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Is the anti-correlation between the X-ray variability amplitude and black hole mass of AGNs intrinsic? *(Research Note)*

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ABSTRACT

Aims. Both the black hole mass and the X-ray luminosity of active galactic nuclei (AGNs) have been found to be anti-correlated with the normalized excess variance ($\sigma^2_{\rm rms}$) of the X-ray light curves. We investigate which correlation with $\sigma^2_{\rm rms}$ is the intrinsic one.
Methods. We divided a full sample of 33 AGNs (O' Neill et al. 2005, MNRAS, 358, 1405) into two subsamples. The black hole masses of 17 objects in subsample 1 were determined by reverberation mapping or stellar velocity dispersion. The black hole masses of the remaining 16 objects were estimated from the relationship between broad-line region radius and optical luminosity (subsample 2). We then performed partial correlation analysis, ordinary least-squares regression, and K–S tests on the full sample and the subsamples, respectively.
Results. We found that $\sigma^2_{\rm rms}$ seems to be intrinsically correlated with the black hole mass in the full sample. However, this seems to be caused by including subsample 2 in the analysis, which introduces an extra correlation between the black hole mass and the luminosity and strengthens any correlation with the black hole mass artificially. Therefore, the results from the full sample may be misleading. The results from the subsample 1 show that the correlation between $\sigma^2_{\rm rms}$ and the X-ray luminosity may be the intrinsic one and, therefore, the anti-correlation between $\sigma^2_{\rm rms}$ and the black hole mass is doubtful.

Key words. X-rays: galaxies – galaxies: active – methods: statistical

1. Introduction

X-ray emission from active galactic nuclei (AGNs) exhibits variability on time scales from minutes to days. This indicates that X-rays are likely to be emitted from the inner most regions of AGNs and the variability may be related to the important properties of the central engine. Lawrence & Papadakis (1993) utilized long-term *EXOSAT* observations to investigate the power-density spectra of 12 AGNs. They found the power-density spectra could be described as a power law $P \propto \nu^{-\alpha}$ with a mean index $\alpha = 1.55$, and the amplitude was anti-correlated with the X-ray luminosity. Detailed studies of the power-density spectra have been performed with *RXTE* and *XMM-Newton* data. The universal relation between the black hole mass and the "break time" in the power-density spectra was found both in stellar mass and supermassive black holes (e.g. Uttely & McHardy 2005). A tighter relation was discovered when the bolometric luminosity was involved, i.e. $T_{\rm B} \propto M^2/L$ (McHardy et al. 2006). However, due to limited observational data, accurate power-density spectra are only available for a small number of AGNs. As an alternative, the normalized excess variance ($\sigma^2_{\rm rms}$) can be easily calculated, and it was found that $\sigma^2_{\rm rms}$ is anti-correlated with X-ray luminosity (e.g. Almaini et al. 2000).

As a result of the progress in determining the black hole masses in AGNs, the relation between the variability and black hole mass has also been investigated. Lu & Yu (2001) found the anti-correlation between the black hole mass and $\sigma^2_{\rm rms}$, and suggested this correlation was an intrinsic one, rather than the apparent anti-correlation between the X-ray luminosity and $\sigma^2_{\rm rms}$. Several authors also addressed this problem following Lu & Yu's work (e.g. Bian & Zhao 2003; Papadakis 2004; O' Neill et al. 2005). These authors confirmed the anti-correlation between the black hole mass and $\sigma^2_{\rm rms}$, and some models have been subsequently constructed to explain this correlation.

In this paper, we revisit this problem by studying the sample of O' Neill et al. (2005), which includes 33 AGNs and uses nearly the same time scale for all these objects. The black hole masses of 17 objects in this sample were determined by reverberation mapping or stellar velocity dispersion (we denote these objects as subsample 1 in the following). The black hole masses of the remaining 16 objects were estimated from the relationship between broad-line region radius and optical luminosity (we denote these objects as subsample 2 in the following). We found that the optical luminosity, which is used in determining the black hole mass for subsample 2, has an obvious correlation with the X-ray luminosity in 2–10 keV band, as shown in Fig. 1a. The values of the correlation coefficients between optical luminosity and X-ray luminosity for subsample 1 and subsample 2 are 0.907 and 0.910, respectively. Even if the datum of NGC 4395 is excluded from subsample 2, the value of the correlation coefficient is still 0.819. It is well known that there is a strong correlation between the optical luminosity and the black hole mass (Kaspi et al. 2000). Thus, if $\sigma^2_{\rm rms}$ is intrinsically correlated with one of them, an artificial correlation with the other will appear. However, there will be an additional artificial correlation for subsample 2 due to the utilization of optical luminosity in determining the black hole mass, whereas the black hole mass of subsample 1 is independently obtained by reverberation mapping or stellar velocity dispersion. Therefore, the result from the

