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Relation between the "Double-Hump" Behavior in the Radio Band and the Broad-Line Luminosity for Blazars

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Abstract The physics behind the spectral energy distribution (SED) of blazars remains open. We assembled 36 blazars to tackle the factors that control their SED. Now, many blazar spectra have the "double hump" feature in the radio and far-IR frequencies. For these a parameter, $\triangle$, is created to characterize the behavior of the SED. We found a significant correlation between the broad-line luminosity ($L_{\rm BLR}$) and $\triangle$. Because $L_{\rm BLR}$ is an indicator of the accreting power of the source in blazars, we derived a linear correlation, $\triangle \propto \dot{M}^{1/3.18}$, which suggests that the SED of blazars may depend on the accretion rate, like that of BL Lac objects. We also found a significant correlation between $\dot{m}$ and $\triangle$ for a sample of 11 blazars (out of one of 36) with available black hole masses. This implies the Eddington accretion ratio may influence the shape of the SED of blazars.

Key words: accretion: accretion disks — black hole physics — galaxies: active — galaxies: emission lines — galaxies: nuclei

1 INTRODUCTION

It is well known that the spectral energy distributions (SEDs) of blazars are characterized by a global double-humped shape (i.e., two distinct global maxima), with the lower-frequency emission originating from synchrotron radiation in relativistic beamed jets, and the high-frequency radiation from Inverse-Compton processes. For many blazars, there is also the special spectral feature of two distinct local maxima, one near centimeter band in the blazar rest frame (the "cm peak") and one near submillimeter or millimeter wavelengths (the "mm peak") (Punsly 1996a). To characterize the local "double hump" behavior at the radio band, a parameter, Δ, is introduced, defined as the logarithm of the ratio of the fluxes at the cm peak to the mm peak (Punsly 1996a),

$$\Delta = \log\Big[\frac{(F_\nu)_{\rm cm}}{(F_\nu)_{\rm mm}}\Big]. \tag{1}$$

On the basis of 118 quasi-simultaneous spectra belonging to 56 core-dominated radio sources, Punsly (1996) found that Δ is strongly correlated with the accretion rate ($\dot{M}$) and nuclear gas density. In addition, based on Cao & Jiang (1999) and Celotti et al. (1997), the luminosity in the broad-line region can be taken as an indictor of the accreting power for both steep and flat-spectrum quasars. On the other hand, using a large sample of BL Lac objects, Wang, Staubert & Ho (2002) have found some interesting results that the peak frequency of the SED, $\gamma_{\rm pk}$, and the peak luminosity of the SED are correlated with the accretion rate, thus, the SEDs of BL Lac objects depend on the accretion rates. These interesting results motivated us to ask what the main physical parameters are that control the SEDs of blazars. We study this issue in this paper based on the work of Wang et al. (2002), and using the relation between Δ and the broad-line luminosity.

