Jet Formation and the Evolutionary Sequence of Blazars

Xinwu Cao

(*Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai* 200030)
Email: cxw@center.shao.ac.cn

Abstract The distribution of line luminosity $L_{\mathrm{H}\beta}$ of 23 BL Lac objects suggests a bimodal nature, although this cannot be statistically proven on the basis of the present, rather small sample. We found that standard thin disks are probably in the sources with $L_{\mathrm{H}\beta} > 10^{41}\,\mathrm{erg\,s^{-1}}$. The central black holes in these sources have masses of $10^{8-10}M_{\odot}$, if the matter is accreting at the rate of $0.025\dot{M}_{\mathrm{Edd}}$. For the sources with $L_{\mathrm{H}\beta} < 10^{41}\,\mathrm{erg\,s^{-1}}$, the accretion flows have transited from standard thin disk type to the ADAF type. The lower limits on the mass of the black hole in these sources are in the range of $1.66 - 24.5 \times 10^{8}\ M_{\odot}$. The results support the evolutionary sequence of blazars: FSRQ→LBL→HBL.

1 Introduction

For most AGNs, the central black hole masses can be inferred from the velocities of the clouds in broad line regions (BLRs) and the sizes of BLRs (Dibai 1981). However, most BL Lac objects have featureless optical and ultraviolet continuum spectra, and only a small fraction of BL Lac objects show very weak broad emission lines. It is therefore difficult to estimate their central black hole mass from the kinematics of their BLRs.

Ghisellini et al. (1998) used a large sample of blazar broadband spectra to study the blazar sequence. They suggested a sequence: HBL→LBL→FSRQ (???). This sequence represents an increasing energy density of the external radiation field that leads to an increasing amount of Compton cooling. The decrease of the maximum energy in the electron distribution causes the synchrotron and Compton peaks to shift to lower frequencies. Georganopoulos, Kirk, & Mastichiadis (2001) argued that the radiating jet plasma is outside the broad line scattering region in weak sources and within it in powerful sources, and the model fits to the spectra of several blazars proposed a sequence: FSRQ→LBL→HBL. The evolutionary sequence: FSRQ→LBL→HBL, has recently been suggested by D'Elia & Cavaliere (2000). In this evolutionary sequence, less gas is left to fuel the central engine for BL Lac objects, and the advection dominated accretion flows (ADAFs) may be in most BL Lac objects.

There are several tens of BL Lac objects in which one (or more) broad emission line has been detected. It is therefore possible to infer the central ionizing luminosity through their broad line emission for these BL Lac objects. The limits on the central black hole mass can be obtained, if the accretion type in the central engine is known.

2 Estimate on the Ionizing Luminosity

It is not possible to measure the ionizing luminosity directly from observations on BL Lac objects, since the observed continuum emission from the jets is strongly beamed to us.

In this case, the optical emission line luminosity can be used to estimate the central ionizing luminosity .

We can estimate the ionizing continuum luminosity $L_{\lambda,\rm ion}$ at the given wavelength λ_0 as

$$L_{\lambda,\rm ion}(\lambda_0) = \frac{L_{\rm line}}{EW_{\rm ion}}, \tag{1}$$

where λ_0 is the wavelength of the line, $EW_{\rm ion}$ is the equivalent width of the broad emission line corresponding to the ionizing continuum emission (different from the observed continuum emission).

The uncertainty in Eq. (1) is the value of $EW_{\rm ion}$, which may be different for individual sources. We estimate the value of $EW_{\rm ion}$ from the PG sample (???). This sample contains all 87 PG quasars ($z < 0.5$) with high quality optical spectra. The average value of $EW_{\rm H\beta}$ is 100Å for 70 radio-quiet quasars. We will take $EW_{\rm ion} = 100$Å and use the broad emission line Hβ to estimate the ionizing continuum luminosity of BL Lac objects. The BL Lac objects seem to follow the statistical behavior of quasars in the correlations between radio and broad line emission (Cao & Jiang 1999; 2001). It may imply that the properties of BLRs in BL Lac objects are not significantly different from that in quasars. If the $EW_{\rm ion}$ of BL Lac objects deviates from that of quasars systematically, then the estimated black hole mass could be modified with $EW_{\rm ion}$ (see further discussion in Sect. 5).

3 Estimate of the Black Hole Mass

For a standard thin disk, the ionizing continuum luminosity is mainly determined by the central black hole mass and accretion rate. For a low accretion rate, the accretion flow will transit from standard thin disk type to the ADAF type .

