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Iron line spectroscopy with Einstein–dilaton–Gauss–Bonnet black holes

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ABSTRACT

Einstein–dilaton–Gauss–Bonnet gravity is a well-motivated alternative theory of gravity that emerges naturally from string theory. While black hole solutions have been known in this theory in numerical form for a while, an approximate analytical metric was obtained recently by some of us, which allows for faster and more detailed analysis. Here we test the accuracy of the analytical metric in the context of X-ray reflection spectroscopy. We analyze innermost stable circular orbits (ISCO) and relativistically broadened iron lines and find that both the ISCO and iron lines are determined sufficiently accurately up to the limit of the approximation. We also find that, though the ISCO increases by about 7% as dilaton coupling increases from zero to extremal values, the redshift at ISCO changes by less than 1%. Consequently, the shape of the iron line is much less sensitive to the dilaton charge than expected.

1. Introduction

Einstein's theory of gravity has been the standard framework for describing gravitational effects in our universe. Since its proposition, it has been applied quite successfully in various astrophysical scenarios. Its predictions have largely been validated in the so called weak field regime [1], whereas in the strong field regime it is largely untested. Tests in strong field gravity are becoming more accessible and popular with latest technology. As one of the most compact objects predicted by general relativity, black holes are natural laboratories for testing strong gravity. Within general relativity, most black holes are expected to be described by the uncharged and rotating metric discovered by Kerr [2].[1] Besides charge, which is expected to be extremely small for these objects, all the deviations from a Kerr solution are quickly radiated away [4,5] and the no-hair theorem [6,7] holds for these objects.

Despite its successes, there are some fundamental questions, e.g., dark matter and dark energy, that are unresolved within Einstein's theory. Moreover, combining Einstein's theory with quantum mechanics results in a non-renormalizable effective theory, which breaks down at the Planck scale. This remains an outstanding problem in physics and a number of alternative theories have been proposed to resolve these issues. One of the most interesting alternatives is the *Einstein–dilaton–Gauss–Bonnet* (EdGB hereafter) theory. It has an additional (to Einstein's theory) term in the action which is second-order in curvature, known as the Gauss–Bonnet term, and is coupled to a dynamical scalar field. This model emerges naturally in string theory where the scalar field is the dilaton [8,9]. Black hole solutions in numerical form are known in this theory, for spherically symmetric [8] as well as rotating cases [10,11]. (See also perturbative solutions at [12,13].) Various potentially observable properties of the EdGB black hole have been recently studied in a number of works. Slowly rotating solutions were studied in [14], quasinormal modes were computed in [15], while the shadows were found first in [16] for the perturbative solution and in [17] for the numerical one.

A promising technique for probing the strong field region of black holes is X-ray reflection spectroscopy. The standard approach to analyze black holes with this technique is the disk-corona model [18]. In this model, the black hole is surrounded by a geometrically thin and optically thick disk [19] with accreting matter and possesses a "corona". The disk is formed of material either from a companion star, in case of stellar-mass black holes in binary systems, or the interstellar medium, in case of supermassive black holes at galactic centers. The disk emits like a blackbody locally,

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[1] There are additional assumptions like four dimensions, asymptotic flatness, etc. See, e.g., [3].

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and as a multi-temperature blackbody when integrated radially. The temperature of the inner part of the accretion disk typically is in the soft X-ray band (0.1–1 keV) for stellar-mass black holes and in the optical/UV band (1–100 eV) for the supermassive ones. The corona is a hotter (∼100 keV) and optically thin source near the black hole. The morphology of the corona is not very well understood. (See, e.g., [20,21].) Thermal photons from the disk gain energy via inverse Compton scattering off the hot electrons in the corona, and transform into X-rays with a characteristic power-law distribution. These reprocessed photons return to the disk, producing a reflection component with fluorescent emission lines. The strongest feature of the reflection spectrum is the iron Kα line, since the disk is usually abundant in iron and the fluorescent yield for iron is higher than lighter elements, with emission lines at 6.4 keV in the case of neutral or weakly ionized iron but can go up to 6.97 keV for H-like ions.

While the iron Kα line is a narrow line in the rest-frame of the disk, relativistic effects due to the gravity of the central black hole cause this *line* to broaden and skew for observers far away. Combination of all such broadened lines, from different ionizations of iron as well as from other elements present in the accretion disk, produces the *reflection spectrum*. With high quality observations and suitable model of the disk, corona, etc., analysis of the reflection spectrum can be a powerful tool for probing the strong gravitational fields of accreting black holes [22–24]. For the rest of this paper, we focus our attention on the iron line, since the phenomenologies of a single line and the complete reflection spectrum are similar.

