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Thermodynamics of 4D dS/AdS Gauss–Bonnet black holes according to consistent gravity theory in the presence of a cloud of strings

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Abstract

By looking at the Lovelock theorem one can infer that the gravity model given by [1] cannot be applicable for all types of 4D Einstein–Gauss–Bonnet (EGB) curved space-time. The reason for this is that in 4D space-time, the Gauss–Bonnet invariant is a total derivative and hence it does not contribute to gravitational dynamics. Hence, the authors of [2] presented an alternative consistent EGB gravity model instead of [1] by applying a break-of-diffeomorphism property. In this work, we use the alternative model to produce a de Sitter (dS)/Anti-de Sitter (AdS) black hole metric and then investigate its thermodynamic behavior in the presence of a cloud of Nambu–Goto strings. Mathematical derivations show that the resulting diagrams of pressure vs specific volume at a constant temperature are similar to that for a van der Waals gas/fluid in an ordinary thermodynamic system in the dS sector but not in the AdS background. From this, we infer that the black hole participates in the small-to-large black hole phase transition in the dS background, while it exhibits a Hawking–Page phase transition in the AdS background. In the latter case, an evaporating black hole eventually reaches an AdS vacuum space because of its instability.

Keywords: Lovelock gravity, string, Nambu–Goto, Gauss–Bonnet, black hole, thermodynamic, cosmological constant, phase transition

(Some figures may appear in colour only in the online journal)

1. Introduction

Among the various higher-order derivative gravitational models described in the literature, Lovelock gravity [3] is quite special, as it is free of ghosts [4–10]. In fact, many of the higher-order derivative metric theories which have been presented exhibit Ostrogradsky instability (see [11, 12] for a good review). In this sense, the actions that contain higher-order curvature terms introduce equations of motion with fourth- or higher-order metric derivatives in which linear perturbations reveal that the graviton should be a ghost. Fortunately, the Lovelock model is free of ghost terms, and so has field equations involving no more than second-order derivatives of the metric. The action functional of Lovelock gravity is given by combinations of various terms, as follows. The first term is the cosmological constant Λ, the second term is the Ricci scalar $R = R^{\mu}_{\mu}$, and the third and fourth terms are the second-order Gauss–Bonnet (GB) [13] and third-order Lovelock terms (see equation (22) in [14]), respectively. Without the latter term, the Lovelock gravity reduces to the simplest form called the Einstein–Gauss–Bonnet (EGB) theory, in which the Einstein–Hilbert action is supplemented with a quadratic curvature GB term as the source of the self-interaction of gravity. The importance of this form of the gravity model is more apparent when we observe that it is generated from the effective Lagrangian of low-energy string theory [15–19]. In fact, for more than four dimensions of curved space-time, the GB coupling parameter, which is calculated by the dimensional regularization method, has some