Extreme Variability Quasars in Their Various States. I. The Sample Selection and Composite SDSS Spectra

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Abstract

Extreme variable quasars (EVQs) are a population of sources showing large optical photometric variability revealed by time-domain surveys. The physical origin of such extreme variability is yet unclear. In this first paper of a series, we construct the largest-ever sample of 14,012 EVQs using more than 15 yr of photometric data from the Sloan Digital Sky Survey (SDSS) and Pan-STARRS1. We divide the EVQs into five subsamples according to the relative brightness of each EVQ during SDSS spectroscopic observation compared with the mean brightness from photometric observations. Corresponding control samples of normal quasars are built with matched redshift, bolometric luminosity, and supermassive black hole mass. We obtain the composite SDSS spectra of EVQs in various states and their corresponding control samples. We find EVQs exhibit clearly bluer SDSS spectra during bright states and clearly redder spectra during dim states, consistent with the “bluer-when-brighter” trend widely seen in normal quasars. We further find that the line equivalent widths (EWs) of broad Mg II, C IV and [O III] (but not broad H\alpha, which is yet puzzling) gradually decreases from the dim state to the bright state, similar to the so-called intrinsic Baldwin effect commonly seen in normal active galactic nuclei. In addition, EVQs have consistently larger line EWs compared with the control samples. We also see that EVQs show slight excess in the very broad line component compared with control samples. Possible explanations for the discoveries are discussed. Our findings support the hypothesis that EVQs are in the tail of a broad distribution of quasar properties but are not a distinct population.

1. Introduction

Quasars and active galactic nuclei (AGNs) can be observationally classified into type 1 and 2, that is, with and without broad emission lines (BELs), respectively. The unified model indicates that two types of objects are intrinsically identical but merely viewed at different orientations (Antonucci 1993; Urry & Padovani 1995). With the accumulation of long-term repeated observations, a unique and rare class of quasars showing dramatic emergence or disappearance of the BELs has been discovered (e.g., Denney et al. 2014; LaMassa et al. 2015; MacLeod et al. 2016; McElroy et al. 2016; Ruan et al. 2016; Runnoe et al. 2016; Stern et al. 2018; Wang et al. 2018; Yang et al. 2018; MacLeod et al. 2019; Trakhtenbrot et al. 2019; Sheng et al. 2020). These objects, dubbed “changing-look” quasars (CLQs), often also show strong UV/optical continuum variations with a factor $\geq 10$ (e.g., MacLeod et al. 2016) within a typical timescale of decades. The prominent changes in the BELs and continuum on such short timescales are difficult to explain by the traditional thin disk theory, which predicts a much longer timescale (associated with the viscous timescale, typically $\sim 10^4$ yr) for accretion rate change. Instead they are likely associated with changes of unclear cause in the innermost regions of the accretion disk (e.g., Ross et al. 2018; Stern et al. 2018).

The variability is a hallmark signature of quasars across all wavelengths and timescales (e.g., Mushotzky et al. 1993; Ulrich et al. 1997). In rest-frame UV/optical, the continuum emission from the accretion disk of quasars typically varies by $\sim 0.2$ mag on timescales of days to years (e.g., Vanden Berk et al. 2004; Sesar et al. 2007). However, it is yet unclear whether such normal variations in quasars and the rare strong variations in CLQs are caused by the same mechanism(s).

Rumbaugh et al. (2018) identified $\sim 1000$ quasars with extreme variability (EVQs) in $g$-band ($\Delta g > 1$ mag, $\sim 10\%$ of all quasars searched) utilizing photometric light curves spanning more than 15 yr. Rumbaugh et al. (2018) found that EVQs have larger BEL equivalent widths (EWs) and lower Eddington ratio compared with a control sample with matched redshift and optical luminosity, and suggested that “EVQs seem to be in the tail of a continuous distribution of quasar properties, rather than standing out as a distinct population.” Strikingly, MacLeod et al. (2019) spectroscopically confirmed $\geq 20\%$ of EVQs they selected as CLQs (i.e., CLQs belong to a subset of EVQs). EVQs, which are more common than CLQs and can be identified merely with photometry, are thus ideal targets of statistical studies (e.g., Rumbaugh et al. 2018; Luo et al. 2020). It is thus worthwhile to build larger samples of EVQs and to explore whether they have other special physical properties different from ordinary quasars. In addition, multiple spectroscopic observations, which are essential to probe the spectral variabilities in EVQs, have only been reported for very small samples (MacLeod et al. 2019; Yang et al. 2020; Guo et al. 2020a).
In this work, we compile a large sample of 14,012 EVQs selected using Sloan Digital Sky Survey (SDSS) and Pan-STARRS1 photometric observations of SDSS quasars. We point out that, for an EVQ with only single-epoch spectroscopy available, comparing its synthetic spectroscopy magnitude with mean magnitude from the photometric light curve, one can determine whether the spectrum was obtained during a bright, normal, or dim state. We thus could divide the sample into five subsamples according to the deviation of SDSS synthetic spectroscopy magnitude from the mean photometric magnitude. The subsamples represent EVQs observed during their extremely bright state, bright state, median state, dim state, and extremely dim state, respectively. We study the spectral properties (line EWs, co-added spectra, and line profiles) and their evolution (from dim to bright states) of EVQs by comparing the five subsamples with corresponding control samples with matched redshift, luminosity, and supermassive black hole (SMBH) mass.

We stress that comparison of EVQs with control samples with matched luminosity and SMBH mass (thus matched Eddington ratio) is essential to this work, as the spectral properties of quasars could be sensitive to these parameters. For instance, while it is well known that the UV/optical emission line EW is anti-correlated with the underlying continuum luminosity (the so-called ensemble Baldwin effect, eBeff, e.g., Baldwin 1977; Dietrich et al. 2002), the Eddington ratio could be one of the dominant key factors behind the eBeff (Baskin & Laor 2004; Dong et al. 2009).

Another closely related phenomenon is the “intrinsic Baldwin effect” (iBeff): for individual AGNs, it has also been found that the line EW decreases when the AGN brightens (e.g., Kinney et al. 1990; Pogge & Peterson 1992; Homan et al. 2020), and the slope of the iBeff is usually steeper than the eBeff for the same lines (Kinney et al. 1990; Pogge & Peterson 1992). Comparing the spectra of EVQs among different brightness states, we would be able to determine whether EVQs also exhibit the iBeff.

The structure of this paper is as follows: We describe the data and reduction in Section 2. The selection criteria for EVQs and their control samples are presented in Section 3. In Section 4 we present the composite spectra for EVQs (and control samples) and their emission line properties. We discuss our results in Section 5 and summarize in Section 6. Throughout this paper, we adopt a flat $\Lambda$CDM cosmology with $\Omega_{\Lambda} = 0.7$, $\Omega_m = 0.3$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. The Data and Reduction
2.1. Photometric Observations

We start from the SDSS data release 14 (DR14) quasar catalog (DR14Q, Pâris et al. 2018), which contains 526,356 spectroscopically confirmed quasars with luminosity $M_\text{r}([-20.5, 9376$ deg$^2$. Note that the DR14Q catalog only provides single-epoch photometry (i.e., the primary SDSS magnitude) for each source. In order to select EVQs, we construct the $g$- and $r$-band light curves for each quasar through further gathering all archive photometric observations from both SDSS and Pan-STARRS1 (PS1) databases.

