Testing the Kerr nature of the supermassive black hole in Ark 564

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Einstein’s theory of general relativity has been extensively tested in weak gravitational fields, mainly with experiments in the Solar System and observations of radio pulsars, and current data agree well with the theoretical predictions. Nevertheless, there are a number of scenarios beyond Einstein’s gravity that have the same predictions for weak fields and present deviations only when gravity becomes strong. Here we try to test general relativity in the strong field regime. We fit the X-ray spectrum of the supermassive black hole in Ark 564 with a disk reflection model beyond Einstein’s gravity, and we are able to constrain the black hole spin $\alpha$, and the Johannsen deformation parameters $\alpha_{13}$ and $\alpha_{22}$. For $\alpha_{22} = 0$, we find $\alpha_1 > 0.96$ and $-1.0 < \alpha_{13} < 0.2$ with a 99% confidence level. For $\alpha_{13} = 0$, we get $\alpha_1 > 0.96$ and $-0.1 < \alpha_{22} < 0.9$ with a 99% confidence level.

I. INTRODUCTION

Einstein’s theory of general relativity has successfully passed a large number of observational tests, mainly experiments in the Solar System and accurate radio observations of binary pulsars [1]. The interest is now shifting to testing Einstein’s gravity in the strong field regime, which is largely unexplored. The best laboratory for testing strong gravity is the spacetime around astrophysical black holes [7–10].

In 4-dimensional Einstein’s gravity, the only stationary and asymptotically-flat vacuum black hole solution, which is regular on and outside the event horizon, is the Kerr metric [11,12]. The spacetime around astrophysical black holes formed by gravitational collapse is expected to be well approximated by the Kerr geometry [13]. Nevertheless, there are a number of scenarios beyond Einstein’s gravity that predict macroscopic deviations from the Kerr spacetime [14]. In particular, several authors have recently pointed out that quantum gravity may show up at the gravitational radius of a system rather than at the tiny Planck scale, suggesting the possibility of observing a signature of quantum gravity from astrophysical black holes [7–10].

X-ray reflection spectroscopy is potentially a powerful tool for testing the strong gravity region around astrophysical black holes [11]. In the past ten years, this technique has been developed and employed to measure black hole spins under the assumption that the spacetime metric around these objects is described by the Kerr solution [12,13]. Recently, the possibility of using X-ray reflection spectroscopy to test general relativity in the strong gravity regime has been explored [14,21].

REXLII is currently the most advanced X-ray reflection model to describe the reflection spectrum of thin disks around Kerr black holes [22,23]. Recently, we have extended this model to REXLII-NK [24]. REXLII-NK can include a variety of parametrically deformed Kerr black hole metrics. Together with the spin parameter $\alpha_1$, these metrics are characterized by some “deformation parameters”, which are introduced to quantify possible deviations from the Kerr spacetime.

Presently, REXLII-NK includes the phenomenological metric proposed by Johannsen [25]. In Boyer-Lindquist coordinates, the line element of the Johannsen metric with the deformation parameters $\alpha_{13}$ and $\alpha_{22}$ reads (we use units in which $G_N = c = 1$) [25]

$$ds^2 = -\frac{\Sigma (\Delta - a^2 A_2^2 \sin^2 \theta)}{B^2} dt^2 + \frac{\Sigma \Delta}{B^2} dr^2 + \Sigma \sin^2 \theta \, d\theta^2 + \left[ (r^2 + a^2)^2 A_1^2 - a^2 \Delta \sin^2 \theta \right] \Sigma \sin^2 \theta \, d\phi^2 - \frac{2a (r^2 + a^2) A_1 A_2 - \Delta \Sigma \sin^2 \theta}{B^2} dt \, d\phi,$$

where $M$ is the black hole mass, $a = J/M$, $J$ is the black hole spin angular momentum, $\Sigma = r^2 + a^2 \cos^2 \theta$, $\Delta = r^2 - 2Mr + a^2$, and

$$A_1 = 1 + \alpha_{13} \left( \frac{M}{r} \right)^3, \quad A_2 = 1 + \alpha_{22} \left( \frac{M}{r} \right)^2, \quad B = (r^2 + a^2) A_1 - a^2 A_2 \sin^2 \theta.$$

The Kerr metric is recovered when $\alpha_{13} = \alpha_{22} = 0$. Note that the Johannsen metric is not expected to be “physical”, it only serves as a way to quantify deviations from the Kerr metric.