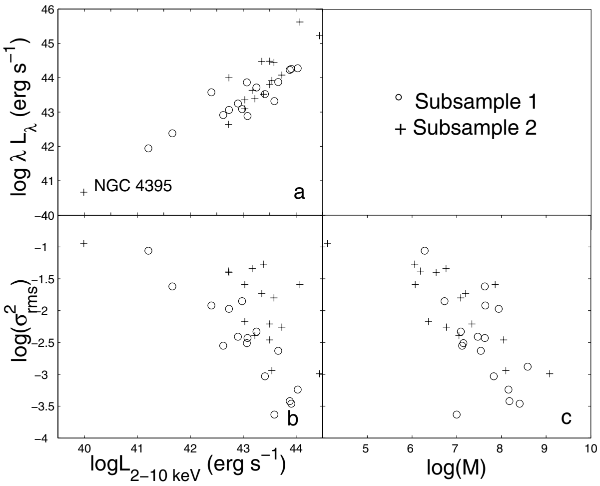

Fig. 1. a) The correlation between X-ray luminosity (2–10 keV) and optical luminosity (λ = 5100 Å). The point in the lower left corner is NGC 4395, which is a dwarf Seyfert galaxy. The value of the correlation coefficient is not significantly influenced by whether this point is included or not (see the text for details). **b)** The data of the normalized excess variances and the X-ray luminosities (2–10 keV). **c)** The data of the normalized excess variances and black holes masses. The values of black hole masses are in units of $M_{\odot}$. The data are obtained from O' Neill et al. (2005) and the references therein.

full sample (especially for that from the subsample 2) may be misleading. Furthermore, due to the less reliable black hole mass of subsample 2, some unclear systematic biases may have been introduced into the analysis. To find out which correlation is intrinsic, we performed the partial correlation analysis on subsample 1 and subsample 2 separately in Sect. 2.1. We demonstrated the ordinary least-squares regression results are in Sect. 2.2 as another approach to this problem. We performed K–S tests in Sect. 2.3 to test whether subsample 1 and subsample 2 are drawn from the same parent population. In Sect. 3, we discuss our results and make conclusions.

2. Data analysis

2.1. Partial correlation analysis

The partial correlation analysis is an appropriate method to disentangle the correlation between variables. The definition of the first-order partial correlation coefficient between variables x and y is (Kendall & Stuart 1977), $r_{xy.z} = \frac{r_{xy}-r_{xz}r_{zy}}{\sqrt{(1-r_{xz}^2)(1-r_{zy}^2)}}$, where z is the controlled variable and r_{xy} is the correlation coefficient between variables x and y.

We adopt the data of the black hole mass, the X-ray luminosity, and $\sigma^2_{\rm rms}$ from O' Neill et al. (2005) and present them in Fig. 1b and 1c for clarity. The correlation analysis is performed on the full sample and the subsamples, respectively. The results are shown in Table 1.

For the full sample, both the black hole mass and the X-ray luminosity show strong apparent anti-correlations with $\sigma^2_{\rm rms}$ (Fig. 1b and c). However, it appears that after the black hole mass is controlled, the correlation between the luminosity and $\sigma^2_{\rm rms}$ is not significant. On the contrary, the correlation between the black hole mass and $\sigma^2_{\rm rms}$ is still significant after the luminosity is controlled. These results seem to support Lu & Yu's suggestion that the correlation between the black hole mass and $\sigma^2_{\rm rms}$ is intrinsic. However, as discussed in Sect. 1, since any correlation between the black hole mass may be strengthened artificially by subsample 2, we should exclude subsample 2 when investigating the intrinsic correlation. For subsample 1, the correlation between the black hole mass and $\sigma^2_{\rm rms}$ disappears when the luminosity is controlled, whereas the correlation between the luminosity and $\sigma^2_{\rm rms}$ is still significant. The results of subsample 2 are consistent with those of the full sample. Both of them indicate $\sigma^2_{\rm rms}$ is intrinsically correlated with the black hole mass, rather than the luminosity. However, the analysis of the more reliable subsample 1 shows results to the contrary. Due to the limited size of the present sample, we conclude that the results of subsample 2 is doubtful, and perhaps the correlation between luminosity and $\sigma^2_{\rm rms}$ is the intrinsic one. A more robust conclusion will be deduced when a larger sample is available.

