Extending the Eigenvector 1 Space to the Optical Variability of Quasars

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ABSTRACT

We introduce a new physical parameter, the optical variability amplitude, to the well-established Eigenvector 1 space of quasars and test a sample of long-term B-band light curves of 42 PG quasars monitored by Giveon et al. (1999). We find that the optical variability amplitude strongly correlates with the intensity ratio of Fe II to H$\beta$, H$\beta$ width and peak luminosity at 5007 Å. We briefly discuss the physical meaning of our findings and suggest that the Eddington ratio may be a key factor in determining a quasar’s variability.

Subject headings: galaxies: active — quasars: general

1. Introduction

During the last few decades, quasars have been monitored in multi-wavelength observations, from radio to X-rays, by many research programs. Our understanding of the central engine of quasars has been greatly improved by the correlations found between the variability properties and other observational parameters (e.g., luminosity, redshift, rest-wavelength, timescales and emission-line width). An anticorrelation between the amplitude of variability and luminosity was reported by Pica & Smith (1983), and confirmed by many subsequent studies (e.g., Cristiani et al. 1990; Hook et al. 1994; Cristiani et al. 1997; Giveon et al. 1999 (hereafter G99); Garcia et al. 1999; Vanden Berk et al. 2004), although there have also been reports to the contrary (e.g., Trevese et al. 1989; Giallongo et al. 1991; Cimatti et al. 1993). The relationship between the variability amplitude and redshift was discussed...
in many studies. Some authors found that the variability amplitude is anticorrelated with redshift (e.g., Barbieri et al. 1983; Cristiani et al. 1990; Hook et al. 1994; Cristiani et al. 1996), while others reported an opposite trend (e.g., Giallongo et al. 1991; Treverse et al. 1994; Cid Fernandes et al. 1996). Moreover, it was found that the optical spectra usually become harder as quasars turn brighter (Cutri et al. 1985; G99). Kollatschny et al. (2006) examined the variability properties of a sample of 10 Palomar-Green quasars with the line width of $H\beta$ larger than 5000 km $s^{-1}$. They found a marginal correlation between the optical continuum variability amplitude and $H\beta$ line width, which provides useful information for understanding the structure of BLR.

On the other hand, Boroson & Green (1992; hereafter BG92) examined a sample of 87 bright low redshift PG quasars and found that most of the variance is connected to two sets of correlations, which were then defined as Eigenvector 1 (hereafter E1) space and Eigenvector 2 space. The E1 space is dominated by the strong anticorrelation between the optical FeII and [OIII], and Eigenvector 2 by the correlation between the optical luminosity and HeII equivalent width (see Sulentic et al. 2000a for a review). By calculating the virial black hole mass ($M_{\text{BH}}$) using the well established empirical $R-L$ relationship (e.g., Kaspi et al. 2000), Boroson (2002) suggested that the E1 space is dominantly driven by the Eddington ratio $L/L_{\text{Edd}}$, and the Eigenvector 2 by $M_{\text{BH}}$ (see also in Sulentic et al. 2000b).

In this paper, we will investigate whether the quasar’s optical variability amplitude is related with the E1 space. We test a sample of 42 PG quasars. The paper is structured as follows. The sample selection and our analysis are described in Section 2. The results are presented in Section 3, and discussions in Section 4. Throughout this paper, the ΛCDM cosmology (Spergel et al. 2003) with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70$ km $s^{-1}$ Mpc$^{-1}$ are adopted.

### 2. Sample and Analysis

We searched the literature for suitable results of quasars’ optical variability. In particular, the light curves should be well sampled in the temporal domain, with adequate total observation time and sampling interval. It is found that the G99 subset of the PG quasars is well suited for our purpose, because the optically selected PG quasars are not only nearly statistically complete but also studied comprehensively in multi-wavelength observations. G99 monitored 42 nearby ($z < 0.4$), bright ($B < 16$ mag) PG quasars in the B and R bands for a seven-year period at Wise Observatory. The typical temporal sampling interval was 40 days, and the objects were observed at 30-60 epochs with a photometry uncertainty of $\sim 0.01$ mag. All the objects showed intrinsic rms variability amplitudes of $5\% < \sigma_B < 34\%$. 
and $4\% < \sigma_R < 26\%$.

