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Reverberation Mapping of High-redshift, High-luminosity Quasars

S. KASPI[1], H. NETZER[1], D. MAOZ[1], O. SHEMMER[1], W. N. BRANDT[2], and
D. P. SCHNEIDER[2]
(1) School of Physics and Astronomy, Tel-Aviv University, Tel-Aviv, Israel
(2) The Pennsylvania State University, University Park, Pennsylvania, USA

Abstract

Current reverberation mapping studies and mass determinations exist for Active Galactic Nuclei (AGNs) with λL_λ(5100Å) luminosity up to 10^{46} ergs s^{-1}. To further extend our knowledge to higher luminosity quasars (up to 10^{48} ergs s^{-1}), we are undertaking a monitoring program of high-redshift ($2 < z < 3.4$) quasars. Monthly photometric observations were taken over the past 8 years of a sample of 11 quasars, and 7 of them were monitored spectrophotometrically over the past 2.5 years. The observations are carried out at the Hobby-Eberly Telescope and at the Wise Observatory. We present preliminary results from this monitoring program which is aimed at measuring the masses of the most massive black holes in the Universe. So far we do not detect line variations due to the long timescales involved. We find that the continua of the high-luminosity quasars have smaller variability amplitudes and longer variability timescales than low-luminosity AGNs.

1.1 Introduction

While the origin of Active Galactic Nuclei (AGNs) continuum variability is still unclear, it is possible to use reverberation mapping to study their emission-line gas. In such studies, the time lag between the variations in the continuum flux and the emission-lines flux is used to estimate the Broad Line Region's (BLR) size and to map its geometry (Netzer & Peterson 1997).

In the past decade 20 low-luminosity AGN (Seyfert 1 galaxies) were spectrophotometrically monitored and their BLR sizes were measured (e.g., Wandel, Peterson & Malkan 1999; Onken et al. 2003). Kaspi et al. (2000) measured, using the reverberation mapping technique, the BLR sizes of 17 high-luminosity AGN (quasars) and increased the luminosity range of objects with known BLR size by two orders of magnitude.

Kaspi et al.'s study (combined with the data from the previous studies) determined for the first time the size–mass–luminosity relations in an AGN sample over a luminosity range of 5 orders of magnitude (10^{41}–10^{46} erg s^{-1}): $R \propto L^{0.70\pm0.03}$, $M \propto L^{0.5\pm0.1}$, where L is the rest-frame 5100 Å luminosity, R is the BLR size implied from reverberation mapping of Balmer lines, and M is the AGN's central mass.

However, the current sample of AGN which have reverberation data is luminosity and redshift limited because of the small size of the telescopes used. In order to increase the luminosity range to above 10^{46} erg s^{-1} we need to monitor high-redshift, high-luminosity quasars. Continuum variability of such quasars has been studied in the past to a limited extent, but very little is known about their emission-line variability. A few of the many open questions are: Do higher luminosity quasars' emission lines respond to continuum changes, as seen in the lower luminosity ones? What is the relative amplitude of the response? What is the time-lag of the response? Does the scaling of quasars' BLR-sizes and masses with luminosity remain the same in higher luminosity quasars?

1.2 Ongoing Monitoring

For the past 8 years we have been monitoring photometrically a sample of 11 high-redshift ($2.1 \lesssim z \lesssim 3.2$) high-luminosity ($10^{45.6} \lesssim \lambda L_\lambda(5100\text{Å}) \lesssim 10^{47}$ erg s^{-1}) quasars (Table 1.1). The sample was chosen from the Veron-Cetty & Veron 5th. catalog based only on observational criteria (limits on redshift, declination, observed luminosity, etc.). The observations are carried out every month at the Wise Observatory 1 m telescope using broad-band filters (B & R); thus we have good coverage of the continuum variability.

For the past 2 years we have monitored part of this sample spectroscopically with the 9 m Hobby-Eberly Telescope (HET; Ramsey et al. 1998) and the Wise Observatory telescope to check for the line (Lyα and C IV λ1549) responses to the continuum variations. The method used is to observe a comparison star with the quasar simultaneously in the spectrograph's slit. Observations for each object are done about once every two months when possible.

