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EVIDENCE FOR ANISOTROPIC MOTION OF THE CLOUDS IN BROAD-LINE REGIONS OF BL LACERTAE OBJECTS

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ABSTRACT

The masses of central massive black holes in BL Lac objects are estimated from their host galaxy absolute magnitude $M_R$ at $R$-band by using the empirical relation between $M_R$ and black hole mass $M_{bh}$. Only a small fraction of BL Lac objects exhibit weak broad-line emission, and we derive the sizes of the broad-line regions (BLRs) in these BL Lac objects from the widths of their broad emission lines on the assumption of the clouds being virialized in BLRs. It is found that the sizes of the BLRs in these sources are usually 2–3 orders of magnitude larger than those expected by the empirical correlation $R_{BLR} \sim \lambda L_{\lambda}(3000 \text{ Å})$ defined by a sample of Seyfert galaxies and quasars. We discuss a variety of possibilities and suggest that this difference can probably be attributed to anisotropic motion of the BLR clouds in these BL Lac objects. If the BLR geometry of these sources is disklike, the viewing angles between the axis and the line of sight are in the range $\sim 2^\circ$–$12^\circ$, which is consistent with the unification schemes.

Subject headings: accretion, accretion disks — BL Lacertae objects: general — black hole physics — galaxies: active

1. INTRODUCTION

There is a tight correlation between the black hole mass $M_{bh}$ and the stellar dispersion velocity $\sigma$ (Ferrarese & Merritt 2000; Gebhardt et al. 2000). This tight correlation $M_{bh}$-$\sigma$ is widely used to estimate the central black hole masses of active galactic nuclei (AGNs). Unfortunately, $\sigma$ is limited only for a small fraction of AGNs. McLure & Dunlop (2002) derived a very tight correlation between host galaxy absolute magnitude $M_R$ at $R$-band and $M_{bh}$.

Cao (2003) used this relation $M_{bh}$-$M_R$ to estimate the central black hole masses of 29 BL Lac objects. The central black hole masses of three sources in their sample have also been measured from the stellar dispersion velocity (Falomo et al. 2002; Barth et al. 2003), and these agree well with the $M_{bh}$ values estimated from $M_R$. O’Dowd et al. (2002) also found that the $M_{bh}$ values estimated from the host galaxy luminosity are quite reliable for radio galaxies.

The broad-line region (BLR) sizes $R_{BLR}$ of broad-line H$\beta$ 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 $R_{BLR}$ and optical continuum luminosity $\lambda L_{\lambda}$. Using the width of the broad emission line and measured $R_{BLR}$, they estimated the central black hole masses of the sources in their sample assuming the clouds in BLRs to be virialized. For sources at high redshifts, the H$\beta$ line emission is usually unavailable. Instead, the width of the Mg $\Pi$ line can be used to estimate the central black hole masses (McLure & Jarvis 2002). In common with H$\beta$, Mg $\Pi$ is a low-ionization line and thus is expected to be produced in the same region as H$\beta$; this is supported by the tight correlation between the FWHMs of Mg $\Pi$ and H$\beta$ ($\text{FWHM}(\text{Mg} \, \Pi) \sim \text{FWHM}(\text{H} \beta)$) found by McLure & Jarvis (2002). It is therefore reasonable to expect that Mg $\Pi$ and H$\beta$ are produced in the same region. Using the same sample and the $R_{BLR}$ values measured by Kaspi et al. (2000), McLure & Jarvis (2002) obtained a correlation between $R_{BLR}$ and the monochromatic continuum luminosity at 3000 Å, which is useful for the estimation of $M_{bh}$ values of the sources at high redshifts with only Mg $\Pi$ emission-line profiles.

