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QUASAR OPTICAL VARIABILITY AND BLACK HOLE MASS

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RESUMEN

Para investigar la dependencia de la variabilidad óptica-UV de cuásares con respecto a parámetros físicos fundamentales como la masa del agujero negro, hemos empatado cuásares de la exploración de variabilidad QUEST1 con objetos de líneas-anchas del SDSS. A partir de espectros de Sloan y de magnitudes de variabilidad de las curvas de luz de QUEST1 se estiman las masas y las luminosidades bolométricas de los agujeros negros. Las amplitudes de variabilidad de largo período (en el sistema en reposo, las escalas temporales son de 0.5–2 años) se encuentran correlacionadas con la masa del agujero negro a un nivel significativo del 99% ó mejor. Esto significa que los cuásares con agujeros negros más masivos tienen un porcentaje mayor en sus variaciones de flujo. Un análisis de correlación de rango parcial muestra que la correlación no puede ser explicada por efectos obvios de selección inherentes en muestras limitadas por flujo. Discutimos si la correlación es una manifestación de una relación entre la masa del agujero negro y las escalas temporales en el disco de acreción térmicas, ó si es debida a cambios en la profundidad óptica del disco de acreción con la masa del agujero negro. Tal vez la explicación más adecuada es que los agujeros negros más masivos estan hambrientos, y producen grandes variaciones en su flujo porque no tienen una caída constante de combustible gaseoso.

ABSTRACT

In order to investigate the dependence of quasar optical-UV variability on fundamental physical parameters like black hole mass, we have matched quasars from the QUEST1 variability survey with broad-lined objects from the SDSS. Black hole masses and bolometric luminosities are estimated from Sloan spectra, and variability amplitudes from the QUEST1 light curves. Long-term variability amplitudes (rest-frame time scales 0.5–2 yrs) are found to correlate with black hole mass at the 99% significance level or better. This means that quasars with larger black hole masses have larger percentage flux variations. Partial rank correlation analysis shows that the correlation cannot be explained by obvious selection effects inherent to flux-limited samples. We discuss whether the correlation is a manifestation of a relation between BH mass and accretion disk thermal time scales, or if it is due to changes in the optical depth of the accretion disk with black hole mass. Perhaps the most likely explanation is that the more massive black holes are starving, and produce larger flux variations because they do not have a steady inflow of gaseous fuel.

Key Words: quasars: general

1. INTRODUCTION

Variability is a characteristic property of quasars. It is non-periodic in nature and shows erratic behavior. Optical-UV variability (in unbeamed quasar continua) occurs on time scales of days to decades, with fluctuations typically a few tenths of a magnitude, increasing at longer time scales. Variability is recognized as an important diagnostic of the physical processes responsible for black hole activity. It is also important as the only method by which the smallest physical scales in AGN can be resolved. The behavior of quasar optical variability with luminosity and redshift is well understood (see Vanden Berk et al. 2004, and references therein), but the real cause of the fluctuations remain opaque. In order to shed light on the origin of quasar variability, relationships between variability and AGN fundamental parameters, such as black hole mass and Eddington ratio, may be investigated. Here we describe a study that correlates quasar long-term variability with BH mass. Details are provided by Wold, Brotherton, & Shang (2007).

2. SAMPLE SELECTION

We form a sample of 104 quasars by matching broad emission line objects in the SDSS DR2 (Abazajian et al. 2004) with sources in the 200k Light Curve Catalog of the QUEST1 variability survey (Rengstorf et al. 2004). Redshifts were constrained to $z < 0.75$ to keep the redshifted Hβ line within the spectral coverage of the SDSS, and to

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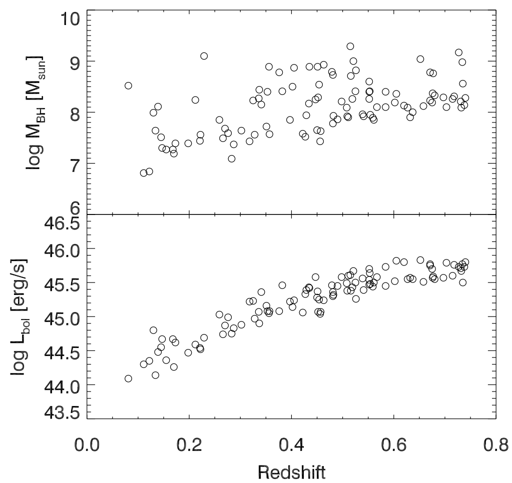

Fig. 1. BH mass and bolometric luminosity as a function of redshift for the SDSS-QUEST1 sample.