Table 1 Radio and BLR Data of the Sample

Source (1)	Class (2)	z (3)	Δ (4)	$\log F_{\rm BLR}$ (5)	$\log L_{\rm BLR}$ (6)	$L^{\rm ob}_{\rm bol}$ (7)	$\log \Delta t_{\rm min}$ (8)	Ref. (9)	α (10)	δ (11)	$\log(M_{\rm H}/M_\odot)$ (12)	$\log \dot{m}$ (13)
2136+141	LQ	2.430	0.95	–12.65	45.51	46.31						
0945+556	HQ	0.901	0.88	–12.63	44.69	45.67						
2134+004	LQ	1.936	0.75	–12.13	45.82	46.47						
2145+067	LQ	0.990	0.75	–11.93	45.45	46.19						
0212+735	HQ	2.367	0.73	–13.69	44.46	46.02						
0836+710	LQ	2.170	0.66	–12.12	45.93	46.65						
0923+392	LQ	0.698	0.62	–11.55	45.52	45.63						
1611+343	LQ	1.401	0.55	–12.17	45.57	45.93						
0906+015	HQ	1.020	0.52	–12.62	44.78	45.86						
2230+114	HQ	1.040	0.51	–11.87	45.55	48.16	4.60	X04	1.0	3.17	9.0	–1.56
2201+315	LQ	0.300	0.50	–11.00	45.33	45.54						
1741–038	HQ	1.057	0.50	–13.27	44.16	45.72						
1803+784	BL	0.680	0.485	–12.75	44.30	46.15						
0016+731	LQ	1.760	0.460	–13.36	44.51	45.65						
1532+016	HQ	1.440	0.450	–13.26	44.46	45.70						
1641+399	HQ	0.595	0.440	–11.69	45.24	46.80	3.90	X05	1.0	2.06	8.5	–1.37
1226+023	LQ	0.158	0.430	–10.27	45.43	47.10	4.57	Ba83	1.0	1.97	9.0	–1.68
1954+513	LQ	1.220	0.410	–13.02	45.01	45.59						
0906+430	HQ	0.670	0.400	–13.95	43.08	45.32						
1055+018	HQ	0.888	0.400	–13.06	44.23	45.56						
0420–014	HQ	0.915	0.395	–12.70	44.60	47.0	4.65	Ba83	1.0	1.81	8.9	–2.41
1253–055	HQ	0.538	0.380	–12.42	44.08	46.10	3.69	X99	1.0	1.87	8.0	–2.03
2223–052	HQ	1.404	0.372	–12.46	45.22	45.00						
0133+476	HQ	0.860	0.370	–11.79	44.17	45.53						
1510–089	HQ	0.360	0.330	–12.00	44.44	46.90	3.51	X04	1.0	2.94	8.1	–1.77
2251+158	HQ	0.859	0.290	–11.88	45.39	46.80						
1308+326	BL	0.996	0.280	–12.60	44.70	44.70						
1101+384	BL	0.031	0.275	–12.94	41.33	45.70	3.26	X98	0.92	1.90	7.6	–4.38
1538+149	BL	0.605	0.270	–14.07	42.88	46.40						
1633+382	LQ	1.810	0.265	–12.52	45.30	46.15						
0954+658	BL	0.368	0.225	–14.04	42.47	45.35						
0736+017	LQ	0.191	0.220	–11.80	44.15	44.61	4.16	Cle03	1.0	1.00	8.4	–2.36
0851+202	BL	0.306	0.140	–12.88	43.43	46.40	3.70	X01	1.20	2.10	8.1	–2.78
2200+420	BL	0.069	0.130	–12.49	42.48	45.00	3.44	Wei73	2.30	1.20	7.7	–3.33
1823+568	BL	0.644	0.120	–13.96	43.08	45.20						
0235+164	BL	0.940	0.100	–13.79	43.51	47.77	4.67	Ba83	1.89	2.56	9.0	–3.60

References: Ba83: Bassani et al. (1983); X98: Xie et al. (1998); X99: Xie et al. (1999); X01: Xie et al. (2001); X04: Xie et al. (2004b); X05: Xie et al. (2005); Wei73: Weitrop et al. (1973); Cle03: Clements et al. (2003).

2 THE SAMPLE

Based on the catalogue of emission data of radio-loud source compiled by Cao & Jiang (1999) and quasi-simultaneous spectral properties of core-dominated radio sources from radio to far-infrared wavelengths observed by Punsly (1996a), we have compiled a sample of 36 blazars, for which the quantity Δ and the broad-line luminosity have been obtained by Punsly (1996a) and Cao & Jiang (1999), respectively. Among them nine objects are BL lac objects and 27 objects are radio-loud QSOs. For these sources, mean values of Δ, $\bar{\Delta}$, will be taken when available, otherwise the individual values Δ. See Table 1 Column 4.

