Testing the strong field gravity regime with QPO observations

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1. Introduction

Experimental test of General Relativity (GR) have mostly probed the weak field regime of the theory.[1] Therefore, many strong-field GR predictions still remain to be verified.[2,3] Astrophysical systems containing black holes (BHs) and neutron stars (NSs), provide the best arena to study the properties of the strong gravitational fields in their close surroundings. In this respect, very fast flux variability produced by matter orbiting close to BHs and NSs is a potential probe of geodetic motion in the strong-gravity regime.[4] This diagnostics became available when fast quasi-periodic oscillations (QPOs) at X-ray energies and frequencies close to those expected from bound orbits at characteristic radii of $\lesssim 10GM/c^2$, were discovered. Several models have been proposed to interpret QPOs, virtually all of them involving the frequencies characterising the motion of matter in the strong-field regime.

It is expected that future high throughput X-ray instruments will detect simultaneous QPO signals from a number of BH systems, measuring their frequency with enough accuracy to verify GR predictions in the strong-field/high-curvature regime. Proposed X-ray astronomy satellites like *LOFT* and *eXTP* with their extremely high effective area offer the best prospects for exploiting the QPO diagnostics.[3,5]

QPOs can be used to test General Relativity against alternative theories.[1,2,6] In this work, on the basis of the results of Maselli et al. 2014,[7] we show that the azimuthal and epicyclic frequencies of a slowly rotating BH in Einstein-Dilaton-Gauss-Bonnet (EDGB) gravity,[8] differ from their GR equivalent. Using the Relativistic Precession Model[9,10] (RPM) to interpret the QPOs from accreting BHs, we develop a data analysis strategy to prove that such differences can be large enough to be measured with the next generation, of very large area X-ray satellites.

1.1. *The relativistic precession model and the epicyclic frequencies*

The aim of the RPM is to interpret both the twin QPOs observed around ~ 1 kHz and a low-frequency QPO mode of NSs in low-mass X-ray binaries. The higher- and lower-frequency kHz QPOs are associated with the azimuthal frequency ν_φ, and the periastron precession frequency, $\nu_{\rm per} = \nu_\varphi - \nu_r$, of matter orbiting in quasi-circular orbits; here ν_r is the radial epicyclic frequency. The low-frequency QPO is related to the nodal precession frequency, $\nu_{\rm nod} = \nu_\varphi - \nu_\theta$, where ν_θ is the vertical epicyclic frequency. $\nu_\varphi, \nu_{\rm per}$ and $\nu_{\rm nod}$ are supposed to be emitted at the same radius in the accreting disk. A full application to BHs involving three QPO modes became possible only with the observation of GRO J1655-40, where high and low-frequency QPOs were measured by the *RXTE* satellite with frequencies (in Hz): $\nu_\varphi = 441^{+2}_{-2}$, $\nu_{\rm per} = 298^{+4}_{-4}$, $\nu_{\rm nod} = 17.3^{+0.1}_{-0.1}$. By fitting these QPOs (hereafter the QPO triplet) with the frequencies from the Kerr metric, precise values of the BH mass $M = (5.31 \pm 0.07) M_\odot$, spin parameter $a^\star = 0.290 \pm 0.003$, and emission radius r, were determined.[11] The detection of a single QPO triplet yields only the three quantities cited above. If more triplets are detected, the redundancy will provide additional information concerning the properties of the strong gravitational field in the neighbourhood of a BH horizon. The calculations made in this paper are based on the proposed mission *LOFT* which, owing to its extremely large effective area, will provide a factor of ~ 15 improved precision relative to the *RXTE* measurements.

1.2. *Testing gravity with LOFT*

According to the RPM, each simultaneous QPO triplet provides in GR a system of three equations for the three unknown parameters $(M, a^\star, r)$, which can be solved analytically. In the EDGB theory, however, there is an extra parameter, i.e. α/M^2, which measures deviations from GR. Therefore, we need at least one more triplet to measure such quantity. In the following, we explore the chance to use QPO observations to discriminate GR against EDGB gravity, focusing on the case in which two different triplets are measured.

We consider BH configurations with fixed mass $\bar{M} = 5.3\ M_\odot$ and spins ($\bar{a}^\star = 0.1, 0.2$). Moreover we choose values of the EDGB coupling constant $\alpha/\bar{M}^2$ consistent with the theoretical bound $\alpha/\bar{M}^2 < 0.691$.[12] Using the EDGB equations, we generate two sets of frequencies $\nu_{\rm ref1} = (\nu_\varphi, \nu_{\rm per}, \nu_{\rm nod})_1$ and $\nu_{\rm ref2} = (\nu_\varphi, \nu_{\rm per}, \nu_{\rm nod})_2$ emitted at different radii $r_1/r_{\rm ISCO} = 1.1$ and $r_2/r_{\rm ISCO} = 1.4$, respectively. We assume that these QPO frequencies are measured by *LOFT*, with uncertainties 15 times smaller than those measured with *RXTE* from GRO J1655-40.