Following Ref. [25], we can exclude a violation of Lorentzian signature or the existence of closed time-like curves in the exterior region imposing, respectively, that the metric determinant is always negative and that $g_{\phi\phi}$ is never negative for radii larger than the radius of the event horizon. This leads to the following restrictions to the values of $\alpha_{13}$ and $\alpha_{22}$

$$\alpha_{13} > - \left( 1 + \sqrt{1-a_1^2} \right)^3, \quad (3)$$
$$\alpha_{22} > - \left( 1 + \sqrt{1-a_1^2} \right)^2, \quad (4)$$

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where $a_* = a/M$ is the dimensionless spin parameter. The Johannsen metric is also singular when $B = 0$. Imposing that this never happens for radii larger than the radius of the event horizon, we find the following constraint on $\alpha_{13}$ for $\alpha_{22} = 0$

$$\alpha_{13} \geq -\frac{1}{2} \left( 1 + \sqrt{1 - a_*^2} \right)^4. \quad (5)$$

Eq. (5) is a stronger constraint on $\alpha_{13}$ than the bound in Eq. (3). Our reflection model RELXILL\_NK only covers the parameter region satisfying the constraint in Eq. (5).

In Ref. [29], we analyzed some XMM-Newton, NuSTAR, and Swift data of the supermassive black hole in 1H0707–495 with RELXILL\_NK and we constrained the Johannsen deformation parameter $\alpha_{13}$. 1H0707–495 indeed shows strong reflection signatures [27, 28], and it was thus a good source for testing RELXILL\_NK.

In this paper, we report our analysis of the Suzaku observation of the supermassive black hole in Ark 564 of [29]. Ark 564 is classified as a narrow line Seyfert 1 galaxy at redshift $z = 0.0247$. This source looks suitable for tests of general relativity for the following reasons. Firstly, previous studies have shown that the inner edge of the disk may be very close to the central object, which maximizes the signatures of the strong gravity region [29]. Secondly, the source has a simple spectrum. There is no obvious intrinsic absorption to complicate the determination of the reflected emission.

II. OBSERVATIONS AND DATA REDUCTION

Suzaku observed Ark 564 on 26-28 June 2007 (Obs. ID 702117010) for about 80 ks. For low energies ($< 10$ keV), Suzaku has four co-aligned telescopes used to collect photons onto its CCD detectors X-ray Imaging Spectrometer (XIS) [30]. XIS is comprised of four detectors; XIS0, XIS2, and XIS3 are front-illuminated and XIS1 is back-illuminated. We only used data from the front-illuminated chips because XIS1 has a lower effective area at 6 KeV and a higher background at higher energies. XIS2 data were not used in our analysis because of the anomaly after 9 November 2006.

We used HEASOFT version 6.22 and CALDB version 20180312 for the data reduction. The raw data were reduced to screened products using AEPipeline script of the HEASOFT package. The XIS data were screened with the standard criterion using the ftool XSELECT [30]. The XIS source was extracted from the 3.5 arc minutes radius centered at the source. The background region of the same size is taken from a region as far as possible from the source to avoid contamination from the latter. Response files and area files were generated using the script XISRMFGEN and XSSIMARFEN, respectively. Lastly, the data from XIS0 and XIS3 were combined into a single spectrum using ADDASCASPEC. The data were grouped to have a minimum of 30 counts per bin in order to use $\chi^2$ statistics in our spectral analysis. We excluded the energy range 1.7-2.5 keV because of calibration issues.

III. SPECTRAL ANALYSIS

In our analysis, we employed Xspec v12.9.1 [31]. We fitted the data with five models, which are briefly described below. For every model, first we explore the possibility that $\alpha_{13}$ may not vanish and we assume $\alpha_{22} = 0$, and then we consider the opposite case in which $\alpha_{13} = 0$ and $\alpha_{22}$ can vary.

Model $a$

$$\text{TBABS}^*\text{ZPOWERLAW}.$$

TBABS describes the galactic absorption [32] and we fixed the galactic column density to $N_H = 6.74 \cdot 10^{20}$ cm$^{-2}$ [33, 34]. ZPOWERLAW describes a redshifted photon power-law spectrum. The data to best-fit model ratio is shown in panels (a) in Fig. [1] where we can see an excess of photon count at low energies and a broad iron line around 6.4 keV. The best-fit values are reported in the second column in Tab. [I] and Tab. [II]. Since this model does not include the Johannsen deformation parameters, Tabs. [I] and [II] show the same result.