The table headings are: (1) Source; (2) Class: the class of the source; (3) z: red-shift; (4) Δ; (5) the flux of the emission line $\log F_{\rm BLR}$ in units of erg cm^{-2} s^{-1}; (6) the logarithm of luminosity of emission line in units of erg s^{-1}. In Column 2 we have LQ: Low polarization quasars; HQ: High polarization quasars; and BL: BL Lac objects. For emission lines, we use the data from Cao & Jiang (1999), except for the two objects, 1101+384 and 2200+420, whose data are taken from Morganti et al. (1992) and Vermeulen et al. (1995), respectively. Moreover, here $H_0 = 75$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$ are adopted.

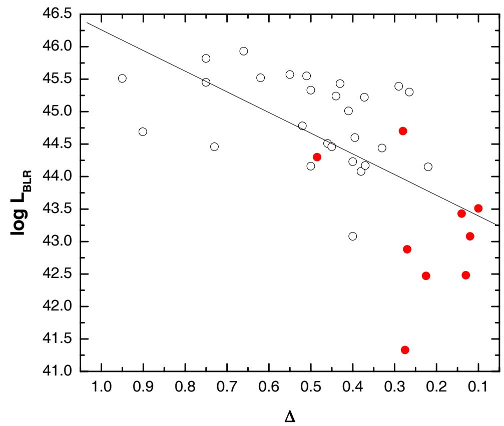

Fig. 1 Relation between broad-line luminosity and Δ. The empty circles represent quasars and the filled circles BL Lac objects.

3 RELATIONS BETWEEN $L_{\rm BLR}$ AND Δ

The relations between $L_{\rm BLR}$ and Δ are shown in Figure 1, in which the circle and the filled circle represent BL Lac objects and quasars, respectively. A linear regression analysis for the relevant data was applied to the correlation between $L_{\rm BLR}$ and Δ. A significant correlation was found between $L_{\rm BLR}$ and Δ for our sample. The correlation coefficient is $\gamma = 0.61$ and the chance probability is less than 10^{-4}. The linear regression equation is

$$\log L_{\rm BLR} = 3.1845\Delta + 43.0755. \tag{2}$$

These results show there is a strong correlation between $L_{\rm BLR}$ and Δ for radio-loud quasars and BL Lac objects.

The results in this section seem to show that the luminosity of the broad-line emission can be used as an indictor of the accretion power.

It is well known that the accretion rate is an important parameter for understanding the nature of AGNs. Punsly (1996) has demonstrated that the physical parameter Δ is strongly correlated with the accretion rate ($\dot{M}$) and the nuclear gas densities. On the other hand, the broad-line region is photon- ionized by a nuclear source (probably radiation from the disc), so the broad-line emission can be used as an indictor of the accreting power for both steep-spectrum and flat-spectrum quasars (Celotti et al. 1997; Cao & Jiang 1999). The luminosity in the broad-line region can be taken as an indicator of the accreting power of the source (Celotti et al. 1997). In addition, on the basis of present theories of accretion disk, Maraschi & Tavecchio (2003) obtained

$$L_{\rm disk} = \varepsilon \dot{M} c^2, \tag{3}$$

and

$$L_{\rm disk} = \frac{1}{\tau} L_{\rm BLR}, \tag{4}$$

where $L_{\rm disk}$ is the luminosity of the accretion disk, $\dot{M}$ is the accretion rate, $L_{\rm BLR}$ is the luminosity of the broad-line region, and $\varepsilon \approx \tau \approx 0.1$ (Maraschi & Tavecchio 2003). From Equations (3) and (4), we have

$$L_{\rm BLR} \approx \varepsilon \tau \dot{M} c^2. \tag{5}$$

Comparing Equation (5) with Equation (2), one can see that the correlation found in this paper between $L_{\rm BLR}$ and Δ proves straightforwardly a close link between the broad-line luminosity and the accretion rate on to the central black hole. In addition, from Equations (5) and (2), we have