The SDSS photometric observations were taken by the drift-scan camera (30 k × 2k CCDs) installed on the 2.5-m Sloan telescope (Gunn et al. 2006). In the SDSS DR14Q catalog, the primary photometric observations were obtained with SDSS-I/II, lasting from 2000 to 2007 (covering 11,663 deg$^2$), and SDSS-III (before 2009) on ∼3,000 deg$^2$ of new sky area. Using a matching radius of 1", we gather all available SDSS g- and r-band photometry for DR14Q quasars. Referring to the recommendation on the use of photometric processing flags from SDSS, we reserve detections with mode = 1 or 2, “clean” flags, and point spread function (PSF) magnitude error < 0.2 mag in both g- and r-band. Approximately 45% quasars (237,099 quasars, specifically) have multiphoch SDSS photometry (and 28,672 of them had been observed over more than 5 epochs).

We also collect the g- and r-band photometry from the PS1 3π survey, with up to four exposures in each band per year, conducted from 2009 to 2013. In total, within a matching radius of 1", 510,838 SDSS DR14 quasars have counterparts in the PS1 archive (with mean epochs of around 10 and 12 in g- and r-band, respectively). Similar to the processing of SDSS data, we also filter the matched PS1 detections according to their photometric info flags. We rule out PS1 detections with PSF magnitude error > 0.2 mag or flagged as:

1. Peak lands on diffraction spike, ghost or glint;
2. Poor moments for small radius, try large radius or could not measure the moments;
3. Source fit failed or succeeds but with low signal-to-noise ratio (S/N), high Chi square or too large for PSF;
4. Source model peak is above saturation;
5. Size could not be determined;
6. Source has crNSigma above limit;
7. Source is thought to be a defect;
8. Failed to get good estimate of object’s PSF;
9. Detection is astrometry outlier.

After conversion between PS1 and SDSS photometry (see Section 2.2), we are able to merge photometric data points from both SDSS and PS1, and obtain for every quasar relatively long-term g- and r-band light curves with lengths of 4 ~ 15 yr. We further remove from the light curves a small fraction of photometric measurements that could be unreliable according to the consistency check between g- and r-band light curves (see Section 2.3).

A mean magnitude $g_{\text{mean}}$ is then derived from the clean light curve for each quasar. We need such a mean magnitude to represent the average brightness of a quasar over a long duration, and to be compared with the synthetic magnitude $g_{\text{spec}}$ derived from the SDSS spectrum to determine whether the spectrum was captured during a bright, normal, or dim state. In order to avoid the mean magnitude being dominated by a few measurements with very small uncertainties, we simply calculate the mean without error weighting. The light curves of most quasars contain far more data points from PS1 than from SDSS (and the reverse for quasars in SDSS Stripe 82). To avoid the mean magnitudes being dominated by data from one instrument or by data from a single observing season with a large number of epochs, we first calculate the yearly mean magnitudes and then the final mean from the yearly mean values.

\footnote{https://skyserver.sdss.org/casjobs/}
\footnote{https://mastweb.stsci.edu/ps1/casjobs/home.aspx}
\footnote{https://www.sdss.org/dr16/algorithms/photo_flags_recommend/}
Figure 1. The distributions of photometry difference between PS1 and SDSS, $\Delta g_{\text{PS1}} = g_{\text{PS1}} - g_{\text{SDSS}}$ (top panel) and $\Delta r_{\text{PS1}} = r_{\text{PS1}} - r_{\text{SDSS}}$ (bottom panel), versus redshift for SDSS DR14 quasars. In each panel, the colored contour represents the distribution density, while the dark blue line represents the mean photometry difference of 0.05 in the redshift bin. For comparison, assuming the redshift bin of $z = 0.05$ represents the distribution density, while the dark blue line represents the mean versus redshift for SDSS DR14 quasars. In each panel, the colored contour transmission curves between PS1 and SDSS. For example, $\Delta g_{\text{PS1}}$ ranges from -1.0 to 1.0 in the top panel and from -1.0 to 1.0 in the bottom panel. This is owing to the slight difference of the mean quasar spectrum of Yip et al. (2004; the dotted-dashed lines in Figure 1). Note that the mean spectrum extends down to 900 Å in the rest frame, thus resulting in a cut at $z \sim 3.4$ (for g band).

To eliminate the systematic offsets between PS1 and SDSS magnitudes for our quasars, we apply a correction to the PS1 magnitudes of each quasar using the mean $\Delta g_{\text{PS1}}$ ($\Delta r_{\text{PS1}}$) of its closest 1000 neighbors in redshift space.

2.3. Reject Defects in Photometry

A commonly used criterion for selecting EVQs is to ask for a change in magnitude of $|\Delta g| > 1$ mag between any two epochs in the light curve (e.g., MacLeod et al. 2016; Rumbaugh et al. 2018; Guo et al. 2020a). By applying $|\Delta g| > 1$ on our sample, we can get ~56,000 candidates; however, more than 1/6 of them have $|\Delta r| < 0.5$. These are highly suspect and are likely due to defects in photometry measurements, such as by ghost, glint, cosmic ray, CCD problem, or unknown instrumental effects. Such defects should be rejected before we could build a reliable sample of EVQs.

In Figures 2 and 3, we present the g- and r-band light curves for two sources, each showing a clear defect in g-band photometry during an individual epoch. In Figure 2, the SDSS g-band cutout of the problematic epoch (marked in red) shows much blurrier and more diffuse signal compared with the corresponding r-band data and another g-band image obtained 116 days later. In Figure 3, the red dot marks an epoch during which the PS1 g-band signal is clearly contaminated by an artificial CCD feature.

Such epochs could be identified through checking the consistency between g- and r-band variability revealed in the light curves. For SDSS, simultaneous g- and r-band photometry is always available. However, this is not true for PS1. For each PS1 g-band photometry, we identify an r-band counterpart that was obtained closest in time. In Figure 4, we plot the distribution of the time intervals between g-band and the corresponding (closest in time) r-band exposures. For most PS1 g-band exposures, we could pair each one with an r-band exposure obtained within 30 days, and use this quasimultaneous r-band data to examine the reliability of the g-band
pairs with the “problematic” epoch involved are plotted in gray, yielding a butterfly-shaped distribution and demonstrating the inconsistency between $\Delta g$ and $\Delta r$ caused by photometry defects.

2.4. Spectroscopic Observations and Spectral Fitting

We consider all available SDSS spectra for the DR14Q quasars and compare their synthetic magnitudes (spectrophotometry) with the aforementioned photometric mean magnitudes (see Section 2.1) to determine their spectral states. As with the photometric magnitude, we require a g-band synthetic magnitude error of $< 0.2$ mag. In total, approximately $1/7$ of the spectra were taken during SDSS-III or earlier, with approximately half taken after PS1.

We fit the quasar spectra mainly following Shen et al. 2011 (hereafter S11) and using the PyQSOFit code (Guo et al. 2018). For each spectrum, after correcting for the Galactic extinction by adopting the dust map of Schlegel et al. (1998) and the Fitzpatrick (1999) extinction law assuming RV = 3.1, we shift the spectrum to the rest frame using the redshift given in the DR14Q catalog. A global continuum including a power law and an iron emission template pseudo continuum (Boroson & Green 1992; Vestergaard & Wilkes 2001; Salvianti et al. 2007) is fitted with tens of separated line-free spectral windows, and the monochromatic luminosity—at $\lambda = 5100 ~\text{Å}$ ($L_{5100}$), 3000 $\text{Å}$ ($L_{3000}$), and 1350 $\text{Å}$ ($L_{1350}$) for quasars at various redshifts—is then derived. The host galaxy contamination is not considered, as most of our sources are high-redshift luminous quasars (see S11).