2.2. Ordinary least-squares regression

To verify the results obtained in Sect. 2.1, we performed the ordinary least-squares regression on the full sample, subsample 1, and subsample 2, respectively. The regression equation is, $\log(\sigma^2_{\rm rms}) = A\log M + B\log L + C$.

The results of the regression for the three samples are summarized in Table 2. In Fig. 2, we show the comparison between the values of $\sigma^2_{\rm rms}$ predicted by the results of the regression and the observed values.

The results of F statistic demonstrate the high significance of the linear correlation. However, the values of χ^2 are still large, especially for the full sample. We should notice that the dependence on the black hole mass and the luminosity seems to be different for the two subsamples. For subsample 1, $\sigma^2_{\rm rms}$ appears to depend weakly on the black hole mass, whereas it depends more strongly on the X-ray luminosity. Due to the small sample, the difference between values of A and B are not very significant (they are coincidental within the 95% confidence interval). However, if subsample 2 is included, the dependence on the black hole mass is strengthened and the goodness of the regression decreases dramatically. The value of the total χ^2 of the subsamples is 139 (27); therefore, the probability of improvement by chance is only about 10^{-9} (obtained by F-test). Thus, the above results indicate that subsamples 1 and 2 are likely to obey different correlation relationships and it is not appropriate to combine them into one sample.

2.3. K–S tests

To investigate whether the two subsamples are drawn from the same parent distribution, we first performed the 1D K–S test on them. We first calculated the cumulative distribution functions of the two samples. Then, we used the maximum value of the absolute difference between two cumulative distribution functions as the statistic to obtain the significance of the difference (see details of the K–S test in Press et al. 1992). The significances of the differences are 89%, 25%, and 96% for the distributions of the black hole mass, the luminosity, and $\sigma^2_{\rm rms}$, respectively (the cumulative distribution functions are shown in Fig. 3). Clearly, except for the X-ray luminosity distribution, both the black hole mass and $\sigma^2_{\rm rms}$ for the two subsamples are not likely to be drawn from the same parent population. There is no obvious reason for the differences. Therefore, this result is likely due to some unknown selection effects, which should be investigated further in the future.

Since it seems visually that the difference between the distributions of subsample 1 and subsample 2 in Fig. 1b is more significant than that in Fig. 1c, we perform the 2D K–S test to

Table 1. Results of partial correlation analysis.

	$r_{L\,\sigma}$	$r_{M\,\sigma}$	$r_{L\,\sigma.M}$	$r_{M\,\sigma.L}$
Full sample	–0.636 (>99.99%)	–0.697 (>99.99%)	–0.277 (87.6%)	–0.452 (99.1%)
Subsample 1	–0.856 (>99.99%)	-0.560 (98%)	–0.781 (>99.99%)	–0.003 (0.8%)
Subsample 2	–0.605 (98.7%)	–0.784 (>99.99%)	0.238 (60.8%)	–0.653 (99.2%)

Table 2. Results of ordinary least-squares regression. The significance of the linear correlation is obtained by the *F* statistic. The value of χ^2 is calculated from the regression result to estimate the goodness of the regression. The errors corresponding to 95% confidence intervals are shown.