Iron line spectroscopy was first applied to EdGB black hole metrics in [25]. They used the numerical metric of [10,11] to simulate observations of iron lines with current (NuSTAR[2]) and future (LAD/eXTP [26]) instruments. They tried to recover the input parameters with the standard Kerr iron line data analysis model RELLINE [27]. The logic behind this approach is as follows: a good fit with RELLINE precludes the possibility of detecting non-Kerr metrics (the EdGB black hole metric in this case) with iron line spectroscopy. If a good fit is not possible, it suggests that the non-Kerr metric sufficiently alters the iron line to make this technique a useful approach for testing this non-Kerr metric. They found some unresolved features in LAD/eXTP simulations which could not be fitted with a Kerr model. This suggests that X-ray spectroscopy in near future would be able to test EdGB black hole metrics with real observations.

For this proof-of-principle study a numerical metric sufficed, but there are various drawbacks in using such metrics:

1. Calculating propagation of photons along geodesics is relatively slower in numerical metrics, since metric coefficients and Christoffel symbols need to be calculated through interpolation.
2. Errors due to interpolation require delicate handling to ensure they are within acceptable limits.
3. Pathologies may appear in non-Kerr metrics which would not be apparent if the metric is available only in a numerical form.

While a numerical metric was sufficient to claim that the EdGB black holes would have observational signatures distinct from Kerr, to quantify the differences and develop a model that can calculate the differences with real observational data, it is crucial to have analytical expressions for the metric. Recently, some of us obtained an approximate analytical metric for the spherically symmetric EdGB black holes [28], based on the continued fraction expansion of [29]. The expressions are relatively compact and provide excellent accuracy for the metric components.

In the present work we test the accuracy of the approximate analytical metric for X-ray reflection spectroscopy. We compare the radius of the innermost stable circular orbit (ISCO), which usually determines the inner edge of the accretion disk and has a strong effect on the low energy part of the iron line, calculated with the numerical metric and the analytical metric. We then compare the iron line with numerical and analytical metrics and show that the analytical metric can produce the iron line with sufficient accuracy. We also discuss an interesting feature where although the dilaton charge changes the radius of the ISCO, the change in the shape of the iron line is much weaker than expected.

The paper is organized as follows: In Section 2, we review the numerical and analytical black hole metrics in EdGB theory. In Section 3, we review the calculation of iron line and compare iron lines calculated with the numerical and analytical metrics. An interesting feature regarding the effect of the dilaton charge on the iron line is described and explained in Section 4. Conclusion follows in Section 5. Throughout, we employ units where $c = G = \hbar = 1$ and the metric has the signature $(-+++)$.

2. Black hole metric in EDGB theory

Following [28], the Lagrangian in Einstein–dilaton–Gauss–Bonnet gravity is given as

$$\mathcal{L} = \frac{1}{2}R - \frac{1}{4}\partial_\mu \partial^\mu \phi + \frac{\alpha'}{8g^2}e^\phi \left(R_{\mu\nu\rho\sigma}R^{\mu\nu\rho\sigma} - 4R_{\mu\nu}R^{\mu\nu} + R^2\right), \tag{1}$$

where ϕ is the dilaton field and α' and g are coupling constants. α' has units of (length)^2 while g and ϕ are dimensionless. By a conformal rescaling of the dilaton field, $\alpha'/g^2 \to 1$. To describe non-rotating black holes, a spherically symmetric spacetime is chosen:

$$ds^2 = -e^{\Gamma(r)}dt^2 + e^{\Lambda(r)}dr^2 + r^2\left(d\theta^2 + \sin^2\theta\, d\phi^2\right). \tag{2}$$

The dilaton field $\phi(r)$ and the metric functions are defined as follows:

$$\phi''(r) = -\frac{d_1(r,\Lambda,\Gamma,\phi,\phi')}{d(r,\Lambda,\Gamma,\phi,\phi')}, \tag{3}$$

$$\Gamma''(r) = -\frac{d_2(r,\Lambda,\Gamma,\phi,\phi')}{d(r,\Lambda,\Gamma,\phi,\phi')}, \tag{4}$$

$$e^{\Lambda(r)} = \frac{1}{2}\left(\sqrt{Q^2 - 6\phi' e^\phi \Gamma'} - Q\right), \tag{5}$$

where

$$Q \equiv \frac{\phi'^2 r^2}{4} - 1 - \left(r + \frac{\phi'^2 e\phi}{2}\Gamma'\right), \tag{6}$$

while the expressions for d, d_1 and d_2 can be referred from [8]. These equations can be solved with the following initial conditions at the event horizon r_0:

$$\phi(r_0) = \phi_0, \tag{7}$$

$$\phi'(r_0) = r_0 e^{-\phi_0}\left(\sqrt{1 - 6\frac{e^{2e_0^\phi}}{r_0^4}} - 1\right), \tag{8}$$

$$\Psi(r_0) = 1, \tag{9}$$

[2] https://www.nustar.caltech.edu/.