Following S11, we fit various emission lines separately. For H/β (of objects with $z \leq 0.89$), we use a power-law continuum with iron template to fit within the wavelength windows of [4435, 4700] $\text{Å}$ and [5100, 5535] $\text{Å}$. The emission lines are fitted within [4700, 5100] $\text{Å}$ with eight Gaussians, three for the broad components of H/β with full width at half maximum (FWHM) $> 1200 $ km s$^{-1}$, one for the narrow component with FWHM $< 1200 $ km s$^{-1}$, and the rest four for the narrow [O III] $\lambda 4959,5007$ doublet (one core and one wing component for each line). The FWHMs and the velocity offsets of H/β narrow line and the [O III] core component are tied up. The same restriction is also applied on the wing component of [O III]. For Mg II $(0.35 \leq z \leq 2.25)$, we fit the continuum spectra utilizing the same continuum model as above, but within the spectral windows of [2200, 2700] $\text{Å}$ and [2900, 3090] $\text{Å}$ and the line over [2700, 2900] $\text{Å}$ with three Gaussians for the broad component and one for narrow. For C IV $(z \geq 1.5)$, only a power-law continuum is used over windows of [1445, 1465] $\text{Å}$ and [1700, 1705] $\text{Å}$ and only 3 Gaussians for broad component over the spectral range of [1465, 1700] $\text{Å}$. We note that, for simplicity and reproducibility, the numbers of broad Gaussians we used for the lines are fixed rather than variable as in S11. To ensure the reliability of the fitting, we only adopt the results of lines with a median spectral S/N around the line-fitting region $> 3$, which roughly corresponds to a ±20% fitting bias of FWHM and EW for high-EW objects (Shen et al. 2011). We finally stress that hereafter, unless otherwise stated, the H/β or Mg II line refers to the broad component we derive from the spectral fitting.

Using the best-fit broad Gaussian models, we measure for each line the EW and FWHM with PyQSOFit, and the line asymmetry with Pearson’s skewness coefficient: skewness $= 3(\lambda_{\text{mean}} - \lambda_{\text{median}})/\sigma_\lambda$ (Vanden Berk et al. 2001). The $\lambda_{\text{median}}$ is
Figure 5. The g- and r-band magnitude variability between any pairs of epochs. Epoch pairs from all quasars are plotted. The green dashed line is the orthogonal distance regression (ODR) fitting result of the whole data set with a linear model. We define a green zone within which \( \Delta g \) and \( \Delta r \) of a pair of epochs appear consistent with each other (i.e., is unlikely to have been affected by photometry defect; see text for details). Aided by the green zone, we identify “problematic” epochs potentially affected by photometry defects (in either g or r band). The epoch pairs with “problematic” epochs involved, accounting for 0.49% of the whole data set, are plotted in gray (with 1\( \sigma \), 2\( \sigma \), 3\( \sigma \) and 99.97% density contours). The blue dots (with 1\( \sigma \), 2\( \sigma \), 3\( \sigma \) and 99.97% density contours) are free from “problematic” epochs, and represent 99.51% of the whole data set.

where the wavelength bisects the area of the emission line model, while the \( \lambda_{\text{mean}} \) is defined as

\[
\lambda_{\text{mean}} = \frac{\int_{-\infty}^{+\infty} f(\lambda)d\lambda}{\int_{-\infty}^{+\infty} f(\lambda)d\lambda}.
\]

We stress that the skewness determined by the above method can reveal the shape of the emission line model only, regardless of the systematic shift.

We estimate the black hole (BH) mass of quasars based on single-epoch spectrum assuming virialized broad-line region (BLR; S11). With the continuum luminosity as a proxy for the BLR radius and the FWHM of broad line as a proxy for virial velocity, the virial BH mass can be given following the expression as

\[
\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = a + b \log \left( \frac{\lambda L_{\lambda}}{10^{44} \text{ erg s}^{-1}} \right) + 2 \log \left( \frac{\text{FWHM}}{\text{km s}^{-1}} \right),
\]

where the \( L_{\lambda} = L_{\text{5100}} \) for H\( \beta \), \( L_{\lambda} = L_{\text{3000}} \) for Mg II and \( L_{\lambda} = L_{\text{1350}} \) for C IV. We adopt the calibration parameters in S11 (see their Equations (5), (8), and (6), respectively):

\[
(a, b) = (0.910, 0.50), \ H\beta
\]

\[
(a, b) = (0.740, 0.62), \ Mg \ II
\]

\[
(a, b) = (0.660, 0.53), \ C IV
\]

3. The EVQ Samples and Control Samples

3.1. EVQs Selection

Using the clean and paired g- and r-band light curve we derived in Section 2.3, we consider a source to be an EVQ if any of its two photometry pairs satisfy \(|\Delta g_{\text{max}}| > 1 \text{ mag and } |\Delta r_{\text{max}}| > 0.8 \text{ mag quasi-simultaneously}\). By this criterion, 14,012 EVQs are selected; a catalog of them will be released in a future paper in this series. We plot \(|\Delta g_{\text{max}}| \) versus \( g_{\text{mean}} \) of the sample in the upper panel of Figure 7. Though most EVQs are faint sources, most of their \(|\Delta g_{\text{max}}| \) are statistically significant (with S/N > 5, lower panel of Figure 7), as we have excluded photometric data points with magnitude error > 0.2 mag (see Section 2).

We note that a simultaneous \(|\Delta r_{\text{max}}| > 0.8 \text{ mag adopted in this work is a strong and conservative requirement, which if set aside would yield 22,740 candidates instead.\textsuperscript{7}}\) Practically, EVQs with \(|\Delta g_{\text{max}}| > 1 \text{ mag and } |\Delta r_{\text{max}}| > 0.8 \text{ mag simultaneously have more extreme variability than those selected with a single } |\Delta g_{\text{max}}| > 1 \text{ mag criterion. This could be clearly seen in Figure 8.}

Before we determine the state of the spectra of EVQs, we first exclude 3991 low-quality spectra (g-band synthetic magnitude error < 0.2 mag), leaving 2447 EVQs with no available spectra. To parameterize the states of the spectra, we calculate the magnitude difference between their synthetic photometry \( g_{\text{spec}} \) derived from SDSS spectra (the AB magnitude evaluated from the spectroFlux given by SDSS, which was derived through convolving the spectrum with the corresponding filter) and the mean photometric magnitude \( g_{\text{mean}} \), see Section 2.1). To derive the stacked spectra and explore possible variation of the spectral feature in different measurements for the DR14Q quasars (Rakshit et al. 2020, hereafter R20) using the same PyQSOFit code and similar parameters. In R20, the continuum components are fitted to the whole spectrum with various templates, while in this work, we prefer to fit the continuum with nearby line-free spectral windows. Compared with the global fit in R20, the local fit performs better in fitting continuum flux with simple models within a limited region, so that it can provide more precise emission line spectra. Moreover, as we will state below, in this work we are more interested in spectra in the most extreme state for EVQs, 1363 of which are not the primary and thus are not included in R20. In addition, in this work, detailed spectral measurements (such as line skewness, bisectional line center, and the properties of composed spectra) are required. Therefore we choose our independent spectral fitting results in this work for the following analyses.

