Measuring the spin of the Supermassive Black Hole RXJ1131

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Abstract: Attempts to constrain the spin parameter and inclination angle of a black hole are ongoing, yet the goal remains elusive. In 2013, Nature published a paper in which the authors (Reis et al. 2013) claimed that they had successfully and unequivocally constrained the spin parameter of the black hole of quasar RXJ1131 to be $0.87 \pm 0.08$. However, our analysis indicates a spin parameter of $0.87 \pm 0.08$ is not consistent with our independent investigation which employs an improved model for the reflection component of the accretion disk created by Thomas Dauser and incorporates different filtering of the data for strong microlensing and high levels of photon pile-up. Moreover, our results suggest constraining a spin parameter to such a small error as indicated in the Reis et al. analysis is not possible with the signal-to-noise ratio of the available X-ray spectra. In our study, we preclude images which exhibit strong microlensing. Furthermore, once combining spectra that were filtered for strong microlensing events and high levels of pile-up, we discovered that no useful constraints could be placed on the spin parameter of the black hole.
1 Introduction

Luminous supermassive black holes, often referred to as quasars, and perhaps the most exotic objects in our universe, are at large distances from us. Since they are located at great redshifts, intervening objects such as galaxies or clusters of galaxies, may occasionally be positioned almost directly in our line of sight. These near alignments can be used to enhance the detection of distant objects through a phenomenon called gravitational lensing. Gravitational lensing occurs as light from source bends around an intervening galaxy or cluster of galaxies as it travels towards us. The gravitational effects thereby magnify the flux that we receive. This phenomenon was first predicted by Einstein in his General Theory of Relativity.

The intrinsic spin parameter of a black hole is the ratio of the black holes angular momentum to its maximum angular momentum often written as $\max_{bh}$. However, it is physically impossible for the spin to be greater than .998 (see "The Science of Interstellar" by Kip Thorne). During the creation of a black hole, as the material collapses, the angular momentum is preserved and the resulting accretion disk will have an amalgam of the previous spins. During the accretion process, material falling into the black hole will transfer its angular momentum to that of the disk as a whole. If its angular momentum vector is in the same direction as that of the black hole spin, then the spin of the black hole will increase; if it is in the opposite direction then the spin of the black hole will decrease. Although the mechanics are considerably more complicated, the same essentially holds true for black hole mergers. The primary long term goal of the ongoing project to determine the spin of a black hole at a considerable distance is to create a "map" of the evolution of black holes in our universe. If astrophysicists can sufficiently determine the spin parameters of a number of different quasars at different redshifts, then we will have an idea of the evolutionary processes of black holes.

The X-ray spectra of quasars contain a number of components including a direct component and a reflection component (see Figures 5.1.1 and 5.1.2). The direct component comes from the inverse Compton scattering of UV photons originating in the accretion disk with high energy electrons in the corona. The reflection component originates from the reflection of X-rays in the corona by the accretion disk.

The reflected component contains a continuum spectrum and an emission line spectrum. The strongest line in the reflected spectrum is the iron K alpha line due to the relative high abundance of Fe in the disk and the high fluorescence yield of iron.

The reflected iron K alpha line is emitted very close to the event horizon and its spectral shape is distorted due to the transverse Doppler shift, beaming, and the gravitational redshift (see Figure 5.1.3). The observed spectrum will also depend on the inclination angle of the disk and will be smeared since the iron emission originates from a range of radii on the accretion disk. The innermost stable orbit of a black hole is a function of its spin parameter (see Figure (5.1.4)). For black holes with high spin values the accretion disk can get very close to the black hole and the red wing tail of the Fe line profile becomes more noticeable and broader than the one predicted in black holes of lesser spin. The study of the relativistically distorted iron line of quasars can provide constraints on various properties of the quasar including its spin parameter, the inclination angle of the disk, and the inner and outer radii of the emitting region.

In 2013, Reis, Reynolds, Miller, and Walton published a paper in Nature entitled "Reflection from the Strong Gravity Regime in a z=0.658 Gravitationally Lensed Quasar". In their paper, they claimed to have successfully measured the intrinsic spin of a super massive black hole. However, we find significant errors in their analysis due to out-dated software, lack of use of all the data available form the XMM-Newton observatory, inaccurate filtering of epochs included in the stacking of spectra taken with the Chandra X-ray Observatory and an incomplete search of the parameter space of their spectral model. Our results advocate very different constraints of the spin parameter of this supermassive black hole.