$$\Delta \propto \dot{M}^{1/3.18}, \tag{6}$$

where Δ, defined in Equation (1) above, is a dimensionless parameter which has been introduced to describe the ubiquitous "double-humped" spectrum found for core-dominated radio quasars in Punsly (1996a). From Equations (6) and (1), we can see that the SED of blazars depends also on the accretion rates of BL Lac like objects which have been found by Wang et al. (2002). Obviously, our results confirmed and developed the results of Wang et al. (2002). On the other hand, our results are consistent with the results of Celotti et al. (1997), Cao & Jiang (1999), and Maraschi & Tavecchio (2003). In addition, it is a new and independent piece of evidence that the luminosity of the broad-line region can be taken as an indicator of the accreting power of the source. In the second place, from Figure 1, we can see that radio-loud QSOs and BL Lac objects are in a continuous evolutionary sequence: radio-loud QSOs occupy the region of high luminosity and larger Δ (higher accretion rates $\dot{M}$), and BL Lac objects occupy the region of low luminosity and smaller Δ (lower accretion rates). The $L_{\rm BLR}$ and Δ diagram seems to show that the evolutionary track of AGNs is from radio-loud QSOs to BL Lac objects. Our results support that of Xie et al. (2004b) and Xie et al. (2006).

A good interpretation of this phenomenon is that QSOs occur in the earlier and violent phase of the evolution of elliptical galaxy when the galxy had significant amounts of gas in their central regions. This gas, as evidenced by the observed emission lines, produced violent radio and optical activity. When the gas was used up or expelled, the emission lines will become very weak or disappear. Moreover, the operation of the central engine became more variable. Then the quasar evolves into a BL Lac object. BL Lac objects are mainly powered by the extraction of the rotational energy of the central super-massive black hole (SMBHs) via the Blandford-Znajek (BZ) mechanism.

4 RELATIONS BETWEEN THE EDDINGTON ACCRETION RATIO AND Δ

A strong correlation between Δ and accretion rate has been found by Punsly (1996a). However, what is the relation between the Eddington accretion ratio and Δ? In this section, we will estimate the black hole mass and test whether there is a relation between the Eddington accretion ratio and Δ.

4.1 Black Hole Mass and Eddington Accretion Ratio

On the basis of Xie et al. (2005), we have a reliable method of estimating black hole mass through the minimum variability and the Kerr black hole theory.

Assuming that the supermassive black hole (SMBH) in the blazar is a Kerr black hole with the maximum possible speed of rotation, the SMBH mass can be estimated by a formula with the minimum variation timescale and the Doppler factor given by Xie, Zhou & Liang (2004c),

$$M_{\rm H} = 1.62 \times 10^4 \frac{\delta}{1+z} \Delta t_{\rm min,ob} M_{\odot}. \tag{7}$$

The Doppler factor, δ, is estimated by the relation presented by Xie et al. (1991),

$$\delta \geq \left[5.0 \times \frac{10^{-43} \Delta L_{\rm ob} / \Delta t_{\rm min,ob}}{0.057} \right]^{\frac{1}{4+\alpha}}. \tag{8}$$

For that, an extensive literature search for reported blazar variability was performed. Depending on two criteria we searched reported sources that have short time variation scale. First we searched for possible quasi-periodic variability in the observed flux curves. We define the quantity $P_{\rm min}$ to be the minimum time interval between local maximum in the flux curves required for a flux change of $\frac{\Delta I}{I} \geq 50\%$ between a local maximum and minimum. In addition, the amplitude of variation on this timescale must be larger than 5σ, σ being the maximum total observational rms error (Xie et al. 2002, 2004a). Secondly, if the observed light curve was found to have only one maximum and one minimum, we define twice the interval between the maximum and minimum as the minimum time scale for flux variations. The observed minimum variation timescales (in seconds) are listed in Table 1, Column 8, and the relevant reference in Column 9. Column 10 gives the spectral index; Column 11, the Doppler factor; and Column 12, the logarithm of the black hole mass.

Based on the assumption that the observed emission lines are photoionized by the central accretion disk, Wang, Staubert & Ho (2002) obtained some important results. Now we also use the line luminosities to estimate the accretion luminosities and accretion rates.

$$\dot{m} = \frac{L_{\rm BLR}}{L_{\rm Edd}}. \tag{9}$$

The item $\log \dot{m}$ is given in Column 13 of Table 1.