Our sample is listed in Table 1. Figure 1a shows the distribution of the redshifts for the sample listed in G99, see also Column (2) of Table 1. The redshifts of these PG quasars are mainly less than 0.2. Column (5) lists the variability amplitude in magnitude for each object. Furthermore, the variability amplitude can be statistically estimated in various ways. We refer the readers to G99 for a brief comment on these different methods. In the current study, the variability is defined as the median value of all possible magnitude difference of a light curve, simply because the median value is a relatively robust estimation, i.e., not strongly affected by the outliers (e.g., Hook et al. 1994, Netzer et al. 1996). Only the variability in the B band is considered in the subsequent analysis since the variability is more significant in the B band than in the R band. G99 examined the correlation between the variability amplitude defined by magnitude and quasar spectral properties defining the E1. However, no significant correlations were found by them. It should be pointed out that the variability amplitude defined in magnitude represents a relative change in luminosity. For a constant change defined in luminosity, a small (large) change in magnitude could be simply caused if the object is (less) luminous. In order to overcome this problem, the median of absolute change in luminosity is used in this paper, that is

$$\Delta L = L_{bol} \times (1 - 10^{-0.4\times|\text{median}(\Delta B)|})$$

where $\text{median}(\Delta B)$ is the median of variability in the B band and $L_{bol}$ the fiducial luminosity of the quasar. Note that $\Delta L$ is always positive according to this definition. $\Delta L$ represents the characteristic variability of each quasar in the absolute luminosity change, which directly reflects the absolute change of the amount of the fueling gas. Regarding two quasars with the same change in the $\text{median}(\Delta B)$, the one with a larger bolometric luminosity would have a larger $\Delta L$.

The bolometric luminosity can be estimated in two ways. First, we use an widely accepted empirical relationship

$$L_{bol} = 9\lambda L_{\lambda}(5100\text{Å})$$

as given by Kaspi et al. (2000), where the luminosities at the rest-frame wavelength 5100Å are adopted from Vestergaard & Peterson (2006). In another way, we also calculate the $L_{bol}$ from the median apparent magnitudes in the B band given by G99, using the formula

$$\log(L_{bol}/\nu_B L_{\nu_B}) = 0.80 - 0.067\mathcal{L} + 0.017\mathcal{L}^2 - 0.0023\mathcal{L}^3$$

of Marconi et al. (2004), where $\mathcal{L} = (\log L_{bol} - 12)$. A comparison of between the values of $L_{bol}$ obtained from Equation (2) and those from Equation (3) is made (see Figure 2). There is a strong correlation (with slope $\sim 1$) between the two sets of $L_{bol}$, indicating that the two
independent measurements are highly consistent with each other. So we adopt the value of $L_{bol}$ obtained from Equation (2), and then calculate the $\Delta L$ using Equation (1). The calculated $\Delta L$ in the logarithm is shown in Column (6) of Table 1 for each quasar.

3. Results

The main goal of the present paper is to investigate whether the variability amplitude of quasars is related to E1 space. The E1 space is dominated by significant correlations between RFe (=FeII/H$\beta$), FWHM(H$\beta$), and [OIII] strength, and has been discussed by many authors (e.g. BG92; Xu et al. 2003; Grupe 2004; Sulentic et al. 2000a). We list the E1 parameters of our PG quasar sample in Table 1. Column (7) gives the FWHM of the broad component of H$\beta$, Column (8) the ratio of the peak height of [OIII] $\lambda$5007 to that of H$\beta$ (Peak $\lambda$5007), Column (9) the ratio of the flux of FeII integrated in the rest frame wavelength range from $\lambda$4434 to $\lambda$4684 to that of H$\beta$ (RFe), Column (10) the logarithm of R, i.e., the ratio of radio flux at 6 cm to optical flux density. All of these parameters are adopted from BG92.

