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Attempt to find a correlation between the spin of stellar-mass black hole candidates and the power of steady jets: Relaxing the Kerr black hole hypothesis

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The rotational energy of a black hole can be extracted via the Blandford-Znajek mechanism and numerical simulations suggest a strong dependence of the power of the produced jet on the black-hole spin. A recent study has found no evidence for a correlation between the spin and the power of steady jets. If the measurements of the spin and of the jet power are correct, it leads one to conclude that steady jets are not powered by the black-hole spin. In this paper, I explore another possibility: I assume that steady jets are powered by the spin and I check if current observations can be explained if astrophysical black hole candidates are not the Kerr black hole predicted by general relativity. It turns out that this scenario might indeed be possible. While such a possibility is surely quite speculative, it is definitively intriguing and can be seriously tested when future, more accurate measurements will be available.

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I. INTRODUCTION

Jets and outflows are a quite common feature of accreting compact objects. In the case of stellar-mass black hole (BH) candidates in x-ray binary systems, we observe two kinds of jets [1]. *Steady or continuous jets* occur in the hard spectral state. *Transient or episodic jets* appear most significantly when the source switches from the hard to the soft state. Most efforts so far concentrate on the formation mechanism of steady jets. One of the most appealing scenarios to explain the formation of steady jets is the Blandford-Znajek mechanism [2], in which magnetic fields threading the BH event horizon are twisted and can extract the rotational energy of the spinning BH, producing an electromagnetic jet. Numerical simulations show that this mechanism can be very efficient and depends strongly on the BH spin [3–5] (but see also Ref. [6] for different conclusions). At the moment it is not clear if the Blandford-Znajek mechanism can be responsible for the production of steady jets, and in the literature there are some controversial results. The spin scenario is surely attractive, but still unproved. Recently, there have been some studies investigating if there is observational evidence for a correlation between BH spin and jet power in current data.

In Ref. [7], Fender *et al.* considered (separately) all the spin measurements of BH binaries reported in the literature and inferred from the continuum-fitting method [8,9] and the Kα iron line analysis [10]. For steady jets in the hard spectral state, they estimate the jet power via a normalization C, defined by

$$\log_{10} L_{\mathrm{radio}} = C + 0.6(\log_{10} L_{\mathrm{X}} - 34), \tag{1}$$

where L_{radio} and L_{X} are, respectively, the radio and x-ray luminosity of the object. Independently, they also consider an estimate of the jet power from near-infrared data:

$$\log_{10} L_{\mathrm{NIR}} = C + 0.6(\log_{10} L_{\mathrm{X}} - 34). \tag{2}$$

Their plots clearly show no evidence for a correlation between BH spin and jet power. They thus conclude that (i) the methods used to estimate the spin parameter are wrong, and/or (ii) the methods used to estimate the jet power are wrong, and/or (iii) there is indeed no relation between BH spin and jet power.

In Ref. [11], Narayan and McClintock proposed that the Blandford-Znajek mechanism is responsible for the formation of transient jets. They considered the most recent spin measurements obtained via the continuum-fitting method from the Harvard group (which are supposed to be more reliable) and used a different proxy for the jet power—the peak radio flux normalized at 5 GHz, which they claimed to be model-independent. They found a correlation between BH spin a_* and jet power P_{jet}, which is consistent with both the theoretical prediction

$$P_{\mathrm{jet}} \propto a_*^2 \tag{3}$$

obtained in Ref. [2] for $a_*^2 \ll 1$ and the more accurate one,

$$P_{\mathrm{jet}} \propto \Omega_{\mathrm{H}}^2 \propto a_*^2/r_{\mathrm{H}}^2, \tag{4}$$

where Ω_{H} and r_{H} are, respectively, the angular frequency and the radius of the event horizon, found in Ref. [4] and valid even when a_* is quite close to 1. In this case, the measurement of the jet power could be used to test the geometry of the space-time around stellar-mass BH candidates, as discussed in Ref. [12]. However, numerical studies of the Blandford-Znajek mechanism show the production of steady jets, while the origin of transient jets remains unclear and other scenarios may look more appealing, such as episodic ejection of plasma blobs [13].

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In this paper, I explore a more speculative possibility. I assume that steady jets are powered by the spin of the compact object and that the method used in Ref. [7] to estimate the jet power is correct. I also assume that the continuum-fitting method is a robust technique, but that the spin measurements reported in the literature are wrong because the BH candidates in x-ray binary systems are not Kerr BHs.

II. SPIN MEASUREMENTS

A geometrically thin and optically thick accretion disk in a stationary, axisymmetric, and asymptotically flat space-time can be conveniently described by the Novikov-Thorne model [14]. In a Kerr background, the thermal spectrum of this disk depends on five parameters: BH mass M, BH spin a_*, mass accretion rate $\dot{M}$, viewing angle i, and distance from the observer d. If M, i, and d can be measured by optical observations, one can fit the thermal spectrum of the disk to infer a_* and $\dot{M}$. This technique is called the continuum-fitting method [8,9] and can be used only for stellar-mass BH candidates: the disk temperature scales as $M^{-0.25}$, so the peak of the spectrum is around 1 keV for stellar-mass objects, but falls in the UV range for the supermassive BH candidates with $M \sim 10^5\text{–}10^9 M_\odot$. In the latter case, the data are not good because of dust absorption.