We present in Figure 6 the comparison of our measurements of luminosity, line EW, and FWHM with those of R20 and S11, showing negligible deviations and small scatter between the measurements.

We will not go deeper discussing the details of the weak deviation and smaller scatter between the measurements; however, adopting the measurements from R20 does not alter the results presented in this work.

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\textsuperscript{7} This number is still considerably smaller than ~56,000 aforementioned if applying \(|\Delta g_{\text{max}}| > 1 \text{ mag on the g-band light curves before the “cleaning” process described in Section 2.3}. This is because the “cleaning” process has excluded potentially problematic epochs that could yield spuriously large \( \Delta g \) (see Figure 5), as well as a portion of g-band data points without paired (obtained within 30 days) r-band PS1 exposures (see Figure 4).
states, rebinning the sample is necessary. According to the
commonly used EVQs criterion \(D_\text{g}_{\text{max}}\), we classify the
spectra with \(|g_{\text{spec}} - g_{\text{mean}}| > 0.5\) into extreme states (sym-
metrically into extremely bright state or extremely dim state).
We further divide the remaining 8376 spectra into three classes (see
below for details), so that the whole sample is divided into five
classes, which enables us to explore the gradual variation of
spectral features from extremely dim to extremely bright states.
On the whole, the criterion can be expressed as follow:

1. \(-0.5 \leq g_{\text{spec}} - g_{\text{mean}} < 0.5\) : Extremely Bright State (EBS);
2. \(-0.5 \leq g_{\text{spec}} - g_{\text{mean}} < -0.2\) : Bright State (BS);
3. \(-0.2 \leq g_{\text{spec}} - g_{\text{mean}} < 0.2\) : Median State (MS);
4. \(-0.2 \leq g_{\text{spec}} - g_{\text{mean}} < 0.5\) : Dim State (DS);
5. \(0.5 \leq g_{\text{spec}} - g_{\text{mean}} < \Delta g_{\text{max}}\) : Extremely Dim State
(EDS),

where the \(\Delta g_{\text{max}}\) is the greatest magnitude change in each g-band
photometric light curve. A sketch of the above criteria is shown
in Figure 9. For those 2341 EVQs with multiple SDSS spectra,
we only keep the most extreme spectrum the g-band synthetic
magnitude that departs most from the mean photometric
magnitude from SDSS and PS1. We defer the study of spectral

Figure 6. Comparisons of the continuum luminosity, line EW, and FWHM between S11, R20, and this work. The mean and standard deviations of the difference are indicated in the upper left corner of each panel. In each panel, the inner and outer contours are the 1σ and 2σ density contours, respectively.
variability in these individual EVQs with multiple spectra to a future work in this series. We note that dividing the parent sample into more classes would reduce the number of quasars in each class, and adopting different number of classes or using boundaries different from what we adopt would not alter the results in this work. Furthermore, there could be other strategies to rebin the EVQs into various states. For instance, one may choose to rebin according to \((g_{\text{spec}} - g_{\text{mean}}) / D_{g_{\text{max}}})\) (instead of \(g_{\text{spec}} - g_{\text{mean}}\); see Appendix), that is, to normalize the magnitude deviation \(g_{\text{spec}} - g_{\text{mean}}\) by the maximum variability amplitude seen. However, \(D_{g_{\text{max}}}\) only represents the maximum variability amplitude of a quasar seen by SDSS and PS1 photometric survey (i.e., would be significantly affected by the sampling), but it is not necessary an intrinsic physical property of the quasar. Moreover, this alternative strategy would not alter the results in this work.

There are a few EVQs with too bright (13) or too dim (32) synthetic magnitude \((g_{\text{spec}} - g_{\text{mean}}) > D_{g_{\text{max}}})\). We note that the SDSS spectra taken by recent BOSS campaigns have a smaller fiber diameter (2″ versus 3″) than the former SDSS campaigns. The smaller fiber might increase the possibility of the fiber drop that results in biased spectra with significantly low flux density, which has been reported in literature (e.g., Shen et al. 2015; Sun et al. 2015; Guo et al. 2020a). More information about fiber drop can be found in Dawson et al. (2012). We suspect the majority of the too-dim spectra of 32 EVQs (4 from SDSS-I and II and 28 from SDSS-III and IV) were due to fiber drop, and exclude them from this study. The too-bright spectra of 13 EVQs may be physically real signals or spurious (such as due to natural or artificial solar system objects accidentally passing through the line of sights during spectroscopic observations). Presently, we also exclude them from this paper, and defer studies on these individual sources to a future work.

In total, 11,520 EVQs remain, including 2152 in EBS, 3142 in BS, 3615 in MS, 1619 in DS, and 992 in EDS. In the following analyses, to avoid confusion caused by plotting too many subsamples in a single plot, when necessary we also merge the EBS/BS subsamples into ABS (all bright states) and the EDS/DS into ADS (all dim states). We note that there are considerably fewer sources in DS (EDS) compared with BS (EBS). That is because a clear portion of sources that should belong to DS (EDS) are excluded for their poor synthetic magnitude. Nevertheless, even if we keep those sources with too-faint spectra, the dim samples are still considerably smaller. This could be a selection bias \(^8\) that if a quasar was in a dim

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\(^8\) See Shen & Burke (2021) for a different manifestation of this kind of bias caused by AGN variability.
state, it may not have been spectroscopically identified, or even may not have been selected for spectroscopic observation, and would be missed by the quasar catalogs. However such biases would not affect the following analyses in this work, as the control samples (see Section 3.2 below) are built to have matched redshift and spectra-derived monochromatic luminosity (thus matched brightness in the spectra) with our EVQ samples.

3.2. Control Samples

We then build control samples of subtly variable quasars with essentially the same physical parameters including redshift, bolometric luminosity, and SMBH mass with our EVQs, for the comparison of the spectra properties between EVQs and the control samples. The matching in redshift, bolometric luminosity, and SMBH mass is critical as the spectral properties of quasars could significantly evolve (intrinsically or due to intricate observational effects) with such parameters.

The subtly variable quasars samples are selected out of quasars with $|\Delta g_{\text{max}}| < 0.4$ and also $|g_{\text{spec}} - g_{\text{mean}}| < 0.4$ (approximately 140,000 quasars satisfy such criteria). We build the first set of control samples using the $L_{\text{bol}}$ and $M_{\text{BH}}$ of EVQs measured directly from their single-epoch spectra (Section 2.4), by selecting the most alike subtly variable quasar for each EVQ in the space of $L_{\text{bol}}$, $M_{\text{BH}}$, and redshift (hereafter direct control sample, or DCS). Naturally, each DCS has the same size and matched redshift, $L_{\text{bol}}$, $M_{\text{BH}}$, broad-line FWHM, and Eddington ratio ($\eta_{\text{Edd}}$) as those of its corresponding EVQ sample.