Model $b$

This is the next-to-simplest model and adds the reflection spectrum from the accretion disk

$$\text{TBABS}^*\text{RELXILL\_NK}.$$

RELXILL\_NK would describe both the power-law component and the disk’s reflection spectrum, but we find that, once we have added the reflection spectrum, the power-law component is not necessary and therefore we set the reflection fraction $R = -1$ (no power-law component). The data to best-fit model ratios are shown in panels (b) in Fig. [1] and the best-fit values are reported in the third column in Tab. [I] ($\alpha_{13}$ free and $\alpha_{22} = 0$) and Tab. [II] ($\alpha_{13} = 0$ and $\alpha_{22}$ free).

Model $c$

We consider a double reflection model, which is currently quite a popular choice to fit the X-ray spectrum of some narrow line Seyfert 1 galaxies

$$\text{TBABS}^*(\text{RELXILL\_NK} + \text{RELXILL\_NK}).$$
Asume the same iron abundance and is independent of the background metric \[36\]. We as-
warm material at a larger distance from the black hole describes the reflection spectrum from some xillver.

Table I. Summary of the best-fit values for the spectral models \(a\) to \(e\) assuming \(\alpha_{13}\) free and \(\alpha_{22} = 0\). The reported uncertainty corresponds to the 90% confidence level for one relevant parameter. * indicates that the parameter is frozen to the value obtained from independent measurements.

| Model | \(a\) | \(b\) | \(c\) | \(d\) | \(e\) |
|-------|-------|-------|-------|-------|-------|
| \(\text{TBABS}\) | 6.74* | 6.74* | 6.74* | 6.74* | 6.74* |
| \(N_{H}/10^{20}\) cm\(^{-2}\) | 6.74* | 6.74* | 6.74* | 6.74* | 6.74* |
| \(\text{ZPOWERLAW}\) | \(\Gamma\) | 2.768\(\pm\)0.003 | \(-0.003\) | \(-\) | \(-\) |
| | \(z\) | 0.0247* | \(-\) | \(-\) | \(-\) |
| \(\text{RELXILL\_NK}\) | \(q\) | \(-\) | 6.447\(\pm\)0.013 | 6.32\(\pm\)0.08 | 6.812\(\pm\)0.025 | 5.87\(\pm\)0.12 |
| | \(i\) [deg] | \(-\) | \(<11\) | \(<20\) | \(<60\) | \(<22\) |
| | \(a_{\ast}\) | \(-\) | 0.996\(\pm\)0.001 | 0.985\(\pm\)0.003 | \(-0.008\) | \(>0.988\) | \(0.979\(\pm\)0.006\) |
| | \(\alpha_{13}\) | \(-\) | \(-0.65\(\pm\)0.15\) | \(-0.5\(\pm\)0.2\) | \(-0.2\(\pm\)0.3\) | \(-1.0\(\pm\)1.0\) |
| | \(z\) | \(-\) | 0.0247* | 0.0247* | 0.0247* | 0.0247* |
| | \(\log \xi\) | \(-\) | 3.090\(\pm\)0.007 | 4.56\(\pm\)0.13 | 2.71\(\pm\)0.24 | 2.726\(\pm\)0.072 |
| | \(A_{Fe}\) | \(-\) | 0.519\(\pm\)0.0 | 0.53\(\pm\)0.03 | 0.85\(\pm\)0.06 | 0.61\(\pm\)0.0 |
| | \(R\) | \(-\) | \(-\) | \(-1\) | \(-1\) | \(-1\) |
| \(\text{RELXILL\_NK}\) \(\log \xi'\) | \(-\) | \(-\) | \(-3.00\(\pm\)0.06\) | \(-0.69\) | \(-\) | \(-1.30\(\pm\)0.16\) |
| \(\text{XILLIVER}\) \(\log \xi''\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-\) | \(-4.34\(\pm\)0.23\) | \(-0.9\) | \(-0.9\) | \(-4.56\(\pm\)0.16\) |
| \(\chi^2/\text{dof}\) | 4356.16/1403 | 1547.91/1397 | 1544.85/1395 | 1474.30/1395 | 1469.88/1393 |
| | \(-3.105\) | \(-1.108\) | \(-1.107\) | \(-1.057\) | \(-1.055\) |