The basic (astrophysical) assumptions of the continuum fitting-method have been tested and verified by observations and theoretical studies (see, e.g., Ref. [9] and references therein) and the technique seems to be robust. However, it relies on the fact that BH candidates in x-ray binary systems are Kerr BHs, which is still to be proved [15]. If we consider an accretion disk around a compact object with mass, spin, and a deformation parameter (measuring possible deviations from the Kerr geometry), the thermal spectrum of the disk depends on six parameters. In this case, the continuum-fitting method provides an estimate of the mass accretion rate $\dot{M}$, which is deduced from the intensity of the spectrum in the low-frequency region, where the details of the geometry of the background are not important, and an estimate of the radiative efficiency $\eta = 1 - E_{\rm ISCO}$ [16], where $E_{\rm ISCO}$ is the specific energy of a particle at the innermost stable circular orbit (ISCO), which is supposed to be the inner edge of the disk in the Novikov-Thorne model. It is thus clear that the continuum-fitting method cannot distinguish a Kerr BH with spin parameter a_* and radiative efficiency η from a non-Kerr object with a different spin parameter (not necessarily with $|a_*| \leq 1$ as for a Kerr BH [17]) but the same radiative efficiency. One the other hand, a jet powered by the Blandford-Znajek mechanism should still be correlated with the spin of the compact object. Let us notice that the existence of the event horizon is not strictly necessary here; for example, even neutron stars may have spin powered jets—we just need magnetic fields anchored on the neutron star. On the basis of general arguments, we should expect that the jet power can be written in the following form:

$$P_{\rm jet} = A_0 + \sum_{n=1}^{+\infty} A_n |a_*|^{2n}, \tag{5}$$

where A_0 takes into account a possible nonspin contribution ($A_0 \geq 0$, as $P_{\rm jet}$ cannot become negative for $a_* = 0$) and the other terms are due to (some version of) the Blandford-Znajek mechanism. The latter must depend only on even powers of a_*, because the direction of the spin should not be important (at least at first approximation).

III. NON-KERR SPACE-TIMES

As a non-Kerr background, here I consider the Johannsen-Psaltis (JP) metric, which was explicitly proposed in Ref. [18] to test the geometry around BH candidates. Such a metric does not satisfy Einstein's vacuum equations (unlike, for instance, the Manko-Novikov solution studied in Ref. [16]), but it can be seen as a simple and useful approximation to describe BHs in putative alternative theories of gravity, whose gravitational force is either stronger or weaker than the one around a Kerr BH with the same mass and spin. In Boyer-Lindquist coordinates, the JP metric is given by the line element

$$\begin{aligned} ds^2 = &-\left(1 - \frac{2Mr}{\Sigma}\right)(1+h)dt^2 + \frac{\Sigma(1+h)}{\Delta + a^2 h \sin^2\theta} dr^2 \\ &+ \Sigma d\theta^2 - \frac{4aMr\sin^2\theta}{\Sigma}(1+h)dt d\phi \\ &+ \left[\sin^2\theta\left(r^2 + a^2 + \frac{2a^2Mr\sin^2\theta}{\Sigma}\right)\right. \\ &\left. + \frac{a^2(\Sigma + 2Mr)\sin^4\theta}{\Sigma} h\right] d\phi^2, \end{aligned} \tag{6}$$

where $a = a_* M$, $\Sigma = r^2 + a^2\cos^2\theta$, $\Delta = r^2 - 2Mr + a^2$, and

$$h = \sum_{k=0}^{\infty}\left(\epsilon_{2k} + \frac{Mr}{\Sigma}\epsilon_{2k+1}\right)\left(\frac{M^2}{\Sigma}\right)^k. \tag{7}$$

This metric has an infinite number of deformation parameters ϵ_i and the Kerr solution is recovered when all the deformation parameters are set to zero. However, in order to reproduce the correct Newtonian limit, we have to impose $\epsilon_0 = \epsilon_1 = 0$, while ϵ_2 is strongly constrained by Solar System experiments [18]. Properties and observational features of the JP space-times have been discussed in Refs. [19–21]. In this work, I will only examine the simplest cases where either $\epsilon_3 \neq 0$ or $\epsilon_4 \neq 0$, while the rest of the deformation parameters are set to zero.

TABLE I. The five stellar-mass BH candidates of which the spin parameter a_* has been estimated with the continuum-fitting method and for which we can get an estimate of the power of steady jets. The accretion efficiency in the third column has been deduced from the corresponding a_* for a Kerr background. The normalizations C in the fourth and fifth columns have been inferred from Fig. 4 of Ref. [7].