For most AGNs, $R_{BLR}$ values have not been measured directly by the reverberation-mapping method and the empirical relation $R_{BLR} \sim \lambda L_{\lambda}$ is used to derive $R_{BLR}$. Combining the line width, the central black hole masses can be estimated by assuming the motion of clouds in BLRs to be virialized. The estimated $M_{bh}$ depends sensitively on the velocity of the clouds in BLRs ($\propto v_{BLR}^2$). The broad-line width is mainly governed by the component of the cloud velocity $v_{BLR}$ projected onto the line of sight. If the motion of BLR clouds is anisotropic (e.g., disklike BLR geometry), the estimate of $M_{bh}$ becomes complicated (e.g., Jarvis & McLure 2002). McLure & Dunlop (2001) argued that BLRs in some AGNs have disklike geometry. If disklike BLR geometry is indeed present, the observed broad-line width depends sensitively on the orientation of the disk axis, and the orientation is therefore crucial for the estimate of $M_{bh}$ from broad-line width. In the unification schemes, 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 narrowed if disklike BLRs are present perpendicular to the jets; this can be used to test the geometry of BLRs in BL Lac objects. In this paper, we use the observed broad emission line widths and $M_{bh}$ derived from host galaxy luminosity to test the geometry of BLRs in BL Lac objects if $M_{bh}$ can be estimated by an independent method. The cosmological parameters $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, and $H_0 = 70 \text{ km s}^{-1}\text{ Mpc}^{-1}$ have been adopted in this paper.

2. BLACK HOLE MASS

In order to estimate the central black hole masses of BL Lac objects, we use the relation between $M_R$ at $R$-band and $M_{bh}$ proposed by McLure & Dunlop (2004),

$$\log_{10}(M_{bh}/M_\odot) = -0.50(\pm0.02)M_R - 2.75(\pm0.53).$$

(1)
There are different surveys on host galaxies of BL Lac objects (e.g., Urry et al. 2000; Pursimo et al. 2002; Nilsson et al. 2003). In this paper, we search 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 exhibit broad-line emission, we finally obtain a sample of 16 BL Lac objects. All data collected are listed in Table 1, and the derived parameters of these sources are listed in Table 2. The apparent magnitudes of the host galaxies at $R$-band listed in Table 1 are Galactic extinction– and $K$-corrected. Only upper

| Source | Redshift | $m_B$(host) | References | FWHM(Mg ii) (km s$^{-1}$) | References | log $L_{\lambda}$ (W) | EW of [O ii] (Å) | References |
|--------|----------|-------------|------------|--------------------------|------------|---------------------|----------------|------------|
| 0138–097 | 0.733 | >18.38 | 1 | 4842 | 2 | 37.23 | 0.52 | 2 |
| 0521–365 | 0.055 | 14.35 | 1 | 3000$^{ab}$ | 3 | 36.30$^{ac}$ | ... | 4 |
| 0715–259 | 0.465 | 16.76 | 1 | 5200 | 5 | 36.70 | 1.3 | 5 |
| 0820+225 | 0.951 | >19.38 | 1 | 2959 | 6 | 35.84$^{ad}$ | ... | 6 |
| 0823+033 | 0.506 | >19.04 | 1 | 5455 | 6 | 39.48$^{a}$ | ... | 8 |
| 0851+202 | 0.306 | 18.44 | 7 | 2635$^{a}$ | 8 | 37.28$^{b}$ | ... | 8 |
| 0954+658 | 0.367 | >18.85 | 1 | 2079$^{a}$ | 9 | 36.72 | 0.22 | 2 |
| 1144–379 | 1.048 | >19.93 | 1 | 2492 | 8 | 37.13$^{d}$ | ... | 8 |
| 1308+326 | 0.996 | >18.36 | 7,10 | 4016 | 6 | 37.45$^{d}$ | ... | 6 |
| 1538+149 | 0.605 | 18.73 | 1 | 2411 | 6 | 37.15 | 0.44 | 6 |
| 1803+784 | 0.684 | >19.15 | 1 | 3082 | 2 | 37.41 | 1.9 | 6 |
| 1807+698 | 0.069 | 14.55 | 1 | 4260$^{a}$ | 11 | 35.46$^{c}$ | ... | 6 |
| 2200+420 | 0.069 | >20.22 | 1 | 2753 | 6 | 38.06 | 1.4 | 6 |

