Chin. J. Astron. Astrophys. Vol. 6 (2006), No. 6, 649–654
(*http://www.chjaa.org*)

Chinese Journal of
Astronomy and
Astrophysics

On the Geometry of Broad-Line Regions in BL Lac Objects *

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Received 2006 March 8; accepted 2006 April 22

Abstract The geometry of broad-line regions (BLRs) in active galactic nuclei (AGNs) is still controversial. We use a sample of BL Lac objects, of which the black hole masses $M_{\rm bh}$ are estimated from their host galaxy absolute magnitude at R-band, M_R, by using the empirical relation between M_R and black hole mass $M_{\rm bh}$. The sizes of the broad-line regions for $\rm Mg{\small II}$ are derived from the widths of $\rm Mg{\small II}$ lines and the black hole masses. Compared with the empirical relation between BLR size $R_{\rm BLR}$ and MgII line luminosity $L_{\rm MgII}$, it is found the BLR sizes in the BL Lac objects derived in this paper are 2–3 orders of magnitude higher. If the BLR geometry of these sources is disklike, then the viewing angle between the axis and the line of sight is in the range of $\sim 2^\circ - 15^\circ$, which is consistent with the unification scheme.

Key words: galaxies: active—BL Lacertae objects: general—accretion, accretion disks—black hole physics

1 INTRODUCTION

The tight correlation between the black hole mass and stellar velocity dispersion($M_{\rm bh}$–σ relation) is widely used to estimate the central black hole masses of active galactic nuclei (AGNs) (Ferrarese & Merritt 2000; Gebhardt et al. 2000). Unfortunately, the stellar velocity dispersion σ is available only for a small fraction of AGNs. Now, McLure & Dunlop (2002) derived a very tight correlation between the host galaxy absolute magnitude in the R-band, M_R, and $M_{\rm bh}$, and this relation is alternatively used to estimate the black hole mass when σ is unavailable.

The sizes of the BLR (broad line region) from the broad-line Hβ were measured by Kaspi et al. (2000) for a sample of quasars and Seyfert galaxies using the reverberation mapping method. They found a tight correlation between the BLR size and optical continuum luminosity λL_λ. Using the width of the broad emission line and measured BLR size, they estimated the central black hole masses of the sources in their sample assuming the clouds in the BLR to be virialized. For sources at high redshifts, the emission line Hβ is usually unavailable. Instead, the width of the $\rm Mg{\small II}$ line can be used to estimate the central black hole mass (McLure & Jarvis 2002). The $\rm Mg{\small II}$ line is a low-ionization line, like Hβ, so it is expected to be produced in the same region as Hβ, and this expectation is supported by the tight correlation between the FWHMs (FWHM = Full-Width at Half-Maximum) of Mg II and Hβ ($V_{\rm FWHM}$(MgII)≈ $V_{\rm FWHM}$(Hβ)) found by McLure & Jarvis (2002). It is therefore reasonable to expect that $\rm Mg{\small II}$ and Hβ lines are produced in the same region. However, for blazars, the optical/UV continuum emission may be dominated by jet emission. Using the value of the BLR size of the reverberation mapping sample from Peterson et al. (2004), Kong et al. (2006) obtained a correlation between the BLR size and the $\rm Mg{\small II}$ emission line luminosity. Wu et al. (2004) suggested a correlation between $R_{\rm BLR}$ and $L_{\rm H\beta}$, which may be suitable even for blazars (see Kong et al. 2006 for the cases in the UV waveband).

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* Supported by the National Natural Science Foundation of China.

For most AGNs, their BLR sizes have not been measured directly by reverberation mapping, so the empirical relation $R_{\rm BLR}$–$L_{\rm line}$ is used to derive $R_{\rm BLR}$. Combining the line widths, the central black hole masses can be estimated by assuming the motion of clouds in BLRs to be virialized. The estimated black hole masses depend sensitively on the velocity of the clouds in the BLR ($\propto V_{\rm BLR}^2$). The broad-line width is mainly governed by the projected component of the cloud velocity $V_{\rm BLR}$ on the line of sight. Now, if the motion of BLR clouds is anisotropic (e.g., if the BLR has a disk-like geometry), then estimation of the black hole mass becomes complicated (e.g., Jarvis & McLure 2002; Wu & Han 2001). Moreover, Mclure & Dunlop (2001) argued that the BLRs in some AGNs do have a disk-like geometry. If a disk-like BLR geometry is indeed present, then the observed broad-line width depends sensitively on the orientation of disk axis, making the orientation crucial in the estimation of the black hole mass from the broad-line width.

