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Black holes and accretion in strong $f(R)$ gravity

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Abstract. We discuss the characteristics of rotating black holes in modified theories of gravity. We present relativistic accretion disk models for matter falling into the black holes and elaborate about possible tests of gravity in the strong regime based on X-ray observations of systems like Cygnus X-1.

Resumen. En este trabajo discutimos las características de agujeros negros rotantes en teorías modificadas de la gravedad. Presentamos modelos relativistas de acreción de materia sobre estos objetos que permitirían testear teorías de la gravedad en régimen de campo fuerte mediante observaciones en rayos X de sistemas tales como Cygnus X-1.

1. Introduction

The so-called $f(R)$ theories of gravity (e.g. Capozziello and Faraoni 2010) form an extension class of General Relativity (GR) where the Lagrangian of the Hilbert-Einstein action, given by:

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

is generalized to:

$$S[g] = \frac{c^3}{16\pi G}\int (R + f(R))\sqrt{-g}\, d^4x, \tag{2}$$

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

Although the present revival of $f(R)$ theories is mainly due to their use in the description of phenomena that take place for low values of the Riemann curvature, these theories have also been applied to gravity in the opposite regime. As there is no direct evidence of the behaviour of the gravitational field for very large values of the curvature, the early universe and compact objects offer the possibility to find deviations from GR. Few exact solutions that represent black holes are known in $f(R)$ gravity. Those with constant curvature have the particular interesting feature that can be used to mimic the effects of a cosmological constant in GR.

In this work we investigate the temperature and the spectral energy distributions of relativistic accretion disks (Page & Thorne 1974) around $f(R)$-Kerr black holes of constant Ricci curvature (Carter 1973, Cembranos at al. 2011) and compare the results obtained with current X-ray observations of Cygnus X-1.

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

In a previous work we have studied the existence of stable circular orbits in $f(R)$-Kerr space time for different values of the Ricci scalar (Pérez et al. 2012). Our results showed that stable circular orbits are possible for R_0[1] $\in (-1.3 \times 10^{-1}, 1.45 \times 10^{-1})$. If we adopt for the innermost stable circular orbit $r_{\rm isco} = 1.4545 r_{\rm g}$[2], the outer edge of the disk is approximately $16 r_{\rm g}$[3]. For positive values of the Ricci scalar, stable circular orbits are possible within a maximum radius. If $\mathsf{R}_0 > 6.67 \times 10^{-4}$ then $r_{\rm out} < 16\, r_{\rm g}$. We will calculate the temperature and luminosity of accretion disks for $\mathsf{R}_0 \in [-1.25 \times 10^{-1}, 6.67 \times 10^{-4}]$.

We calculate numerically the temperature and luminosity distributions taking into account the corrections coming from the gravitational redshift. For negative values of the Ricci scalar the results are displayed in Figures 1, 2 and Table 1. The temperature of the disk increases for smaller values of R_0. The ratio of the maximum temperature between the GR and $f(R)$ cases, with $\mathsf{R}_0 = -1.25 \times 10^{-1}$, is 1.20. The peak of the emission rises a factor of 2, and the corresponding energy is shifted towards higher energies. For $\mathsf{R}_0 > 0$, we show in Table 2 the values of the location of the last stable circular orbit, maximum temperature, luminosity, and the energy of the peak of the emission. In this case, the differences between $f(R)$-Kerr black holes and Kerr black holes in GR are minor.

3. Discussion and conclusions

The results presented in the last section can be compared with current observational data to derive some constraints on a given $f(R)$ theory. We shall consider Cygnus X-1 as a test object, which is the most intensively studied black hole binary system in the Galaxy. A series of recent high-quality papers (Reid et al. 2011, Orosz et al. 2011, Gou et al. 2011) 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. This opens the possibility to

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

[2]Differences with GR appear at a level of 10^{-5}.

[3]We adopt for the radius of the outer edge of the disk (Dove et al. 1997) $r_{\rm out} = 11 r_{\rm isco}$, where $r_{\rm isco}$ is the radius of the innermost stable circular orbit.

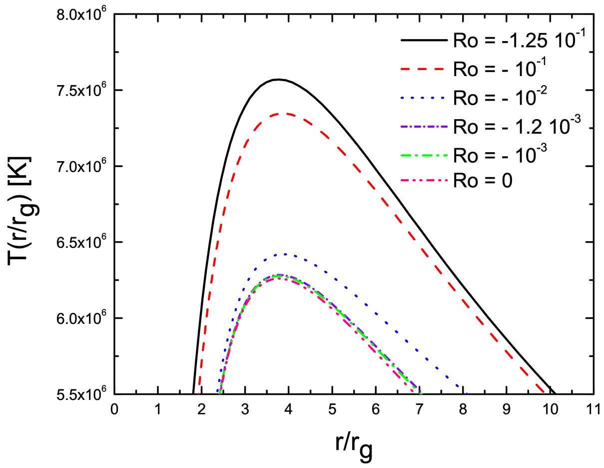

Figure 1. Plot of the temperature as a function of the radial coordinate for some values of $\mathsf{R}_0 < 0$ of a $f(R)$-Kerr black hole of angular momentum $\mathsf{a} = 0.99$, corrected by gravitational redshift.