We then investigate the correlations between $\Delta L$ and E1 parameters in our sample. Figure 3 displays the correlations of $\Delta L$ versus FWHM(H$\beta$), peak $\lambda$5007, RFe, and the radio loudness log $R$, respectively. The spearman rank-ordered correlation coefficients $r_s$ of the four correlations are listed in Table 2, where $P_s$ is the probability of null correlation. Figure 3a shows a significant correlation between the $\Delta L$ and FWHM(H$\beta$). A spearman rank-ordered analysis yields a correlation coefficient $r_s=0.450$ with a significance level $P_s=0.004$. This means that the quasars with larger widths of H$\beta$ would have larger changes in luminosity. We also find a correlation between $\Delta L$ and peak $\lambda$5007 (Fig.3b, $r_s=0.445$, $P_s=0.004$). The anti-correlation between $\Delta L$ and RFe is plotted in Fig.3c. The calculated correlation coefficient is $r_s=-0.441$, and the significance level $P_s=0.005$. Kollatschny et al. (2006) did not find a significant correlation between the continuum variability amplitude at 5100Å and radio power at 5GHz in their sample. In current studies, a correlation ($r_s=0.476$, $P_s=0.0023$) is identified between the radio loudness log $R$ and $\Delta L$, and is shown in Fig.3d. Since log $R = 1$ is widely used to separate the radio-loud and radio-quiet quasars (Kellermann et al. 1989), the diagram shows that all the radio-loud quasars (log $R > 1$) have large optical variability amplitudes (log($\Delta L$) $> 45$), although the radio-quiet quasars (log $R < 1$) are nearly evenly distributed in terms of variability amplitude. The fact that radio-loud quasars have large variability amplitudes implies that the optical continuum of radio-loud quasars is contaminated by the high energy tail of their radio emissions, which boosts the variability amplitude because of the beam effect of the jets.

The correlations found above suggest that the E1 space could be extended to include
the variability amplitude. This hypothesis can be verified by a principal component analysis (PCA) of our sample. The PCA is performed using the following 11 parameters, which are: log $R$, the equivalent width of $\mathrm{H}\beta$, $R(\lambda 5007)$, $R(\lambda 4686)$, RFe, Peak($\lambda 5007$), FWHM($\mathrm{H}\beta$), $\mathrm{H}\beta$ shift, $\mathrm{H}\beta$ shape, $\mathrm{H}\beta$ asymmetry, and log($\Delta L$), each potentially providing unique information. Except for log($\Delta L$), the former ten parameters are directly collected from BG92. We refer the reader to BG92 for the definitions of these parameters. The PCA results are presented in Table 3, which lists the first four most significant eigenvectors. The second row shows the cumulative percentage of the variance. One can see that the first four eigenvectors together account for more than 70 percent of the variance, and that the first principal component dominates the observed properties of quasars. Similar to BG92, the E1 is dominated by the anticorrelation between the strength of FeII and Peak ($\lambda 5007$). In addition, our E1 is strongly effected by log($\Delta L$). It is clear that log($\Delta L$) has a projection of 0.54 on E1, and 0.57 on the Eigenvector 2. Although at first sight, the projection on Eigenvector 2 is larger than on E1, taking the larger cumulative percentage of the E1 into account, we conclude that the E1 space can be extended to log($\Delta L$).