However, EVQs are experiencing extreme variations, thus the bolometric luminosity derived from the single-epoch spectrum must have been biased by such variations, particularly for those quasars with spectra captured in their extreme states. To better represent the long-term average brightness of a quasar, we apply a correction to the aforementioned single-epoch bolometric luminosity ($L_{\text{bol}}$) and also the monochromatic...
luminosity $L_\lambda$) for each quasar:

$$\log L_{\text{bol, cor}} = \log L_{\text{bol}} + \frac{g_{\text{spec}} - g_{\text{mean}}}{2.5}$$

We then build the second set of control samples (luminosity-“corrected” control samples, hereafter LCS) with matched redshift, $L_{\text{bol, cor}}$, and single-epoch SMBH mass. Note that during the correction we simply assume that the variability amplitude of $L_{\text{bol}}$ is the same as that of $g$ band luminosity. Alternatively, we may simply request matching in average $g$ band luminosity (effectively in $g_{\text{mean}}$ since redshift is also matched), which, however, would not alter the results in this work.

Besides, the single-epoch virial BH mass estimates may also be biased by variability (the breathing of broad-line region, i.e., the change of line width with luminosity in individual AGNs). It was found that while $H\beta$ line display normal breathing expected from the virial relation (Denney et al. 2008; Gibson et al. 2008; Park et al. 2011; Barth et al. 2015; Runco et al. 2016), Mg II shows much weaker breathing (e.g., Shen 2013; Yang et al. 2019; Homan et al. 2020; Guo et al. 2020b), and C IV exhibits antibreathing (e.g., Richards et al. 2002; Willhite et al. 2005a; Shen et al. 2008; Sun et al. 2018; Wang et al. 2020). Simply assuming no breathing of Mg II and C IV (i.e., the line width does not vary with luminosity), we could further apply a correction to the single-epoch SMBH mass by replacing $L_\lambda$ with $L_{\lambda, \text{cor}}$ during the calculation of mass in Equation (5):

$$\log \left( \frac{M_{BH, \text{cor}}}{M_\odot} \right) = a + b \log \left( \frac{\lambda L_{\lambda, \text{cor}}}{10^{44} \text{ erg s}^{-1}} \right) + 2 \log \left( \frac{\text{FWHM}}{\text{km s}^{-1}} \right).$$

The third set of control samples (for Mg II and C IV samples only) are selected to have matched redshift, $L_{\text{bol, cor}}$, and $M_{BH, \text{cor}}$ (Mass-“corrected” control samples, MCS hereafter). Further note that it has been shown $M_{BH}$ estimated using high-ionization emission lines like C IV (e.g., Sulentic et al. 2007; Shen & Liu 2012; Runnoe et al. 2013; Coatman et al. 2016, 2017) should be used with cautious as C IV may not be virialized. In this case, the control samples could be interpreted more precisely as matched in C IV line FWHM (but not necessarily in SMBH mass).

Note that neither the LCS nor MCS samples are perfect control samples of our EVQs, because the broad-line breathing, the bolometric correction factors, and the calibration parameters for the virial mass might be different for EVQs and normal quasars, or might vary from source to source. However, further meticulous fix is outside of the scope of this work and seems unnecessary; as we will show later, our results in this work are insensitive to the choice of the three control samples we built.

4. Results

Due to the limited SDSS spectral coverage and the fact that we utilize monochromatic luminosity at different wavelengths

9 The broad-line breathing in EVQs could be explored using individual EVQs with multiple spectra. We would defer this to a future work in this series.
quasars at the wavelength of which we derive the monochromatic luminosity (see Section 2.4, also marked in Figure 12) and derive a geometric mean spectrum. To avoid confusion in the plots, we merge EVQs in BS and EBS into EVQs (ABS), and those in DS and EDS into EVQs (ADS). Their corresponding control samples are similarly treated. The composite spectra of EVQs and control samples are plotted in Figure 12.

Figure 12. The stacked (geometric mean) spectra and the spectral ratio of EVQs and their corresponding direct control samples. EVQs (ABS): in all bright states, including EBS and BS; EVQs (MS): in median states; EVQs (ADS): in all dim states, including EDS and DS. The vertical dashed lines mark the wavelengths we adopted to normalize the spectra. The composite spectra are cut at the blue and red ends, where <5% of sources in the sample contribute to the stacking.
Compared with the control samples, EVQs in brighter states exhibit clearly bluer spectra, and conversely redder spectra in dim states. The trend is consistent with the so-called “bluer-when-brighter” pattern widely seen in AGNs and quasars (see Section 5.1 for discussion).

From Figure 12, we also see clear line residuals in the spectra ratios of EVQs and the control samples, particularly for EVQ(ADS) and EVQ(Median), showing that EVQs tend to have stronger emission lines compared with their control samples. We present detailed comparison of the line EW in Section 4.2 and line profile in Section 4.3.

Note that in Figure 12 we only plot the DCSs (to avoid confusion). Replacing DCSs with LCS/MCS will not alter the results. A minor note is that the DCSs for ABS, MS, and ADS somehow exhibit slightly different spectral slopes between themselves, but this is only significant in the low redshift bin (H\(\beta\) sample). This is likely because these DCSs for EVQs have lower bolometric luminosity in dim states compared with those in bright states, which is largely the relatively stronger host contamination yields a redder spectrum. The effect of host contamination is much weaker at shorter rest-frame wavelength, thus the difference almost disappears in higher redshift bins, which is also consistent with previous studies which found that near-UV spectral slopes of quasars show little dependence on luminosity (e.g., Telfer et al. 2002; Bonning et al. 2007).

### 4.2. Line Equivalent Widths

Following the procedures we adopt to fit the individual spectra, we also fit the composite spectra to derive the line parameters. To illustrate the difference of the line EW between EVQs and their control samples, we plot in Figure 13 the best-fit line EWs (of [O III], C IV, broad Mg II, and H\(\beta\)) derived from the stacked spectra of EVQs in various states (and of their control samples).

Clearly, using the control samples as references (the main results we present below are indeed insensitive to the choice of control samples), we find that EVQs in EDS and DS tend to have larger line EWs and contrarily smaller EWs in EBS and BS. This could be primarily attributed to the so-called iBeff, by which emission line EW in individual AGNs often decreases when AGNs brighten (e.g., Pogge & Peterson 1992; Kinney et al. 1990; Homan et al. 2020).

Puzzlingly, the broad H\(\beta\) line behaves differently. Though the iBeff has been clearly detected in individual AGNs (Goad et al. 2004; Rakić et al. 2017), the stacked spectra of our EVQs exhibit no iBeff of broad H\(\beta\).

We further find that, from the overall trend, EVQs tend to have larger emission line EWs compared with the control samples, though the extent varies from dim to bright states due to the iBeff. By comparing the EW in MS, which is free from the iBeff, we find that the EW of broad Mg II in EVQs is higher by ∼47% compared with the control sample. For broad H\(\beta\), [O III], and C IV, the numbers are ∼27%, ∼25%, and ∼25%, respectively. Spectra ratio plots in Figure 12 also reveal clear line residuals around [O III], Mg II, and C IV lines, further demonstrating that EVQs have systematically larger line EWs compared with control samples. A minor note is that in Figure 12 we could barely see line residuals around H\(\beta\). The larger best-fit EW of H\(\beta\) in EVQs shown in Figure 13 might be due to the excess of the very broad component of H\(\beta\) in EVQs (see Section 4.3).