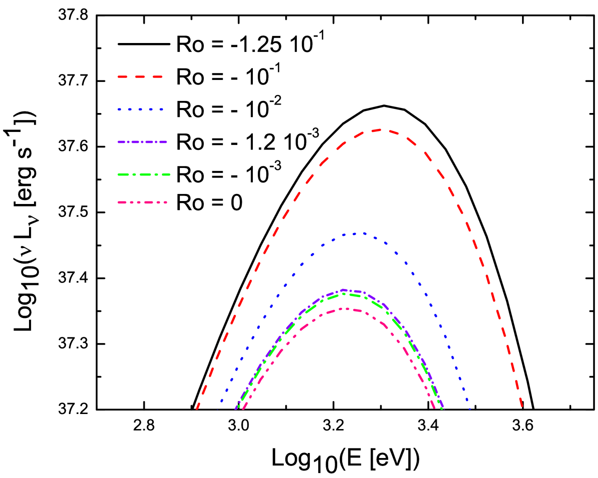

Figure 2. Plot of the luminosity as a function of the energy for some values of $\mathsf{R}_0 < 0$, for a $f(R)$-Kerr black hole of angular momentum $\mathsf{a} = 0.99$.

$f(R)$-Kerr	$\mathsf{R}_0 = 0$	$\mathsf{R}_0 = -10^{-3}$	$\mathsf{R}_0 = -1.2 \times 10^{-3}$
$r_{\rm isco}/r_{\rm g}$	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	$\mathsf{R}_0 = -10^{-2}$	$\mathsf{R}_0 = -10^{-1}$	$\mathsf{R}_0 = -1.25 \times 10^{-1}$
$r_{\rm isco}/r_{\rm g}$	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}

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	$\mathsf{R_0} = 0$	$\mathsf{R_0} = 10^{-4}$	$\mathsf{R_0} = 6.67 \times 10^{-4}$
$r_{\rm isco}/r_{\rm g}$	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}

Table 2. Values of the location of the last stable circular orbit, location in the radial coordinate of the maximum temperature, maximum temperature and luminosity, and the energy of the peak of the emission for an accretion disk around a $f(R)$-Kerr black hole with $\mathsf{R_0} > 0$ and $\mathsf{a} = 0.99$.

constrain modified theories of gravity with rather local precision observations of astrophysical objects in the Galaxy.

The accretion rate and the spin parameter of the hole are $\sim 0.472 \times 10^{19}$ g s^{-1} and 0.99, respectively, according to estimates from a Kerr plus blackbody disk model (Gou et al. 2011). These GR models yield a spectral energy distribution with a maximum at $E_{\rm max} \sim 1.6$ keV. On the contrary, $f(R)$-models with negative curvature correspond to a low maximum temperature, lower even than what is expected for the (unrealistic) case of a Schwarzschild black hole. Therefore, we can presume that a fit of $f(R)$-Kerr models to the data would also prefer high values of maximum temperature, i.e., ones with non-negative curvature. Models with accretion rates and spin close to those obtained by Gou et al. (2011) and small positive curvature seem viable, something that is consistent with an asymptotic behaviour corresponding to a de Sitter space-time endowed with a small and positive value of the cosmological constant.

Deep X-ray studies with *Chandra* satellite might impose more restrictive limits, especially if independent constraints onto the accretion rate become available.

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References

Capozziello S. & Faraoni V. 2010, Beyond Einstein Gravity. A survey of Gravitational Theories for Cosmology and Astrophysics, (Springer, Dordrecht-Heidelberg-London-New York)

Carter, B. 1973, in *Les Astres Occlus* ed. C. DeWitt and B. DeWitt (New York, Gordon & Breach)

Cembranos, J. A. R., de la Cruz-Dombriz, A., & Jimeno Romero, P., 2011 arXiv:1109.4519v1

Dove, J. B., Wilms, J., Maisack, M., & Begelman, M. 1997, ApJ 487, 759

Gou L. et al. 2011, ApJ 742, 85

Orosz, J. A. et al., 2011 ApJ 742, 84

Page, D. N. & Thorne, K. S. 1974 ApJ 191, 499

Pérez D., Romero G.E. & Perez Bergliaffa, S.E. 2012, A&A in press. DOI: 10.1051/0004-6361/201220378

Reid, M. J. et al. 2011, ApJ 742, 83