4.2 Eddington Accretion Ratio and Δ

Figure 2 shows the dependence of Δ on the Eddington accretion ratio. We find that Δ correlates significantly with the Eddington accretion ratio for 11 blazars whose black hole masses are available in our sample of 36 blazars. In addition, there is a significant correlation between Δ and $\dot{m}$,

$$\log \dot{m} = 4.8981\Delta - 3.9708, \tag{10}$$

with $\gamma = 0.7221$ and $p = 1.21 \times 10^{-2}$. This implies $\dot{m} \propto \Delta$. That is, the ratio of flux at the cm peak to the flux at the mm peak of SED of blazar correlates with the Eddington accretion ratio. Obviously, this result is very interesting as it shows that the Eddington accretion ratio could influence the shape of the SED of blazars.

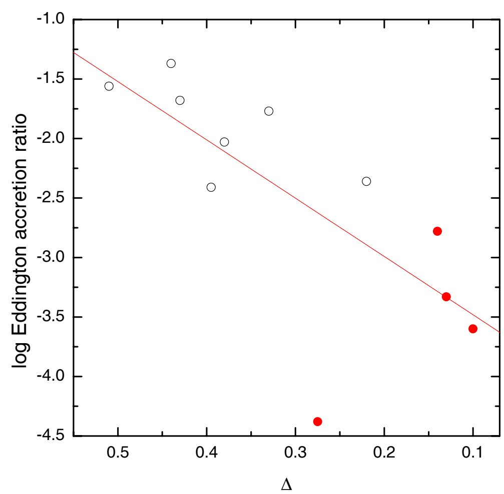

Fig. 2 Relation between $\dot{m}$ and Δ. The empty circles represent quasars and the filled circles, BL Lac objects.

5 CONCLUSIONS AND DISCUSSION

Using a sample of blazars with available information on their "Double-Hump" behaviour in radio band and on their emission-line luminosities, we found that FSRQs (flat-spectrum radio QSOs) have significantly higher accretion rates and Eddington accretion ratio than BL Lac objects. The broad-line luminosity of blazars correlates significantly with a physical parameter Δ, —the logarithm of the ratio of the flux at cm peak to the flux at the mm peak. We argue that these results indicate the SED of blazars also depends on the accretion rates like BL Lac objects. Our results support the theoretical model of Wang et al. (2002). In addition, using the minimum variability timescale and the Kerr black hole theory, one can estimate the black hole mass for 11 sources with available black hole mass in our sample of 36 blazars and find that Δ correlates with the Eddington accretion ratio, albeit for a more limited sample. These results directly support the view that the Eddington accretion ratio influences the SED of blazars. In Punsly's (1996a) sample, one notes that most objects with small Δ have smaller redshifts, while objects of large Δ have higher redshifts. One could therefore be worried whether the correlations may be results of selection effect. We therefore applied a partial correlation regression analysis to our respective samples of 36 and 11 blazars. It is well known that in the case of three variables, the correlation between two of them, excluding the effect of the third one, is (with r_{ij} denoting the correlation coefficient between x_i and x_j),

$$r_{12,3} = \frac{r_{12} - r_{13}r_{23}}{(1 - r_{13}^2)^{1/2}(1 - r_{23}^2)^{1/2}}. \quad (11)$$

Thus, after the effect of the redshift is excluded, for the sample of 36 blazars, we obtain the partial correlation coefficient between $\log L_{\rm BRL}$ and Δ, $r_{\rm BLR\Delta,z} \approx 0.431$ with a chance probability $p \approx 8.61 \times 10^{-3}$; and for the sample of 11 blazars, we obtained $r_{\rm BLR\Delta,z} \approx 0.683$ with a chance probability $p \approx 2.56 \times 10^{-2}$. These results show that the correlation between the broad-line luminosity and Δ and that between the Eddington accretion ratio and Δ is convincing. However, the second sample is rather small, and it would be of interest to perform photometric monitoring of blazars to search for the short variability timescale of the sample.

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