### 4.3. Line Profiles

We plot in Figure 14 the stacked emission line spectra of our EVQs in various states, in comparison with the control samples. Following Vanden Berk et al. (2001), the stacked emission line spectra were obtained through normalizing each spectrum by the continuum flux density at the corresponding line center, median stacking the spectra, fitting the median spectra, and subtracting the continuum models. From Figure 14, we could barely see differences in the line profiles...
between EVQs and the control samples. This is actually expected, as the control samples were built to have matched luminosity and SMBH mass with EVQs (thus matched broad-line FWHM, as the SMBH mass is a virial product of continuum luminosity and line FWHM). Note that the situation is slightly different for LCS. LCSs were built to have matched long-term averaged luminosity and single-epoch spectroscopy-based SMBH mass (compared with EVQs), thus the matching in line FWHM is not guaranteed. In fact, the LCSs for EVQs in bright (dim) states tend to have slightly larger (smaller) broad-line FWHMs. However, as we will show below, such an effect is weak and negligible. For MCS, since we use the long-term averaged luminosity to derived SMBH mass, matching in broad-line FWHM is also guaranteed. We again stress that the results we provide below are insensitive to the choice of the control samples.

To further explore potential subtle differences in the line profiles between EVQs and the control samples, we plot in Figure 15 the broad-line spectra normalized by accumulated line fluxes. The stacked line profile of broad H\(\beta\) and Mg II seem symmetric, and the C IV line exhibits clear redward skewness. Through plotting the spectra in logarithm space in Figure 15, we find that EVQs tend to have stronger broad-line wings compared with the control samples. The excesses in such broad-base components are generally seen in all three broad lines we consider (H\(\beta\), Mg II, and C IV) and all states of EVQs. They seem symmetric in Mg II (with excesses seen in both the blue and red wings), but redward asymmetric in C IV (only seen in the red wing) and probably also in the DSs of H\(\beta\).

We also plot in Figure 16 the distribution of Pearson skewness measured from individual sources for our EVQs and control samples. The patterns illustrated in Figure 16 are consistent with what we have revealed from the stacked line profiles (Figure 15). The median skewness values of broad H\(\beta\) and Mg II are much closer to zero than that of C IV, showing that H\(\beta\) and Mg II are mainly symmetric while C IV exhibits redward asymmetry. Because of the clear excess of the redshifted broad-base component, the C IV line of EVQs is dramatically more redward skewed compared with the control samples, and the K-S test gives \(p = 1.1 \times 10^{-32}\) between EVQs and DCSs and \(p = 2.1 \times 10^{-37}\) between EVQs and LCSs. The K-S test (see Figure 16) also reveals statistical difference
between the skewness parameter distributions between EVQs and their control samples for $\text{H}\beta$ and Mg II, suggesting that $\text{H}\beta$ and Mg II are also skewed slightly more redward in EVQs, though their median skewness values (of EVQs and control samples) are very close.

To explore the contribution of the excess quantitatively, the broad lines are further fitted with core and wing components. We use two Gaussians with FWHM < 6000 km s$^{-1}$ to represent the core component and one Gaussian with FWHM > 6000 km s$^{-1}$ for the very broad component (wing). The stacked spectra of EVQs in each state and of their corresponding control samples are fitted together, the line widths and line center are linked, and the normalization factor is free to vary. As a result, we find the very broad component in EVQs accounts for higher fraction of the total line flux compared with their control samples. The fraction contributed by the very broad component in EVQs (and in their control samples) to total line flux is $\sim$55.0% (39.5%) for $\text{H}\beta$, $\sim$47.6% (36.1%) for Mg II, and $\sim$55.2% (47.6%) for C IV, respectively.

5. Discussion

In this work we build a large sample of EVQs and divide them into subsamples according to their brightness states during spectroscopic observations. We carefully build control samples with matched redshift, luminosity, and SMBH mass. The comparison between EVQs and such control samples enables us to probe the nature and consequences of the extreme variability, precluding potential effects of these parameters. The control samples (with matched redshift, spectroscopic monochromatic luminosity, and line FWHM) also allow the comparison to be free from intricate observational biases (e.g., spectroscopic identification of quasars and spectral fitting may rely on spectral quality and line FWHM).

5.1. The “Bluer-When-Brighter” Pattern

Through comparing the composite spectra of EVQs at various states, we find that EVQs follow the general “bluer-when-brighter” pattern widely seen in quasars and AGNs (e.g., Cutri et al. 1985; Wamsteker et al. 1990; Clavel et al. 1991; Giveon et al. 1999; Webb & Malkan 2000; Trevese & Vagnetti 2001; Vanden Berk et al. 2004; Wilhite et al. 2005b; Meusinger et al. 2010; Sakata et al. 2011; Bian et al. 2012; Schmidt et al. 2012; Zuo et al. 2012; Ruan et al. 2014; Sun et al. 2014; Cai et al. 2016; Guo & Gu 2016; Cai et al. 2019; Guo et al. 2020a). The color variation is actually also visible in Figure 5, in which we could see that EVQs (which contribute
been attributed to host galaxy contamination (variation. Historically, the “bluer-when-brighter” pattern had been demonstrated in individual AGNs. For instance, a study like $H\beta$ of EVQs, but also to the clear iBeff of $H\beta$. This is not only contrary to the trend seen in eBeff: that the eBeff (see Figure 13). Clearly here using LCS or MCS as reference is less biased in probing the iBeff of EVQs here.

We see significant iBeff of Mg II and C IV in our EVQs, and the iBeff slopes are comparable to those reported in the literature for individual AGNs with multiple spectra. Statistically, the slope of Mg II iBeff is slightly steeper than that of C IV, which is contrary to the trend seen in eBeff: that the eBeff is stronger for lines with higher ionization energy (Dietrich et al. 2002), which might indicate that the physical origins of the iBeff and eBeff are not connected (Rakić et al. 2017). One possibility is that Mg II line is produced at larger distance and does not respond to continuum variation as fast as C IV, thus a stronger iBeff is expected.

However, it is rather puzzling that the broad $H\beta$ line of EVQs does not show clear iBeff. This is not only contrary to Mg II and C IV of EVQs, but also to the clear iBeff of $H\beta$ commonly detected in individual AGNs. For instance, a study on a few (six) long-term monitored AGNs revealed the iBeff of $H\beta$ in all subsets of type 1 AGNs (i.e., Seyfert 1, narrow line Seyfert 1 or high-luminosity quasars) with $\beta > -0.4$ (Rakić et al. 2017). But note that the reported iBeff slopes in the literature vary from source to source, or even from year to year for the same source (Goad et al. 2004; Rakić et al. 2017). We notice that the host galaxy contamination could reduce the continuum variability amplitude and thus alter the iBeff slope (see Section 3.6 in S11 for relevant discussion of the role of host contamination on the eBeff). However, even if after we restrict our search to EVQs at $\log L_{bol} > 45.8$ (the most luminous ∼10% EVQs in the $H\beta$ sample), we still get rather weak iBeff (with slopes well above −0.12).

