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THE BLACK HOLE MASS OF BL LACERTAE OBJECTS FROM THE STELLAR VELOCITY DISPERSION OF THE HOST GALAXY

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ABSTRACT

The correlation between black hole mass M_{BH} and stellar velocity dispersion σ in nearby elliptical galaxies affords us a novel way to determine M_{BH} in active galaxies. We report on measurements of σ from optical spectra of seven BL Lacertae host galaxies. The derived values of σ are in the range of 160–290 km s^{-1} corresponding to M_{BH} of 5×10^7–1×10^9 $M_\odot$. The average ratio of M_{BH} to the host galaxy mass is 1.4×10^{-3}, consistent with that estimated in other active and inactive galaxies. The velocity dispersions and the derived values of M_{BH} of the BL Lac objects are similar to those obtained for low-redshift radio galaxies, in good agreement with the predictions of the unified models for radio-loud active galaxies.

Subject headings: BL Lacertae objects: general — galaxies: active — galaxies: elliptical and lenticular, cD — galaxies: kinematics and dynamics — galaxies: nuclei

1. INTRODUCTION

The mass of the central black hole (BH) is of paramount importance in theoretical models of active galactic nuclei (AGNs). In particular, the dependence of BH mass (M_{BH}) on the global host galaxy properties provides us with clues to the role of BHs in galaxy formation and evolution. The dynamical determination of M_{BH} in AGNs is difficult because of the bright emission from the nucleus. The main method that has proved to be successful for AGNs is reverberation mapping of broad emission lines, which is extremely time-consuming and gives results on M_{BH} that depend on the assumed geometry of the accretion disk. Therefore, for only a few well-studied quasars and Seyfert galaxies is the M_{BH} known (see, e.g., Kaspi et al. 2000, Nelson 2000, Wandel 2002, and references therein). Reverberation mapping cannot be employed for BL Lacertae objects because they lack prominent broad emission lines; therefore, other methods need to be applied. The discovery of a correlation between M_{BH} and the luminosity of the bulge in nearby early-type galaxies (e.g., Magorrian et al. 1998) offered us a new tool for evaluating M_{BH} (see the recent reviews by Merritt & Ferrarese 2001a, hereafter MF01, and Kormendy & Gebhardt 2001). So far, this correlation has been applied to a sample of nearby quasars (McLure & Dunlop 2001) and BL Lac objects (Treves et al. 2002).

Recently, a stricter correlation was found relating M_{BH} with the stellar velocity dispersion σ of the spheroidal component in nearby inactive galaxies (Gebhardt et al. 2000; Ferrarese & Merritt 2000). This relationship clearly demonstrates a connection between BHs and bulges of galaxies and has spurred a substantial effort in theoretical modeling (e.g., Silk & Rees 1998; Haehnelt & Kauffmann 2000; Adams, Graff, & Richstone 2001). The relationship appears to predict the M_{BH} more accurately but requires the measurement of σ in the host galaxies of AGNs that is difficult to obtain, in particular for objects at moderate or high redshift and with very luminous nuclei. On the other hand, BL Lac objects have relatively fainter nuclei than quasars (e.g., Falomo et al. 1999), and for them this measurement (at least for low-redshift objects) can be secured with a single spectrum observable with a medium-sized telescope.

Here we present medium-resolution optical spectroscopy of the host galaxies of seven BL Lac objects from which we derive the stellar velocity dispersion. According to the shape of their spectral energy distributions (SEDs), BL Lac objects are broadly distinguished into two types (see Padovani & Giommi 1995): those whose SEDs peak at the near-infrared/optical and the γ-ray MeV regions (low-frequency peaked BL Lac objects [LBLs]) and those that have SEDs peaking in the UV/X-ray and the γ-ray TeV energies (called high-frequency peaked BL Lac objects [HBLs]). Our selection of nearby ($z < 0.2$) BL Lac objects includes five HBLs and two LBLs. For all observed targets, high-quality images have been obtained either from the ground (Falomo & Kotilainen 1999) or with the *Hubble Space Telescope* Wide Field Planetary Camera 2 (Urry et al. 2000; Falomo et al. 2000). From these images, the characterization of the host galaxies and the nuclear luminosity can be obtained.