In the unification scheme, the jets of BL Lac objects are supposed to be inclined at small angles with respect to the line of sight (see Urry & Padovani 1995 for a review), so the broad-line profiles will be significantly narrower if the disk-like BLR is perpendicular to the jets. This circumstance can be used to test the geometry of the BLRs in BL Lac objects. In a previous paper, this geometry was explored by using a fixed equivalent width EW$_{\rm ion}$ to estimate the ionizing luminosities from the observed broad-line emission of the BL Lac object (Cao 2004). The derived inclination angles are quite small, consistent with the unification scheme.

In this paper, we estimate the black hole masses of BL Lac objects from their host galaxy luminosities. Using the observed broad-line widths and luminosities instead of using an assumed EW$_{\rm ion}$ to estimate the ionizing luminosity, we can test the geometry of the BLR through a comparison with the empirical relation between $R_{\rm BLR}$ and $L_{\rm MgII}$.

The cosmological parameters, $\Omega_{\rm M} = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 70\ {\rm km\ s^{-1}\ Mpc^{-1}}$, have been adopted in this paper.

2 BLACK HOLE MASS

To estimate the central black hole mass $M_{\rm bh}$ of a BL Lac object, we use its relation to its host galaxy absolute magnitude M_R at R-band proposed by McLure & Dunlop (2004),

$$\log_{10}(M_{\rm bh}/M_\odot) = -0.50(\pm 0.02)M_R - 2.75(\pm 0.53). \quad (1)$$

There are different surveys of host galaxies of BL Lac objects (e.g., Urry et al. 2000; Pursimo et al. 2002; Nilsson et al. 2003). In this paper, we searched the literature for all BL Lac objects with both measured host galaxies and broad emission line profiles. As only a small fraction of BL Lac objects exhibits broad-line emission, we finally obtained a sample of 16 such objects. All the data collected are list in Table 1, the Columns are: (1) Source name, (2) Redshift, (3) Galactic extinction- and K-corrected R-band magnitude of the host galaxy, (4) References for R-band magnitude of the host galaxy, (5) FWHM of broad-line Mg II, (6) References for FWHM(Mg II), (7) The luminosity of Mg II emission line, and (8) References for $L_{\rm MgII}$. The apparent magnitudes of the host galaxies at R-band listed in Table 1 are galactic extinction- and K-corrected. The derived parameters of these sources are listed in Table 2. The columns are: (1) Source name, (2) Black hole mass, (3) BLR size for Mg II (light-day), and (4) Inclination angle of the jet with respect to the line of sight. Only upper limits on host galaxy luminosity are available for nine of the sources of our sample. We estimate the central black hole masses of these BL Lac objects from their host galaxy luminosities, and their broad-line profiles are used to explore their BLR geometry. The black hole masses of two sources in our sample have been measured from the stellar velocity dispersion σ, which gives $\log(M_{\rm bh}/M_\odot)$=8.65 (for 0521−365), 8.51 (for 1807+698) (Barth et al. 2003), and 8.90 (for 1807+698) (Falomo et al. 2002), respectively. The black hole masses of these two sources derived from their host galaxy luminosity are $\log(M_{\rm bh}/M_\odot)$=8.56 (for 0521−365), 8.88 (for 1807+698) (see Table 2). We can conclude that the black hole masses derived from the host galaxy luminosity are quite reliable.