The $H\beta$ line has been previously known to be exceptional in the eBeff. The eBeff always occurs in high-ionization emission lines whose correlation will be steeper when ionization energy goes higher (Dietrich et al. 2002). However, the Balmer lines, like $H\alpha$ and $H\beta$, exhibit no correlation (e.g., Kovačević et al. 2010; Popović & Kovačević 2011) or even a weak positive correlation (Croston et al. 2002; Greene & Ho 2005) between the EW and luminosity of continuum, although the Ly$\alpha$ line does exhibit eBeff (e.g., Dietrich et al. 2002). Meanwhile, a
recent work of Kang et al. (2021) found that while more variable quasars have clearly stronger (with larger EW) Mg II, [O III], and C IV lines (after correcting the effects of bolometric luminosity, BH mass, and redshift), broad Hβ shows rather weaker correlation between EW and UV/optical variability amplitude. This trend is also visible in Figures 13 and 14 in this work, such that while EVQs have systematically stronger Mg II and C IV lines compared with the control samples, the difference is less prominent for broad Hβ. It is yet unclear why Hβ behaves exceptionally. Dietrich et al. (2002) proposed that the lack of eBeff of Balmer lines might be due to the intricate and unclear radiation processes of Balmer lines (Netzer 2020).

We finally note that it would be intriguing to examine the iBeff of individual EVQs with multiple spectra. We will defer this to a future paper of this series.

5.3. EVQs Have Stronger Emission Lines

In Figure 13, we see that EVQs have systematically larger line EWs compared with their control samples. The difference is highly prominent for EVQs in the EDS because of the iBeff, remains statistically significant in the MS, and is even visible in the EBS for Mg II. A similar conclusion, free from our sample division, can also be found in Table 1 where we fit the correlation between the logEW/EWctrl and the $g_{\text{spec}} - g_{\text{mean}}$ of our EVQs. Compared with all three control samples, the intercepts are well above zero in the three emission line samples, further support our findings in stacked spectra.

Rumbaugh et al. (2018) reported that EVQs seem to have systematically larger EW in UV emission lines (compared with normal quasars with matched redshift and luminosity), and attributed such phenomenon to the overall lower Eddington ratio of EVQs. However, in this work, we find that EVQs have stronger emission lines, even compared with a group of control sample with matched luminosity and SMBH mass, and thus matched $\eta_{\text{Edd}}$. The results are unaltered if we rectify the measurements of bolometric luminosity and the virial BH mass, which might be biased by the extreme variability (see the comparison with LCS and MCS in Figure 13).

The discovery that EVQs have systematically stronger emission lines is in good agreement with a recent study by Kang et al. (2021), who found that the UV/optical variation amplitude of quasars in SDSS Stripe positively correlate with emission line EWs,\footnote{Kang et al. (2021) showed that the correlation between broad Hβ line EW and variability amplitude is, however, much weaker. This is also consistent with the pattern shown in our Figures 12 and 13.} after controlling for the effects of redshift, luminosity, and SMBH mass. One possible explanation for such correlation is that stronger disk fluctuations could lead to harder quasars SED (Cai et al. 2018), and thus provide relatively more ionizing photons. Alternatively, stronger disk turbulence may be able to launch BLR clouds with larger sky coverage.

Notably, Ross et al. (2020) reported several C IV changing-look quasars, which show iBeff of C IV line, and have larger C IV line EWs comparing with sources with matched SMBH mass (see Figure 3 of Ross et al. 2020). Therefore, we can see that normal quasars, EVQs, and CLQs exhibit similar iBeff, and they follow the same trend that more variable quasars tend to have systematically larger line EWs. These facts suggest common physical processes behind these various populations.

| Sample          | $\beta$      | $\alpha$     | Spearman’s Rank $\rho$ | $P$     |
|-----------------|--------------|--------------|------------------------|---------|
| Hβ EVQs-DCS     | −0.097 ± 0.030 | 0.054 ± 0.006 | −0.063                 | .003    |
| EVQs-LCS        | 0.038 ± 0.038 | 0.060 ± 0.006 | 0.018                  | .401    |
| EVQs-MCS        | 0.025 ± 0.036 | 0.053 ± 0.007 | 0.009                  | .670    |
| Mg II EVQs-DCS  | −0.387 ± 0.014 | 0.143 ± 0.003 | −0.286                 | $<10^{-10}$ |
| EVQs-LCS        | −0.649 ± 0.015 | 0.141 ± 0.003 | −0.443                 | $<10^{-10}$ |
| EVQs-MCS        | −0.628 ± 0.014 | 0.139 ± 0.003 | −0.439                 | $<10^{-10}$ |
| C IV EVQs-DCS   | −0.236 ± 0.040 | 0.107 ± 0.005 | −0.109                 | $<10^{-10}$ |
| EVQs-LCS        | −0.526 ± 0.030 | 0.105 ± 0.005 | −0.237                 | $<10^{-10}$ |
| EVQs-MCS        | −0.475 ± 0.033 | 0.107 ± 0.005 | −0.231                 | $<10^{-10}$ |

Table 1

Note. The iBeff slope of EVQs presented in Figure 17, (3) and (4) are the best-fit slope $\beta$ and the intercept $\alpha$ in Equation (11). (5) and (6) are the Spearman’s rank correlation coefficient $\rho$ and the corresponding confidence level $P$ value.
Comparing the broad-line profiles of EVQs with their control samples, we find that EVQs exhibit subtle excess of the very broad-line component (VBC, see Figure 15). The excess is similarly visible in all states of EVQs. Statistical studies on line profiles have suggested the BLR of quasars consists of two components: a very broad-line region (VBLR) closer to the central SMBH and an intermediate line region (ILR) at larger distance (Wills et al. 1993; Brotherton et al. 1994; Sulentic et al. 2000). The existence of multiple BLR components is further supported by variation studies that revealed distinct variation patterns of the two line components (e.g., Sulentic et al. 2000; Hu et al. 2020; Guo et al. 2020a). Since the VBLR lies closer to the SMBH, the VBC could easily reverberate (respond to the variation of the central ionizing continuum) in a short time. Contrarily, the ILR may appear nonreverberating or reverberating at a much longer time. The observed “antibreathing” of CIV line (i.e., the line broadens when luminosity increases) could also be attributed to the combination of the two components (e.g., Denney 2012; Wang et al. 2020).

The likely physical origin of the VBLR is optically thin gas located near the BH (Popovic et al. 1995; Corbin 1997a, 1997b). The Keplerian velocity of that gas could lead to a very broad-line width, and the SMBH gravity could yield systematic line redshift. The excess of the VBC we discover in EVQs suggests that the small disk turbulence associated with the extreme variability could launch more gas into the VBLR from the accretion disk.

The excess of the VBC is clearly redward skewed in CIV, but not in MgII and Hβ. This is likely because the dominant ILR CIV flux comes from the accretion disk wind, which is significantly outflowing, thus yielding systematically blue-shifted emission (see also Section 5.6), whereas the VBLR is not outflowing. Furthermore, the gravitational redshift of the VBLR could be more prominent for CIV, which could locate at smaller radii compared to MgII and Hβ.

5.5. Radio Loudness

It’s interesting to note that radio-loud AGNs and blazars tend to show excess of redshifted VBCs of BELs, particularly in high-ionization line CIV (Punsly et al. 2020), and the CIV red wing luminosity excess was found to correlate with radio-loudness (the spectral index from 10 GHz to 1350 Å, Punsly 2010). Such redshifted VBC could be produced by gas lying deep within the gravitational potential of the central SMBH, and for the nearly face-on orientation in blazars, the gravitational redshift could be comparatively large (Punsly et al. 2020). The redward excess is somehow similar to what we find in the CIV profile in EVQs. However, our study to radio-quiet quasars (quasars with $f_{o cm}/f_{2500}>10$ based on FIRST detections, assuming a radio spectral index of $\alpha = -0.5$, are defined as radio-loud, Jiang et al. 2007) does not alter the results in this work. Furthermore, the radio-loud fraction in our EVQ sample ($-5.06\% \pm 0.18\%$) is also comparable to that in the control samples ($-3.95\% \pm 0.16\%$). Thus the discoveries in this work are due to a small fraction of radio-loud quasars in our samples, but represent the properties of the general population of EVQs.

