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Supplementary information

Light bending and X-ray echoes from behind a supermassive black hole

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Supplementary Information

Alternative Explanations of the Short-Timescale Variability

The observed shift in the centroid of the iron K emission line in the residual spectra (Figure 4) during the flare, while predicted by models of X-ray reverberation from the accretion disk, cannot readily be explained by other models of the variability. Variation in the X-ray continuum between time bins is accounted for when the residuals are computed, thus are not seen here. High column density, ionized outflows can reduce produce broad absorption features up to 2 keV, however variation in these outflows cannot explain the shift in the line centroid between 3 and 6 keV. Furthermore, outflows capable of producing such significant absorption would be inconsistent with the observed X-ray spectrum (the X-ray spectrum during the flare shows no evidence for significant absorption). Changes in the ionization of the accretion disk can change the rest frame energy of the iron K line between 6.4 and 6.97 keV and over-ionization of the inner disk can weaken the redshifted line emission seen between 3 and 5 keV relative to that at 6 keV but is likewise not able to produce the pattern of variability and the shift in the emission line centroid that is seen.

The Mass of the Black Hole

The mass of the black hole measured from the X-ray reverberation model is consistent with that obtained from the width of the Hβ line in the optical spectrum, $M_{BH} = 2.8^{+0.6}_{-0.7} \times 10^7 M_\odot$ [36], though we note that X-ray reverberation from the inner disk and measurement of the narrow re-emergence peaks in the light curve is more constraining of the lower mass bound, since such a low mass would require an X-ray source too high above the disk to produce strong peaks. Optical reverberation mapping using Hβ lines emitted from the broad line region finds the mass to be $M_{BH} = 9.3^{+1.3}_{-1.4} \times 10^6 M_\odot$ [35], apparently in tension with both the mass derived from the line width and the best fitting value in our X-ray reverberation model. We note however that this analysis assumed the virial factor, which empirically represents the relationship between the black hole mass, line width and reverberation timescale, to be unity. This low value of the mass suggests accretion at a rate close to or slightly in excess of the Eddington limit, in which case the virial factor can be a factor of two to three higher [37]. It is therefore likely that optical reverberation mapping underestimates the mass of the black hole in I Zw 1 by a factor of two to three.

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