ACCRETION DISKS AROUND KERR BLACK HOLES IN MODIFIED GRAVITY

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We study orbits and accretion disks around Kerr black holes in $f(R)$ gravity with constant curvature and compare the results of the emitted spectra with what is expected in General Relativity (GR). Effects like Comptonization and Thompson absorption are taken into account in order to allow a comparison with observational data of the black hole candidate Cygnus X-1 in the high-soft state.

Keywords: Black Holes; Accretion disks; Gravitation; $f(R)$ gravity

1. Introduction

$f(R)$-gravity is a class of Extended Theories of Gravity, where the Lagragian of the Hilbert-Einstein action is generalized to:

$$S[g] = \frac{c^3}{16\pi G}\int (R + f(R))\,\sqrt{-g}\; d^4x, \tag{1}$$

where g is the determinant of the metric tensor, and $f(R)$ is an arbitrary function of the Ricci scalar.

$f(R)$ Kerr-Newman black holes solutions with constant Ricci scalar were firstly discovered by Carter,[1] and have been recently studied by Cembranos and collaborators.[2] The aim of this work is to analyze the main features of relativistic accretion disks[3,4] around $f(R)$-Kerr black holes with constant Ricci scalar and compare our results with current observational data to constrain the free parameters of these theories. We adopt the following values for the mass, mass accretion rate and angular momentum of the black hole: $M = 14.8M_{\odot}$, $\dot{M} = 0.472\ \times 10^{19}$ g s^{-1}, and a[a]$= 0.99$.[5,6]

2. Accretion disks around $f(R)$-Kerr black holes

The axisymmetric, stationary and constant R_0 Ricci scalar space-time matric that describes a black hole with mass M and angular momentum in the equatorial plane

[a] a is an adimensional quantity defined as $\mathsf{a} \equiv a/r_{\rm g}^2$, where $r_{\rm g} = GM/c^2$.

takes the form:[1,2]

$$ds^2 = -\frac{c^2}{r^2\Xi^2}\left(\Delta_r - a^2\right)dt^2 + \frac{r^2}{\Delta_r}dr^2 - \frac{2ac}{r^2\Xi^2}\left(r^2 + a^2 - \Delta_r\right)dtd\phi \qquad (2)$$
$$+ \frac{d\phi^2}{r^2\Xi^2}\left[\left(r^2+a^2\right)^2 - \Delta_r a^2\right],$$

where:

$$\Delta_r = \left(r^2+a^2\right)\left(1 - \frac{R_0}{12}r^2\right) - \frac{2GMr}{c^2}, \qquad (3)$$

$$\Xi = 1 + \frac{R_0}{12}a^2. \qquad (4)$$

By studying the effective potential derived from Eq. (2) for different values of R_0, and taking for the radius of the outer edge of the disk[7] $r_{\rm out} = 16 r_{\rm isco}$, we find that accretion disks are possible for R_0[b] $\in \left[-1.25\times10^{-1}, 6.67\times10^{-4}\right]$. We proceed to calculate the temperature and spectral energy distributions for accretion disks in such space-times geometries.

For negative values of the Ricci scalar the results are displayed in Table (1). The temperature of the disk increases for smaller values of R_0. The ratio of the maximum temperature between GR and the $f(R)$ cases, with $\mathsf{R}_0 = -1.25\times10^{-1}$, is 1.20. The peak of the emission rises a factor of 2, and the corresponding energy is shifted towards higher energies. For $\mathsf{R}_0 \in (0, 6.67\times10^{-4}]$, as we show in Table 2, the temperature and energy distributions have no significant differences with Kerr's distributions in GR.

Table 1. Location of the last stable circular orbit and maximum temperature, maximum temperature, luminosity, and energy of the peak of the emission for an accretion disk around a $f(R)$-Kerr black hole with $\mathsf{R}_0 < 0$ and $\mathsf{a} = 0.99$.

