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Results From Five Years of Spectrophotometric Monitoring of 28 Palomar-Green Quasars

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Abstract. We present 5 years of results from a spectrophotometric monitoring program of 28 quasars. The typical sampling intervals are several months. We show the light curves obtained for two quasars, PG 0804+762 and PG 0953+414. Both sources show Balmer emission-line variations which follow those of the continuum with a time lag of order 100 days. This is the first reliable measurement of such a lag in active galactic nuclei with luminosity $L > 10^{45}$ erg s^{-1}. The broad-line region (BLR) size that is implied is almost an order of magnitude larger than that measured in several Seyfert 1 galaxies and is consistent with the hypothesis that the BLR size grows as $L^{0.5}$.

1. Introduction

Reverberation mapping has became one of the major tools for studying the distribution and kinematics of the gas in the broad-line region (BLR) of active galactic nuclei (AGNs). During the past decade a few tens of Seyfert 1 spectroscopic monitoring campaigns were carried out and about a dozen of them produced high-quality data amenable to reverberation-mapping techniques, mainly cross-correlation. Those campaigns determined the BLR size in Seyfert galaxies to be of order of light-days to light-weeks. On the other hand, only few spectroscopic campaigns were carried out on quasars, the high-luminosity end of the AGN phenomenon, and few of them produced high-enough quality data (see, e.g., Zheng et al. 1987, Jackson et al. 1992, and the review by D. Maoz in these proceedings). The BLR size in quasars is therefore still unknown. The main goal of the study presented here is to apply reverberation mapping to quasars in the manner that has been applied to Seyfert 1 galaxies in the past years.

Since mid-1991, we have been monitoring a well-defined sub-sample of 28 quasars from the Palomar-Green (PG) sample (Schmidt & Green 1983) with typical sampling intervals of 1–4 months. The sample's observed magnitude range is from 13 to 16 mag, the redshift range is from 0.06 to 0.38, and the luminosity[2], L, covers about 2 orders of magnitude, from 4×10^{44} to 3×10^{46} erg s^{-1}. The

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[2]Determined between 0.1–1 μm by assuming a power-law ($f_\nu \propto \nu^{-\gamma}$) continuum normalized at the observed optical flux ($H_0 = 75\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$, $\gamma = 0.5$).

sample and results of the first 1.5 years were presented in Maoz et al. (1994) where it was shown that most quasars had undergone continuum variations in the range of 10–70%. Balmer-line variations that are correlated with continuum changes were detected in several objects. In the following, we present 5 years of data for two radio-quiet quasars from our sample, PG 0804+762 ($z = 0.1$, $L \approx 2 \times 10^{45}$ erg s^{-1}) and PG 0953+414 ($z = 0.239$, $L \approx 5 \times 10^{45}$ erg s^{-1}). For more details, see Kaspi et al. (1996).

2. Observations and Analysis

The observations were carried out at the Steward Observatory 2.3-m telescope and the Wise Observatory 1-m telescope. For each quasar, the spectrograph was rotated to the appropriate angle in order to observe it simultaneously with a nearby comparison star within the slit. The quasar spectrum is flux calibrated relative to that of the comparison star. This technique provides excellent calibration of the quasar's relative flux even during poor weather conditions. Accuracies of order 1–2% can be achieved and variation of 5% can be easily detected.

We also carried out monthly broad-band CCD photometry at the Wise Observatory. This provided additional epochs for the continuum light curve, and was used to verify the non-variability of the comparison star.

Figure 1 shows light curves for our best-sampled object, PG 0804+762. The continuum light curve shows about 40% variability ($F_{max}/F_{min} - 1$) and the emission-line light curves, Hα and Hβ, show 18% variability. The line variations lag behind the continuum and the 'smearing' effect expected from an extended BLR is detected.

Figure 2 shows light curves for PG 0953+414, which has the typical sampling of our program. Here the continuum variations are 35% and the line light curves for Hβ and Hγ follow the continuum variations with an amplitude of order of 15%.

We have used two methods for correlating the first 4 years of the Hβ light curve with the continuum: the partly interpolated cross-correlation (Gaskell 1994) and the z-transform discrete correlation (Alexander 1996). The results from both methods agree well, and a centroid fit to the cross-correlation function peak yields time-lags of 93 days for PG 0804+762 and 111 days for PG 0953+414. Monte-Carlo simulations (Maoz & Netzer 1989) give time-lag error estimates of ±30 days and ±55 days, respectively.

These time lags are about an order of magnitude larger then the time lags measured for Seyfert 1 galaxies. In Fig. 3, we plot the relationship between the radius of the BLR, R_{BLR}, and L for all studied AGNs where a significant correlation of the Balmer lines and the continuum light curves has been detected. The values of R_{BLR} are the means of values for the time lag, taken from different studies and corrected by a $(1+z)^{-1}$ factor. Caution must be taken when interpreting the diagram, since each study has used its own method to deduce R_{BLR} and its uncertainty. For the Seyfert nuclei ($\log\ L < 44.5$) alone there is no clear correlation given the narrow luminosity range sampled. Adding the results from the present study introduces the first clear trend, and indicates that R_{BLR} may scale with L with the expected theoretical slope of 0.5.