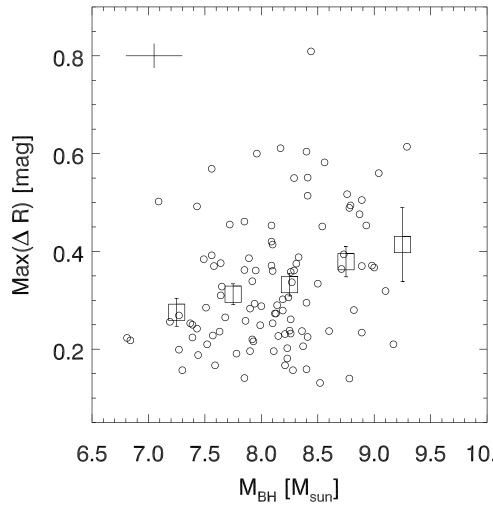

Fig. 2. Variability amplitude as a function of BH mass. The mean amplitude in five different BH mass bins is over-plotted as squares.

limit time dilation effects. From single epoch Sloan spectra we estimate virial BH masses using the Hβ line width and the rest-frame quasar luminosity at 5100 Å following the scaling relationships of Vestergaard & Peterson (2006). The bolometric luminosity of each quasar is evaluated as $L_{\rm bol} = 9 \times \lambda L_{\lambda 5100}$ and the Eddington luminosity as $L_{\rm Edd} = 1.51 \times 10^{38}$ $M_{\rm BH}/M_{\odot}$ erg s^{-1}. Black hole mass and $L_{\rm bol}$ are plotted as a function of redshift in Figure 1.

2.1. *Variability measurements*

Quasar variability is characterized by computing the distribution of all possible variability amplitudes (i.e. magnitude differences) on the quasar light curves, $\Delta m_{ij} = m_i - m_j$, where $i < j$. The variability of one quasar is described by the standard deviation, mean, median and/or maximum of its distribution of Δm (e.g., Giveon et al. 1999). In Figure 2 we show the maximum variability amplitude for every quasar as a function of BH mass, and an increasing trend of variability with BH mass is seen. Sources displaying the largest variability amplitudes have on average higher BH masses. The correlation is also illustrated in Figure 3, where it can be seen that most of the variability is detected at longer time scales.

3. VARIABILITY-BH MASS CORRELATION

Pearson correlation analysis shows that the correlation between BH mass and variability is significant at the $\approx 3\sigma$ level. The strongest correlation is measured between BH mass and maximum variability (correlation coefficient 0.285 and a two-sided probability of arising by chance of 0.3%). Other measures of variability have qualitatively similar, but

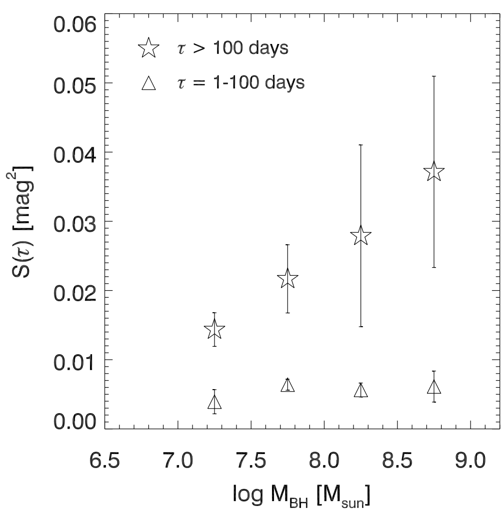

Fig. 3. BH mass versus the structure function, $S(\tau)$, which measures how variability is distributed over rest-frame time scale τ, here for time scales 1–100 and > 100 days (up to ≈2 years for the SDSS-QUEST1 sample).

somewhat less significant correlations with BH mass. There are no significant correlations detected between variability and Eddington ratio, $L_{\rm bol}/L_{\rm Edd}$, possibly because of the small sample size. The Eddington ratio is clearly an interesting parameter to correlate with variability as it measures whether variability is related to how effectively the quasar converts accreted matter into luminosity (assuming a standard optically thick accretion disk as described by e.g. Shakura & Sunyaev 1973).