The general idea behind this model is that there are certain inhomogeneities in the accretion disk, but the origin and nature of these inhomogeneities can vary. For instance, the density of the disk photosphere may be patchy, leading to mixed regions of high and low ionization \[33\]: the surface of the disk may have regions of different density \[27\]; it is possible that we are looking at a disk with different layers \[28\]. Note that the parameters of the two reflection components are tied with the exception of the ionization \(\xi\) and the normalization. As we can see from panels \(d\) in Fig. 1 and the fourth column in Tab. I \((\alpha_{13} \text{ free and } \alpha_{22} = 0)\) and in Tab. II \((\alpha_{13} = 0 \text{ and } \alpha_{22} \text{ free})\), adding a second reflection component only leads to a very modest improvement.

**Model d**

We consider the model \(\text{TBABS}^\ast(\text{RELXILL\_NK} + \text{RELXILL\_NK} + \text{XILLIVER})\).

\text{RELXILL\_NK} describes the disk’s reflection spectrum. \text{XILLIVER} describes the reflection spectrum from some warm material at a larger distance from the black hole and is independent of the background metric \[50\]. We assume the same iron abundance \(A_{Fe}\) in \text{RELXILL\_NK} and in \text{XILLIVER}, while the ionization is independent. As we can see from panels \(d\) in Fig. 1, the fit is better than models \(b\) and \(c\). The best-fit values are reported in the fifth column in Tab. I and in Tab. II.

Lastly, we consider a double reflection model for the accretion disk and a warm non-relativistic material

\(\text{TBABS}^\ast(\text{RELXILL\_NK} + \text{RELXILL\_NK} + \text{XILLIVER})\).

In the three reflection components, the iron abundance is the same, while the ionization parameters are all independent. The data to best-fit model ratios are shown in panels \(e\) in Fig. 1 and the best-fit values are reported in the sixth column in Tab. I and in Tab. II. As we could have expected on the basis of previous results, the improvement with respect to model \(d\) is modest: the data do not seem to require a double reflection spectrum.

In all models with \text{RELXILL\_NK}, we find a high value of the photon index \(q\); that is, most of the radiation seems to come from the very inner part of the accretion disk. The spin parameter \(a_\ast\) is always very close to 1. This was
found even in Ref. [20] assuming a Kerr background. Our best-fit values of \( a_\star \) are somewhat higher than the result in Ref. [20], consistent with the fact that the RELXILL package finds higher spin values than RELPLXION, which is the reflection model employed in [20]. The inclination angle of the disk with respect to our line of sight, \( i \), is not high but cannot be constrained well. The iron abundance \( A_{Fe} \) (in units of Solar iron abundance) is always less than 1. Note that, in models d and e, the non-relativistic component described by XILLVER is subdominant with respect to the relativistic one described by RELXILL-NR. This permits us to get measurements of \( a_\star \) and of the deformation parameters.

IV. RESULTS

The main goal of our study is to constrain the spacetime metric around the supermassive black hole in Ark 564, getting a measurement of \( a_\star, \alpha_{13}, \) and \( \alpha_{22} \). Our best model seems to be model d, while a double reflection model does not seem to be justified. The constraints on \( a_\star, \alpha_{13}, \) and \( \alpha_{22} \) from model d are shown in Fig. 2. In the left panel, we have the constraints on \( a_\star \) and \( \alpha_{13} \) assuming \( \alpha_{22} = 0 \). In the right panel we have the opposite case with the constraints on \( a_\star \) and \( \alpha_{22} \) for \( \alpha_{13} = 0 \).

The red, green, and blue lines indicate, respectively, the 68\%, 90\%, and 99\% confidence level contours for two relevant parameters. The black horizontal lines at \( \alpha_{13} = 0 \) and \( \alpha_{22} = 0 \) mark the Kerr solution. The gray region in the left panel is not covered in our analysis because the metric is singular there.

Our results are consistent with the hypothesis that the supermassive object in Ark 564 is a Kerr black hole. Assuming \( \alpha_{22} = 0 \), the constraints on \( a_\star \) and \( \alpha_{13} \) are (99\% confidence level)

\[
a_\star > 0.96, \quad -1.0 < \alpha_{13} < 0.2.
\]

For the case \( \alpha_{13} = 0 \), we find the following constraints on \( a_\star \) and \( \alpha_{22} \) (still 99\% confidence level)

\[
a_\star > 0.96, \quad -0.1 < \alpha_{22} < 0.9.
\]

This constraint on \( \alpha_{13} \) can be compared to that obtained previously in [20] from the supermassive black hole in 1H0707–495. The constraint reported here is stronger than the constraint from 1H0707–495 obtained with XMM-Newton data, and comparable to the constraint from the 250 ks data of NuSTAR.

