Black hole masses of BL Lac objects

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Abstract. The correlation between black hole mass $M_{BH}$ and the central stellar velocity dispersion $\sigma$ in nearby elliptical galaxies affords a novel way to determine $M_{BH}$ in active galaxies. We report on measurements of $\sigma$ from optical spectra of 7 BL Lac host galaxies. The range of $\sigma$ (160 – 290 km s$^{-1}$) corresponds to estimated $M_{BH}$ of $5 \times 10^7$ – $9 \times 10^8$ M$_\odot$. The average ratio of $M_{BH}$ to the host galaxy mass is $1.4 \times 10^{-3}$, consistent with that estimated in other active and inactive galaxies. The range of $\sigma$ and $M_{BH}$ of the BL Lacs 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.

1. Introduction

The mass of the central black hole (BH) is of paramount importance in theoretical models of AGN. In particular, the dependence of BH mass ($M_{BH}$) on global host galaxy properties provides clues to the role of BHs in galaxy formation and evolution. Dynamical determination of $M_{BH}$ in AGN is difficult because of the bright nuclear emission. The main method that has proved to be successful for AGN is the time-consuming reverberation mapping of broad emission lines. Only for a few quasars and Seyfert galaxies $M_{BH}$ is thus known (e.g. Kaspi et al. 2000; Wandel 2002). Reverberation mapping cannot obviously be employed for BL Lac objects because they lack prominent broad emission lines. The discovery of a correlation between $M_{BH}$ and the bulge luminosity in nearby early-type galaxies (e.g. Magorrian et al. 1998) offered a new tool for evaluating $M_{BH}$ (see Merritt & Ferrarese 2001). This correlation has been applied so far for nearby quasars (McLure & Dunlop 2001) and BL Lacs (Treves et al. 2002).

Recently, a tighter correlation was found relating $M_{BH}$ with the stellar velocity dispersion $\sigma$ of the bulge in nearby inactive galaxies (Gebhardt et al. 2000; Ferrarese & Merritt 2000). This relationship clearly demonstrates a con-
nection between BHs and bulges of galaxies and has spurred substantial effort in theoretical modelling (e.g. Silk & Rees 1998; Hähnelt & Kauffmann 2000). The relationship predicts more accurately $M_{BH}$, but requires the measurement of $\sigma$ in AGN host galaxies that is difficult, in particular for objects at high redshift and with luminous nuclei. On the other hand, BL Lacs have relatively fainter nuclei than quasars, and for low redshift BL Lacs this measurement can be secured with a single spectrum observable with a medium-sized telescope.

We have carried out medium resolution optical spectroscopy of the host galaxies of nearby ($z < 0.2$) BL Lac objects to derive $\sigma$ and to determine $M_{BH}$. Here we present results based on a sample of 7 BL Lacs including 2 LBLs (3C 371 and PKS 2201+04) and 5 HBLs (see also Falomo, these proceedings; and full discussion in Falomo, Kotilainen & Treves 2002). For all of them, high quality images have been obtained either from the ground (Falomo & Kotilainen 1999) or with HST (Urry et al. 2000; Falomo et al. 2000). From these images, the characterization of the host galaxies and the nuclear luminosity can be obtained. In Falomo, Kotilainen & Treves (in prep.), we shall discuss the implications of the results of the full sample of 11 BL Lacs for the unified models of radio-loud AGN.

2. Observations and data analysis

The observations were obtained using the 2.5m Nordic Optical Telescope (NOT) equipped with ALFOSC. 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 Å pixel$^{-1}$ and 1.3 Å pixel$^{-1}$ dispersion, respectively. This allows us to measure the absorption lines of H$\beta$ (4861 Å), Mg I (5175 Å), Ca E-band (5269 Å), Na I (5892 Å) and the TiO + CaI (6178 Å), TiO + FeI (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 $\sigma$ measurement of $\sim 60 – 80$ km s$^{-1}$, which is adequate for the expected range of $\sigma$ in luminous ellipticals (e.g. Djorgovski & Davis 1987; Bender, Burstein & Faber 1992) such as the hosts of BL Lacs. In addition, we acquired spectra of bright stars of type G8-III to K1-III, that exhibit low rotational velocity ($V \times \sin (i) < 20$ kms$^{-1}$) to be used as templates of zero velocity dispersion. Furthermore, spectra of the well studied nearby elliptical galaxy NGC 5831 were secured to provide a test of the adopted procedure to derive $\sigma$.