BH Binary	a_*	$\eta^{\rm obs}$	$C^{\rm obs}$ (Radio)	$C^{\rm obs}$ (NIR)	Reference
GRS 1915 + 105	$0.975,\ 0.95 < a_* < 1$	$0.224,\ 0.190 < \eta < 0.423$	29.25 ± 0.3	33.45 ± 0.3	[22]
4U 1543-47	0.8 ± 0.1	$0.122^{+0.034}_{-0.018}$	29.2 ± 0.3	33.95 ± 0.3	[23]
GRO J1655-40	0.7 ± 0.1	$0.104^{+0.018}_{-0.013}$	28.1 ± 0.3	33.3 ± 0.3	[23]
XTE J1550-564	0.34 ± 0.24	$0.072^{+0.017}_{-0.011}$	27.9 ± 0.3	32.95 ± 0.3 33.55 ± 0.3	[24]
A0620-00	0.12 ± 0.19	$0.061^{+0.009}_{-0.007}$	29.0 ± 0.3	· · ·	[25]

IV. OBSERVATIONS

Let us now consider the objects studied in Ref. [7], with the most recent spin measurements obtained from the continuum-fitting method in the case of a Kerr background. The list of these objects is reported in Table I. The spin measurements (second column) can be easily translated into radiative efficiency measurements (third column). One can then determine the spin parameter of a non-Kerr compact object with a specific deformation parameter by looking for the system with the same radiative efficiency, as discussed in Ref. [12]. In this work, I do not consider the measurements from the Kα iron line because this technique has not yet been well studied for non-Kerr metrics; in particular, I am not aware of any simple rule to translate a spin measurement obtained in the Kerr background to an allowed region in the spin parameter-deformation parameter plane.

In the case of a Kerr background, the estimates of the jet power via the radio and near-infrared normalization show no evidence for a correlation with the spin measurements obtained with the continuum-fitting method; see Fig. 1. The two panels in Fig. 1 are essentially the two right panels in Fig. 4 of Ref. [7], with the sole difference being that here I am using only the most recent measurements of the continuum-fitting method reported in Refs. [22–25]. For the objects XTE J1550-564 and A0620-00, the spin uncertainty is the one reported in Refs. [24,25]. For GRS 1915 +105, 4U 1543-47, and GRO J1655-40, the spin uncertainty reported in Refs. [22,23] has been doubled, as done, for instance, in Ref. [11], because the analysis of these objects were performed a few years ago within a less sophisticated theoretical framework. The uncertainty in C is (rather arbitrarily) assumed to be 0.3 dex, as in Ref. [7]. This normalization as a proxy for the jet power has been criticized as model-dependent by Narayan and McClintock [11]. In the case of the near-infrared normalization, the object XTE J1550-564 has two measurements, indicated by the two blue crosses in the right panel of Fig. 1, obtained respectively from the rise and from the decay of an outburst.

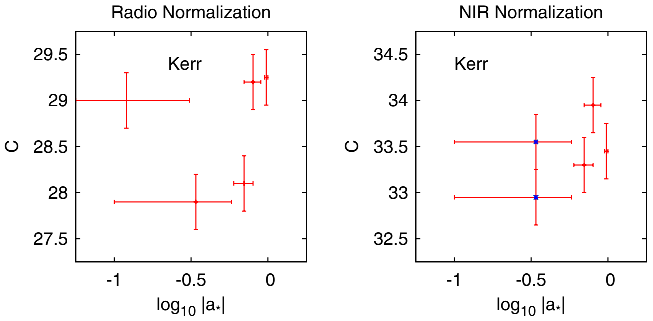

FIG. 1 (color online). Estimates of the jet power from the radio (left panel) and near-infrared (right panel) normalizations against the measurements of the BH spin parameter obtained from the continuum-fitting method and under the assumption of a Kerr background. In the case of the near-infrared normalization, the object XTE J1550-564 has two measurements, indicated by the two blue crosses. The two panels are essentially the right panels of Fig. 4 in Ref. [7].

Figure 1 clearly shows no evidence for a correlation between BH spin and radio/near-infrared normalization. However, in order to be more quantitative, especially for the discussion of possible deviations from the Kerr geometry, we need to consider a specific theoretical prediction for the value of C and define a χ^2 which properly takes into account the uncertainty in the measurements of the continuum-fitting method and in the estimate of C.

V. JET MODEL 1: $P_{\rm jet} = \alpha|a_*|^\beta$

If we neglect a possible nonspin contribution to the power of the jet, a simple form for $P_{\rm jet}$ is

$$P_{\rm jet} = \alpha|a_*|^\beta, \tag{8}$$

and therefore

$$C^{\rm th} = \beta \log_{10}|a_*| + \alpha', \tag{9}$$

where $\alpha' = \log_{10}\alpha$. α' and β are the two parameters of the jet model: if we knew all the details of the jet formation, they could be theoretically computed, but here they will be determined by fitting the data. Let us notice that β does not necessarily need to be an even integer number, because Eq. (8) is a simplified form of Eq. (5), in which there are potentially many terms of the form $(a_*)^{2n}$. β should be close to 2 if the first term is the dominant one, and it should be larger than 2 if $A_n \neq 0$ for some $n > 1$.

