The origin and evolution of C IV Baldwin effect in QSOs from the Sloan Digital Sky Survey

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Abstract

Using a large sample of 26 623 quasars with redshifts in the range 1.5 ≤ z ≤ 5.1 with C IV line in Fifth Data Release of the Sloan Digital Sky Survey (SDSS), we investigate the cosmological evolution of the Baldwin effect, i.e. the relation between the equivalent width (EW) of the C IV emission line and continuum luminosity. We confirm the earlier result that there exists a strong correlation between the C IV EW and the continuum luminosity, and we find that, up to z ≈ 5, the slope of the Baldwin effect seems to have no effect of cosmological evolution. A subsample of 13 960 quasars with broad C IV emission line from SDSS is used to explore the origin of the Baldwin effect. We find that C IV EW have a strong correlation with the mass of supermassive black hole (SMBH), and a weak correlation with the Eddington ratio, L_Bol/L_Edd. This suggests that the SMBH mass is probably the primary drive for the Baldwin effect.

Key words: black hole physics – galaxies: active – galaxies: nuclei.

1 INTRODUCTION

The discovery of an anticorrelation between the equivalent width (EW) of C IV 1549 Å emission line and the continuum luminosity measured at 1450 Å in quasar rest frame, known as the Baldwin effect, was first made by Baldwin (1977) (e.g. see a review by Shields 2006). This correlation was explored in active galactic nuclei (AGNs) for other broad emission lines, such as Lyα, C IV 1909, He II 1640, Mg II 2800, Si IV 1400, O VI 1034, N v 1240, Hβ 4861 Å. For narrow emission lines, such as [O III] λ5007, [O II] λ3727, [N V] λ3462, [N II] λ3869; even for the Fe Kα emission line in X-ray spectrum (e.g. Wampler et al. 1984; Baldwin, Wampler & Gaskell 1989; Boroson & Green 1992; Netzer, Laor & Gondhalekar 1992; Iwasawa & Taniguchi 1993; Francis & Koratkar 1995; Laor et al. 1995; Green 1996; Nandra et al. 1997; Croom et al. 2002; Dietrich et al. 2002; Baskin & Laor 2004; Page et al. 2004; Warner, Hamann & Dietrich 2004; Zhou & Wang 2005; Netzer et al. 2006). Over the past 30 yr, a significant amount of effort has been expended to confirm this effect and explore its origin and evolution.

The slope of line EW versus the luminosity for different ions depends on their ionization energy (e.g. Dietrich et al. 2002). However, we are not sure whether the slope of the Baldwin effect evolves with redshift.

Several interpretations about the origin of Baldwin effect have been proposed. It is not clear whether the Baldwin effect is driven by the underlying physical parameters, such as the redshift, eigenvector of Boroson & Green (1992), the Eddington ratio (i.e. the ratio of the bolometric luminosity to the Eddington luminosity), the mass of supermassive black hole (SMBH), the gas metallicity (e.g. Dietrich et al. 2002; Shang et al. 2003; Bachev et al. 2004; Baskin & Laor 2004; Warner et al. 2004; Sulentic et al. 2007). Baskin & Laor (2004) found a strong correlation between the C IV EW and the Eddington ratio, and suggested that the Eddington ratio is the primary physical parameters driving the Baldwin effect. However, Shang et al. (2003) used the method of spectral principal component (SPC) to find there is no correlation between the Baldwin effect and the Eddington ratio or the mass as underlying physical parameters.

With the reverberation mapping result, we may calculate the virial SMBH mass from the broad lines (e.g. Hβ, Hα, Mg II, C IV, Kaspi et al. 2000; Bian & Zhao 2004; Vestergaard & Peterson 2006; Salviander et al. 2007). It provides the possibility to explore these underlying physical parameters for the origin of C IV Baldwin effect.