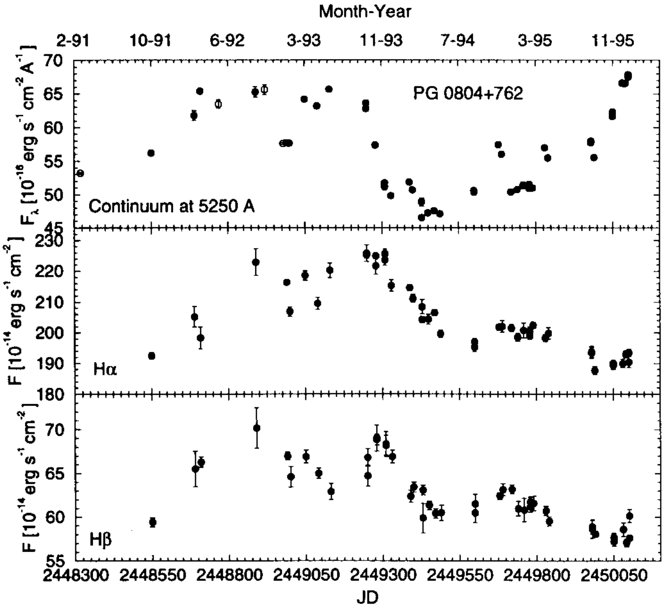

Figure 1. PG 0804+762 light curves. *Top:* Continuum flux density at 5244 Å. *Middle:* Hα emission-line flux. *Bottom:* Hβ. Filled circles are spectrophotometric measurements from Wise and Steward Observatories. Open circles are B-band photometric measurements from Wise Observatory.

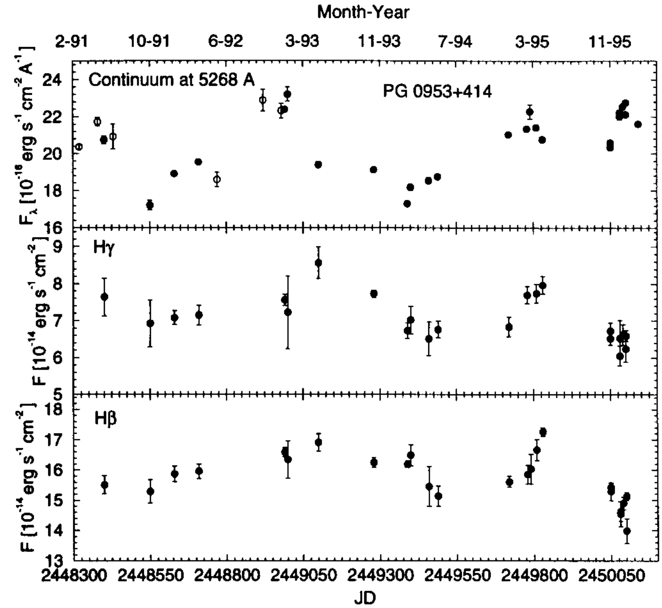

Figure 2. PG 0953+414 light curves. *Top:* Continuum at 5268 Å. *Middle:* Hγ. *Bottom:* Hβ. Symbols as in Fig. 1.

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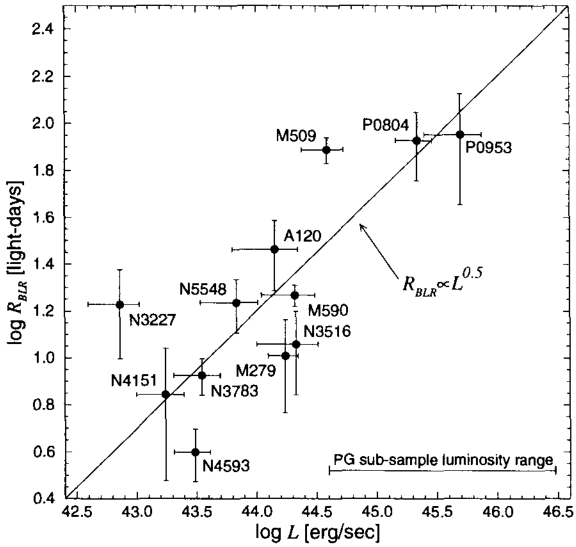

Figure 3. The BLR radius–luminosity relationship. All sizes based on Balmer-line lags. See references in Kaspi et al. (1996).

In our sample of 28 objects, we currently have about 10 objects which have shown continuum and line variations, and their light-curve sampling is as good as the ones shown here. Once we analyze these light curves, we will be able to add about 10 more points to the high-luminosity region of Fig. 3, about the same number of points as we currently have in the low-luminosity region. Thus we will be able to determine the relation between R_{BLR} and the luminosity. By using line-profile information we can then derive a mass-luminosity relation for AGNs.

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