Including the possibility of a (generic) deformation parameter ϵ, the χ^2 can be defined as

$$\chi^2(\alpha', \beta, \epsilon) = \min_{\{a_{*i}\}}\Bigg[\sum_{i=1}^{N} \frac{[C^{\rm th}(\alpha', \beta, a_{*i}) - C_i^{\rm obs}]^2}{\sigma_C^2} + \sum_{i=1}^{N} \frac{(a_{*i} - a_{*i}^{\rm obs})^2}{\sigma_i^2}\Bigg], \tag{10}$$

where $\sigma_C = 0.3$, $a_{*i}^{\rm obs} = a_{*i}^{\rm obs}(\epsilon, \eta_i^{\rm obs})$, and

$$\sigma_i = \begin{cases} \sigma_i^+ & \text{if } a_{*i} > a_{*i}^{\rm obs} \\ \sigma_i^- & \text{if } a_{*i} > a_{*i}^{\rm obs} \end{cases} \tag{11}$$

is the uncertainty on $a_{*i}^{\rm obs}$ (as $a_{*i}^{\rm obs}$ is obtained from $\eta_i^{\rm obs}$, $\sigma_i^+ \neq \sigma_i^-$). χ^2 has three degrees of freedom, as the spins $\{a_{*i}\}$ are considered as measured quantities. In this and in the next section, I will consider only the radio measurements, while the near-infrared data will be briefly discussed in Sec. VII. As we have five radio estimates of C, $\chi^2_{\rm red} = \chi^2$. If we assume the Kerr background, χ^2 has two degrees of freedom, and therefore $\chi^2_{\rm red} = \chi^2/2$.

A. Kerr black holes

If we assume that the BH candidates are the Kerr BHs predicted by general relativity, we have only two fit parameters, α' and β. The best fit is found for

$$\alpha' = 29.3, \qquad \beta = 2.8, \tag{12}$$

with $\min\chi^2_{\rm red} = 6.03$, which clearly confirms there is no correlation between jet power and BH spin.

B. JP black holes with ϵ_3 constant

Let us now consider the possibility that the BH candidates in x-ray binary systems are not necessarily the Kerr BHs predicted by general relativity, but that the geometry of the space-time around them can be described by the JP metric with a deformation parameter. In the case of a background with arbitrary ϵ_3 and $\epsilon_i = 0$ for $i \neq 3$, one finds the best fit for

$$\epsilon_3 = 7.5, \qquad \alpha' = 30.1, \qquad \beta = 2.46, \tag{13}$$

with $\min\chi^2_{\rm red} = 0.94$. The plot spin vs C for $\epsilon_3 = 7.5$ is shown in the left panel of Fig. 2, in which the dashed blue line has slope 2.46. Such a value for β is not far from the theoretical expectation of 2 found in Ref. [2].

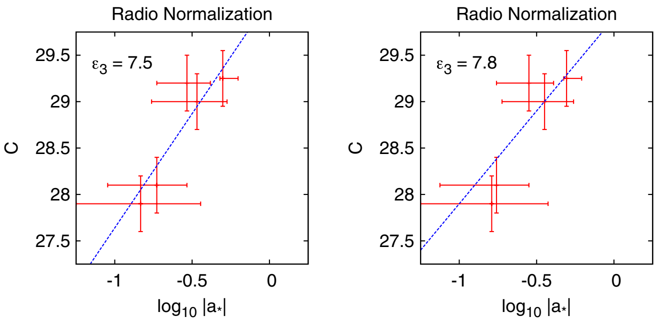

FIG. 2 (color online). Best fit in the case of the JP background with nonvanishing deformation parameter ϵ_3, for the jet model 1 (left panel) and the jet model 2 (right panel). See text for details.

Let us notice that the possibility of a nonvanishing deformation parameter is in contradiction with the finding of Ref. [12], where it was concluded that ϵ_3 must be small. The assumptions of the two papers are indeed different. Here, we assume that *steady jets* are powered by the spin and we try to find the most favorable metric deformation to recover a correlation between the measured spins and jet powers. At the same time, we do not believe that *transient jets* originate from the Blandford-Znajek mechanism, despite the correlation found by Narayan and McClintock in Ref. [11]. In Ref. [12], we believed in the correlation found by Narayan and McClintock and that it was enough to say that ϵ_3 must be small. It is important to stress that, even when adopting individual deformation parameters, it is impossible to reconcile the contradicting claims: the point is that for the object A0620-00 we have a powerful steady jet and a weak transient jet, which demand respectively a high and a low value of the spin parameter if the jet is really powered by the spin.