Then using GR, we determine the values of $(M_j, a^\star_j, r_j)_{j=1,2}$ corresponding to the two QPO sets. If the triplets $\nu_{\rm ref1}, \nu_{\rm ref2}$ were generated in GR, i.e. $\alpha/\bar{M}^2 = 0$, this procedure would yield $M_1 = M_2$ and $a_1^\star = a_2^\star$, within statistical and numerical uncertainties. Conversely, when $\alpha/\bar{M}^2 \neq 0$, it can be expected that $M_1 \neq M_2$ and $a_1^\star \neq a_2^\star$. To quantify this difference, given the selected values of $\bar{M}, \bar{a}^\star, \alpha/\bar{M}^2$, we generate $2 \times (N = 10^5)$ triplets $(\nu_\varphi, \nu_{\rm per}, \nu_{\rm nod})_{j=1,2}$, with a Gaussian distribution, centred around $\nu_{\rm ref1}$ and $\nu_{\rm ref2}$, with standard deviation given by LOFT uncertainties.

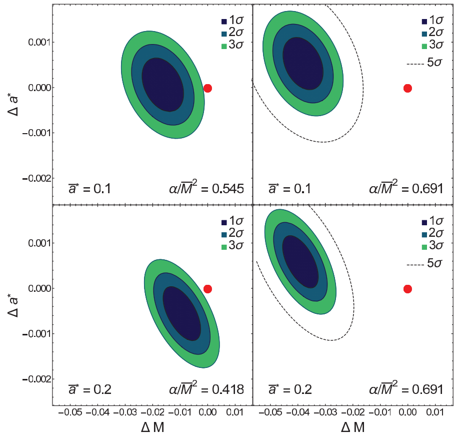

Figure 1. Confidence levels with which GR can be tested against the EDGB theory (see text) are plotted in the $(\Delta M, \Delta a^\star)$ plane. The red dot is the origin of the plane.[7]

Then, to determine whether these distributions are compatible with $M_1 = M_2$ and $a_1^\star = a_2^\star$, i.e., with GR, we follow this strategy: (i) we define $\Delta M = M_1 - M_2$, $\Delta a^\star = a_1^\star - a_2^\star$ and $\Delta r = r_1 - r_2$, verifying that the distribution of $\vec{\mu} = (\Delta M, \Delta a^\star, \Delta r)$ is consistent with a Gaussian distribution $\mathcal{N}(\vec{\mu}, \Sigma = \Sigma_1 + \Sigma_2)$ with zero expectation value; (ii) we build a chi-square variable $\chi^2 = (\vec{x} - \vec{\mu})^{\rm T}\Sigma^{-1}(\vec{x} - \vec{\mu})$ with 3 degrees of freedom. $\chi^2 = c$ defines the ranges of ΔM, $\Delta a^\star$, and Δr at the confidence level specified by c. In particular, $c = 3.53, 8.03, 14.16$ correspond to the 1σ, 2σ, and 3σ confidence levels in a Gaussian distribution equivalent.

In the four panels of Figure 1, we show the regions in the parameter space $(\Delta M, \Delta a^*)$ which correspond to the 1σ, 2σ, and 3σ confidence levels, when three values of $\alpha/\bar{M}^2$, ($\sim$ 0.418, 0.545, 0.691) are considered. The red dot corresponds to $\Delta M = \Delta a^* = 0$. In the right panel, the maximum value of α/M^2 is used; the red circle lies well outside the 5σ confidence ellipse, demonstrating that the two QPO triplets are inconsistent with GR. Furthermore, for $\alpha/\bar{M}^2 = 0.545$ and $\alpha/\bar{M}^2 = 0.418$, ΔM would be incompatible with 0 at 3σ for $\bar{a}^\star = 0.1$ and $\bar{a}^\star = 0.2$ respectively. Choosing 3σ as a threshold to assess the compatibility of these data with GR predictions Figure 1 indicates that, when $\bar{a}^\star = 0.1$, EDGB theory could be discriminated from GR for values of the coupling constant $\alpha/\bar{M}^2 \in (0.545, 0.691)$. As the BH spin increases, this strategy allows to explore regions of lower α/M^2.

Conclusion

In this work we have used QPO frequencies as interpreted in the RPM to test GR against alternative theories of gravity in the strong-field regime. Focusing on the EDGB theory, we have shown that the X-ray satellite *LOFT* can provide constraints on the parameter α/M^2 which characterises this theory. These bounds would be $\sim 4-5$ times stronger than current constraints coming from the orbital decay rate of low-mass X-ray binaries.[13]

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