In the past, most of the work was made by using relatively small samples. For a sample of 20 quasars, Baldwin (1977) first discovered this effect. Wills et al. (1999) used a complete sample of 22 quasi-stellar objects (QSOs) from the Bright Quasar Survey (BQS) to discuss the relation between the Baldwin effect and the eigenvector 1. For a sample of 993 quasars from the Large Bright Quasar Survey (LBQS), Green, Forster & Kuraszkiewicz (2001) studied the relations of C IV EW with the continuum luminosity and redshift. Dietrich et al. (2002) used a large sample of 744 type 1 AGNs

1 Their luminosity at 2500 Å is derived from the Bα photometric magnitude, since the LBQS spectra are not spectrophotometric.
From $0 < z < 5$ from International Ultraviolet Explorer (IUE) and Hubble Space Telescope (HST) to discuss the correlations of continuum and emission-line properties in the rest-frame ultraviolet and optical spectral ranges.

Here we use a large sample of 26,623 quasars with C\textsc{iv} emission line from the Fifth Data Release (DR5; Adelman-McCarthy et al. 2007) catalogue of the Sloan Digital Sky Survey (SDSS) to discuss C\textsc{iv} Baldwin effect and its evolutionary effect, and we also use a large sample of 13,960 quasars with broad C\textsc{iv} emission line to discuss the underlying physical parameters of the Baldwin effect. The sample is described in Section 2, the results and the analysis are given in Section 3 and the conclusions are presented in Section 4.

2 SAMPLE

The sample used in this paper is selected from SDSS-I DR5 (Adelman-McCarthy et al. 2007). SDSS-I was completed and DR5 (Adelman-McCarthy et al. 2007) was made public on 2006 June 30. The SDSS Quasar Survey is continuing via the SDSS-II Legacy Survey. SDSS-I DR5 covers an imaging area of about 8000 deg$^2$ and a spectroscopic area of about 5740 deg$^2$. SDSS DR5 catalogue consists of 90,611 objects with automated spectral classification in SDSS DR5. Recently, Schneider et al. (2007) presented a quasars catalogue from SDSS DR5, consisting of 77,429 quasars with $M_j < -22$. The wavelength coverage of SDSS spectrum is 3800 to 9200 Å and we select 33,943 quasars with redshift $1.5 \leq z \leq 6.0$ to make C\textsc{iv} $\lambda 1549$ available in SDSS spectrum.

There are three stages during the pipeline of SDSS spectral fit. The first two stages are used to find lines to determine the line redshift. The third stage is used to measure the line feature by a single Gaussian fit for the continuum-subtracted spectrum. The chi-squared values can be used to evaluate the quality of the fit. We select the following parameters of these quasars for our discussion: redshift ($z$), mid of observation (mjd), plate ID (plate), fiber ID (fiberID), $\sigma$ of fitted gaussian (sigma), error of $\sigma$ (sigma_err), equivalent width (EW), error in equivalent width (EW_err), continuum flux value at 1549 Å ($f_{1549}$), $\chi^2$ of fit (chisq) and degree of freedom (nu, v).

Through the SQL search language, we get 27,545 objects from SpecLine table in the SDSS DR5 with automated spectral classification of quasar, redshift $1.5 \leq z \leq 6.0$ and the redshift confidence not less than 95 per cent. 922 objects with negative values of C\textsc{iv} EW or with EW_err values larger than the values of its EW are excluded. At last, we have a sample of 26,623 quasars with C\textsc{iv} emission line to discuss the C\textsc{iv} Baldwin effect and its evolutionary effect. In Fig. 1 we show the histogram of the redshift. Only two quasars have redshifts larger than 5, their redshifts are 5.032.