Notes.—Col. (1): Source name. Col. (2): Redshift. Col. (3): Galactic extinction– and $K$-corrected $R$-band magnitude of the host galaxy. Col. (4): References for $R$-band magnitude of the host galaxy. Col. (5): FWHM of broad-line Mg ii. Col. (6): References for FWHM(Mg ii). Col. (7): Ionizing luminosity at 3000 Å estimated from $L_{3000}$. Col. (8): Measured equivalent width of [O ii] corrected to the source frame. Col. (9): References for $L_{3000}$.

| Source | log $M_{\text{black}}/M_{\odot}$ | log $R_{\text{BLR}}$ (pc) | $f$ | $i$ (deg) |
|--------|-------------------------------|----------------------|----|--------|
| 0138–097 | <9.70 | <3.16 | <5.8 | >4.9 |
| 0521–365 | 8.56 | 2.34 | 4.2 | 6.9 |
| 0715–259 | 9.91 | 3.31 | 9.2 | 3.1 |
| 0820+225 | <9.55 | <3.43 | <16.8 | >1.7 |
| 0823+033 | <8.88 | <2.24 | <2.9 | >9.8 |
| 0851+202 | <8.78 | <2.78 | <3.6 | >7.9 |
| 0954+658 | <8.56 | <2.68 | <4.8 | >5.9 |
| 1144–379 | <9.40 | <3.44 | <8.5 | >3.4 |
| 1308+326 | <10.12 | <3.75 | <10.1 | >2.8 |
| 1538+149 | 9.27 | 3.34 | 7.4 | 3.8 |
| 1803+784 | <9.22 | <3.08 | <4.8 | >6.0 |
| 1807+698 | 8.88 | 3.46 | 12.2 | 2.3 |
| 1823+568 | 9.47 | 3.11 | 4.7 | 6.2 |
| 2131–021 | <10.39 | <4.11 | <13.3 | >2.2 |
| 2200+420 | 8.71 | 2.18 | 5.5 | 5.2 |
| 2240–260 | <8.85 | <2.81 | <2.5 | >1.7 |

Notes.—Col. (1): Source name. Col. (2): Black hole mass. Col. (3): BLR size for Mg ii (light-day). Col. (4): Derived correction factor $f$ for BLR geometry. Col. (5): Inclination angle of the jet with respect to the line of sight.
limits on host galaxy luminosity are available for nine sources in this sample. We estimate the central black hole masses of these BL Lac objects from their host galaxy luminosity, and their broad-line profiles are used to explore their BLR geometry. The $M_{bh}$ of two sources in our sample have been measured from the stellar dispersion velocity $\sigma$, which gives log ($M_{bh}/M_\odot$) = 8.65 (0521-365), 8.51 (1807+698) (Barth et al. 2003), and 8.90 (1807+698) (Falomo et al. 2002). The $M_{bh}$ of these two sources derived from their host galaxy luminosities are log ($M_{bh}/M_\odot$) = 8.56 (0521-365) and 8.88 (1807+698) (see Table 2). We can conclude that the $M_{bh}$ derived from host galaxy luminosity is quite reliable.