3 SIZE OF THE BLR OF BL LAC OBJECTS

The BLR size can be derived from the FWHM of the broad line

$$R_{\rm BLR} = \frac{GM_{\rm bh}}{f^2 V_{\rm FWHM}^2}, \quad (2)$$

Table 1 Data of BL Lac Objects

Source (1)	Redshift (2)	m_R(host) (3)	Ref. (4)	FWHM(Mg II) (5)	Ref. (6)	log $L_{\rm MgII}$ (7)	Ref. (8)
0138−097	0.733	>18.38	1	4842	4	42.07	4
0521−365	0.055	14.35	1	$3000^{\rm a,b}$	5	41.76	11
0715−259	0.465	16.76	1	5200	6	42.41	6
0820+225	0.951	>19.38	1	2995	7	41.87	7
0823+033	0.506	>19.04	1	5455	7	42.18	7
0851+202	0.306	18.44	2	$2635^{\rm c}$	8	41.67	8
0954+658	0.367	>18.85	1	$2079^{\rm a}$	9	42.71	4
1144−379	1.048	>19.93	1	2492	8	42.16	8
1308+326	0.996	>18.36	2,3	4016	7	43.48	7
1538+149	0.605	18.73	1	2411	7	41.89	7
1803+784	0.684	>19.15	1	3082	4	43.12	9
1807+698	0.051	13.54	1	$1326^{\rm a}$	3	42.47	7
1823+568	0.664	18.57	1	3952	4	42.13	7
2131−021	1.285	>18.50	1	3602	4	42.45	4
2200+420	0.069	14.55	1	$4260^{\rm a}$	10	41.58	7
2240−260	0.774	>20.22	1	2753	7	42.31	7

a: FWHM of Hα. b: The profile of broad-line Hα in this source is asymmetric with a red wing of FWHM $\simeq$ 3000 km s^{-1} and a blue wing of FWHM$\simeq$ 1500 km s^{-1} Scarpa, Falomo & Pian (1995). Here, we conservatively take FWHM=3000 km s^{-1}. c: FWHM of Hβ.

References: (1) Urry et al. (2000); (2) Rector & Stocke (2001); (3) Scarpa, Falomo & Pian (1995); (4) Tadhunter et al. (1993) (5) Carangelo et al. (2003); (6) Stickel, Fried & Kühr (1993); (7) Pursimo et al. 2002; (8) Stickel, Fried & Kühr (1989); (9) Lawrence et al. (1996); (10) Nilsson et al. (2003); (11) Corbett et al. (1996).

Table 2 Derived Parameters of BL Lac Objects

Source (1)	log $M_{\rm bh}/M_\odot$ (2)	log $R_{\rm BLR}$ (3)	i (°) (4)
0138−097	<9.70	<3.16	>5.7
0521−365	8.56	2.34	12.3
0715−259	9.91	3.31	6.1
0820+225	<9.55	<3.43	>3.7
0823+033	<8.88	<2.24	>8.3
0851+202	<8.78	<2.78	>9.3
0954+658	<8.56	<2.68	>15.1
1144−379	<9.40	<3.44	>4.4
1308+326	<10.12	<3.75	>7.4
1538+149	9.27	3.34	4.2
1803+784	<9.22	<3.08	>12.8
1807+698	8.88	3.46	5.8
1823+568	9.47	3.11	6.4
2131−021	<10.39	<4.11	>2.4
2200+420	8.71	2.18	13.1
2240−260	<8.85	<2.81	>10.2

when the central black hole mass $M_{\rm bh}$ is available. The correction factor is $f = 1/(2\sin i)$ for a pure disk-like BLR with axis inclined to the line of sight at an angle i (McLure & Dunlop 2001), and is $f = \sqrt{3}/2$ for clouds moving at random inclinations (Wandel et al. 1999; Kaspi et al. 2000). Eleven sources in our sample have been measured FWHM of the broad-line Mg II, and four of Hα and one of Hβ. The broad-line $\rm Mg II$ is expected to be produced in the same region of the BLR as the Hβ line, so we take $V_{\rm FWHM}(\rm MgII) = \rm V_{FWHM}(H\beta)$ for the source of which only the line width of Hβ is available. Using the black hole mass $M_{\rm bh}$ derived from the host galaxy luminosity and velocity $V_{\rm FWHM}$, we can calculate the BLR size by using Equation (2) on the assumption of isotropic motion of clouds in the BLR, setting $f = \sqrt{3}/2$. We convert the size $R_{\rm BLR}({\rm H}\alpha)$ to $R_{\rm BLR}({\rm H}\beta)$ using equation (2) in Kaspi et al. (2000),