3.1 Standard thin accretion disks

The standard thin accretion disks are thought to be in most quasars. In this case, the luminosity at optical wavelength can be related with the disk luminosity by $L_{\rm d} \simeq 9\lambda L_{\lambda,\rm ion}(5100\text{Å})$. The central black hole mass $M_{\rm bh}$ is then estimated by $M_{\rm bh} \simeq 10^{-38}(L_{\rm d}/\dot{m})M_{\odot}$, where $\dot{m} = \dot{M}/\dot{M}_{\rm Edd}$. The ionizing luminosity $L_{\lambda,\rm ion}$ can be inferred from $L_{\rm H\beta}$, and we can finally estimate the black hole mass from the broad line luminosity $L_{\rm H\beta}$, if $\dot{m}$ is known. For $\dot{m} = 1$, the lower limit of the black hole mass is available.

3.2 ADAFs

The transition of the accretion flow from the thin disk type to the ADAF type occurs while $\dot{m}$ decreases to a value below $\dot{m}_{\rm crit}$ (Narayan & Yi 1995; Yi 1996).

The spectrum of an ADAF: $L_{\lambda}(M_{\rm bh}, \dot{m}, \alpha, \beta)$ can be calculated if the parameters $M_{\rm bh}$, $\dot{m}$, α, and the fraction of the magnetic pressure β are specified. The parameter β is defined as $p_{\rm m} = (1-\beta)p_{\rm tot}$. We can calculate the spectra of ADAFs using the approach proposed by Mahadevan (1997). For the fixed black hole mass $M_{\rm bh}$, the optical luminosity L_{λ} increases with α. For AGNs, the viscosity α could be as high as 1, as suggested by Narayan (1996). In this work, We set $\alpha = 0.3$ to calculate optical luminosity L_{λ}. The fraction of magnetic pressure $\beta = 0.5$ for equipartition cases. In fact, our numerical results show that the maximal optical luminosity $L_{\lambda}^{\rm max}$ always requires $\beta = 0.5$, if all other parameters are fixed. The accretion rate $\dot{m} < \dot{m}_{\rm crit} \simeq 0.28\alpha^2$ should be satisfied for an ADAF . So, varying the accretion rate $\dot{m}$, we can find the maximal optical luminosity at λ_0 numerically for $\alpha = 0.3$ and $\beta = 0.5$. We plot the maximal value of $\lambda L_{\lambda}^{\rm max}(\lambda_0)$ varying with black hole mass $M_{\rm bh}$ in Fig. 1. We can obtain a lower limit on the mass of the black hole from $L_{\rm H\beta}$ using the relation $\lambda L_\lambda^{\max} - M_{\rm bh}$ plotted in Fig. 1.

For BL Lac objects, most accretion power may be carried by strong jets and the accretion flows may probably be described by the adiabatic inflow-outflow solutions (ADIOSs) (Blandford & Begelman 1999). In this case, the flow is fainter than the pure ADAF considered here. The maximal $\lambda L_\lambda^{\max}(\lambda_0)$ is therefore still valid for an ADIOS. It will not affect our estimate of the black hole mass limits.

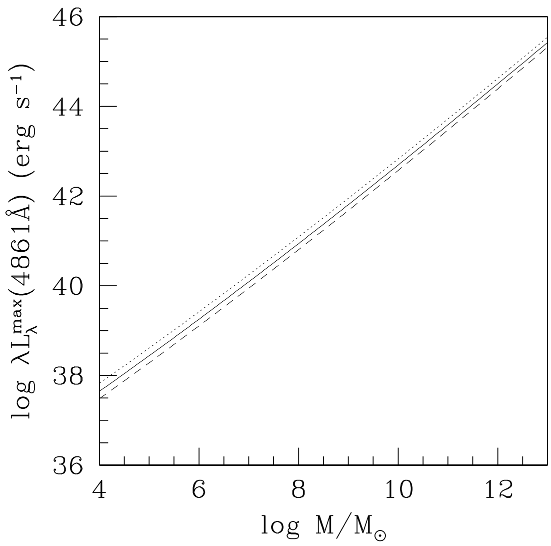

Fig. 1 The maximal optical luminosity of ADAFs at 4861 Å as functions of black hole mass for different values α: α =0.1 (dashed line), 0.3 (solid), and 1 (dotted).