1.3 Preliminary Results

The continuum light curves of the objects in our sample are shown in Figure 1.1. Most of the objects show continuum variations of about 10% peak-to-peak. Combining our data with data from monitoring lower luminosity AGNs we confirm two trends: (1) high-luminosity AGNs have longer variability time scales (2) higher luminosity AGNs have

Table 1.1. *The sample*

Object name (1)	m_V (2)	z (3)	$\lambda L_\lambda(5100\text{Å})$ (4)	std(L)/$\overline{\text{L}}$ (5)	$(\Delta t)_{campaign}$ (6)
S5 0014+81	16.5	3.387	806.4	3.1	757
S5 0153+74	16.0	2.338	48.2	3.6	757
S4 0636+68	16.6	3.177	762.9	3.5	638
S5 0836+71	16.5	2.172	112.1	12.8	588
TB 0933+733	17.3	2.525	392.9	4.4	756
SBS 1116+603	17.5	2.628	137.1	5.7	712
SBS 1233+594	16.5	2.824	417.2	4.1	675
SBS 1425+606	16.5	3.200	922.9	2.4	607
HS 1700+6416	16.1	2.722	1065.2	3.4	714
HS 1946+7658	15.8	3.051	1105.2	3.8	822
S5 2017+74	18.1	2.191	51.0	7.5	772

Notes: Col.(1): QSO name. Col.(2): V magnitude from Veron 7th. catalog.
Col.(3): Redshift from Veron 7th. catalog. Col.(4): Rest-frame $\lambda L_\lambda(5100\text{Å})$ in units of 10^{44} ergs s^{-1} computed from the published flux at 1450 Å (rest frame) and using a power law of $\nu f_\nu \propto \nu^{-0.5}$. Col.(5): Standard deviation of the R-band continuum light curve over the mean (computed after converting the R magnitudes to fluxes).
Col.(6): Rest-frame period of the campaign in days.