$$R_{\rm BLR}({\rm H}\alpha) = 1.19(\pm 0.23) R_{\rm BLR}({\rm H}\beta) + 13(\pm 19)\ \ {\rm lt-day}, \qquad (3)$$

for those sources of which only the line widths of Hα are available.

4 THE LUMINOSITY OF MgII EMISSION LINE

The observed continuum luminosity of an AGN is mainly contributed by its nucleus in most cases, while in some cases, especially in radio-loud quasars and BL Lac objects, contribution of nonthermal emission of jet and the host galaxy is also important. Jet emission has so far been detected in all types of radio sources at optical/UV/X-ray/γ-ray bands (Jester 2003). More than ten UV/optical jets have been found (O'Dea et al. 1999; Scarpa & Urry 2002; Parma et al. 2003; Scarpa et al. 1999). To diminish the jet contribution, as well as the continuum radiation from host galaxy (though it is much weaker than the AGN), the line luminosity should be used to deduce the $R_{\rm BLR}$–L relation. Wu et al. (2004) have suggested a new relation between the BLR size and the Hβ emission line luminosity. Similar to that of Hβ line, the MgII line luminosity may be a better tracer of the ionizing luminosity for radio-loud AGNs than the UV continuum luminosity. Although the detailed line radiation mechanisms are different (Hβ being a recombination line and MgII being collisionally excited lines), the two lines are both permitted lines produced by photo-ionization. Kong et al. (2006) obtained a correlation between the BLR size and MgII emission line luminosity,

$$\log \frac{R_{\rm BLR}^{\rm emp}}{\rm lt.days} = (1.13 \pm 0.13) + (0.57 \pm 0.12) \log \left(\frac{L_{\rm MgII}}{10^{42}\,{\rm erg\ s^{-1}}} \right), \qquad (4)$$

which is especially useful for sources at high redshifts. In order to avoid confusion with the BLR sizes derived from Equation (2), we use $R_{\rm BLR}^{\rm emp}$ to represent the BLR sizes derived from the empirical relation (4).

5 RESULTS AND DISCUSSION

We plot the relation between the luminosity $L_{\rm MgII}$ at 2798 Å and BLR size $R_{\rm BLR}$ in Figure 1. The BLR size $R_{\rm BLR}$ is derived from the width of the broad line MgII and the black hole mass $M_{\rm bh}$ on the assumption of isotropic motion of clouds in the BLR, i.e., by putting $f = \sqrt{3}/2$ in Equation (2). We can also derive the BLR size $R_{\rm BLR}^{\rm emp}$ using the empirical relation (4). If the motion of BLR clouds is indeed isotropic, one may

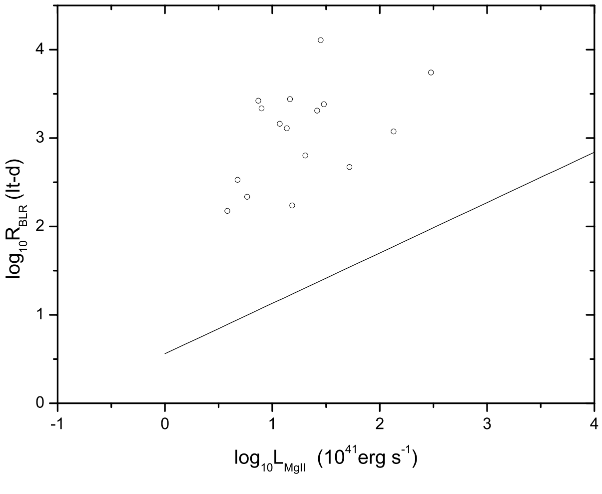

Fig. 1 Relation between the BLR size $R_{\rm BLR}$ and the luminosity of MgII emission line. The line represents the relation between the $R_{\rm BLR}^{\rm emp}$ and $L_{\rm MgII}$ defined by Seyfert 1 galaxies and quasars (Kong et al. 2006).

expect similar BLR sizes derived by the two different methods. However, it is found that the sizes of BLRs in all these sources are ∼2–3 orders of magnitude larger than $R_{\rm BLR}^{\rm emp}$ expected from Equation (4).