2. OBSERVATIONS AND DATA ANALYSIS

The observations were obtained in 2001 June using the 2.5 m Nordic Optical Telescope (NOT) equipped with the Andalucia Faint Object Spectrograph and Camera (ALFOSC).[1] Spectra were secured using two grisms to cover the spectral ranges 4800–5800 Å (setup A) and 5700–8000 Å (setup B) at 0.54 and 1.3 Å pixel^{-1} dispersion, respectively. This allows us to measure the absorption lines of Hβ (4861 Å), Mg I (5175 Å), Ca *E* band (5269 Å), and Na I (5892 Å) and the TiO + Ca I (6178 Å), TiO + Fe I (6266 Å), and other absorption line blends from the host galaxies at a spectral resolution $R \sim 3000$.

The chosen grisms, combined with a 1″ slit, yield a spectral resolution for a velocity dispersion measurement of ~60–80 km s^{-1}, which is adequate for the expected range of σ in luminous elliptical galaxies (e.g., Djorgovski & Davis 1987; Bender, Burstein, & Faber 1992) such as the hosts of BL Lac

[1] See http://www.not.iac.es for instrument characteristics.

TABLE 1
JOURNAL OF OBSERVATIONS AND RESULTS

Object	z	Setup	Exposure (s)	S/N	σ (km s^{-1})
NGC 5831	0.0055	A	600	45	167 ± 5
		B	600	55	185 ± 10
Mrk 421	0.031	B	3600	40	220 ± 10
Mrk 180	0.045	A	3600	40	225 ± 10
Mrk 501	0.034	A	2400	40	265 ± 10
		B	3600	55	280 ± 15
I Zw 187	0.055	B	3600	30	253 ± 15
3C 371	0.051	A	2400	40	255 ± 15
		B	3600	35	265 ± 20
1ES 1959+65	0.048	B	2400	18	180 ± 15
PKS 2201+04	0.027	A	3600	30	148 ± 5
		B	2400	50	153 ± 8

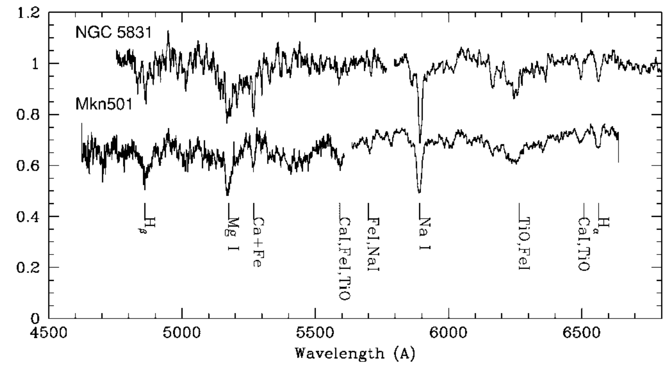

FIG. 1.—Optical spectra of the BL Lac object Mrk 501 ($z = 0.034$) and of the nearby elliptical galaxy NGC 5831 ($z = 0.0055$). The spectra are normalized to the continuum and plotted in the rest frame.

objects. In addition to the spectra of the BL Lac hosts, we acquired spectra of bright stars of type G8 III–K1 III that exhibit a low rotational velocity ($V \sin i < 20$ km s^{-1}). These are used as templates of zero velocity dispersion. Furthermore, spectra of the well-studied nearby elliptical galaxy NGC 5831 were also secured in order to provide a test of the adopted procedure to derive σ.

During the observations, seeing ranged between 1″ and 1.″5. The targets were centered into the slit or positioned 1″ away from the nucleus, and then the one-dimensional spectrum was extracted from an aperture of 3″–5″ diameter, which is in all cases within the effective radius of the host galaxy. In one case (Mrk 180), spectra were taken with the object both centered into the slit and off-centered by 1″, but no significant difference was apparent in the shape of the spectral features. Standard data reduction was applied to the spectra using the tasks available in the IRAF[2] package. The procedure includes the bias subtraction, flat-fielding, wavelength calibration, and extraction of one-dimensional spectra. For each observation, we took two spectra and combined them in order to remove cosmic-ray hits and other occasional spurious signals in the detector. In Table 1, we report the list of our targets together with the instrumental setup and the signal-to-noise ratio (S/N) of each spectrum derived from the continuum in the middle of the observed spectral range.