4 Masses of Black Holes in BL Lac Objects

Donato et al. (2001) complied a sample of blazars observed in the X-ray band, which includes almost all HBLs, IBLs, and many LBLs. We collect all BL Lac objects in their sample and 1 Jy+S4+S5 catalogues as our start sample. This sample includes most identified LBLs and HBLs. We search the literature for all sources with broad emission line fluxes, and this leads to a sample of 23 sources. One can find the list of the sources in Cao (2002). Most of them are LBLs, except three HBLs: 0651+428, Mkn 421, and Mkn 501. The sources with relatively strong broad emission lines ($EW > 10$ Å) are considered as genuine HPQs by Veron-Cetty & Veron (2000). and are therefore not included in our sample. The source 3C 279 (1253−055) is classified as a BL Lac object in due to its small broad line equivalent width, though this source is usually regarded as a quasar in other literature. The distribution of the line luminosity $L_{\rm H\beta}$ is plotted in Fig. 2.

We use Eq. (1) and the line luminosity $L_{\rm H\beta}$ to estimate the ionizing continuum luminosity at 4861 Å. The central black hole masses $M_{\rm bh,1}$ and $M_{\rm bh,2}$ can be estimated in the cases of a thin disk and an ADAF, respectively. The mass derived for the standard thin disk case also depends on accretion rate $\dot{m}$. The lower limit of $M_{\rm bh,1}$ can be available by setting $\dot{m} = 1$. If the transition of the accretion flow from the thin disk type to the ADAF type

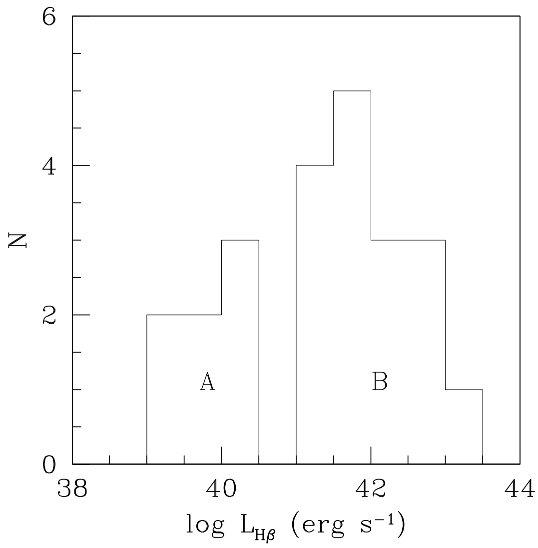

Fig. 2 The distribution of the broad emission line luminosity $L_{\mathrm{H}\beta}$.

occurs at $\dot{m} \sim \dot{m}_{\mathrm{crit}}$, we can have an upper limit on $M_{\mathrm{bh},1}$ setting $\dot{m} = 0.025$ for $\alpha = 0.3$. For ADAFs, $M_{\mathrm{bh},2}$ is the lower limit, since the maximal optical continuum luminosity is calculated for the given black hole mass. The values of the derived black hole masses can be found in Cao (2002).

5 Discussion

The distribution of line luminosity $L_{\mathrm{H}\beta}$ of all these BL Lac objects suggests a bimodal nature, although this cannot be statistically proven on the basis of the present, rather small sample (see Fig. 2). We define the sources with $L_{\mathrm{H}\beta} < 10^{41}$ ergs s^{-1} as population A, and all others are in population B. It is still not clear whether this bimodal nature of line luminosities would hold for a larger sample. It would be interesting to perform high-sensitivity optical observations on a large sample of BL Lac objects.

For thin disk cases, the lower limits on the hole mass would be in 10^{4-8} $M_\odot$, while the upper limits on the hole mass would be in 10^{6-10} $M_\odot$ if $\dot{m} \sim 0.025$. For accretion rate $\dot{m} < 0.025$, the accretion flow would be in ADAF state. In this case, the lower limits on the black hole mass are in: 10^{8-12} $M_\odot$. Noting that this is the lower limit, the black hole mass could be much higher if the accretion rate is low or/and the viscosity α is small.

The masses of black holes in all sources of population B are in 10^{6-8} $M_\odot$ if $\dot{m} \sim 1$. It would be interesting to pay much attention on the seven sources in population A. If the accretion flows in these sources are in thin disk state, their central black holes would have masses 10^{4-6} $M_\odot$ for any value of $\dot{m}$. If the accretion rate $\dot{m}$ is lower than the critical value $\dot{m}_{\mathrm{crit}}$, the accretion flows in these sources are in the ADAF state. The lower limits on the mass of the black hole in these sources are in the range of $1.66 - 24.5 \times 10^8$ $M_\odot$. Falomo, Kotilainen, & Treves (2001) found that the mass of the black hole in Mkn 501 is $3.2 \times 10^8\ M_\odot$ from the measurement of bulge velocity dispersion, while Barth, Ho, & Sargent (2002) derived the mass of $(0.9 - 3.4) \times 10^9\ M_\odot$. Considering that our estimate $(1.66 \times 10^8\ M_\odot)$ is the lower limit, the central black hole mass can be higher than the limit if the accretion rate is sufficiently low or/and the viscosity α is small. Our result is consistent with their results of Mkn 501 derived from bulge velocity dispersion. It may probably that the sources in population A have already been in ADAF state.