Observations of RXJ 1131 were performed with the Chandra X-ray observatory between .2 and 10 keV. They were further broken down into a soft an hard band, from .2-2keV and 2-10keV respectively. Chandra has a spatial resolution of about 0.5 arcsec and can resolve the lensed images of the gravitationally lensed quasar. RXJ 1131 was also observed with the XMM-Newton observatory on March 5th 2014 via the use of Directors Discretionary Time obtained by proposer R. C. Reis. XMM-Newton has a spatial resolution of about 6 arcsec and cannot resolve the lensed images. The spectral analysis therefore of the XMM-Newton observation of RXJ 1131 includes all four images combined. The images are created from Gravitational Lensing and can be micro lensed separately. We consider the effects of microlensing in the analysis of the Chandra spectra of RXJ 1131.

2 Methods

2.1 Chandra Data Reduction

The Chandra data were reduced using the software package CIAO provided by the Chandra X-ray Center. The data was screened for grade, status, and time intervals of acceptable aspect solution and background levels. This reduction results in a "cleaned" CCD event file that contains the time stamped positions and energies of all X-ray photons detected by the CCD camera. Quasar RXJ1131 was previously analyzed by Chartas et al. (2009) and Dai et al. (2010). For such purposes, the quasar was imaged 38 times between April 12, 2004 and July 12, 2014. Using Event Browser, a tool written in IDL to browse CCD event files, (Patrick Broos, Software engineer at PSU), We displayed the images of the Chandra observations and determined circular ex-
traction regions for each lensed quasar image. We also extracted nearby circular regions free of sources to model the background levels. We corrected the X-ray fluxes of the brightest images A and B for pile-up effects. Pileup can lead to incorrect results by misrepresenting accurate counts of photons and summing energy. Essentially, if two or more events are recorded on the same CCD pixel within the time separating two successive readouts of the CCD (typically of the order of 0.5 seconds) only one event will be recorded having an energy equal to the sum of the energies of the photons that were recorded in that pixel. A spectral fitting tool LYNX (Chartas 2010) was used to correct for pileup. We used standard CIAO tools provided by the Chandra X-ray Center to extract spectra from each extraction region and the NASA provided software tool XSPEC to fit the extracted spectra with models (provide reference for XSPEC).

2.2 XMM-Newton
   Data Reduction

In order to correctly reduce the XMM data, PN and MOS data were filtered to only include events with instrument PATTERNS in the 0-4 range for the PN and the 0-12 range for the MOS. When the full-field count rates of the CCDs exceeded an acceptable amount (24 counts per second), the data were precluded from the analysis. We used \( \chi^2 \) statistics to fit various spectral models to the data. XMM data was grouped at a minimal of 140 counts per energy bin. PN and MOS spectra were fit using the spectral fitting tool XSPEC V. 12.8.1 (Arnaud).

2.3 Modeling
   2.3.1 XMM-Newton

We assumed a variety of models of increasing complexity to fit the XMM-Newton spectrum of RXJ 1131. Following is a list of the models used.
1. A power-law model modified by Galactic absorption (PHABS*POWER)
2. A gaussian model (GAUSS)
3. A reflection spectrum fitting model (RELLINE)
4. A relativistic smearing component (RELCOMP)
5. A reflection spectrum fitting model (RELXILL)

We note that Reis et al. 2013 used the spectral model RELXILL convolved with RELCONV to model the spectra reflection of an AGN accretion disk. This model however has been recently shown to be inaccurate and is superseded by the model RELXILL. According to the Homepage of Thomas Dauser, RELLINE is meant to calculate relativistic line profiles and to be compatible with XSPEC. The model includes an addition, RELCONV, which calculates relativistic smearing effects. The RELXILL model was created to be an improvement over the RELLINE model by combining the RELLINE code and the XILLVER code (smearing code). The primary advantage is RELXILL’s ability to properly create a reflection spectrum for each point on the accretion disk. This allows for a more in depth analysis of the region surrounding a black hole. For more detail, please visit Thomas Dauser’s web page, http://www.sternwarte.uni-erlangen.de/dauser/research/index.html.

