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Measuring the Innermost Stable Circular Orbits of Supermassive Black Holes

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Abstract

We present a promising new technique (*g*-distribution method) for measuring the innermost stable circular orbit (ISCO), the inclination angle (i), and the spin of a supermassive black hole. The g-distribution method involves measurements of the distribution of the energy shifts of the relativistic iron line emitted from the accretion disk of a supermassive black hole that is microlensed by stars in a foreground galaxy and a comparison of the measured g-distribution with microlensing caustic simulations. The method has been applied to the gravitationally lensed quasars RXJ1131−1231 (z_s = 0.658, z_l = 0.295), QJ0158−4325 (z_s = 1.29, z_l = 0.317), SDSS1004+4112 (z_s = 1.73, z_l = 0.68) and Q2237−0305 (zs = 1.69, z_l = 0.04). For RXJ1131 our initial results indicate an ISCO radius of < 5 gravitational radii and i ~ 65 degrees. Further monitoring of lensed quasars will provide tighter constraints on their inclination angles, ISCO radii, and spins.

Methodology

In our method, we start by performing a systematic spectral analysis of all epochs and all images searching for the presence of the Fe Kα lines in the spectra. We determine the statistical significance of these lines and produce distributions of the generalized Doppler shifts $g = E_{obs}/E_{rest}$ of the Fe Kα line detected at the >90% and the >99% confidence levels in all images. The functional dependence of *g* with ISCO, inclination angle and caustic crossing angle, is calculated for the case of a spinning black hole. We assume that the most redshifted line component is produced by Fe Kα emission originating close to the ISCO. The red and blue cut-offs of the *g*-distributions provide upper limits on the ISCO and inclination angle of the black hole, respectively.

Object	z_s	z_l	L_{Bol}/L_{Edd}	$\log(M_{BH})$ $M_\odot$	$\log(R_E)$ cm	$\log(r_g)$ cm	R_E/v_e years	$10r_g/v_e$ months	v_e km/s	μ
RXJ1131	0.658	0.295	0.8	7.8	16.4	13.0	11.1	0.5	720	57
QJ0158	1.29	0.317	0.4	8.2	16.5	13.4	18.0	1.5	600	5
SDSS1004	1.73	0.68	0.05	8.6	16.4	13.8	9.4	2.9	785	70
Q2237	1.69	0.04	0.02	9.1	17.0	14.3	8.1	1.8	3890	16

***Figure 1**: Object Summary*. M_{BH} and R_E are the black hole mass and Einstein radius (⟨M⟩ = 0.3M☉) with $r_g = GM_{BH}/c^2$. R_E/ve and rg/ve are the crossing times given the effective velocity ve (see Mosquera & Kochanek 2011). We have assumed a 2−10keV bolometric correction factor of 30. μ is the total flux magnification of the background quasar.

Chandra Observations of Lensed Quasars

For the 6 available *Chandra* observations of QJ0158 with exposure times of ~19 ks we find that the iron line is detected in 5 out of the 12 spectra (6 epochs × 2 images) at >90% confidence and in 1/12 spectra at >99% confidence. For the 6 available Chandra observations of SDSS1004 with exposure times of ~25 ks we find that the iron line is detected in 12 out of the 24 spectra (6 epochs × 4 images) at > 90% confidence and in 6/24 spectra at > 99% confidence. For the 14 available Chandra observations of Q2237 with exposure times of ~30 ks we find that the iron line is detected in 12 out of the 56 spectra (14 epochs × 4 images) at > 90% confidence and in 5/56 spectra at > 99% confidence.