In order to explore whether the Eddington ratio or and the SMBH mass is/are the underlying physical parameters for the origin of the Baldwin effect, we calculate the SMBH mass for quasars with broad C\textsc{iv} line. For a sample of 130 AGNs with HST archival spectra, Sulentic et al. (2007) suggested subtracting a narrow component of C\textsc{iv} $\lambda 1549$ Å with full width at half-maximum (FWHM) $\leq$ 1500 km s$^{-1}$ to discuss C\textsc{iv} $\lambda 1549$ Å as an eigenvector 1 parameter. Then in our paper, from SDSS DR5, a subsample of 13,960 quasars with broad C\textsc{iv} emission line is selected by the following criterions: (1) $\sigma / (1+z) \geq 3.3$ Å, corresponding 1500 km s$^{-1}$ of C\textsc{iv}

$$\chi^2 / \nu < 1.5,$$ showing acceptable one Gaussian fit of C\textsc{iv} emission line.

3 RESULTS AND DISCUSSION

3.1 The slope and correlation coefficient of the Baldwin effect

The C\textsc{iv} EW is from the result of SQL searching. The continuum luminosity $L_\lambda(1549\ \text{Å})$ at rest frame is calculated from its flux ($f_{1549}$) by the following formula:

$$L_\lambda(1549\ \text{Å}) = 4\pi d_L^2 f_{1549},$$

where $d_L$ is the luminosity distance. For flat universe,

$$d_L = c(1+z)H_0^{-1} \int_0^z dz\left[(1+z)^2(1+\Omega_Mz) - z(2+z)\Omega_L\right]^{-1/2},$$

where $c$ is the speed of light, $H_0$ is the present Hubble constant, $\Omega_M$ is the mass density and $\Omega_L$ is the vacuum density. The cosmological

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2 http://cas.sdss.org/astrodr5/en/help/docs/algorith.asp
3 http://cas.sdss.org/astro/en/help/docs/sql_help.asp

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Table 1. Results of the previous studies and of our work. Column (1): the article; column (2): the sample of the work; column (3): redshift; column (4): the slopes of the linear fit for the Baldwin effect of the studies.

| Article                        | Sample                          | Redshift          | Slope         |
|-------------------------------|---------------------------------|-------------------|---------------|
| Our paper                     | 26 623 quasars from SDSS DR5    | $1.5 \leq z < 5.1$ | $-0.156 \pm 0.0002$ |
| Kinney et al. (1990)          | 101 quasars and 88 type 1 Seyfert galaxies | $z < 2.0$       | $-0.17 \pm 0.04$  |
| Espey & Andreadis (1999)      | 200 AGNs                        | $z > 1.0$        | $-0.17 \pm 0.03$  |
| Zamorani et al. (1992)        | Five ‘complete’ samples         | $0.001 \leq z \leq 3.822$ | $-0.13 \pm 0.03$  |
| Kuraszkiewicz et al. (2002)   | 158 AGNs                       | $0 \leq z \leq 5.0$ | $-0.198 \pm 0.036$ |
| Dietrich et al. (2002)        | 744 AGNs                       |                   | $-0.14 \pm 0.02$  |

Fig. 3. The log–log correlation between the C iv EW and the continuum luminosity at 1549 Å (in erg s$^{-1}$ Å$^{-1}$) for the DR5 sample of 26 623 quasars in different redshift bins. Each redshift bin is marked in every graph. Solid lines are the linear fits.

Table 2. Results for the samples in different redshift bins. Column (1): different redshift bins; column (2): number of quasars in different redshift bins; column (3): correlation coefficient of the linear fit; column (4): slope of the linear fit together with its error; column (5): intercept of the linear fit with its error at $\log L_\lambda (1549$ Å) = $10^{42}$ erg s$^{-1}$; column (6): the possibility of null hypothesis.

| $z$                          | $N$     | $R$  | Slope              | Intercept             | $P$       |
|------------------------------|---------|------|--------------------|-----------------------|-----------|
| $1.5 \leq z < 2.0$          | 14 370  | $-0.360$ | $-0.231 \pm 0.0003$ | $1.980 \pm 0.022$   | $<10^{-4}$ |
| $2.0 \leq z < 2.5$          | 6 076   | $-0.349$ | $-0.251 \pm 0.0005$ | $2.050 \pm 0.032$   | $<10^{-4}$ |
| $2.5 \leq z < 3.5$          | 4 338   | $-0.384$ | $-0.251 \pm 0.0006$ | $2.176 \pm 0.035$   | $<10^{-4}$ |
| $3.5 \leq z \leq 5.1$       | 1 839   | $-0.337$ | $-0.237 \pm 0.0015$ | $2.210 \pm 0.092$   | $<10^{-4}$ |