3. BLR SIZES $R_{BLR}$ OF BL LAC OBJECTS

The $R_{BLR}$ can be derived from the FWHM of the broad line,

$$ R_{BLR} = \frac{GM_{bh}}{c^2 \sigma_{FWHM}}. \quad (2) $$

if $M_{bh}$ is available. The correction factor $f = 1/(2 \sin i)$ for a pure disklike BLR, the axis of which is inclined to the line of sight at an angle $i$ (McLure & Dunlop 2001), while $f = 3^{1/2}/2$ for the clouds moving at random inclinations (Wandel et al. 1999; Kaspi et al. 2000). In our sample, 11 sources have a measured FWHM for broad-line Mg $\ii$, and four for H$\alpha$ and another for H$\beta$. The broad-line Mg $\ii$ is expected to be produced in the same region of the BLR as H$\beta$, so we take $\sigma_{FWHM}(\text{Mg}\ ii) = \sigma_{FWHM}(\text{H}\beta)$ for the source for which only the line width of H$\beta$ is available. Using the $M_{bh}$ derived from the host galaxy luminosity and velocity $\sigma_{FWHM}$, we can calculate $R_{BLR}$ by using equation (2) on the assumption of isotropic motion of clouds in the BLR; i.e., $f = 3^{1/2}/2$ is adopted. We convert $R_{BLR}(\text{H}\alpha)$ to $R_{BLR}(\text{H}\beta)$ using relation (2) in Kaspi et al. (2000),

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

for the sources for which only the line widths of H$\alpha$ are available.

4. THE IONIZING LUMINOSITY

BL Lac objects exhibit nonthermal continuum emission, which is believed to be dominated by the emission from the jets moving at relativistic speed at small angles with respect to the line of sight (Blandford & Rees 1978). The observed optical continuum emission is a mixture of the emission from the disk and beamed emission from the jet, which prevents us from measuring ionizing luminosity directly from observed optical continuum emission for BL Lac objects (see Urry & Padovani 1995 and references therein for a review). Narrow-line emission is suggested to be a good tracer for ionizing luminosity of radio-loud AGNs (Rawlings & Saunders 1991). We use the luminosity of the narrow-line [O $\ii$] at 3727 $\AA$ to estimate the optical ionizing luminosity. For those sources for which the emission data of [O $\ii$] is unavailable, we estimate the [O $\ii$] emission from other emission lines, adopting the line ratio proposed by Francis et al. (1991). The measured equivalent widths of narrow-line [O $\ii$] corrected to the source frame corresponding to the measured continuum emission are usually around a few $\AA$, or less than 1 $\AA$ for the BL Lac objects for which the narrow-line emission is detected (e.g., Stickel et al. 1989, 1993; Lawrence et al. 1996; also see Table 1 for the sources in our sample). As the observed optical continuum emission may be dominated by the beamed jet emission, the equivalent width $EW_{\text{ion}}$ of narrow-line [O $\ii$] corresponding to the ionizing continuum emission from the accretion disk should be larger than $EW_{\text{obs}}$ measured directly from the observed spectrum. The narrow-line emission is isotropic and independent of the jet orientation and we can therefore use the narrow-line luminosity $L_{[\text{O}\ ii]}$ to estimate the ionizing luminosity at 3000 $\AA$ for these BL Lac objects. Here we use the EW of the line [O $\ii$], $EW_{[\text{O}\ ii]} = 10 \AA$, corresponding to the ionizing continuum emission, which is suggested by Willott et al. (1999) to estimate the ionizing luminosity of radio-loud AGNs.

Using the same sample and the $R_{BLR}$ derived by Kaspi et al. (2000), McLure & Jarvis (2002) obtained a correlation between $R_{BLR}$ and the monochromatic continuum luminosity at 3000 $\AA$,

$$ R_{BLR}^{emp} = (25.2 \pm 3.0) \left(\frac{\lambda L_{\lambda}(3000)}{10^{37} \text{ W}}\right)^{0.47 \pm 0.05}, \quad (4) $$

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

5. RESULTS AND DISCUSSION

We plot the relation between the ionizing luminosity $\lambda L_{\lambda}(3000)$ at 3000 $\AA$ and $R_{BLR}$ in Figure 1. $R_{BLR}$ is derived from the width of broad line Mg $\ii$ and $M_{bh}$ on the assumption of isotropic motion of clouds in the BLR; i.e., $f = 3^{1/2}/2$ is adopted in equation (2). We can also derive the BLR size $R_{BLR}^{emp}$ using the empirical relation (4). If the motion of BLR clouds is indeed isotropic, one may expect similar $R_{BLR}$ and $R_{BLR}^{emp}$ values to be derived by these two different methods. However, it is found that the $R_{BLR}$ values in all these sources are $\sim 2$–3
orders of magnitude larger than the $R_{\text{BLR}}^{\text{emp}}$ values expected by relation (4).