The stellar velocity dispersion σ was determined using the Fourier quotient method (e.g., Sargent et al. 1977) implemented in the IRAF STSDAS package. The spectra were first normalized by subtracting the continuum, converted to a logarithmic scale, and then multiplied by a cosine bell function that apodizes 10% of the pixels at each end of the spectrum. Finally, the Fourier transform of the galaxy spectra was divided by the Fourier transform of template stars, and σ was computed from a χ^2 fit with a Gaussian-broadening function (see Bertola et al. 1984 and Kuijken & Merrifield 1993 for further details on this method). The rms scatter of the σ results using different template stars was typically ∼10 km s^{-1} and can be considered as the minimum uncertainty of the measurement. The observed values of σ and their estimated errors are reported in the last column of Table 1.

For three objects, we have spectra in both spectral ranges. The resulting stellar velocity dispersions are in all cases in good agreement, with an average difference of 12 km s^{-1}, ensuring the sufficient homogeneity of data taken with different grisms and/or resolution. Note, however, that there is a tendency for the red grism (lower resolution) data to result in a slightly larger value of σ. For the nearby elliptical galaxy NGC 5831, we obtained $\sigma = 167 \pm 5$ and 185 ± 10 km s^{-1} for the setups A and B, respectively. These values are in good agreement with previous measurements in the literature ($\langle\sigma\rangle = 168$ km s^{-1}; Prugniel et al. 1998). In Figure 1, we show an example of the spectrum of the BL Lac object Mrk 501 compared with that of the elliptical galaxy NGC 5831 observed in both spectral ranges.

Since early-type galaxies exhibit some gradients in the velocity dispersion (Davies et al. 1983; Fisher, Illingworth, & Franx 1995), the measured value of σ depends somewhat on the distances of the galaxies and the size of the aperture used. In order to compare our values of σ with the data available in the literature (in particular, with the MF01 relationship), we applied aperture corrections according to the procedure given in Jørgensen, Franx, & Kjærgaard (1995). The individual measurements of σ are therefore corrected to a circular aperture with a metric diameter of 1.19 h^{-1} kpc, equivalent to 3.″4 at the distance of the Coma Cluster to derive the central velocity dispersion σ_c, which is given in the third column of Table 2. When measurements of σ in two spectral ranges are available, the average is reported.

No previous systematic study of the stellar velocity dispersion

[2] IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

TABLE 2
VELOCITY DISPERSION AND BH MASSES OF BL LAC OBJECTS

Object	Type	σ_c (km s^{-1})	log $(M_{BH})_\sigma$ ($M_\odot$)	M_R	R_e (kpc)	log $(M_{BH})_{bulge}$ ($M_\odot$)	log M_{host} ($M_\odot$)
Mrk 421	HBL	236 ± 10	8.50 ± 0.18	−23.12	3.4	8.65	11.20
Mrk 180	HBL	244 ± 10	8.57 ± 0.19	−22.81	5.0	8.50	11.45
Mrk 501	HBL	291 ± 13	8.93 ± 0.21	−23.87	15	9.00	11.59
I Zw 187	HBL	253 ± 15	8.65 ± 0.18	−22.22	4.7	8.20	11.39
3C 371	LBL	284 ± 18	8.88 ± 0.20	−23.67	2.9	8.90	11.32
1ES 1959+65	HBL	195 ± 15	8.12 ± 0.13	−22.48	6.6	8.30	11.27
PKS 2201+04	LBL	160 ± 7	7.72 ± 0.13	−22.36	5.1	8.27	11.00

