves during inflation [51,52]. (iv) From astrophysical point of view, the existence of maximum mass of neutron stars more than $3.2M_{\odot}$ is possible in the massive gravity context [44]. (v) Considering the massive gravitons results into the existence of remnant for the temperature of black holes after evaporation which could explain the information paradox [43]. (vi) The existence of van der Waals behavior and critical phenomena for topological black holes is another interesting property of massive gravity [53].

On the other hand, one of the interesting higher derivative gravity models is the Lovelock theory which is the most generalization of Einstein gravity that includes properties of Einstein's tensor in the higher dimensions. This gravity enjoys only first and second-order derivatives of the metric function in the field equations, and also it is a ghost-free theory of gravity. It is notable that, in 4-dimensions, the Lovelock gravity reduces to the Einstein theory without any additional term. In other words, by considering the Lovelock gravity in higher dimensions, the additional terms will appear. The first three terms of Lovelock gravity is including the Einstein and Gauss–Bonnet (GB) gravities in the presence of cosmological constant. The GB gravity has interesting properties such as: (i) It is free of ghost particles [54,55]. (ii) The natural next-to-leading order term of the heterotic superstring effective action which plays a fundamental role in Chern–Simons gravitational theories is GB term [56]. (iii) The presence of GB gravity in addition to Einstein gravity may lead to the modified Renyi entropy [57]. This entropy violates specific inequality which must be hold for Renyi entropy. (iv) Regarding AdS/CFT correspondence, it was shown that considering GB gravity will modify shear viscosity, entropy, thermal conductivity and electrical conductivity [58]. The black holes, wormholes, cosmological solutions, stability and structure of stars in the context of GB gravity have been investigated in some literature [59–65].

From cosmological point of view, it was proposed that the early universe was plugged with number of phase transitions. During these phase transitions, different regions were collectively regarded different minima in the set of possible states to fall in. This resulted into formation of different regions with specific boundaries. Alongside of these phase transitions, specific symmetries were broken which resulted into formation of different topological defects. These topological defects were located on the boundary of different regions and in the essence, they are due to disagreement between two different regions regarding their choices for the minima. The final structure of the topological defects and their geometrical and physical properties depend on the broken symmetry during the phase transition. Among different topological defects, one can name: (i) Domain walls which are originated from broken discrete symmetry and divide universe into blocks. (ii) Cosmic strings which are arisen from the breaking of the axial or cylindrical symmetry with applications in grand unified particle physics in the electroweak scale. (iii) Monopoles which carry magnetic charge and are formed due to a broken spherical symmetry. (iv) Textures which are due to breaking of several symmetries. The topological defects contain information regarding the early universe and its phase transitions [66,67]. Furthermore, it was argued that they have important role in the large-scale structure of universe [66,67]. The effects of these astrophysical objects on the Cosmic Microwave Background (CMB) have been explored in Refs. [68,69]. In addition, it was proposed that dark matter may be originated from these topological defects [70,71]. Also, it was shown that these topological defects have gravitational lensing property [72] which is due to the modification in trajectory of the photon on these topological defects depending on deficit angle. So far, wide range of studies regarding the topological defects were done which among them one can point out: (i) The cosmic strings in the presence of Maxwell field [73,74]. (ii) The superconducting property of these topological defects in Einstein [75], dilaton [76] and Brans–Dicke [77] theories. (iii) The QCD applications of the magnetic strings [78,79] and their roles in quantum theories [80,81]. (iv) The stability of the cosmic strings through quantum fluctuations [82]. (v) The existence of the limits on the cosmic string tension by extracting signals of cosmic strings from CMB temperature anisotropy maps [83]. (vi) The spectrum of gravitational wave background produced by cosmic strings [84]. (vii) The evolution of domain walls in de Sitter universe [85]. (viii) The production of gravitational waves from decaying domain walls [86]. For further studies regarding the cosmological topological defects, we refer the reader to Refs. [87–92]. Considering the wide applications of topological defects, GB theory and massive gravity, it is interesting to study the effects of GB massive gravity on the properties of conic geometry.

In this paper, we are interested in topological defects which are known as horizonless magnetic solutions (see refs. [90,93,94], for more details). These solutions are not black hole but they contain conic singularity. The main motivation is to understand the effects of the massive gravity alongside of GB gravity on geometrical and physical properties of the magnetic solutions. We will emphasize on the role and effects of different parameters on deficit angle of the solutions and show that depending on choices of different parameters, there might be discontinuity and change of signature for deficit angle which mark the existence of geometrical phase transition for these objects.