We attempted to reproduce several of the results presented in Reis et al. by adopting a similar model as theirs (ZPHABS*PHABS*(ZPOW+ZGAUSS+RELLINE+RELCOMP)) We started the spectra fits with values for the free parameters set at the best-fit values found by Reis et al. and began with fitting only the PN data, since Reis et al. did not incorporate the MOS data in their analysis. We find significant differences in the best-fit values of inclination angle, inner radius, and spin parameter. Moreover, we were able to find considerably better fits with lower reduced \( \chi^2 \) than theirs but with a different set of best-fit parameters of the model.

We next proceeded to simultaneously fit the PN and MOS 1+2 spectra and find even larger discrepancies with the results of Reis et al. 2013. We conclude that a reanalysis of the XMM Newton spectrum of RXJ 1131 using an updated model for the reflection component of the accretion disk and including the MOS1 and MOS2 provides significantly different values for the spin parameter and the constraints one can place on it.

2.3.2 XMM Error Analysis

We performed an extensive error analysis of the spin parameter of our most realistic model listed as ZPHABS*PHABS*(ZPOW+ZGAUSS+RELXILL) in Table 1. Specifically, we stepped the spin parameter between 0.1 and 1 and calculated the \( \chi^2 \) of the best fit for each value of the spin parameter in this range. We repeated this procedure with several model parameters frozen to investigate the sensitivity of our results to what parameters in the model were frozen during the fit. The following list represents the thawed reflection component parameters.
1. Spin parameter and reflection component normalization
2. Spin parameter, reflection component normalization, and reflection fraction
3. Spin parameter, reflection component normalization, reflection fraction, and inclination angle
4. Spin parameter, reflection component normalization, reflection fraction, and inner radius
5. Spin parameter, reflection component normalization, reflection fraction, inclination angle, and inner radius
6. Spin parameter, reflection component normalization, reflection fraction, inclination angle, inner radius, and outer radius.

In Figure 1 we show the \( \chi^2 \) confidence contours of the spin parameter for different model parameters being frozen.

2.3.3 Chandra

Chandra Data was analyzed using the XSPEC program\(^1\). Fits containing previously mentioned models, namely PHABS,POW, and GAUSS. Every
image of every epoch was modeled to ensure accurate results. When modeling the spectra of these images, we looked for distortions of the X-ray spectra that may have arisen from strong microlensing events. When creating the combined spectra which were used to analyze the images, we excluded spectra from epochs that contained strong microlensing events. We also excluded spectra that were significantly affected by pile-up.

Using a software tool created by Dr. Chartas, determined pile-up fractions and categorized all data with pile-up fractions of less than 10%, 20%, and 30%, where pile-up fraction is the fraction of events affected by pile-up. Using the NASA software tool ADDSPECT we combined spectra for each image after removing spectra that were affected by strong microlensing events and had a pile-up fraction below a desired value. See appendix for discussion on removed images. Note that certain epochs (OBSID 4814, 6914, 6915, and 6916) were removed from the combined spectra due to complications involving their background files. Though they were excluded, the exclusion is not believed to skew results, since they showed no explicit signs of a reflection component. Moreover, of the 38 epochs, a loss of 4 is not a statistically significant issue.

The data was fit using 3 models: 1. ZPHABS*PHABS*(ZPOW+ZGAUSS) 2. ZPHABS*PHABS*(ZPOW+ZGAUSS+ZGAUSS+ZGAUSS) 3. ZPHABS*PHABS*(ZPOW+ZGAUSS+RELXILL) The first model is a simple power law and gaussian. The power law is included to take into account the direct spectra while the gaussian handles the iron line. Essentially, the model claims no reflection component. The second model includes 2 emission lines and 2 absorption lines. They were added since the spectrum showed some structure resembling a P-cygni profile and we wanted to determine the statistical significance of this spectral feature. The third model contains a power law to fulfill the direct component. The gaussian fits the iron line while the reflxill component is used to determine spin parameter and inclination angle. All models were fit to the corrected and uncorrected combined data and then further subdivided based on pile-up fraction.