C. JP black holes with $\epsilon_3 = \gamma a_*^2$ and γ constant

The JP space-time is a phenomenological background proposed to describe, at a first approximation, putative non-Kerr BHs. The deformation parameters are used to estimate possible deviations from the Kerr geometry, but their actual physical meaning is not clear. In particular, there is no reason to expect that the value of the deformation parameters must be the same for all the objects. A specific value of ϵ_3 for every BH candidate may sound too arbitrary and even not very natural, as it would recall a conserved charge which belonged to the progenitor star. On the other hand, a deformation parameter depending on the spin sounds much more physical. For instance, the lowest-order deviation from the Kerr background of the space-time around a neutron star is the mass quadrupole moment, which is thought to be well approximated by the form [26]

$$Q = -(1 + \xi)a_*^2 M^3, \tag{14}$$

where ξ ($\xi = 0$ for a Kerr BH) is a parameter of order 1 which depends on the matter equation of state, i.e., on the microphysics. The simplest guess for the form of the deformation parameter of non-Kerr BHs is

$$\epsilon_3 = \gamma a_*^2, \tag{15}$$

because the deformation should not depend on the spin orientation and higher-order terms in a_* may be subdominant.

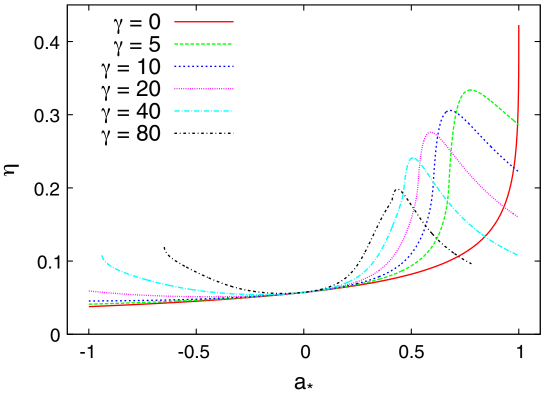

FIG. 3 (color online). Radiative efficiency $\eta = 1 - E_{\rm ISCO}$ as a function of the spin parameter a_* for the JP background with nonvanishing deformation parameter $\epsilon_3 = \gamma a_*^2$.

One can then repeat the same procedure with the fit parameters α', β, and γ. However, some caution is necessary here. In the case of Kerr BHs, the continuum-fitting method provides a unique estimate of the spin parameter of the compact object because there is a one-to-one correspondence between the radiative efficiency η and a_*. This is no longer true in a Kerr background with an arbitrary value of a_*; for instance, for every Kerr BH there is a Kerr naked singularity (i.e., with $|a_*| > 1$) with the same value of η. However, Kerr naked singularities may be excluded for theoretical reasons, as they are apparently impossible to produce and, even if created, they would be very unstable [27]. As discussed in Ref. [12], the same conclusions may be true for JP BHs with a constant ϵ_3. However, this does not seem to be true if we assume a constant γ and ϵ_3 given by Eq. (15). The radiative efficiency $\eta = 1 - E_{\rm ISCO}$ as a function of the spin parameter a_* is shown in Fig. 3 for some values of γ. These BHs can potentially be spun up by the accreting material (for instance, the envelope of the progenitor star), and then have a counter-rotating disk (formed by the gas coming from the stellar companion). It turns out that some values of η are common to two configurations with different spin. In the computation of χ^2, I thus include both the possibilities. Actually, this problem exists only for A0620-00 when $\gamma > 42$. The minimization of χ^2 requires

$$\gamma = 45, \qquad \alpha' = 31.2, \qquad \beta = 5.65, \tag{16}$$

and $\min\chi^2_{\rm red} = 2.60$. In this case, β is significantly larger than 2. The best fit is shown in the left panel of Fig. 4.

D. JP black holes with ϵ_4 constant

It may be instructive to see what happens if we consider a different deformation from the Kerr background. If we take the deformation parameter ϵ_4 to be variable and we assume that all the others vanish, we get

$$\epsilon_4 = 18.6, \qquad \alpha' = 30.3, \qquad \beta = 2.16, \tag{17}$$

with $\min\chi^2_{\rm red} = 1.36$. Even in this case, observations would require a compact object more prolate than a Kerr BH with the same mass and spin (as $\epsilon_4 > 0$) in order to be consistent with the Blandford-Znajek scenario. The best fit is shown in the left panel of Fig. 5.

As long as we consider a single deformation parameter, the effects produced by ϵ_3 or by any ϵ_i with $i > 3$ is very similar. This point can be quickly understood by having a look at Figs. 2 and 4 in Ref. [28], which show the behavior of the radiative efficiency η as a function of the spin for ϵ_3, ϵ_4, and ϵ_5. Actually, the situation is even more general, and the same qualitative features can be found by plotting the same figure for the Manko-Novikov space-time with a single deformation parameter. In the case of two or more nonvanishing deformation parameters, the picture is more complicated. If these parameters produce similar deformations (e.g., JP parameters that are all positive or all negative), we should still expect the same effects. Otherwise, different parameters may produce opposite deformations that compensate one another, and it is not easy to predict what may happen. In Ref. [12], the case of $\epsilon_4 \neq 0$ was not considered. However, on the basis of the above considerations (see also the discussion in Sec. V B), the claim of the present paper and the one we can obtain from the transient