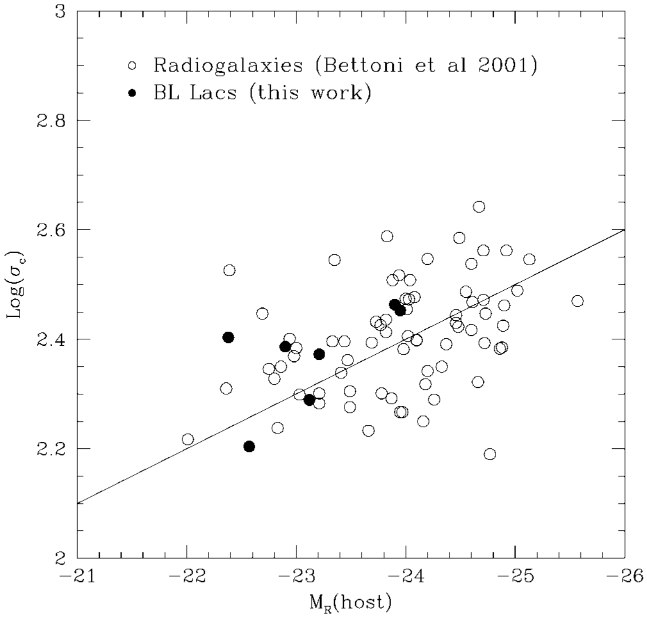

FIG. 2.—Host galaxy stellar velocity dispersion σ_c vs. R-band absolute magnitude for the BL Lac objects (*filled circles*) and for low-redshift radio galaxies (*open circles*; Bettoni et al. 2001). The solid line indicates the original Faber & Jackson (1976) relationship, transformed into the R band.

in BL Lac objects is available, although, recently, Barth, Ho, & Sargent (2002) reported optical spectroscopy for Mrk 501. These authors measured a value of $\sigma = 372 \pm 18$ km s^{-1}, which differs significantly from ours ($\sigma = 291 \pm 13$ km s^{-1}). Their measurement of σ, derived from the 5200–5600 Å region, could be reconciled with our value, given their large scatter (81 km s^{-1}) fitting the data in this range. On the other hand, the higher σ-value obtained from the Ca II triplet lines (8498, 8542, and 8662 Å), which are partly blended with telluric absorptions, appears inconsistent with our value within the estimated errors. Applying aperture correction to the value of Barth et al. (2002), the difference of σ becomes even larger (by ~15 km s^{-1}).

3. RESULTS AND DISCUSSION

We have adopted the relationship between $M_{\rm BH}$ and σ_c found for nearby early-type galaxies that is based on optical spectroscopy (MF01):

$$M_{\rm BH} = (1.48 \pm 0.24) \times 10^8 (\sigma/200)^{4.65 \pm 0.48} \quad [M_\odot]. \quad (1)$$

We assume that this relationship is also valid for AGNs (see, e.g., MF01) and in particular for BL Lac objects. This is consistent with our imaging studies of BL Lac objects (Falomo & Kotilainen 1999; Urry et al. 2000; Falomo et al. 2000), indicating that all our objects are hosted by luminous elliptical galaxies. The derived values of $M_{\rm BH}$ are reported in the fourth column of Table 2, where the errors are the composition in quadrature of uncertainties in σ and in the MF01 relationship. Using the Gebhardt et al. (2000) relationship instead of the one by MF01 tends to yield slightly lower values of $M_{\rm BH}$ but does not substantially modify our main conclusions. The values of $M_{\rm BH}$ in Table 2 span a factor ~20 from 5×10^7 $M_\odot$ for PKS 2201+04 to 9×10^8 $M_\odot$ for Mrk 501.

As mentioned above, $M_{\rm BH}$ is also correlated, but with a larger scatter, with the luminosity of the bulge of the host galaxy. The host galaxy absolute magnitude M_R (uncorrected for extinction) and the effective radii R_e of the seven BL Lac objects are given