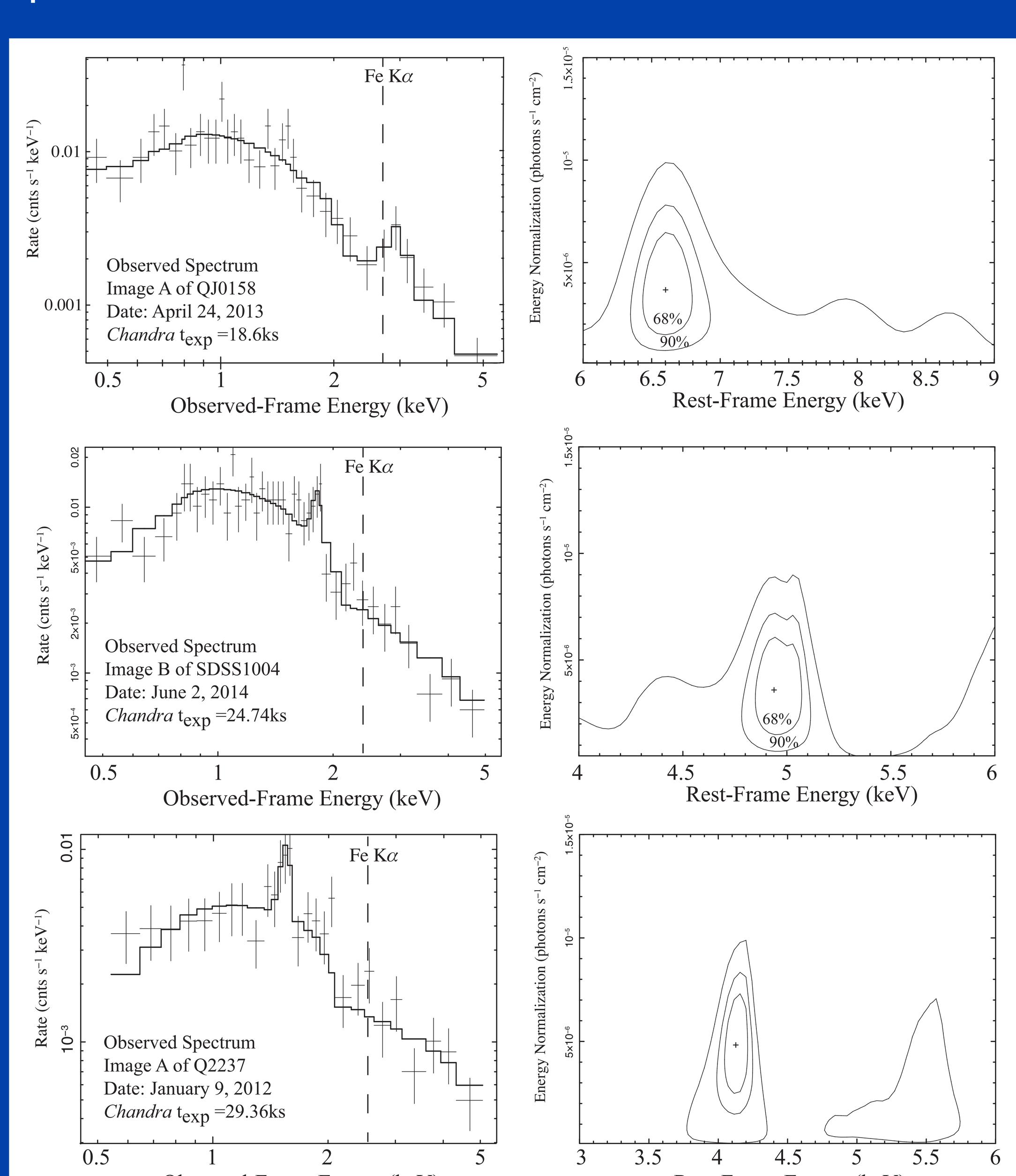

Figure 2 − Demonstrations of the detected shifts of the relativistic Fe Kα line in observed quasars. The dashed line in left images represents the expected observed-frame energy of the iron line emission (6.4 keV). The contours represent 68%, 90%, and 99% c-stat confidence intervals of the flux normalizations of the spectrum. (Top) Detection of the Fe Kα line in image A of QJ0158. Line detected at 6.55 keV, 90% confidence. (Middle) Detection of the Fe Kα line in image B of SDSS1004. Line detected at 4.94 keV at 90% confidence. (Bottom) Detection of the Fe Kα line in image A of Q2237. Line detected at 4.14 keV, 99% confidence.

g-distribution of Quasar RXJ 1131-1231

RX J1131 has been monitored 38 times over a period of 10 years with CXO. As reported in Chartas et al. (2016), both redshifted and blueshifted Fe Kα lines have been detected in the spectra of the lensed images of RXJ1131. Specifically, for RX J1131 we find that the iron line is detected in 58 out of the 152 spectra (38 epochs × 4 images) at > 90% confidence and in 18/152 spectra at > 99% confidence. The exposure times of the observations of RXJ1131 range between 5 ks and 28 ks.