During the observations, seeing ranged between 1″ and 1.5″. The slit was centered on-target or positioned 1″ away from the nucleus and the 1D spectrum was extracted from an aperture of 3″ - 5″ diameter, in all cases within the effective radius of the host galaxy. In one case (Mrk 180), spectra with the slit both on-target and off-centered by 1″ were taken but no significant difference was found in the shape of the spectral features.

The stellar velocity dispersion $\sigma$ was determined using the Fourier Quotient method (e.g. Sargent et al. 1977). The spectra were normalized by subtracting the continuum, converted to a logarithmic scale and multiplied by a cosine bell function that apodizes 10% of the pixels at each end of the spectrum. All regions affected by emission lines (see Fig. 1) have been masked in the analysis. Finally, the Fourier Transform of the galaxy spectra were divided by the Fourier
Transform of template stars and $\sigma$ was computed from a $\chi^2$ fit with a Gaussian broadening function (see e.g. Bertola et al. 1984; Kuijken & Merrifield 1993). The rms scatter of the $\sigma$ results using different template stars was typically $\sim$10 km $s^{-1}$ and can be considered as the minimum uncertainty of the measurement.

For three objects we have spectra in both spectral ranges. The resulting values of $\sigma$ are in good agreement, ensuring 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 slightly larger value of $\sigma$. For the nearby elliptical NGC 5831 we obtained $\sigma = 167\pm5$ and $185\pm10$ km $s^{-1}$ for the setup A and B, respectively, in good agreement with previous measurements ($< \sigma > = 168$ km $s^{-1}$; Prugniel et al. 1998). In Fig. 1 we show the spectrum of the BL Lac object PKS 2201+04, observed in both spectral ranges.

Since early-type galaxies exhibit gradients in velocity dispersion (e.g. Fisher, Illingworth & Franx 1995), the measured value of $\sigma$ depends somewhat on the distance of the galaxies and the aperture size (see Falomo et al. 2002 for details). The individual measurements of corrected $\sigma$ are given in Table 1.

Barth, Ho & Sargent (2002) have recently reported a similar systematic study of $\sigma$ in 11 BL Lac objects, six of which are common with our sample. There are some discrepancies for individual BL Lacs, most notably for Mrk 501 and I Zw 187, for which they derive $\sigma = 372\pm18$ and $171\pm12$ km $s^{-1}$, respectively. These differences are most likely related to the method of deriving $\sigma$ (Fourier Quotient vs. direct fitting) and the different wavelength range used. The average values of $\sigma$, however, are in good agreement in the two samples.
Table 1. Velocity dispersion and BH masses of BL Lacs.

| Object   | z    | $\sigma_c$ (km s$^{-1}$) | log($M_{BH}$)$_\sigma$ [M$_\odot$] | log($M_{BH}$)$_{bulge}$ [M$_\odot$] | log($M_{(host)}$) [M$_\odot$] |
|----------|------|---------------------------|---------------------------------|-----------------------------------|-------------------------------|
| Mrk 421  | 0.031| 236±10                    | 8.50±0.18                       | 8.65                              | 11.20                         |
| Mrk 180  | 0.045| 244±10                    | 8.57±0.19                       | 8.50                              | 11.45                         |
| Mrk 501  | 0.034| 291±13                    | 8.93±0.21                       | 9.00                              | 11.59                         |
| I Zw 187 | 0.055| 253±15                    | 8.65±0.18                       | 8.20                              | 11.39                         |
| 3C 371   | 0.051| 284±18                    | 8.88±0.20                       | 8.90                              | 11.32                         |
| 1ES 1959+65 | 0.048| 195±15                    | 8.12±0.13                       | 8.30                              | 11.27                         |
| PKS 2201+04 | 0.027| 160±7                     | 7.72±0.13                       | 8.27                              | 11.00                         |