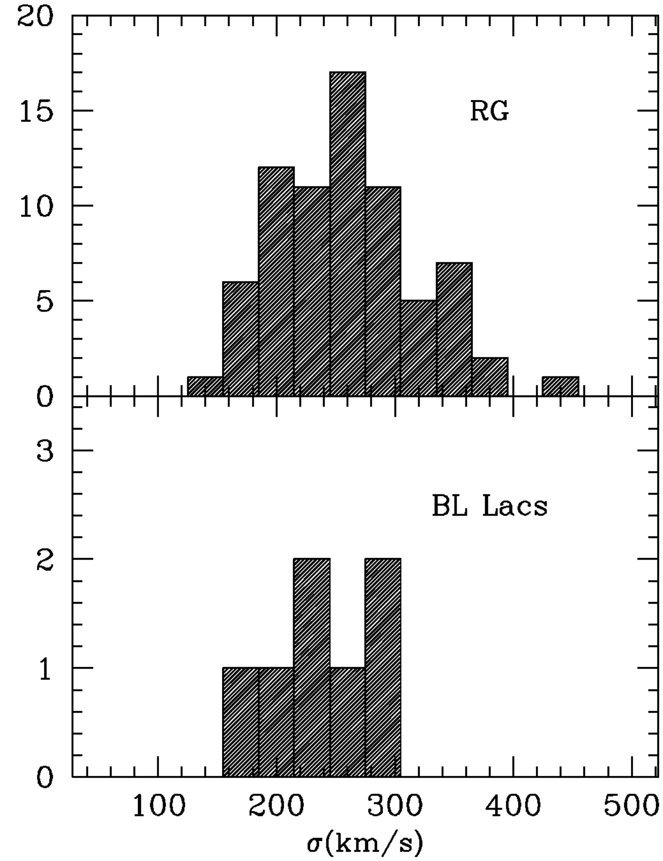

FIG. 3.—Distribution of the stellar velocity dispersion σ_c of low-redshift radio galaxies (*upper panel*; Bettoni et al. 2001) compared with that of the BL Lac objects studied in this Letter (*lower panel*).

in the fifth and sixth columns of Table 2, respectively. $M_{\rm BH}$ was thus calculated following the relationship by McLure & Dunlop (2002):

$$\log M_{\rm BH} = -0.50 \pm 0.05 M_R - 2.91 \pm 1.23 \quad [M_\odot]. \quad (2)$$

The corresponding values of $M_{\rm BH}$ are given in the seventh column of Table 2. For most sources, the difference of $M_{\rm BH}$ derived with the two methods is within the estimated uncertainty. The average values of $M_{\rm BH}$ for our BL Lac objects derived from σ and the host luminosity are $\langle M_{\rm BH} \rangle_\sigma = 8.62 \pm 0.23$ and $\langle M_{\rm BH} \rangle_{\rm host} = 8.66 \pm 0.25$, respectively.

In two cases (I Zw 187 and PKS 2201+04), a factor of ~3 difference in $M_{\rm BH}$ is found. We note that for PKS 2201+04, we derive a significantly lower velocity dispersion with respect to the rest of the observed sources, leading to a low $M_{\rm BH}$. On the other hand, for this target, σ is well determined (with good S/N data and the two spectral ranges giving similar results).

In our sample, there are two LBL-type and five HBL-type BL Lac objects (second column of Table 2). With the caveat that the number of studied objects is very small, we find no significant difference in $M_{\rm BH}$ between the two types of BL Lac objects.

The measurements of σ combined with the effective radii of the host galaxies can be used to estimate the mass of the hosts through the following relationship (Bender et al. 1992):

$$M_{\rm host} = 5\sigma^2 r_e / G. \quad (3)$$

This dynamical mass (eighth column of Table 2) turns out to be in the range of (1–4) × 10^{11} $M_{\odot}$. The ratio between M_{BH} and M_{host} is in the range of (0.5–3.6) × 10^{-3}, with $\langle M_{BH}/M_{host} \rangle = 1.4 \times 10^{-3}$. This is in good agreement with values derived for both AGNs and inactive galaxies ($\langle M_{BH}/M_{host} \rangle = 1.2 \times 10^{-3}$; McLure & Dunlop 2001; Merrit & Ferrarese 2001b).

In the unified model of radio-loud AGNs, BL Lac objects are believed to be drawn from the population of radio galaxies according to their orientation effects (e.g., Urry 1999). It is therefore interesting to compare orientation-independent properties, such as the velocity dispersion of the host galaxy, of BL Lac and radio galaxy populations. We show in Figure 2 a comparison of the host luminosity M_R versus log σ (the Faber-Jackson relationship) for the BL Lac objects with respect to a large sample of low-redshift radio galaxies (Bettoni et al. 2001). Both samples follow quite well the original Faber & Jackson (1976) correlation. The similarity of the distributions of σ for these two samples (Fig. 3) furthermore implies that the distributions of M_{BH} in radio galaxies and BL Lac objects are indistinguishable, consistent with the model that both types of AGNs belong to the same population but are observed from different orientation angles.

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