4. Discussion

4.1. Variability vs. $M_{\text{BH}}$ and Eddington ratio

After extending the E1 space to the variability in amplitude, the dominant physical parameters are discussed in this section. Both of the black hole mass ($M_{\text{BH}}$) and Eddington ratio ($L/L_{\text{Edd}}$) are believed to be the main parameters governing the observed properties in quasars. However, the luminosity variability defined by Equation (1) cannot be used to correlate with $M_{\text{BH}}$ and $L/L_{\text{Edd}}$ because both $M_{\text{BH}}$ and $L/L_{\text{Edd}}$ are estimated in terms of the continuum luminosity which is used to define the variability in luminosity. The variability in magnitude $\text{median}(|\Delta B|)$ is therefore used instead in the subsequent analysis. All $M_{\text{BH}}$ values are adopted from Vestergaard & Peterson (2006). The distribution of $M_{\text{BH}}$ is shown in Figure 1b. One can see that the majority of log($M_{\text{BH}}/M_\odot$) lie between 7.5 and 9.5. $L_{\text{bol}}$ is then estimated using the Equation (2). The values of $M_{\text{BH}}$ and $L/L_{\text{Edd}}$ are listed in Column (3) and (4) in Table 1, respectively.

The relation between the variability amplitude and $M_{\text{BH}}$ or $L/L_{\text{Edd}}$ has been discussed recently. Contradictory results were, however, obtained by different authors. Wold et al. (2007) examined the relation between the quasar variability and black hole mass by studying the optical variability of $\sim$100 quasars monitored by QUEST1 survey (Rengstorf et al. 2004). However, a correlation between the R-band variability and $M_{\text{BH}}$ was marginally obtained only when $M_{\text{BH}}$ was averaged in several bins. Furthermore, they did not detect such a relation
in their PG quasar sample. In contrast, Wilhite et al. (2008) found a correlation between the variability and \( M_{\text{BH}} \) in a sample of \(~\!\sim\!\) 2500 quasars selected from the SDSS. In addition, they reproduced the well-known anti-correlation between the variability and luminosity. By combining the two relations, they suspected that \( L/L_{\text{Edd}} \) is a possible driver for quasar variability in an indirect way.

As \( M_{\text{BH}} \propto (\text{FWHM})^2 \), a possible way to test the correlation between variability and \( M_{\text{BH}} \) is to search for the correlation between the variability and line width, both of which are independent observational parameters. The relation between the variability amplitude and line width was discussed in several papers. G99 found a marginal correlation between the variability amplitude (defined in magnitude) and width of the H\( \beta \) emission line. Their possible, but unlikely explanation, for this trend is the contributions of the emission lines to the broad-band emission. Kollatschny et al. (2006) confirmed the results of G99 in a sample of 43 galaxies. In the above analysis, we find a significant correlation between \( \log(\Delta L) \) and the FWHM of H\( \beta \) (Fig. 3a).

The median(\( \Delta B \)) is plotted against \( M_{\text{BH}} \) in Figure 4a. No significant correlation is, however, found between these two parameters (\( r_s = 0.124, P_s = 0.4267 \)). Wold et al. (2007) did not detect a correlation between variability and \( M_{\text{BH}} \) in their PG quasar sub-sample, and our result confirms their conclusion. However, the current results make it difficult to understand why the correlation between the magnitude variability and the \( M_{\text{BH}} \) is not as good as expected.

It is now generally believed that the E1 spaces is likely driven by \( L/L_{\text{Edd}} \) (e.g., Boroson 2002). The relation between the magnitude variability and \( L/L_{\text{Edd}} \) is directly examined in Figure 4b. We find a significant anti-correlation between the median(\( \Delta B \)) and \( L/L_{\text{Edd}} \) (\( r_s = -0.368, P_s = 0.0012 \)). Although our result agrees with Wilhite et al. (2008), caution must be made when explaining the median(\( \Delta B \))-\( L/L_{\text{Edd}} \) correlation. Taking two quasars with the same \( M_{\text{BH}} \), the more luminous one would have smaller variability in magnitude for a given change in luminosity (accretion rate). Meanwhile, the more luminous quasar would have a larger \( L/L_{\text{Edd}} \). That means that the median(\( \Delta B \))-\( L/L_{\text{Edd}} \) correlation might be caused by an intrinsic relation in mathematics (i.e., the definition of magnitude) rather than in physics. A sample of light curves defined in flux or luminosity is therefore required to test the underlying physics of the relation.
4.2. Implications on variability mechanisms

Several theoretical models have been proposed as mechanisms for variability in quasars, such as disk-instability (Kawaguchi et al. 1998), gravitational microlensing (Hawkins 1993, 1996), and starburst (Terlevich et al. 1992). However, all of them are still far from clear.