3. Results and discussion

We have adopted the relationship between $M_{BH}$ and $\sigma_c$ found for nearby early-type galaxies based on optical spectroscopy (Merritt & Ferrarese 2001):

$$M_{BH} = 1.48 \pm 0.24 \times 10^8 \left(\frac{\sigma}{200 \text{ km s}^{-1}}\right)^{4.65 \pm 0.48} \text{[M}_\odot\text{].}$$

We assume that this relationship is also valid for BL Lacs. This is consistent with imaging studies of BL Lacs (Falomo & Kotilainen 1999; Urry et al. 2000; Falomo et al 2000), indicating that all BL Lacs are hosted by giant ellipticals. The derived values of $M_{BH}$ are reported in Table 1, where the errors are the composition in quadrature of uncertainties in $\sigma$ and in the Merritt & Ferrarese (2001) relationship. Using instead the Gebhardt et al. (2000) relationship tends to yield slightly lower values of $M_{BH}$ but does not substantially modify our main conclusions. The values of $M_{BH}$ (Table 1) span a factor $\sim$20 from $5 \times 10^7$ M$_\odot$ for PKS 2201+04 to $9 \times 10^8$ M$_\odot$ for Mrk 501, with a median value of $4 \times 10^8$ M$_\odot$. These values are in good agreement with those derived by Barth et al. (2002).

As mentioned above, $M_{BH}$ is also correlated with the bulge luminosity of the host galaxy. $M_{BH}$ was calculated following the relationship by McLure & Dunlop (2002):

$$\log M_{BH} = -0.50 \pm 0.05 M_R - 2.91 \pm 1.23 \text{[M}_\odot\text{].}$$

The corresponding values of $M_{BH}$ are given in Table 1. For most sources the difference of $M_{BH}$ derived with the two methods is within the estimated uncertainty. The average values of $M_{BH}$ derived, respectively, from $\sigma$ and the host luminosity are: $<\log M_{BH}>_\sigma = 8.62 \pm 0.23$ and $<\log M_{BH}>_{host} = 8.66 \pm 0.25$.

The measurements of $\sigma$ combined with the effective radii of the host galaxies can be used to estimate the mass of the hosts through the relationship (Bender et al. 1992): $M_{host} = 5\sigma^2 r_e / G$. This dynamical mass (Table 1) is in the range of $1 - 4 \times 10^{11}$ M$_\odot$. The ratio between $M_{BH}$ and $M_{host}$ is in the range of $0.5 - 3.6 \times 10^{-3}$, with average $<M_{BH}/M_{host}> = 1.4 \times 10^{-3}$. This is in good agreement with values derived for both AGN and inactive galaxies ($<M_{BH}/M_{host}> = 1.2 \times 10^{-3}$; McLure & Dunlop 2001; Merritt & Ferrarese 2001).

According to the unified model of radio-loud AGN (e.g. Urry & Padovani 1995), BL Lacs are drawn from the population of FR I radio galaxies viewed along the jet axis. It is therefore interesting to compare orientation-independent properties of BL Lacs and radio galaxies. The largest comparison sample with available measurements of $\sigma$, effective radii and surface brightness is that of 73 low redshift radio galaxies by Bettoni et al. (2001, 2002). In Fig. 2, we compare
the distribution of the BH masses of the BL Lacs and the radio galaxies from Bettoni et al.

Figure 2. The distribution of the $M_{BH}$ of the BL Lac objects compared with that of low redshift radio galaxies (from Bettoni et al. 2002).

The close similarity of the distributions in these samples implies that the distributions of $M_{BH}$ in BL Lacs and radio galaxies are indistinguishable, consistent with both types of AGN belonging to the same parent population, observed from different orientation angles (see also Barth et al. 2002). Additional support to this view is given by the similarity of BL Lacs and radio galaxies on the fundamental plane (see e.g. Falomo, these proceedings; Barth et al. 2002). However, due to the small number statistics of the BL Lacs, and the incompleteness of the samples, this result can not yet be considered conclusive. Furthermore, there is a clear dearth of BL Lacs with the largest $M_{BH}$ ($>10^9 M_\odot$), consistent with BL Lac hosts being biased toward less massive and less luminous host galaxies than radio galaxies (e.g. Urry et al. 2000).
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