We would like to remark that, even if our analysis nicely confirms the Kerr black hole hypothesis, these constraints have to be taken with some caution. Our error only includes the statistical uncertainty, ignoring the systematic uncertainty. On the contrary, our model has a number of simplifications, which inevitably lead to systematic errors in the measurements. For instance, the accretion disk is assumed to be infinitesimally thin and the inner edge of the disk is set at the ISCO radius. The intensity profile is modeled with a simple power-law, which is surely an approximation. The accretion disk has a unique ionization parameter. We plan to improve our reflection model and study the uncertainty related to the astrophysical model in future work.

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| Model  | $a$ | $b$ | $c$ | $d$ | $e$ |
|-------|-----|-----|-----|-----|-----|
| TBABS  | $N_H/10^{20}$ cm$^{-2}$ | $6.74^*$ | $6.74^*$ | $6.74^*$ | $6.74^*$ |
| POWERLAW | $\Gamma$ | $2.768^{+0.003}_{-0.003}$ | $9.86^{+0.08}_{-1.1}$ | $9.62^{+0.16}_{-0.74}$ | $7.0^{+1.6}_{-0.5}$ |
| RELXILL_NK | $q$ | $>8.4$ | $9.86^{+0.08}_{-0.1}$ | $9.62^{+0.16}_{-0.74}$ | $7.0^{+1.6}_{-0.5}$ |
| RELXILL_NK | $i$ [deg] | $26.7^{+2.9}_{-2.7}$ | $26.6^{+2.6}_{-5.3}$ | $36.0^{+4.3}_{-0.7}$ | $<45$ |
| RELXILL_NK | $a^*$ | $>0.987$ | $0.993^{+0.004}_{-0.012}$ | $0.995^{+0.001}_{-0.007}$ | $0.988^{+0.003}_{-0.010}$ |
| RELXILL_NK | $\alpha_{22}$ | $-0.1^{+0.1}_{-0.1}$ | $-0.1^{+0.1}_{-0.1}$ | $0^{+0.3}_{-0.05}$ | $-0.1^{+0.1}_{-0.1}$ |
| RELXILL_NK | $z$ | $0.0247^*$ | $0.0247^*$ | $0.0247^*$ | $0.0247^*$ |
| RELXILL_NK | $\log \xi$ | $3.088^{+0.011}_{-0.011}$ | $4.4^{+0.0}_{-0.0}$ | $2.66^{+0.0}_{-0.04}$ | $2.72^{+0.10}_{-0.23}$ |
| RELXILL_NK | $A_{Fe}$ | $0.525^{+0.0}_{-0.025}$ | $0.53^{+0.0}_{-0.03}$ | $0.88^{+0.12}_{-0.06}$ | $0.7^{+0.0}_{-0.0}$ |
| RELXILL_NK | $R$ | $-1$ | $-1$ | $-1$ | $-1$ |
| XILLVER | $\chi^2/\text{dof}$ | $4356.16/1403$ | $1553.01/1397$ | $1548.65/1395$ | $1474.58/1395$ | $1471.61/1393$ |

Table II. As in Tab. I assuming $\alpha_{13} = 0$ and $\alpha_{22}$ free in the fits. Model $a$ is the same as in Tab. I because it does not include RELXILL_NK, but we report here for completeness.
FIG. 1. Data to best-fit model ratios for the spectral models a to e. In the left panel, $\alpha_{13}$ is free in the fit and $\alpha_{22} = 0$. In the right panel, $\alpha_{13} = 0$ and $\alpha_{22}$ can vary. See the text for more details.

FIG. 2. Constraints on the spin parameter $a_*$ and the Johannsen deformation parameters $\alpha_{13}$ (left panel) and $\alpha_{22}$ (right panel) from the Suzaku data of the supermassive black hole in Ark 564 assuming model d. The red, green, and blue lines indicate, respectively, the 68%, 90%, and 99% confidence level contours for two relevant parameters. The gray region in the left panel is excluded in our analysis because the metric is singular there. See the text for more details.