The sources in population B may have standard thin accretion disks surrounding the black holes, otherwise some black holes should be at least as huge as $10^{12} M_\odot$. If the accretion rate $\dot{m}$ of these sources is as small as ~ 0.025, slightly higher than the critical value below which the accretion flow would be in ADAF state, the black hole mass would be in $10^{8-10}\ M_\odot$. As the fact that most FSRQs have black hole mass higher than $10^8\ M_\odot$ (Laor 2000; Gu, Cao, & Jiang 2001), this is compatible with the unified models of radio-loud quasars.

There are three HBLs in our sample in population A, and all sources in population B are LBLs. It may imply that the accretion flows in all HBLs are in ADAF state. The fact that no broad emission line has been detected for most BL Lac objects may imply that only a small fraction of LBLs have optically thick standard thin accretion disks surrounding the black holes with very low accretion rate close to $\dot{m}_{\rm crit}$. We speculate that these LBLs will finally exhaust the gas near the hole and the disks will transit to ADAFs. Most other LBLs and HBLs without any broad emission line detected may be in population A, and the accretion flows have already been in ADAF state. Otherwise the black holes in these sources should be very small, if the accretion flows are in standard thin disk state. It is most probably that the BL Lac objects studied here with one (or more) broad emission line detected are in the intermediate state of the evolutionary sequence from FSRQ to BL Lac object. The fact that no HBL is in population B may imply that the evolutionary sequence of BL Lac objects should be LBL→HBL. The results present in this work support the evolutionary sequence FSRQ→LBL→HBL suggested by D'Elia & Cavaliere (2000). If this is the case, then the ratio of the BL Lac objects in population B to the remainder offers a clue to study the detailed evolutionary history of blazars, and it can also be a useful test on ADAF models.

If the evolution of blazars is really regulated by the gas near the black hole, the reprocessing optical depth of the BLR would decrease with the depletion of the gas near the hole, and the line $EW_{\rm ion}$ of the blazar would also decrease along the evolutionary sequence. The lower limits on the mass of the hole in evolving blazars should be modified with varying $EW_{\rm ion}$. In this work, we used a single $EW_{\rm ion}$ to derive the masses of holes in blazars and found that the holes have similar masses for these two populations of BL Lac objects. In this case, the lower limits on the mass of the hole in the blazars evolving at a later stage would become systematically higher than that derived in this work. The derived hole masses seem to be consistent with the evolutionary sequence FSRQ→LBL→HBL.

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References

Barth A.J., Ho L.C., Sargent W.L.W., ApJ, 2002, 566, L13
Blandford R.D., Begelman M.C., MNRAS, 1999, 303, L1
Cao X., ApJ, 2002, 570, L13
Cao X., Jiang D.R., MNRAS, 1999, 307, 802

Cao X., Jiang D.R., MNRAS, 2001, 320, 347
D'Elia V., Cavaliere A., PASP, 2000, 227, 252
Dibai E.A., Soviet Astron., 1981, 24, 389
Donato D., Ghisellini G., Tagliaferri G.,et al., A&A, 2001, 375, 739
Falomo R., Kotilainen J., Treves A., ApJ, 2002, in press (astro-ph. 0203199)
Georganopoulos M., Kirk J.G., Mastichiadis A., in ASP Conf. Ser. 227, Blazar Demographics and Physics, ed. Padovani P., C.M. Urry(San Francisco: ASP), 2001
Ghisellini G., Celotti A., Fossati G., et al., MNRAS, 1998, 301, 451
Gu M., Cao X., Jiang D.R., MNRAS, 2001, 327, 1111
Laor A., ApJ, 2000, 543, L111
Mahadevan R., ApJ, 1997, 477, 585
Narayan R., ApJ, 1996, 462, 136
Narayan R., Yi I., ApJ, 1995, 452, 710
Veron-Cetty M.P., Veron P., A&AR, 2000, 10, 81
Yi I., ApJ, 1996, 473, 645