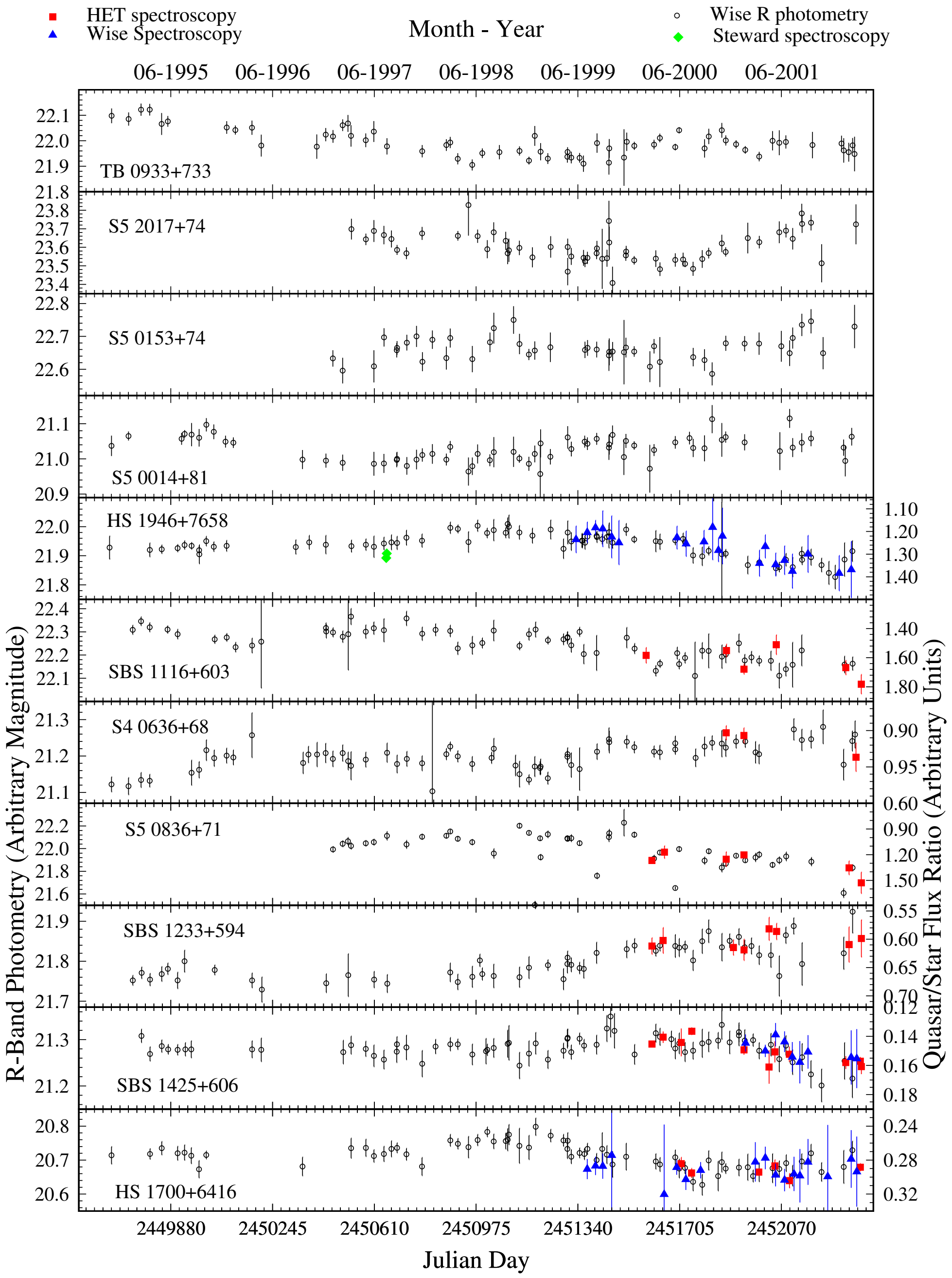

Fig. 1.1. Continuum light curves of the high-luminosity quasars. Black circles are data obtained from R-band photometry at the Wise Observatory and span over eight years. The $\approx$ 0.1 magnitude variations are apparent in all objects. In S5 0836+71 the variation is $\approx$ 0.3 magnitude. Red squares are data obtained from HET spectra, and blue triangles are data obtained from Wise spectra over the past 2–3 years. One data point (marked with green) was taken at Steward Observatory during 1997 and it fits the continuum light curve since it used the same comparison star which was used two years later at Wise.

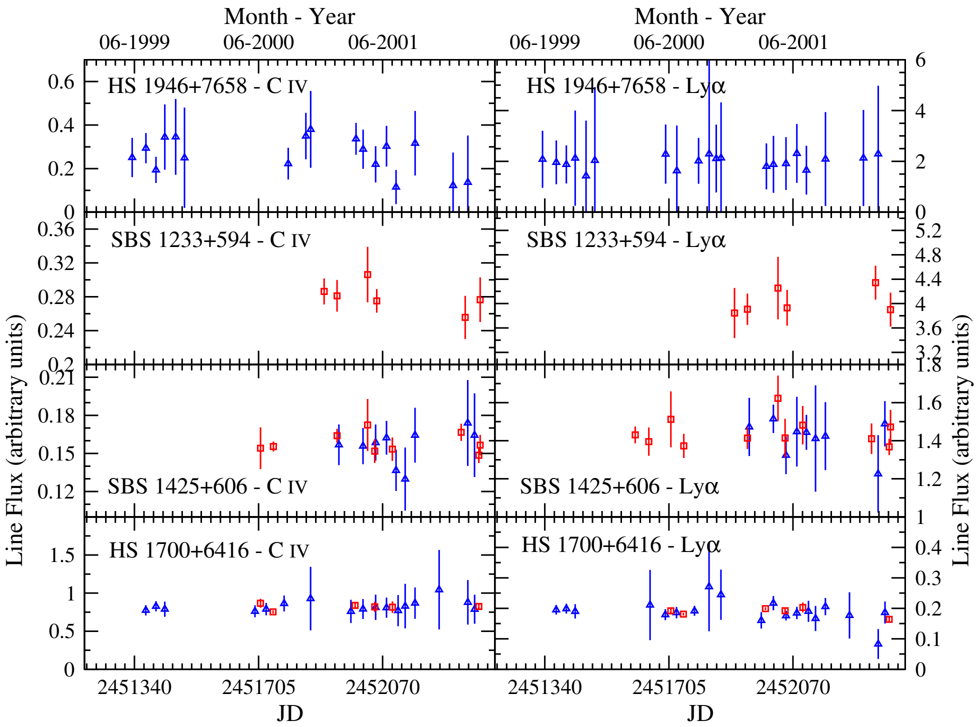

Fig. 1.2. Light curves for C IV and Lyα for several objects. Blue triangles are data from Wise. Red squares are data from the HET. No line variations are detected in the data.

smaller variability amplitudes. Since the rest-frame monitoring period (column 6 in Table 1.1) of the high-luminosity quasars is relatively short most objects seem not to have reached their maximum variability yet.

First results from the spectroscopic monitoring are also shown in Figure 1.1. The spectroscopy data are represented by the quasar/star flux ratios which were shifted and stretched to fit the R-band photometry light curves. For most objects (in particular HS 1700+6416, SBS 1425+606, and S5 0836+71) the **shapes** of the light curves from the two data sets are similar. This confirms the continuum variability of the objects and serves as a check for the reality of the continuum variability.