	A	*B*	*C*	*F* statistic	χ^2 (d.o.f.)
Full sample	–0.38 ± 0.28	–0.22 ± 0.30	10.4 ± 11.4	16.6 (>99.99%)	708.6 (30)
Subsample 1	0.00 ± 0.45	–0.71 ± 0.33	28.3 ± 12.2	19.2 (>99.99%)	46.4 (14)
Subsample 2	–0.56 ± 0.39	0.19 ± 0.45	–6.06 ± 17.3	11.4 (99.86%)	92.6 (13)

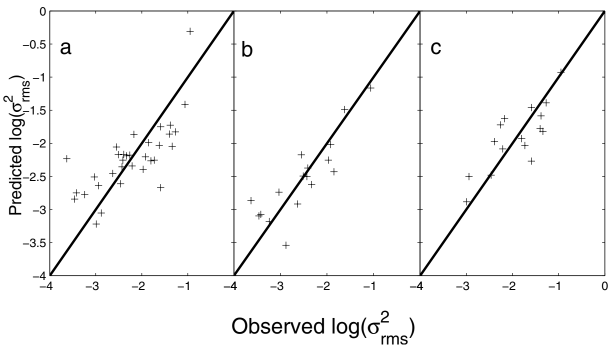

Fig. 2. The comparison between the values of $\sigma^2_{\rm rms}$ predicted by the results of the regression and the observed values. The results from the full sample are shown in **a)**. **b)** The same as **a)** but for the subsample 1. **c)** The same as **a)** but for the subsample 2.

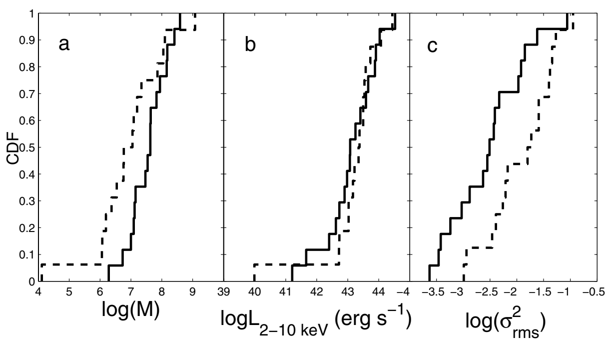

Fig. 3. The cumulative distribution functions (CDF) of the black hole mass **a)**, the X-ray luminosity **b)** and $\sigma^2_{\rm rms}$ **c)**. The solid lines are the data of the subsample 1, and the dashed lines are the data of the subsample 2. The value of black hole mass is in units of $M_\odot$.

investigate this problem. The results of the 2D K-S test show that the significance of the difference in Fig. 1b is 89.4%, whereas significance of the difference in Fig. 1c is 97.6%. This unexpected result is due to the existence of the point of NGC 4395. After this point is removed, the 2D K–S test results of Fig. 1b and c are 96.5% and 92.1%, respectively. Although the significance of the difference in each figure is high, the visual difference between two the figures is not significant.

3. Discussions and conclusions

In Sect. 2, we have performed partial correlation analysis and regression on the sample, and found that the apparent intrinsic correlation between $\sigma^2_{\rm rms}$ and the black hole mass is likely to be caused by including subsample 2 in the analysis. Because the black hole masses of AGNs in subsample 2 were estimated from their optical luminosity, which in turn is positively correlated with their X-ray luminosity, an extra correlation between the black hole mass and X-ray luminosity will be introduced by subsample 2. If the X-ray luminosity is the primary quantity, then this will artificially strengthen any correlation with black hole mass. We, therefore, should exclude them when investigating the intrinsic correlation with $\sigma^2_{\rm rms}$. According to the results from the subsample 1, we conclude that the correlation between $\sigma^2_{\rm rms}$ and the X-ray luminosity may be the intrinsic one, whereas the apparent correlation between $\sigma^2_{\rm rms}$ and the black hole mass is doubtful. Our K-S tests also suggest that subsamples 1 and 2 are not likely drawn from the same parent population.

As discussed in Lu & Yu (2001), several mechanisms may be responsible for the correlation between $\sigma^2_{\rm rms}$ and the X-ray luminosity, such as the hot-spot model, the obscurative variability, and so on. After the apparent correlation between $\sigma^2_{\rm rms}$ and the black hole mass was discovered, some models accounting for this correlation were proposed (e.g. O' Neill et al. 2005; Pessah 2007). However, it needs to be verified whether the correlation is intrinsic. Although the black hole masses of about three dozen AGNs have been determined by the reverberation mapping method, the size of our sample is still limited due to the lack of long-duration, high-quality observation data of these objects. More conclusive results could be obtained when more and higher quality data become available.

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