We note that, for nine of the 16 sources, only upper limits on the black hole mass are available. The BLR sizes may be over-estimated for these nine sources, because of the way the BLR sizes are derived (see Eq. (2)). The black hole masses estimated from the host galaxy luminosities for these 16 sources are in the range of $\sim 10^{8.6} - 10^{10.4}\,M_\odot$ (see Table 2). The deviations of the BLR sizes $R_{\rm BLR}$ from $R_{\rm BLR}^{\rm emp}$ expected by Equation (4) cannot be solely attributed to the overestimation of black hole masses for those nine sources with upper limit on galaxy luminosity, unless the black hole masses have been overestimated by $2-3$ orders of magnitude, for the realistic black hole masses should be in the range of $\sim 10^{6} - 10^{8}\,M_\odot$ for these sources, which seems impossible. It will be more difficult to attribute such deviations to an overestimation of black hole masses for those seven sources with well measured host galaxy luminosities. The black hole mass of the source $1807 + 698$ was measured from its stellar velocity dispersion σ (Falomo et al. 2002; Barth et al. 2003), and is consistent with our estimate of $10^{8.88}\,M_\odot$. For this source, its BLR size derived from Equation (2) is about three orders of magnitude higher than the $R_{\rm BLR}^{\rm emp}$ predicted by Equation (4) between $R_{\rm BLR}^{\rm emp}$ and $L_{\rm MgII}$.

Our estimate of BLR sizes may be greatly overestimated due to anisotropic cloud motion, if the velocity component projected to the line of sight is only a small fraction of its real velocity. A most likely candidate for such anisotropic motion of clouds is the clouds orbiting in a disk-like BLR (e.g., McLure & Dunlop 2001; Wu & Han 2001). For the clouds orbiting in a disk-like BLR, the correction factor f in Equation (2) is $1/(2\sin i)$ (i the angle of inclination of the axis to the line of sight, McLure & Dunlop 2001). If this is the case, we can estimate the inclination angle i of these BL Lac objects assuming them indeed to obey the correlation $R_{\rm BLR}$–$L_{\rm MgII}$ suggested by Kong et al. (2006), i.e., we estimate a value of f by letting $R_{\rm BLR} = R_{\rm BLR}^{\rm emp}$. We then find that the inclination angles are around $\sim 2^\circ - 15^\circ$ for these BL Lac objects. There is evidence that the velocity field of BLR is better described by a combination of a random isotropic component, with characteristic velocity $V_{\rm r}$, and a component only in the plane of the disk, with characteristic velocity $V_{\rm p}$ (Wills & Browne 1986). In this case, the observed FWHM will be given by

$$V_{\rm FWHM} = 2(V_{\rm r}^2 + V_{\rm p}^2 \sin^2 i)^{1/2} \tag{5}$$

(McLure & Dunlop 2001), so $f = 0.5[(V_{\rm r}/V_{\rm p})^2 + \sin^2 i]^{-1/2}$. If the random isotropic component is important, i.e., $V_{\rm r}$ is comparable with $V_{\rm p}$, then the term $(V_{\rm r}/V_{\rm p})^2$ cannot be neglected and the derived inclined angles of the disk axis will be less than that listed in Table 2. This is in general consistent with the unification scheme that the jets of BL Lac objects are inclined at small angles to the line of sight. The results obtained here are quite similar to those obtained by Cao (2004), which are derived by using a fixed $\mathrm{EW}_{\rm ion} = 10$ Å to estimate the ionizing luminosity from the observed narrow-line emission. It implies that $\mathrm{EW}_{\rm ion} = 10$ Å can be adopted to estimate the ionizing luminosity from the narrow-line emission for BL Lac objects (or even flat-spectrum radio-loud quasars).