We note that there are only upper limits on the masses of the black holes in nine of all 16 sources. The $R_{\text{BLR}}$ values may be overestimated for these nine sources because $R_{\text{BLR}}$ is derived from the line widths and $M_{\text{bh}}$ (see eq. [2]). The $M_{\text{bh}}$ values estimated from the host galaxy luminosity for these 16 sources are in the range $\sim 10^{8.6}$–$10^{10.4}$ $M_{\odot}$ (see Table 1). The deviations of $R_{\text{BLR}}$ from $R_{\text{BLR}}^{\text{emp}}$ expected by relation (4) cannot be solely attributed to the overestimate of $M_{\text{bh}}$ for those nine sources with upper limits on galaxy luminosity unless the $M_{\text{bh}}$ values have been overestimated by 2–3 orders of magnitude; i.e., the realistic $M_{\text{bh}}$ values should be in the range $\sim 10^{8}$–$10^{9}$ $M_{\odot}$ for these sources, which seems impossible. It is more difficult to attribute such deviations to the overestimate of $M_{\text{bh}}$ values for those seven sources with well-measured host galaxy luminosity. The $M_{\text{bh}}$ of the source 1807+698 has been measured from its stellar dispersion velocity $\sigma$ (Falomo et al. 2002; Barth et al. 2003), and this is consistent with our estimate of $M_{\text{bh}}$, $10^{8.88}$ $M_{\odot}$. For this source, the $R_{\text{BLR}}$ derived from relation (2) is $\sim 3$ orders of magnitude higher than the $R_{\text{BLR}}^{\text{emp}}$ predicted by relation (4) between $R_{\text{BLR}}^{\text{emp}}$ and $\mathcal{L}_k(3000)$.

The ionizing luminosity at 3000 Å is derived from the luminosity of narrow-line [O II], adopting $EW_{\text{ion}} = 10$ Å (Willott et al. 1999), which is in general consistent with the optical spectroscopic observations of the radio quasars selected from the Molonglo Quasar Sample (MQS), of which the equivalent widths of [O II] in the source frame are in the range from $<1$ to $>100$ Å, with an average of 14.7 Å (Baker et al. 1999). However, using a single value $EW_{\text{ion}} = 10$ Å is still a rough estimate and may induce uncertainties on the estimates of ionizing luminosity. In Figure 1, we find that the deviations of $R_{\text{BLR}}$ from $R_{\text{BLR}}^{\text{emp}}$ will not be solved on the isotropic BLR geometry assumption even if a rather small $EW_{\text{ion}} = 1$ Å is adopted; i.e., the ionizing luminosity is an order of magnitude higher than the present values. In Table 1, we have listed the measured equivalent widths of [O II] in the source frame for the sources in our present sample, which are in the range 0.2–9.2 Å. Considering the optical continuum emission contributed by the beamed emission from the jets in these BL Lac objects, their $EW_{\text{ion}}$ corresponding to the ionizing optical continuum emission should be larger than the measured values listed in Table 1. This implies that the uncertainties in the estimates of the ionizing optical continuum luminosity would not change the conclusion on this point. If photoionization of the gases in the narrow-line region by radiative shocks driven by the radio source is important (e.g., Inskip et al. 2002), the central ionizing luminosity should be lower than the present values, which would lead to even larger deviations.