3.1. *Selection effects*

The variability-BH mass correlation could be caused by more primary correlations with redshift and luminosity as these are known to correlate with variability (e.g. Vanden Berk et al. 2004). For instance, higher-z quasars in the SDSS-QUEST1 sample are biased toward higher BH masses (Figure 1). A correlation between variability and BH mass could therefore be produced if underlying correlations existed between variability and z (or between variability and $L_{\rm bol}$). But Spearman's partial correlation analysis shows that this is not very likely, e.g., the correlation coefficient between variability and BH mass, at constant z, is 0.203 with a probability of 0.0035 of being caused by underlying trends with z. Similarly, Spearman's partial correlation coefficient between variability and BH mass, at constant $L_{\rm bol}$ is 0.254 with a probability of 2×10^{-4} occurring because of underlying correlations with $L_{\rm bol}$.

Can contamination by residual host galaxy light in the spectra artificially enhance a correlation between variability and BH mass? Residual host galaxy light may dilute the variability and would be a potential problem only for the lower-luminosity quasars. However, only very few spectra display clear host galaxy features, and these were treated extra carefully during the spectral fitting. The variability-BH mass correlation is also present within a sub-sample of higher-luminosity quasars which are not expected to suffer from host contamination. Hence we conclude that although host contamination could artificially enhance the correlation, it is a weak effect and unlikely to be important.

Finally, could the correlation be caused by time sampling effects? The best-sampled rest-frame time scale in the QUEST1 survey is 1–2 years and this is also where most of the variability is detected (Rengstorf et al. 2006; Wold et al. 2007). Figure 3 shows that the variability at shorter time scales (1–100 days) corresponds to the noise level in the data (≈ 0.06 mag), but that the variability at longer time scales is *intrinsic* to the quasars. Hence there is a bias toward detecting intrinsic quasar variability only at longer time scales. If a relation between BH mass and variability time scale exists, this may lead to a preference for detecting variability only for quasars with higher BH masses. And quasars with lower-mass BHs would have fluctuations at or below the noise level, thus producing a variability-BH mass correlation. There are certainly arguments that characteristic variability time scale (such as accretion disk thermal time scale) may depend on BH mass (e.g. Collier & Peterson 2001), but this is still controversial and far from established.

4. DISCUSSION

We conclude that there is evidence for a correlation between the BH mass of a quasar and its optical long-term (0.5–2 yrs) variability properties. Quasars with more massive BHs tend to show larger variability amplitudes, i.e., quasars with larger BH masses have larger percentage flux variations. Our favored explanation is that the correlation is real and not caused by selection effects.

But what is its origin? Higher-mass BHs are more likely to be starving than those of lower mass. This is because higher-mass BHs must have swallowed more of their surroundings in order to have grown to their larger masses. Hence the larger flux variations for the more massive BHs could indicate that the BH is running out of gaseous fuel. Because there is not a steady inflow of gaseous fuel from the surroundings, larger fluctuations in the continuum is seen.

The correlation could also be explained in terms of optical depth of the accretion disk. This can come about if the more massive BHs have accretion disks with larger optical depths than those of lower mass. A large optical depth indicates radiatively more efficient accretion, hence any changes in the energy generation mechanism will be more easily transmitted through an optically thick disk.

No significant correlations or anti-correlations could be detected between Eddington ratio and variability, probably because redshift and luminosity effects are difficult to disentangle in this sample. A larger sample, or a sample spanning a longer time base line, is needed to confirm the general robustness of the variability-BH mass correlation.

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