$f(R)$-Kerr	$\mathsf{R}_0 = 0$	$\mathsf{R}_0 = -10^{-3}$	$\mathsf{R}_0 = -1.2\times10^{-3}$
$r_{\rm isco}/r_{\rm g}$	1.4545	1.4523	1.4518
$r_{\rm Tmax}/r_{\rm g}$	3.79	3.79	3.79
$T_{\rm max}$	0.539 keV	0.54119 keV	0.54148 keV
$E_{\rm max}$	1659.4 eV	1659.4 eV	1659.4 eV
$L(E_{\rm max})$	2.26×10^{37}erg s^{-1}	2.38×10^{37}erg s^{-1}	2.41×10^{37}erg s^{-1}
$f(R)$-Kerr	$\mathsf{R}_0 = -10^{-2}$	$\mathsf{R}_0 = -10^{-1}$	$\mathsf{R}_0 = -1.25\times10^{-1}$
$r_{\rm isco}/r_{\rm g}$	1.4325	1.2017	1.0419
$r_{\rm Tmax}/r_{\rm g}$	3.85	3.85	3.78
$T_{\rm max}$	0.553 keV	0.663 keV	0.652 keV
$E_{\rm max}$	1833.52 eV	2025.9 eV	2025.9 eV
$L(E_{\rm max})$	2.94×10^{37}erg s^{-1}	4.23×10^{37}erg s^{-1}	4.60×10^{37}erg s^{-1}

[b] R_0 is an adimensional quantity defined as $\mathsf{R}_0 \equiv R_0/r_{\rm g}^2$, where $r_{\rm g} = GM/c^2$.

Table 2. Location of the last stable circular orbit and maximum temperature, maximum temperature, luminosity, and energy of the peak of the emission for an accretion disk around a $f(R)$-Kerr black hole with $\mathsf{R}_0 > 0$ and $\mathsf{a} = 0.99$.

$f(R)$-Kerr	$\mathsf{R}_0 = 0$	$\mathsf{R}_0 = 10^{-4}$	$\mathsf{R}_0 = 6.67 \times 10^{-4}$
$r_{\rm isco}/r_{\rm g}$	1.4545	1.4547	1.4559
$r_{\rm Tmax}/r_{\rm g}$	3.79	3.79	3.79
$T_{\rm max}$	0.53942 keV	0.53927 keV	0.53843 keV
$E_{\rm max}$	1659.4 eV	1659.4 eV	1659.4 eV
$L(E_{\rm max})$	2.26×10^{37} erg s^{-1}	2.25×10^{37} erg s^{-1}	2.09×10^{37} erg s^{-1}

3. Discussion and conclusions

We shall compare the results presented in the last section with Cygnus X-1's current observational data to introduce some constrains on a given $f(R)$ theory. Cygnus X-1 is the most studied black hole binary in the Galaxy. Recent high-quality papers[5,6,8] have provided an unprecedented set of accurate measurements of the distance, the black hole mass, spin parameter a, and the orbital inclination of this source. The distance to Cygnus X-1 is currently estimated to be $1.86^{+0.12}_{-0.11}$ kpc.[8] This value was determined via trigonometric parallax using the Very Long Baseline Array (VLBA). At this distance, the mass of the black hole is[5] $M = 14.8M_{\odot}$. This is the value adopted in all calculations presented in the previous sections.

The accretion rate and the spin parameter of the hole are $\sim 0.472\times10^{19}$ g s^{-1} and 0.99, respectively, according to estimates from a Kerr plus black-body disk model.[6] Using these data, a maximum temperature for the inner disk of 0.539 ± 0.002 keV is obtained.[6] From Table 1 we see that all models of $f(R)$-gravity with constant Ricci scalar lower than $\mathsf{R}_0 = -1.2 \times 10^{-3}$ have accretion disks with temperatures greater that $0.539 + 0.002$ keV, and should be dismissed. Models with small positive scalar remain viable, which is consistent with an asymptotic behaviour corresponding to a de Sitter space-time endowed with a small and positive value of the cosmological constant.

Future high-precision determination of the parameters of other black hole candidates can be used to impose more restrictive limits to extended theories of gravity.

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