The following formula is used to express the relation between C iv EW and the continuum luminosity:

$$\log \text{EW(C IV)} = \alpha + \beta \log L_\lambda (1549$ Å). (3)
The slope is $\beta = -0.156 \pm 0.0002$ and the intercept is $\alpha = 8.549 \pm 0.011$. An unweighted least-square fitting is also given (denoted with dash line in Fig. 2). We notice that the centroid of the distribution of the data is between these two fit lines. The dash line is shifted vertically with respect to the solid line, which is due to that the C IV lines with lower EWs usually have the larger errors in logarithm space, and thus have smaller weights in our fitting. In the hereafter linear fittings, we just show the results of weighted least-square linear fittings, taking the mean value of the upper and lower errors of C IV EWs as the fitting weights.

By IUE spectra, Kinney, Rivolo & Koratkar (1990) found that the slope is $-0.17 \pm 0.04$ and Espey & Andreadis (1999) found it is $-0.17 \pm 0.03$. By the optical selected sample, Zamorani et al. (1992) found it is $-0.13 \pm 0.03$. For a sample of 158 AGNs observed with the Faint Object Spectrograph on the HST, Kurkaszkiewicz & Green (2002) found it is $-0.198 \pm 0.036$. Dietrich et al. (2002) found the slope is $-0.14 \pm 0.02$ for their total sample, and $-0.20 \pm 0.03$ for objects with $\log L_\lambda (1450 \, \text{Å}) \geq 44 \, \text{erg s}^{-1}$. We get a slope, $\beta = -0.156 \pm 0.0002$, which is consistent with some previous studies (Osmer, Porter & Green 1994; Laor et al. 1995; Green 1996; Dietrich et al. 2002). In Table 1, we list the results of the above researches.

The redshift coverage of our sample is from 1.5 to 5.1 (see Fig. 1). We divide our sample into four parts according to the redshift, and the redshift bins are $1.5 \leq z \leq 2, 2 < z \leq 2.5, 2.5 < z \leq 3.5$ and $3.5 < z \leq 5.1$. Fig. 3 presents the C IV Baldwin effect in different redshift bins. For each redshift bin, considering the error of C IV EW, we use the least-square linear regression to find the correlation between C IV EW and the continuum luminosity at 1549 Å. We find a strong correlation for different redshift bins. The correlation coefficients and the slopes are listed in Table 2. Steeper slopes are found in these four redshift bins, respect to the total sample, and this is similar to the results of the paper from Dietrich et al. (2002). For these four bins, the slopes are almost the same, which shows no cosmological evolution of the C IV Baldwin effect up to $z \approx 5$.

### 3.2 The origin of Baldwin effect

The physical origin for the Baldwin effect is still an open question. It is suggested that the Baldwin effect is driven by the Eddington ratio and/or the SMBH mass (e.g. Baskin & Laor 2004; Warner et al. 2004). Using 81 BQS quasars, Baskin & Laor (2004) found that the correlation coefficient between C IV EW and the continuum luminosity is $-0.154$, and the correlation coefficient between C IV EW and the Eddington ratio is $-0.581$. They suggested that Baldwin effect is driven by Eddington ratio, $L_{\text{Edd}}/L_{\text{Bol}}$.