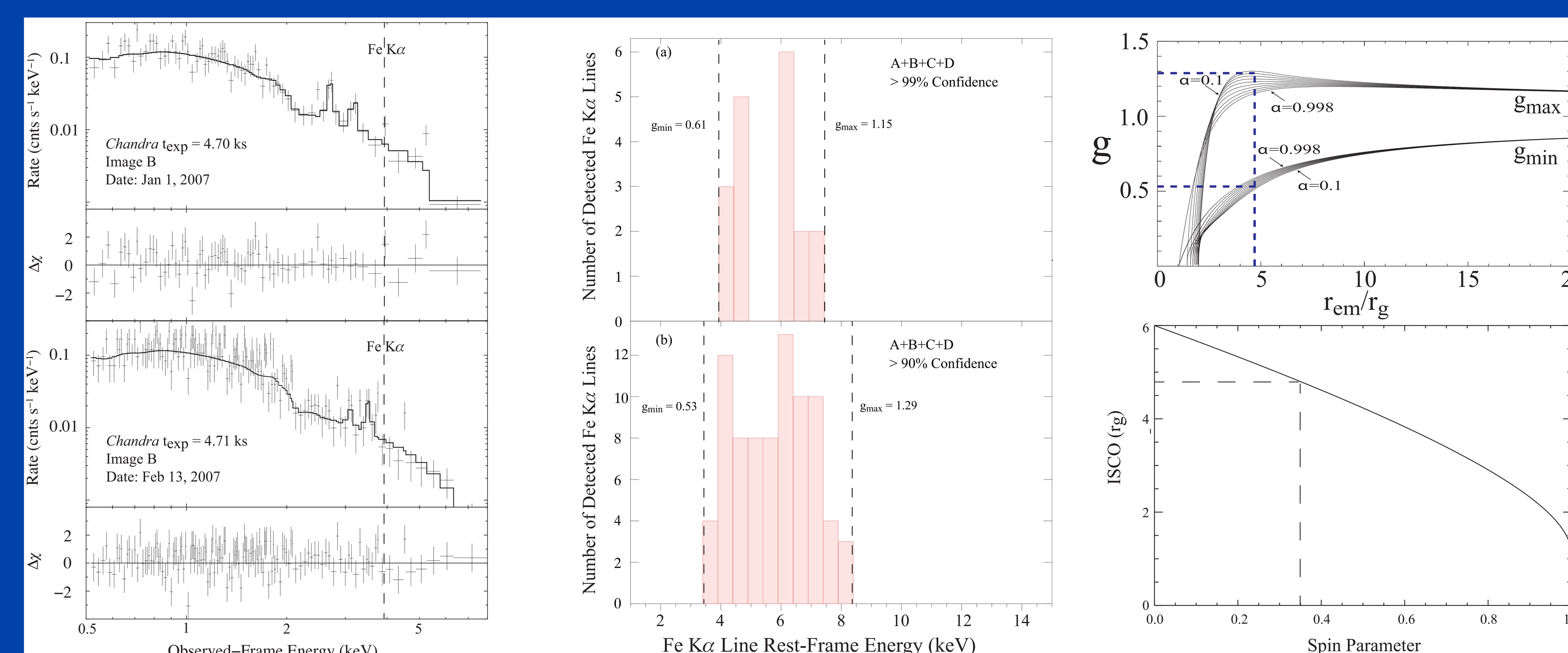

Figure 3 − (Left) Demonstration of shifted Fe Kα line detection in RXJ1131. (Middle) Distribution of the Fe Kα energy-shifts for all images and all 38 epochs of data for RXJ1131. Only cases where the iron line is detected at > 99% (panel a) and at > 90% (panel b) are shown. The vertical lines represent the extreme cut-offs of the distribution. These cut-offs provide upper limits of the ISCO and inclination angle. (Right Top) Extremal shifts of the Fe Kα line energy for spin values ranging between 0.1 and 0.998 in increments of 0.1. Horizontal lines represent the observed values of $g = E_{obs}/E_{rest}$ of the most redshifted and blueshifted Fe Kα lines from all 38 epochs and all images of RXJ1131. The extreme g values are for Fe Kα lines detected at > 90%. The inner radius of the accretion disk is constrained to be $r < 5r_g$ and i ~ 65 degrees. (Right Bottom) The measured constraint on the ISCO places a constraint on the spin parameter of *a* ~ 0.35.

Ongoing Analysis of Remaining Quasars

Additional monitoring observations with *Chandra* will provide more representative and complete distributions of the generalized Doppler shift g values of the Fe Kα line in RXJ1131 as well as in QJ0158, SDSS1004, and Q2237. The g-distribution method provides a new and independent technique of constraining the inclination angle, ISCO radius, and black hole spin of quasars.