Wang & Zhang (2003) found that the $R_{\text{BLR}}$ values of dwarf AGNs are systematically larger than the prediction of the $R_{\text{BLR}}$–$\mathcal{L}_k$ correlation defined by Seyfert galaxies and quasars (Kaspi et al. 2000). They suggested that the flat ionizing spectra are in these dwarf AGNs as predicted by advection-dominated accretion flow (ADAF) models and that the BLRs in these dwarf AGNs have lower ionization or/and lower density than those in the Seyfert 1 galaxies and quasars of the Kaspi et al. (2000) sample. The sources in our present sample have brighter ionizing luminosity than these dwarf AGNs. As most BL Lac objects do not exhibit any line emission, all 16 of these BL Lac objects with measured broad-line profiles and narrow-line emission have relatively high ionizing luminosity compared to all other BL Lac objects (Cao 2002). There is a critical accretion rate $\dot{m}_{\text{crit}}$, and an ADAF can exist only if accreting at a rate $\dot{m} < \dot{m}_{\text{crit}}$ (e.g., Mahadevan 1997), which leads to an upper limit on optical continuum emission from an ADAF for a given $M_{\text{bh}}$ (Cao 2002). Cao (2003) calculated optical spectra of ADAF+SD (standard disk) systems and compared them with the observed spectra, which suggested that only ADAFs themselves are unable to produce such bright ionizing optical continuum emission and that standard thick disks should be present at least in the outer regions of the disks for these BL Lac objects. The ionizing photons are therefore mainly from the standard thin-disk regions in these BL Lac objects, unlike the dwarf AGNs considered by Wang & Zhang (2003). The luminosity $\mathcal{L}_k(3000)$ of the sources in the sample used to derive the correlation $R_{\text{BLR}}$–$\mathcal{L}_k(3000)$ is in the range $\sim 10^{34}$–$10^{39}$ W (McLure & Jarvis 2002). The ionizing luminosity of the BL Lac objects in the present sample at 3000 Å are in the range $\sim 10^{35.8}$–$10^{38}$ W, which is in a range similar to that of their sample. The $R_{\text{BLR}}$–$\mathcal{L}_k(3000)$ relation derived from a sample of quasars and Seyfert galaxies should be valid for these BL Lac objects, unless the physics of BLRs in these BL Lac objects is significantly different from that in the sources of the sample considered by McLure & Jarvis (2002).

We derive the BLR sizes of these BL Lac objects assuming the motion of clouds to be isotropic, which may not be the case in these sources. Our estimate of $R_{\text{BLR}}$ values may be strongly overestimated because of anisotropic cloud motion if the velocity component projected onto the line of sight is only a small fraction of its real velocity. The most likely candidate for such anisotropic motion of clouds is the clouds orbiting in a disky BLR (e.g., McLure & Dunlop 2001). For the clouds orbiting in a disky BLR, the correction factor $f$ in equation (2) is $1/(2\sin i)$, where $i$ is the angle of the axis inclined 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 they indeed obey the correlation $R_{\text{BLR}}$–$\mathcal{L}_k(3000)$ suggested by McLure & Jarvis (2002); i.e., the value of $f$ is estimated by letting $R_{\text{BLR}} = R_{\text{BLR}}^{\text{emp}}$. The derived results are listed in Table 1. We find that the inclination angles are around $\sim 2^\circ$–$12^\circ$ for these BL Lac objects. There is evidence that the velocity field of the BLR is better described by a combination of a random isotropic component, with characteristic velocity $v_p$, and a component only in the plane of the disk, with characteristic velocity $v_p$ (Wills & Browne 1986). In this case, the observed FWHM will be given by

$$v_{\text{FWHM}} = 2(v_p^2 + v_p^2 \sin^2 i)^{1/2}$$

(McLure & Dunlop 2001), so $f = 0.5(v_p/v_p)^2 + \sin^2 i)^{1/2}$. If the random isotropic component is important, i.e., if $v_p$ is comparable with $v_p$, then the term $(v_p/v_p)^2$ cannot be neglected and the derived inclined angle of the disk axis will be less than that listed in Table 2. This is in general consistent with the unification schemes that the jets of BL Lac objects are inclined at small angles to the line of sight.

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