Acknowledgements We thank the anonymous referee for valuable suggestions. This work is supported by the NSFC (Nos. 10325314 and 10333020). This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under a contract with NASA.

References

Baker J. C., Hunstead R. W., Kapahi V. K. et al., 1999, ApJS, 122, 29
Barth A. J., Ho L. C., Sargent W. L. W., 2003, ApJ, 583, 134
Blandford R. D., Rees M. J., 1978, in Wolfe A. N., ed., BL Lac objects, University Pittsburgh Press, Pittsburgh, p.328
Cao X. W., 2002, ApJ, 570, L13
Cao X. W., 2003, ApJ, 599, 147
Cao X. W., 2004, ApJ, 609, 80
Carangelo N., Falomo R., Kotilainen J. et al., 2003, A&A, 412, 651
Corbett E. A., Robinson A., Axon D. J. et al., 1996, MNRAS, 281, 737
Falomo R., Kotilainen J. K., Treves A., 2002, ApJ, 569, L35

Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Francis P. J., Hewett P. C., Foltz C. B. et al., 1991, ApJ, 373, 465
Gebhardt K., Bender R., Bower G. et al., 2000, ApJ, 539, L13
Inskip K. J., Best P. N., Rawlings S. et al., 2003, MNRAS, 337, 1381
Jarvis M. J., McLure R. J., 2002, MNRAS, 336, L38
Kaspi S., Smith P. S., Netzer H. et al., 2000, ApJ, 533, 631
Kong M. Z., Wu X. B., Wang R. et al., 2006, Chin. J. Astron. Astrophys. (ChJAA), 6(4), 396 (astro-ph/0512609)
Lawrence C. R., Zucker J. R., Readhead A. C. S. et al., 1996, ApJS, 107, 541
Mahadevan R., 1997, ApJ, 477, 585
McLure R. J., Dunlop J. S., 2001, MNRAS, 327, 199
McLure R. J., Dunlop J. S., 2002, MNRAS, 331, 795
McLure R. J., Dunlop J. S., 2004, MNRAS, 352,1390M
McLure R. J., Jarvis M. J., 2002, MNRAS, 337, 109
Nilsson K., Pursimo T., Heidt J. et al., 2003, A&A, 400, 95
O'Dowd M., Urry C. M., Scarpa R., 2002, ApJ, 580, 96O
Peterson B. M., Wanders I., Bertram R. et al., 1998, ApJ, 501, 82
Peterson B. M., Ferrarese L., Gilbert K. M. et al., 2004, ApJ, 613, 682
Pursimo T., Nilsson K., Takalo L. O. et al., 2002, A&A, 381, 810
Rawlings S., Saunders R., 1991, Nature, 349, 138
Rector T. A., Stocke J. T., 2001, AJ, 122, 565
Santos-Lleo M., Clavel J., Schulz B. et al., 2001, A&A, 369, 57
Scarpa R., Falomo R., Pian E., 1995, A&A, 303, 730
Stickel M., Fried J. W., Kühr H., 1989, A&AS, 80, 103
Stickel M., Fried J. W., Kühr H., 1993, A&AS, 98, 393
Tadhunter C. N., Morganti R., di Serego-Alighieri S. et al., 1993, MNRAS, 263, 999
Urry C. M., Padovani P., 1995, PASP, 107, 803
Urry C. M., Scarpa R., O'Dowd M. et al., 2000, ApJ, 532, 816
Wandel A., Peterson B. M., Malkan M. A., 1999, ApJ, 526, 579
Wang T.-G., Zhang X.-G., 2003, MNRAS, 340, 793
Willott C. J., Rawlings S., Blundell K. M. et al., 1999, MNRAS, 309, 1017
Wills B. J., Browne I. W. A., 1986, ApJ, 302, 56
Wu X.-B., Han J. L., 2001,ApJ, 561, L59
Wu X.-B., Wang R., Kong M. Z. et al., 2004, A&A, 424, 793