3 Results

Certain discrepancies have been found in the analysis and conclusions of the Nature paper. Primarily, we find that our spectral models are unable to provide significant constraints on the spin of the black hole in RXJ 1131 based on the available X-ray spectra of this quasar. Also, our error analysis indicates that the spin parameter value and its uncertainty reported by Reis et al. is not consistent with our results. For the XMM analysis of RXJ 1131, we found different models that gave different values of the spin parameter, the inclination angle, and the iron abundances, however the spectral fits with these models gave acceptable $\chi^2$ values. We determined the extracted counts for each image at each epoch and found significant discrepancies with the values published in Reis et al. One possibility is that Reis et al. did not perform an accurate PSF correction to the counts in an image when using extraction regions that are considerably smaller than the (Full Width at Half Maximum) FWHM of the instrument. The lower count rates for the images reported by Reis et al. also indicates that their estimated values of pile-up fraction are underestimated since the pile-up fraction depends on the calculated count-rate. When stacking images, Reis et al. likely did not take into account microlensing affects carefully. The Chandra modeling led us to the realization that the use of the reflxill model is unnecessary. In most scenarios model 1 provides an improved reduced $\chi^2$ compared to model 3. In other words, a model excluding the reflxill component, which constrains the spin parameter and inclination angle, is a better approximation of the data. In a few fine tuned cases (with many model parameters frozen) where the reflxill model did result in a better reduced $\chi^2$ than the simpler model, the spin parameter was always found to be at its maximum value ($998$). These models with high spin parameters however are unrealistic because the reflection component is significant larger than the direct component. We also think the main reason that these unrealistic models result in high spin values is that high spin values smear features in the Fe line profile. Since there are no noticeable features resembling a relativistically distorted iron line in the stacked spectrum (just a single line) and since the reflection component is allowed to dominate in these fits the fit drives the spin parameter to high values to smear out the model. A single Gaussian line with no relativistic corrections can provide acceptable fits to both the XMM and Chandra spectra of RXJ 1131.

4 Conclusions

In 2013, Reis et al. released a groundbreaking paper in which they claimed to have confidently constrained the spin parameter of a supermassive black hole. After a detailed examination of the same data, We resolved that their analysis was insufficient due to a number of reasons. In the XMM analysis, the only way to replicate their confidence contour was to freeze most parameters of the reflxill model; this is obviously not an acceptable practice since it takes all the power out of the model and simply delivers the desired results, not necessarily the true results. When We left the model unconstrained, the spin parameter remained unconstrained except for very high values. Therefore, We believe the current methods for constraining the spin parameter are insufficient. In the Chandra analysis, there appears to be a number of serious errors; primarily, they neglected to remove individual images which exhibited microlensing events. In order to correct for this, We examined every image from each epoch and removed those displaying microlensing. More importantly, the data
itself did not demonstrate the necessary structure to indicate a relativistic distortion of the iron line. So why did the relxill model indicate a constrained spin parameter? Note that a spectral fit can produce erroneous high spin parameter values by significantly smearing the relativistic iron line, in order to match spectra that do not show any significant distortion of the iron line.
5 Tables and Figures

5.1 Reflection Component

Figure 5.1.1: The graphic displays a black hole accretion disk. The orange line represents the original photon. The blue cloud is the electron corona, while the pink lines demonstrate the direct and reflected photons. Thanks to Catherine Marie Klosson for the depiction.

Figure 5.1.2: The figure exhibits the two primary modeling components. The dashed line represents the direct component which is reminiscent of an integrated black body curve. The bottom curve demonstrates the reflection component. It shows how strong the Iron Line is. (Reynolds 2013)

Figure 5.1.3: The image displays the expected changes in the Iron K Alpha line due to relativistic distortions. The first image displays two peaks created from the normal Doppler effect. The second shows a taller peak on the right which is due to beaming. The third demonstrates the effects of the gravitational redshift on the emission line. The final represents the line profile when integrated over the entire disk.
Figure 5.1.4: The graph compares the spin parameter of a black hole to its Innermost Stable Circular Orbit (ISCO). Note that a Schwarzschild black hole has minimum spin while a Kerr black hole has maximum spin. The graph is fairly linear until a spin parameter of .9. The unit of ISCO, the gravitational radius ($r_g$), is the same as a Schwarzschild radius.
### 5.2 RELXILL Tables

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Table 1: The Table displays the best fit values from the model with the lowest $\chi^2 = 0.88915$ for 436 degrees of freedom.