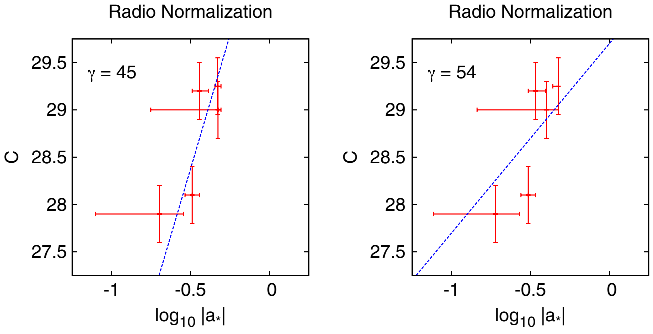

FIG. 4 (color online). Best fit in the case of the JP background with nonvanishing deformation parameter $\epsilon_3 = \gamma a_*^2$, for the jet model 1 (left panel) and the jet model 2 (right panel). See text for details.

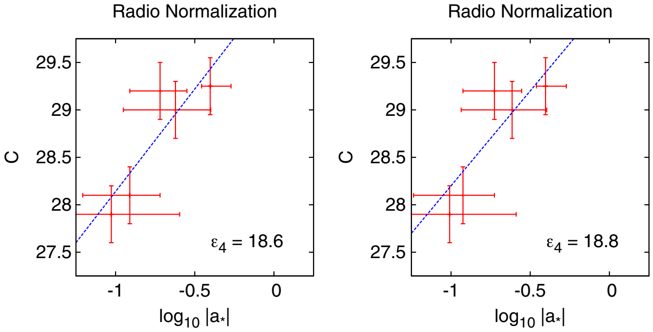

FIG. 5 (color online). Best fit in the case of the JP background with nonvanishing deformation parameter ϵ_4, for the jet model 1 (left panel) and the jet model 2 (right panel). See text for details.

jets discussed by Narayan and McClintock are necessarily in contradiction, and the choice of a different ϵ_i cannot solve the incompatibility.

VI. JET MODEL 2: $P_{\rm jet} = \alpha|a_*|^2 + \beta$

In this section, we explore the possibility that the jet power also receives a contribution from another source of energy and therefore can be written as

$$P_{\rm jet} = \alpha|a_*|^2 + \beta, \qquad (18)$$

where the contribution from the spin of the compact object is assumed to be proportional to $|a_*|^2$ because it is the one expected in the Blandford-Znajek scenario and, even if originally obtained in the limit $a_*^2 \ll 1$, it is thought to be a good approximation even when a_* is not very close to 1. The theoretical proxy C is

$$C^{\rm th} = 2\log_{10}(|a_*| + \beta') + \alpha', \qquad (19)$$

where $\alpha' = \log_{10}\alpha$ and $\beta' = \sqrt{\beta/\alpha}$.

A. Kerr black holes

In the case of the Kerr background, we have to fit only the two parameters of the jet model. The best fit has

$$\alpha' = 29.2, \qquad \beta' = 0.022, \qquad (20)$$

with $\min\chi^2_{\rm red} = 6.06$. As was already made clear in Fig. 1, there is no correlation between measured spins and jet powers, and the model with a nonspin contribution cannot fix the absence of a correlation.

B. JP black holes with ϵ_3 constant

The minimization of χ^2 with the jet model 2 in the JP space-time with constant ϵ_3 suggests the following values for the fit parameters:

$$\epsilon_3 = 7.8, \qquad \alpha' = 29.9, \qquad \beta' = 0.000, \qquad (21)$$

and $\min\chi^2_{\rm red} = 1.05$. It seems like a possible nonspin contribution to the jet power is not necessary. The best fit is shown in the right panel of Fig. 2. Let us notice that here, as well as for the other non-Kerr cases discussed in the next subsections, a negative β' would provide a better fit; for instance, in the present case one finds $\min\chi^2_{\rm red} = 0.82$ for $\epsilon_3 = 7.4$, $\alpha' = 30.1$, and $\beta' = -0.06$. $\beta' < 0$ could be possible in the presence of a mechanism suppressing the formation of the jet powered by the spin. However, it cannot really be a constant independent of the spin, as otherwise we would obtain $P_{\rm jet} < 0$ for a nonrotating object.

C. JP black holes with $\epsilon_3 = \gamma a_*^2$ and γ constant

For a deformation parameter $\epsilon_3 = \gamma a_*^2$, the new jet model requires

$$\gamma = 54, \qquad \alpha' = 29.7, \qquad \beta' = 0.000, \qquad (22)$$

and $\min\chi^2_{\rm red} = 5.9$. The fit is significantly worse than the others, because a correlation is possible with a very strong dependence of $P_{\rm jet}$ on the spin (as found in Sec. V C) and the possibility of a nonspin contribution is not helpful. The best fit is shown in the right panel of Fig. 4.