We calculate the SMBH mass from FWHM of C IV emission line by the following formula (e.g. Vestergaard & Peterson 2006):

$$
\log M_{\text{BH}}(\text{C IV}) = \log \left( \frac{\text{FWHM(IV)}}{1000 \, \text{km s}^{-1}} \right)^2 \left( \frac{\lambda L_\lambda(1350 \, \text{Å})}{10^{44} \, \text{erg s}^{-1}} \right)^{0.55} + (6.66 \pm 0.01),
$$

where FWHM(IV) = 2.35σ/(1 + z) in units of km s$^{-1}$, z is the redshift. The uncertainty of the SMBH mass is due to the errors of FWHM(IV), $\lambda L_\lambda(1350 \, \text{Å})$, and the system error in equations (4) is from the uncertainties of the broad-line regions (BLRs) geometry and dynamics. The uncertainty of our calculated SMBH mass is about 0.5 dex (Vestergaard & Peterson 2006).

We also calculate the Eddington ratio, e.g. the ratio of the bolometric luminosity ($L_{\text{Bol}}$) to the Eddington luminosity ($L_{\text{Edd}}$), where $L_{\text{Edd}} = 1.26 \times 10^{38} (M_{\text{BH}}/M_\odot) \, \text{erg s}^{-1}$. The bolometric luminosity is calculated from the monochromatic luminosity at 1350 Å,

$$
L_{\text{Bol}} = c \, L_{1350},
$$

where $L_{1350}$ is the continuum luminosity at 1350 Å and $c = 3 \sim 5$ (Richards et al. 2006), and we take $c = 4$. Considering the uncertainty of our calculated SMBH mass is about 0.5 dex, the uncertainty of the Eddington ratio is about 0.5 dex or more.

In order to calculate the SMBH mass, we use a subsample of 13 960 quasars with broad C IV emission line from SDSS DR5,
which is stated in Section 2. In Fig. 4, we show the relations between the C iv EW with SMBH mass, the continuum luminosity at 1549 Å and Eddington ratio, \( L_{\text{bol}}/L_{\text{Edd}} \). The results of these three relations are listed in Table 3.

Our results show that the correlation coefficient for the relation between C iv EW and the continuum luminosity is larger than that of the other two relations. Furthermore, the correlation coefficient of C iv EW with SMBH mass is larger than that of C iv EW with Eddington ratio. Therefore, by the larger sample, we cannot confirm the suggestion that the Eddington ratio is the underlying parameter for C iv Baldwin effect, and maybe the SMBH mass is a better driving parameter.

Here we also present the relations between the C iv EW and the continuum luminosity, the SMBH mass and \( L_{\text{bol}}/L_{\text{Edd}} \) in different redshift bins, same to that in Section 3.1 (see Table 4).

### 4 CONCLUSIONS

Baldwin effect has been explored for a long time and we are still doing our efforts to explore it. In our paper, we discuss the Baldwin effect and its evolutionary effect from a large sample of 26 623 quasars (1.5 \( \leq z \leq 5.1 \)) from DR5. And also, using a sample of 13 960 quasars with broad C iv emission line from DR5, we explore the physical parameters that drive the C iv Baldwin effect. The main conclusions can be summarized as follows. (1) Baldwin effect exists in the large sample of 26623 quasars from DR5 of SDSS. (2) According to the slopes in our four redshift bins, up to \( z \approx 5 \), there is no evolutionary effect for the slope of Baldwin effect, however, these slopes are relatively steeper than the slope for the total sample of 26 623 quasars. (3) By the 13 960 quasars with SMBH masses estimate, we find that the relation between C iv EW and SMBH mass is stronger than that between C iv EW and \( L_{\text{bol}}/L_{\text{Edd}} \) (from \( R = -0.344 \) to \( -0.128 \)), SMBH mass seems to be a better underlying physical parameter.

### ACKNOWLEDGMENTS

We thank the anonymous referee for his/her comments and instructive suggestions. This work has been supported by the National Science Foundation of China (Nos 10773010, 10778616, 10633020, 10403005, 10325313, 10233030 and 10521001), the Science-Technology Key Foundation from Education Department of P.R. China (No. 2060503) and the China Postdoctoral Science Foundation (No. 20060400502).

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