(a) Parameter 1 (nH): Column density for our galaxy in the direction of RXJ 1131.
(b) Parameters 2,5,8,18 (z): Redshift of RXJ 1131.
(c) Parameter 3 (nH): Density of intervening gas. Approximately the same as parameter 1.
(d) Parameters 4,19 (PhoIndex): Photon Index is essentially the slope of the power law.
(e) Parameter 6,10,25 (norm): Normalizations of the power law, gaussian, and relxill model, respectively.
(f) Parameter 7 (LineE): Line Energy at rest frame energy. Note this is for the Iron K Alpha Line.
(g) Parameter 9 (sigma): The width of the Iron K Alpha line in keV.
(h) Parameter 11 (Index1): Emissivity index for $r < Rbr$, where emissivity is $r^{-\text{Index1}}$. Emissivity is defined as the effectiveness of a material at emitting energy. In this case, it refers to the accretion disk.
(i) Parameter 12 (Index 2): Emissivity index for $r > Rbr$, where emissivity is $r^{-\text{Index2}}$.
(j) Parameter 13 (Rbr): radius where emissivity changes from Index1 to Index2.
(k) Parameter 14 (a): Intrinsic Spin Parameter.
(l) Parameter 15 (incl): Inclination angle of the disk measure with respect to the normal.
(m) Parameter 16 (Rin): Inner Radius of the disk
(n) Parameter 17 (Rout): Outer Radius of the disk
(o) Parameter 20 (logxi): logarithmic value of the ionization parameter at the inner edge of the disk. The ionization parameter highlights the relationship between the ionizing photon flux and the density of the gas.
(p) Parameter 21 (Afe): Iron Abundance in Solar Units.
(q) Parameter 22 (Ecut): cutoff energy in keV.
(r) Parameter 23 (refl_frac): The ratio of the reflected flux to that of the direct component.
(s) Parameter 24 (angleon): If set to 0, then the model acts as a basic reflection model convolved with a smearing component. If set to 1 then each point of the disk is calculated to have a specific smear component. The creators of the program advise to leave angleon=1.
5.3 Contour Plots from RELXILL MODEL

1. Figure 1

The figure displays the spin parameter vs. the reduced $\chi^2$ for my best fit model of the PN data. The horizontal lines represent the 90%, 96.7%, and the 99% marks respectively. The curves shown represent the relation between the reduced $\chi^2$ and spin parameter based on constraints. The curves with lesser slopes demonstrate the unconstrained models.

2. Figure 2

The figure displays the spin parameter vs. the reduced $\chi^2$ for my best fit model of the PN, MOS1, and MOS2 data. The red line represents the 90% confidence and the green line demonstrates the 95% confidence.
5.4 Reflection Regions

The following images are of the spectral region immediately affected by the reflection component. These demonstrate that the relxill model is unnecessary due to a severe lack of spectral counts demonstrating a distorted Iron K Alpha line. All images are the corrected versions modeled using a simple gaussian (M1). Also, they are all at pileup correction 1.

5.4.1 Image A

![Data and folded model](chart.png)

*chart: s=ftp=200 5.12.36*
5.4.4 Image D

data and folded model
5.5 Removed Images

As previously mentioned, when combining the many epochs of each image, a number of images had to be removed due to microlensing. If these images were indiscriminately added, they would undoubtedly skew results from the RELXILL model since they represent iron lines which are shifted to a new energy due to microlensing. The following includes each image and a brief discussion of why the image was removed.

5.5.1 Epoch 12833 Image A

![Graph showing a strong line centered around 3.9KeV.](image)

Image A displays a strong line centered around 3.9KeV.
Image A displays a strong line centered around 4.1KeV.
Image B displays strong lines centered around 2.7KeV and 3.2KeV.
Image B displays a strong line centered around 3.6KeV
Image C displays strong lines centered around 3KeV and 4.4KeV
Image C displays a strong line centered around 3.6KeV
Image C displays a strong line centered around 3.9KeV and more importantly the line is indubitably smeared due to microlensing.
References