D. JP black holes with ϵ_4 constant

Lastly, we examine the jet model 2 in the JP background with constant ϵ_4. In this case, the result is

$$\epsilon_4 = 18.8, \qquad \alpha' = 30.2, \qquad \beta' = 0.000, \qquad (23)$$

with $\min\chi^2_{\rm red} = 1.37$. As we found for the JP space-time with constant ϵ_3, the data do not require any nonspin contribution to the power of the jets. The best fit is shown in the right panel of Fig. 5.

VII. DISCUSSION

The correlation between spin measurements and power estimates of steady jets found for a nonvanishing deformation parameter, while absent in the Kerr background, can be easily understood as follows. The continuum-fitting method provides an estimate of the radiative efficiency η and, for a given deformation parameter, there is a one-to-one correspondence between η and a_*: η is low for a rapidly rotating object and a counter-rotating disk (a_* negative) and increases as the spin parameter a_* increases. In the Kerr background, all the measurements are consistent with a corotating disk, i.e., $a_* > 0$. In a background with a weaker gravitational force (in the JP metric, ϵ_3 and $\epsilon_4 > 0$), we find the same radiative efficiency for objects with a_* lower than that of a Kerr BH. In this case, the BH candidate A0620-00 is interpreted as a fast-rotating object with a counter-rotating disk. On the contrary, the jet power should be independent, at least at first approximation, of the spin orientation. This difference is enough to find a correlation between spin and jet power in current data. This is the only possibility to have a correlation between spins and jet powers, as A0620-00 has a low radiative efficiency and a powerful steady jet.

From an astrophysical point of view, the possibility of the existence of a fast-rotating object with retrograde spin may be challenging. The continuum-fitting method requires that the disk is perpendicular to the BH spin; if this assumption is not fulfilled, the technique is essentially unusable (see, e.g., Ref. [29]). If the binary system formed from the collapse of the same cloud (rather then after the capture of one of the objects by the other), the disk is indeed expected on the equatorial plane of the BH, but the spin would more likely be parallel—not antiparallel—to the angular momentum of the disk. If for some reason the disk is not initially on the equatorial plane of the system, the action of the Bardeen-Petterson effect can force the inner part of the disk to align on the BH spin. However, the possibility of retrograde disks cannot be excluded *a priori* [9]. Retrograde disks have been proposed, for instance, to explain the radio-loud/radio-quiet dichotomy of active galactic nuclei [30].

The discussion of the possibility of a correlation between jet power and spin in the presence of a suitable deviation from the Kerr geometry has been done considering only the radio data. Is it possible to find a correlation between jet power and spin in the case of the near-infrared data? The answer is no, at least in the case of simple deformations in which there is a one-to-one relation between η and a_*. In the case of the radio normalization, the main problem for a correlation between jet power and spin is the powerful jet of A0620-00, whose spin would be near 0 in the Kerr space-time. If we consider only the other four measurements, the situation is not so bad. In the case of a non-Kerr background, one can explain A0620-00 as a fast-rotating object with a retrograde disk and better adjust the other four objects. Eventually, a correlation is possible. In the case of the near-infrared data, 4U 1543-47 shows a powerful jet, while the ones of objects with higher and lower radiative efficiency seem to be weaker. Since we have only four measurements (or three, as the estimate of C for XTE J1550-564 is ambiguous), every point is very important and it is not possible to find a correlation between jet power and spin with the same trick used for the radio data.

Lastly, as already stressed at the end of Sec. V B, the possibility of a correlation between spin and the power of steady jets in a non-Kerr background cannot be compatible with the one between spin and the power of transient jets found by Narayan and McClintock in Ref. [11], as the latter exists only in Kerr space-times and disappears as the deformation parameter ϵ_3 increases [12].

VIII. CONCLUSIONS

While there are indications suggesting that steady jets in the hard spectral state may be powered by the BH spin, the study reported in Ref. [7] shows that there is no evidence for a correlation between spin measurements and the power of steady jets in BH x-ray binaries. This leads one to conclude that: (i) the spin measurements are wrong, and/or (ii) the estimates of the jet power are wrong, and/or (iii) there is indeed no strong relation between BH spin and jet power. In this paper, I explored the first possibility, focusing only on the most recent measurements obtained from the continuum-fitting method [22–25]. A key ingredient of the standard approach is the assumption of the Kerr BH hypothesis; that is, the stellar-mass BH candidates in x-ray binaries must be the Kerr BH predicted by general relativity. If the BH candidates in x-ray binaries are not Kerr BHs, the continuum-fitting method provides a wrong estimate of the spin parameter. I thus investigated if one can find a correlation between spin measurements and estimates of the jet power in the case that the space-time around these objects deviates from the Kerr geometry. It turns out that such a speculative idea might indeed be possible, as shown in Figs. 2, 4, and 5. While the current sample of data consists of a small number of objects with too large an uncertainty in the spin measurements and jet power estimates, the scenario is definitively intriguing and it can be more seriously tested when future, more accurate data will be available.