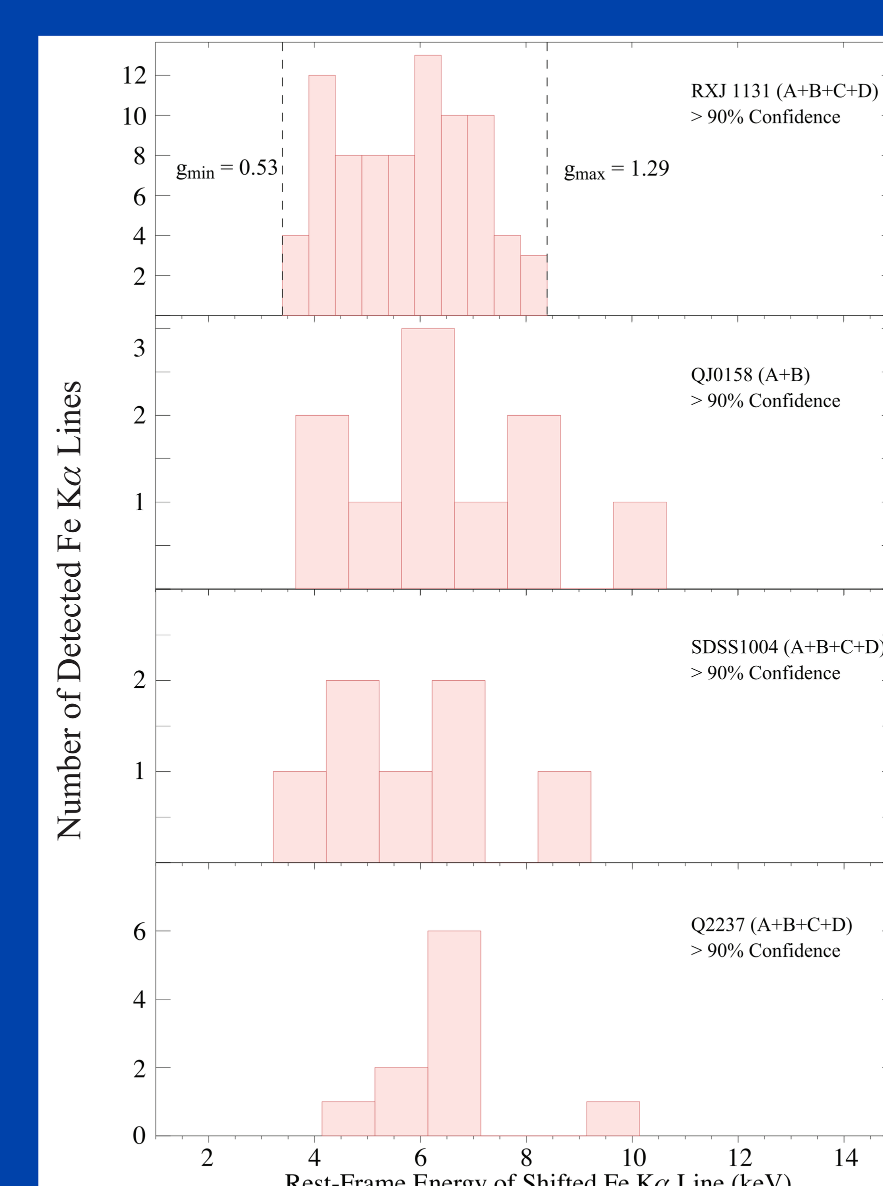

Figure 4 − Distributions of the Fe Kα energy shifts for all quasars listed. While the distributions for the remaining 3 quasars are currently sparse, preliminary analysis suggests conclusions similar to those made of RXJ1131 are possible and promising.

Conclusions

- *We have presented the detection of relativistic shifts of the Fe Kα line produced my microlensing for the lensed quasars, RXJ1131, QJ0158, SDSS1004, and Q2237. The g-distribution of energy shifts places constraints on the ISCO, spin, and inclination angle of the black hole.*
- *The detection of a shifted Fe Kα line(s) in several observations of each quasar in our sample suggests methods incorporating stacking of spectra from different observations and images of lensed quasars can lead to the misinterpretation of the stacked spectra and misleading results.*
- *We have applied our g-distribution method on RXJ1131. Our initial results indicate an ISCO radius of < 5 rg, i ~ 65, and spin parameter a ~ 0.35. The other quasars in our sample show potential for application of the g-distribution method as well once more data is obtained.*

Acknowledgements

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