Hawkins (1993, 1996) explained the observed AGN variability by invoking gravitational microlensing. In this model, a quasar’s light is lensed by a large population of compact bodies with planetary-mass. The microlensing model has two parameters: the Einstein radius of the lenses and their mean transverse velocity (Hawkins 2002). However, the two parameters generally can not be obtained observationally. In addition, microlensing events should be extremely rare at low redshift (Vanden Berk et al. 2004). This explanation can be easily excluded for the PG quasars studied in this paper. We find the quasar’s variability is related with the E1 space, which strongly indicates that the variability must be caused by an intrinsic mechanism rather than an external one.

Someone holds the idea that AGN variability might be caused by a series of discrete outbursts, such as supernova explosions (Aretxaga et al. 1997). However, this model can not explain the relationship between the luminosity and variability amplitude as argued by Pica & Smith (1983). Alternatively, Terlevich et al. (1992) explained the AGN variability as originating from the supernova remnants (SNRs) occurring in the innermost regions of AGNs. The long-term and short-term variability observed in AGNs could be explained by the long-term decay of the SNRs and cooling instability after the onset of the radiative phase, respectively. The cooling time before the radiative phase is ∼0.6 year, and beyond this, the phase is reduced to ∼6 days.

The disk-instability model is much more popular than the other models. This model interprets the variability as an occasional flare event or blob formation caused by the instability in the accretion disk. Kawaguchi et al. (1998) compared the logarithmic slopes of the structure function between the disk-instability model and star-burst model, and their observation of quasar 0957+561 supports the disk-instability model. Vanden Berk et al. (2004) studied photometric variability of 25,000 quasars from SDSS, and found that their results favor the disk-instability model. However, it is still unclear how changes in the accretion rate or the resulting luminosity changes would propagate through the accretion disk. Recently, Li & Cao (2008) proposed a disk model, and suggested that the disk temperature change would lead to systematic spectral shape difference, which could explain the correlation between the variability and $L/L_{\text{Edd}}$ or $M_{\text{BH}}$ discovered by Wold et al. (2007) and Wilhite et al. (2008).

Although our analysis can not discriminate which model, starburst or disk-instability, is favored for a quasar’s variability, the extension of the E1 space to the variability implies that
either: 1) the stability of the accretion rate (or gas supply) changes along the E1 sequence in the disk-instability model, or 2) the intensity of star formation activity changes along the E1 sequence.

5. Conclusions

By studying the variability of the 42 PG quasars monitored by Giveon et al. (1999), using both direct correlations and PCA analysis, we find that the E1 space can be extended to include quasar’s optical variability. The link between this variability and Eddington ratio/black hole mass is discussed, and we propose that the Eddington ratio may be a key factor in determining the variability of quasars.