In Figure 18, we further plot the MgII and CIV line skewness of radio-loud EVQs, compared with the full sample. The median skewness parameters and the K-S test indicate that radio-loud EVQs do show (but slightly) more redward skewness (statistically marginal for CIV).

Punsly et al. (2020) also found that blazars with lower Eddington ratio tend to show strong redward asymmetry, which can be explained as the Eddington ratio influenced the distance of the most efficient BLR to the central BH. However, in this work since the control samples were selected to have matched Eddington ratios, thus the stronger very broad component and more redward asymmetric CIV line profile we found in EVQs cannot not be attributed to lower Eddington ratios.

5.6. C IV Systematical Blueshift

It has been widely reported that the high-ionization BELs in luminous quasars are often significantly shifted blueward with respect to low-ionization lines (e.g., Gaskell 1982; Wilkes 1986; Corbin 1990; Sulentic et al. 2000, 2007; Richards et al. 2002, 2011; Baskin & Laor 2005; Shen et al. 2008; Wang et al. 2011; Denney 2012; Shen & Liu 2012; Coatman et al. 2016, 2017; Sun et al. 2018). Such blueshift is commonly contributed to accretion-disk winds (e.g., Richards et al. 2011; Denney 2012).

We test whether the CIV blueshift in EVQs differs from that in the control samples, using quasars with redshift $1.5 < z < 2.25$ for which the low-ionization MgII line is available to derive the systematical redshift. We measure the velocity offset of the CIV line in each quasar, for both the line peak and the bisectional line center ($\lambda_b$ that bisect the total line flux, Sun et al. 2018), with respect to the systematical redshift determined from the MgII line peak. We find that while both EVQs and their control samples show clear CIV blueshift on average (with negative median values of the offset), the median peak blueshift is marginally ($<2\sigma$) weaker in EVQs (see Figure 19). Note the K-S test shows that the distribution of CIV line peak velocity offset in EVQs is different from that of the control sample DCS with a P value of $6 \times 10^{-10}$. This indicates that, compared with the median line peak blueshift, the line peak velocity offset distribution better reveals the difference between EVQs and the control sample.

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12 Two fractions are slightly different likely because the photometric selection of radio-detected and nondetected quasar candidates for SDSS spectroscopic observations was not uniform (Richards et al. 2002).
We further find the C IV bisectional line center of EVQs shows a redward-skewed distribution (with a positive median velocity offset), clearly different from their control samples (with negative offsets), and the K-S test yields a P value of $5 \times 10^{-18}$ between EVQs and DCS. That is, because of the more redward-skewed line profile of C IV in EVQs, though the line peak is blueshifted, the bisectional line center is contrarily redshifted. This pattern is consistent with what we have revealed from the stacked line profile (see Section 4.3). The difference in the line profile may also partially account for the weaker C IV peak blueshift in EVQs. We note that the series weak emission lines (He II λ1640, [O III] λ1663, and He II λ1671) that reside in the red wing of C IV could also affect the bisectional line center. However, considering that those lines are relatively weak and submerged in the flux of C IV, it is very hard to measure those lines precisely with current low SNR spectra. Nevertheless, given their line centers, which are ∼100 Å away from that of C IV, they are not likely to affect the peak of C IV nor to contribute the red excess of C IV.

It has been theoretically proposed that the disk wind in quasars could be driven by either radiation pressure (continuum and/or UV line) or magneto-centrifugal forces, or some combination thereof (de Kool & Begelman 1995; Murray et al. 1995; Proga et al. 2000). As EVQs have stronger emission line compared with their control samples with matched redshift, UV monochromatic luminosity, and SMBH mass, they may have relatively stronger ionization continuum (see Section 5.3), thus stronger continuum radiation pressure is expected. The fact that the C IV line peak blueshift in EVQs is weaker than that in the control samples disfavors the scenario that the wind acceleration is dominated by continuum radiation pressure.

6. Conclusions

We have built a sample of 14,012 EVQs using the combined SDSS and PS1 light curves with a time span of 4 ~ 15 yr and sorted them into different states according to the deviation of the spectra luminosity of each EVQ from its mean photometric luminosity. Through comparing the EVQ samples in various states and well-defined control samples with matched redshift, luminosity, and SMBH mass, we derive the following main findings:

1. The “bluer-when-brighter” pattern commonly seen in AGNs and quasars is clearly and similarly presented in EVQs (see Figure 12). This finding suggests that the extreme variability might be due to the same mechanism as common variability.

2. We see significantly higher line EWs of broad Mg II and C IV in dimmer states compared with those in brighter states. The trend is both qualitatively and quantitatively similar to the iBeff reported in literature in individual AGNs (see Figure 17). However, it is puzzling that the broad H β line EW in EVQs shows no dependence on brightness state.

3. We find that the EVQs have systematically greater EW, compared with control samples, in both broad (H β, Mg II, and C IV) and narrow ([O III]) lines (see Figure 13). The EW excess of Mg II is the most prominent, reaching ~47%. Such phenomenon could be related to the strong disk fluctuation/turbulence in EVQs, which may produce harder ionizing spectra and/or higher coverage of BLR.

4. We find that EVQs show subtle excess in the VBL component, compared to their control samples (see Figure 15). This is likely because the stronger disk turbulence associated with the extreme variability in EVQs could launch relatively more gas from the inner disk into the VBLR.

5. EVQs show weaker C IV line peak blueshift with respect to the systematic redshift derived from the Mg II line, compared with the control samples. While the blueshifted core of the C IV line might come from an outflowing intermediate line region, the relatively stronger redshifted VBC in EVQs makes the C IV line more redward skewed in EVQs (see Figure 16), compared with the control samples.

In total, 2341 of our EVQs have multiepoch SDSS spectra, including 62 with at least six spectra. This provides us a good chance to explore the spectral variability of continuum and emission lines in a large sample of individual EVQs, which will be presented in a future work in this series.

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Appendix

An Alternative Rebinning Strategy

The underlying population of EVQs from EDS to EBS is continuous without gaps. We divide the EVQs into five classes according to $g_{\text{spec}} - g_{\text{mean}}$ (see Section 3.1). Alternatively, one may choose $(g_{\text{spec}} - g_{\text{mean}})/\Delta g_{\text{max}}$ to define the spectral states (see Figure A1). The new rebinning strategy, however, does not alter the results presented in this work. For instance, see Figure A1. Similar to Figure 9, but using $(g_{\text{spec}} - g_{\text{mean}})/\Delta g_{\text{max}}$ instead of $g_{\text{spec}} - g_{\text{mean}}$ to rebin the EVQ sample.
Figure A2. Similar to Figure 13, but the EVQs were divided into five classes using the alternative strategy demonstrated in Figure A1.

Figure A2 for an updated version of Figure 13 with this new strategy.

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