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[1] R. Fender and T. Belloni, Annu. Rev. Astron. Astrophys. **42,** 317 (2004); R. P. Fender, T. M. Belloni, and E. Gallo, Mon. Not. R. Astron. Soc. **355,** 1105 (2004).

[2] R. D. Blandford and R. L. Znajek, Mon. Not. R. Astron. Soc. **179**, 433 (1977).

[3] J. C. McKinney, Astrophys. J. **630,** L5 (2005).

[4] A. Tchekhovskoy, R. Narayan, and J. C. McKinney, Astrophys. J. **711,** 50 (2010).

[5] A. Tchekhovskoy, R. Narayan, and J. C. McKinney, Mon. Not. R. Astron. Soc. **418,** L79 (2011).

[6] M. Livio, G. I. Ogilvie, and J. E. Pringle, Astrophys. J. **512,** 100 (1999).

[7] R. P. Fender, E. Gallo, and D. Russell, Mon. Not. R. Astron. Soc. **406,** 1425 (2010).

[8] S. N. Zhang, W. Cui, and W. Chen, Astrophys. J. **482,** L155 (1997); L.-X. Li, E. R. Zimmerman, R. Narayan, and J. E. McClintock, Astrophys. J. Suppl. Ser. **157,** 335 (2005).

[9] J. E. McClintock, R. Narayan, S. W. Davis, L. Gou, A. Kulkarni, J. A. Orosz, R. F. Penna, R. A. Remillard, and J. F. Steiner, Classical Quantum Gravity **28,** 114009 (2011).

[10] A. C. Fabian, K. Iwasawa, C. S. Reynolds, and A. J. Young, Publ. Astron. Soc. Pac. **112,** 1145 (2000); C. S. Reynolds and M. A. Nowak, Phys. Rep. **377,** 389 (2003).

[11] R. Narayan and J. E. McClintock, Mon. Not. R. Astron. Soc. **419,** L69 (2012).

[12] C. Bambi, Phys. Rev. D **85,** 043002 (2012).

[13] F. Yuan, J. Lin, K. Wu, and L. C. Ho, Mon. Not. R. Astron. Soc. **395,** 2183 (2009).

[14] I. D. Novikov and K. S. Thorne, in *Black Holes*, edited by C. De Witt and B. De Witt (Gordon and Breach, New York, 1973), p. 343; D. N. Page and K. S. Thorne, Astrophys. J. **191,** 499 (1974).

[15] C. Bambi, Mod. Phys. Lett. A **26,** 2453 (2011).

[16] C. Bambi and E. Barausse, Astrophys. J. **731,** 121 (2011).

[17] C. Bambi, Europhys. Lett. **94**, 50002 (2011); C. Bambi, J. Cosmol. Astropart. Phys. 05 (2011) 009.

[18] T. Johannsen and D. Psaltis, Phys. Rev. D **83**, 124015 (2011).

[19] C. Bambi and L. Modesto, Phys. Lett. B **706**, 13 (2011); C. Bambi, Phys. Lett. B **705**, 5 (2011); C. Bambi, F. Caravelli, and L. Modesto, Phys. Lett. B **711**, 10 (2012); C. Bambi, J. Cosmol. Astropart. Phys. 09 (2012) 014.

[20] T. Johannsen and D. Psaltis, arXiv:1202.6069.

[21] S. Chen and J. Jing, Phys. Lett. B **711**, 81 (2012); Phys. Rev. D **85**, 124029 (2012).

[22] J. E. McClintock, R. Shafee, R. Narayan, R. A. Remillard, S. W. Davis, and L.X. Li, Astrophys. J. **652**, 518 (2006).

[23] R. Shafee, J. E. McClintock, R. Narayan, S. W. Davis, L.-X. Li, and R. A. Remillard, Astrophys. J. **636**, L113 (2006).

[24] J. F. Steiner, R. C. Reis, J. E. McClintock, R. Narayan, R. A. Remillard, J. A. Orosz, L. Gou, A. C. Fabian, and M. A. P. Torres, Mon. Not. R. Astron. Soc. **416**, 941 (2011).

[25] L. Gou, J. E. McClintock, J. F. Steiner, R. Narayan, A. G. Cantrell, C. D. Bailyn, and J. A. Orosz, Astrophys. J. **718**, L122 (2010).

[26] W. G. Laarakkers and E. Poisson, Astrophys. J. **512**, 282 (1999).

[27] E. Barausse, V. Cardoso, and G. Khanna, Phys. Rev. Lett. **105**, 261102 (2010); P. Pani, E. Barausse, E. Berti, and V. Cardoso, Phys. Rev. D **82**, 044009 (2010).

[28] C. Bambi, Phys. Rev. D **85**, 043001 (2012).

[29] P. C. Fragile, Astrophys. J. **706**, L246 (2009).

[30] D. Garofalo, D. A. Evans, and R. M. Sambruna, Mon. Not. R. Astron. Soc. **406**, 975 (2010).