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Fig. 1.— Distribution of redshift (Panel A) and black hole mass (Panel B) for the 42 PG quasars studied in this paper.
Fig. 2.— Comparison between the value of $L_{\text{bol}}$ calculated from Equation 2 and 3. The horizon axis represents the $L_{\text{bol}}$ from Equation 2 (Kaspi et al. 2000), and the vertical axis represents the $L'_{\text{bol}}$ from Equation 3 (Marconi et al. 2004). It is clear that the two independent measurements are consistent with each other.
Fig. 3.— Plots of $\Delta L$ vs E1 parameters. The horizontal axis represents the $\Delta L$, and the vertical axis represents the E1 parameters: (a) log(FWHM(H$\beta$)) ($r_s$=0.450, $P_s$=0.004) (b) peak $\lambda$5007 ($r_s$=0.445, $P_s$=0.0044). (c) RFeII ($r_s$=-0.441, $P_s$=0.0048). (d) log R ($r_s$=0.476, $P_s$=0.0023).
Fig. 4.— Panel A: median magnitude change vs black hole mass ($r_s = 0.124$, $P_s = 0.4267$). Panel B: median magnitude change vs Eddington ratio ($r_s = -0.368$, $P_s = 0.0012$).
| Object   | $z$   | log($\text{MBH}/\text{M}_\odot$) | log($\text{L}_{\text{bol}}/\text{L}_{\text{Edd}}$) | med($\Delta B$) | log($\Delta L$) | FWHM(H$\beta$) | Peak[OIII] |
|----------|-------|---------------------------------|---------------------------------|-----------------|-----------------|----------------|-------------|
| PG 0026+129 | 0.142 | 8.1                             | -0.1                             | 0.16            | 45.1            | 1860           | 2.68        |
| PG 0052+251 | 0.155 | 8.9                             | -1.1                             | 0.22            | 45.0            | 5200           | 2.48        |
| PG 0804+761 | 0.100 | 8.5                             | -0.6                             | 0.15            | 45.1            | 3070           | 0.46        |
| PG 0838+770 | 0.131 | 8.2                             | -0.6                             | 0.16            | 44.7            | 2790           | 0.65        |
| PG 0844+349 | 0.064 | 7.9                             | -0.6                             | 0.11            | 44.5            | 2420           | 0.55        |
| PG 0923+201 | 0.190 | 8.0                             | -0.1                             | 0.18            | 45.0            | 7610           | 0.60        |
| PG 0953+414 | 0.239 | 8.7                             | -0.5                             | 0.14            | 45.4            | 3130           | 0.84        |
| PG 1001+054 | 0.161 | 7.7                             | -0.2                             | 0.15            | 44.7            | 1740           | 0.23        |
| PG 1012+008 | 0.185 | 8.2                             | -0.4                             | 0.12            | 45.0            | 2640           | 1.00        |
| PG 1048+342 | 0.251 | 8.4                             | -0.8                             | 0.27            | 44.7            | 3600           | 1.83        |
| PG 1100+772 | 0.313 | 9.3                             | -0.9                             | 0.09            | 45.6            | 6160           | 3.99        |
| PG 1114+445 | 0.144 | 8.6                             | -1.0                             | 0.12            | 44.7            | 4570           | 1.36        |
| PG 1115+407 | 0.154 | 7.7                             | -0.2                             | 0.16            | 44.6            | 1720           | 0.41        |
| PG 1121+422 | 0.234 | 8.0                             | -0.3                             | 0.14            | 44.9            | 2220           | 2.55        |
| PG 1151+117 | 0.176 | 8.5                             | -1.0                             | 0.16            | 44.8            | 4300           | 1.00        |
| PG 1202+281 | 0.165 | 8.6                             | -1.2                             | 0.28            | 44.6            | 5050           | 2.27        |
| PG 1211+143 | 0.085 | 8.0                             | -0.1                             | 0.15            | 45.1            | 1860           | 0.55        |
| PG 1226+023 | 0.158 | 9.2                             | -0.3                             | 0.10            | 46.0            | 3520           | 0.33        |
| PG 1229+204 | 0.064 | 8.1                             | -0.9                             | 0.17            | 44.4            | 3360           | 1.46        |
| PG 1307+085 | 0.155 | 8.9                             | -1.1                             | 0.15            | 45.0            | 2360           | 2.26        |
| PG 1309+355 | 0.184 | 8.3                             | -0.5                             | 0.09            | 45.0            | 2940           | 1.86        |
| PG 1322+659 | 0.168 | 8.3                             | -0.5                             | 0.08            | 45.0            | 2790           | 0.72        |
| PG 1351+640 | 0.087 | 8.8                             | -1.2                             | 0.11            | 44.8            | 5660           | 2.27        |
| PG 1354+213 | 0.300 | 8.6                             | -0.8                             | 0.16            | 45.0            | 4140           | 2.75        |
| PG 1402+261 | 0.164 | 7.9                             | -0.1                             | 0.09            | 45.0            | 1910           | 0.09        |
| PG 1404+226 | 0.098 | 6.9                             | 0.3                              | 0.11            | 44.4            | 880            | 0.18        |
| PG 1411+442 | 0.089 | 8.1                             | -0.6                             | 0.08            | 44.6            | 2670           | 0.63        |
| PG 1415+451 | 0.114 | 8.0                             | -0.6                             | 0.07            | 44.6            | 2620           | 0.10        |
| PG 1426+015 | 0.086 | 9.1                             | -1.3                             | 0.18            | 44.9            | 6820           | 1.47        |
| PG 1427+480 | 0.221 | 8.1                             | -0.5                             | 0.24            | 44.8            | 2540           | 1.99        |
| PG 1444+407 | 0.267 | 8.3                             | -0.2                             | 0.07            | 45.2            | 2480           | 0.12        |
| PG 1512+370 | 0.371 | 9.4                             | -0.9                             | 0.13            | 45.6            | 6810           | 4.00        |
| PG 1519+226 | 0.137 | 7.9                             | -0.4                             | 0.10            | 44.7            | 2220           | 0.16        |
| PG 1545+210 | 0.266 | 9.3                             | -1.0                             | 0.17            | 45.4            | 7030           | 3.66        |
| PG 1613+658 | 0.129 | 9.2                             | -1.5                             | 0.12            | 44.8            | 8450           | 1.99        |
| PG 1617+175 | 0.114 | 8.8                             | -1.1                             | 0.18            | 44.9            | 5330           | 0.48        |
| PG 1626+554 | 0.133 | 8.5                             | -1.1                             | 0.29            | 44.6            | 4490           | 0.56        |
| PG 1700+518 | 0.292 | 8.6                             | -0.1                             | 0.08            | 45.7            | 2210           | 0.00        |
| PG 1704+608 | 0.371 | 9.4                             | -0.8                             | 0.13            | 45.7            | 6560           | 6.50        |
| PG 2130+099 | 0.061 | 7.9                             | -0.5                             | 0.09            | 44.5            | 2330           | 0.89        |
| PG 2233+134 | 0.325 | 8.0                             | 0.1                              | 0.10            | 45.3            | 1740           | 0.77        |
Table 2: Spearman Rank-Order Correlation Coefficient of the correlations shown in Figure 3