Although we find continuum variations in our sample of 11 quasars, no line variations are yet detected (Figure 1.2); currently we estimate our typical upper limit for line variability to be $\lesssim 25\%$. This is not surprising since these high-luminosity quasars are expected to have BLR sizes of order of 3 light years which corresponds in our observed frame to about a decade (Figure 1.3). Using the $R_{BLR} \propto L^{0.7}$ relation derived from Balmer lines reverberation mapping, we find the Balmer lines BLR size to be of order 3 light years in the rest frame. The UV lines (e.g., C IV) which we monitor, show a smaller BLR size by a factor of roughly 2–3 (e.g., Peterson & Wandel 2000). Hence, reverberation mapping can be feasible in a decade monitoring. We also need to observe a significant variability in the continuum in order for the lines to respond. Since the variability amplitude increases with the monitoring period (Shemmer et al. in preparation) we should be able to detect line variations. When

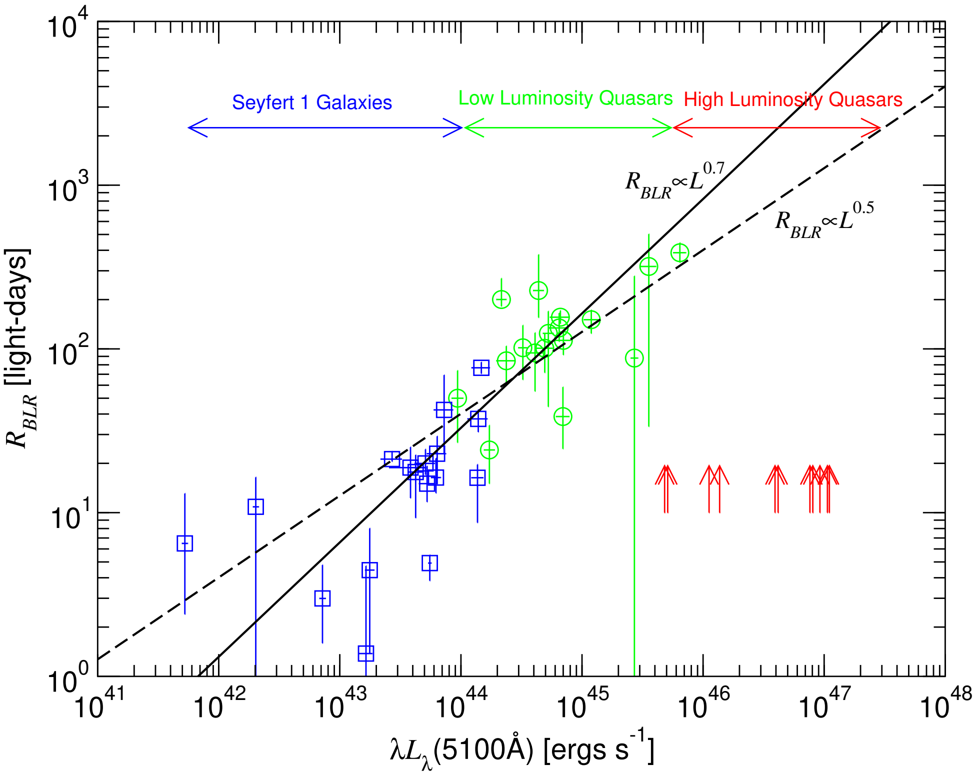

Fig. 1.3. BLR size – Luminosity relation adopted from Kaspi et al. (2000). Red arrows mark the luminosities of the 11 objects in our sample.

this long-term project is concluded, reverberation studies will cover the luminosity range of 10^{41}–10^{47} ergs s^{-1}, 1.5 orders of magnitude more than the current luminosity range.

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References

Kaspi, S., Smith, P. S., Netzer, H., Maoz, D., Jannuzi, B. T., & Giveon, U. 2000, ApJ, 533, 631

Netzer, H., & Peterson, B. M. 1997, ASSL Vol. 218: Astronomical Time Series, ed. D. Maoz, A. Sternberg, & E.M. Leibowitz (Dordrecht: Kluwer), 85

Onken, C. A., Peterson, B. M., Dietrich, M., Robinson, A., & Salamanca, I. M. 2003, ApJ, 585, 121

Peterson, B. M., & Wandel, A. 2000, ApJ, 540, L13

Ramsey, L. W., et al. 1998, SPIE, 3352, 34

Wandel, A., Peterson, B. M., & Malkan, M. A. 1999, ApJ, 526, 579