|                | ∆ L vs | FWHM(Hβ) | Peak λ5007 | RFe | Log R |
|----------------|--------|-----------|-------------|-----|-------|
| $r_s$          | 0.450  | 0.445     | -0.441      | 0.476|
| $P_s$          | 0.004  | 0.004     | 0.005       | 0.002|

Table 3: Correlations of Eigenvectors with line and continuum properties

| Property      | Eigenvector 1 | Eigenvector 2 | Eigenvector 3 | Eigenvector 4 |
|---------------|---------------|---------------|---------------|---------------|
| Eigenvalue    | 3.89          | 1.87          | 1.24          | 1.03          |
| Cumulative    | 35.3%         | 52.3%         | 63.6%         | 73.0%         |
| log R         | 0.68          | 0.54          | -0.15         | 0.03          |
| EW(Hβ)        | -0.05         | -0.60         | -0.55         | -0.08         |
| R (λ5007)     | 0.82          | 0.04          | 0.43          | -0.13         |
| R (λ4686)     | -0.14         | -0.55         | 0.44          | -0.23         |
| RFe           | -0.79         | 0.45          | -0.03         | -0.04         |
| Peak (λ5007)  | 0.92          | -0.07         | 0.24          | -0.12         |
| FWHM(Hβ)      | 0.68          | -0.21         | -0.32         | 0.34          |
| Hβ shift      | -0.10         | 0.39          | 0.46          | 0.05          |
| Hβ shape      | 0.07          | 0.27          | -0.29         | -0.89         |
| Hβ asymm      | -0.70         | -0.33         | 0.02          | 0.15          |
| log (ΔL)      | 0.54          | 0.57          | -0.30         | 0.10          |