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What Governs Lorentz Factors of Jet Components in Blazars?

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Abstract. We use a sample of radio-loud Active Galactic Nuclei (AGNs) with measured black hole masses to explore the jet formation mechanisms in these sources. We find a significant correlation between black hole mass and the bulk Lorentz factor of the jet components for this sample, while no significant correlation is present between the bulk Lorentz factor and the Eddington ratio. Recent investigations suggested that the most super-massive black holes in elliptical galaxies have on average higher spins than the black holes in spiral galaxies. The correlation between black hole mass and bulk Lorentz factor of the jet components found in this work implies that the motion velocity of the jet components is probably governed by the black hole spin. The faster moving jets are magnetically accelerated by the magnetic fields threading the horizon of more rapidly rotating black holes.

Key words. Black hole physics—accretion—galaxies: jets.

1. Introduction

The currently most favoured models of jet formation are the Blandford–Znajek (BZ) and Blandford–Payne (BP) mechanisms (Blandford & Znajek 1977; Blandford & Payne 1982). The apparent motions of the jet components in AGNs were detected by multi-epoch Very Long Baseline Interferometry (VLBI) observations (e.g., Kellermann *et al.* 2004). The Lorentz factor and viewing angle of the jet component can be derived with the measured proper motion of the jet component, if the Doppler factor is estimated. There are several different approaches applied to estimate the Doppler factor of the jets. The inhomogeneous relativistic jet model can reproduce both the flat-spectrum characteristics of some AGNs and dependence of the core size on the observing frequency (Blandford & Königl 1979; Königl 1981). Based on this inhomogeneous jet model, an approach was suggested by Jiang *et al.* (1998) to estimate the jet parameters including bulk Lorentz factor, viewing angle, and electron number density in the jets of AGNs. The relation between jets and the accretion disks was extensively explored in many previous works (e.g., Rawlings *et al.* 1989; Celotti *et al.* 1997; Cao & Jiang 1999, 2001; Gu *et al.* 2009), which indicate that the jets are indeed closely linked to the accretion disks, though the different jet formation mechanisms are still indistinguishable.

In this work, we explore the relationship between black hole mass and the motion of jet components for a sample of blazars with measured proper motion of jet components by multi-epoch VLBI observations. We further compile a sample of blazars with measured black hole masses, of which the jet parameters are estimated with the inhomogeneous jet model, to investigate the relationship of the Lorentz factor of jets with black hole mass, the Eddington ratio, or the strength of the magnetic field in the jets.

2. Correlations between black hole mass and Lorentz factor

We start with a sample of radio-loud quasars and BL Lac objects with measured apparent velocities of jet components. The sample is compiled by searching the literature to include all blazars with available proper motion data of the jets. We find that 146 blazars have reliably measured apparent velocities. Their black hole masses are estimated with the broad-line widths and broad-line/continuum luminosities, which leads to 78 sources with measured black hole masses. The Lorentz factors of the jets are still unavailable, as the viewing angles of the jets are unknown for most sources in this sample. However, we can derive the minimal Lorentz factors from the observed apparent velocities of jet components using

$$\gamma_{\mathrm{min}} = (1 + \beta_{\mathrm{app}}^2)^{0.5}. \qquad (1)$$

In Figure 1, we plot the relation between black hole masses M_{BH} and the minimal Lorentz factors γ_{min} of the jets. The linear regression gives

$$\log \gamma_{\mathrm{min}} = 0.31 \log M_{\mathrm{BH}} - 1.80. \qquad (2)$$

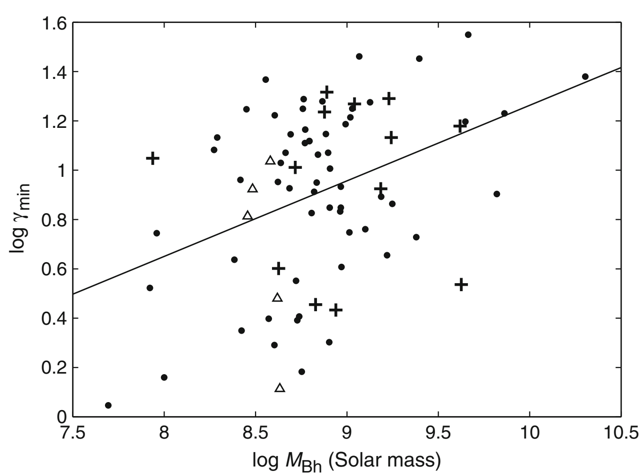

Figure 1. The relation between black hole mass and the minimal Lorentz factor of the jet.

A significant correlation is found between these two quantities at 99.6% confidence (Spearman rank correlation analysis), and the correlation coefficient is 0.33. However, we have not found a correlation between the Eddington ratio and the black hole mass for the sample (see detailed results in Zhou & Cao 2009).

The Lorentz factor of the jets can be derived from an apparent jet velocity if the Doppler factor is known. Gu *et al.* (2009) constructed a sample of 128 sources, of which the jet parameters are derived from VLBI and X-ray data with Königl's inhomogeneous jet model. We search the literature for the black hole mass measurements and finally obtain a sample of 101 sources with measured black hole masses, including 77 quasars, 20 BL Lac objects and 4 radio galaxies.

We plot the relation between black hole mass and the bulk Lorentz factor of the jet components in Figure 2. A strong correlation is found between these two quantities with a Spearman rank correlation coefficient $r = 0.357$ at 99.98% confidence level. Using the linear regression analysis, the correlation can be expressed as

$$\log \Gamma = (0.20 \pm 0.06) \log M_{\mathrm{BH}} - (0.68 \pm 0.52), \tag{3}$$

and it becomes

$$\log \Gamma = (0.21 \pm 0.07) \log M_{\mathrm{BH}} - (0.70 \pm 0.61) \tag{4}$$

for the quasars in the sample with a correlation coefficient $r = 0.376$ at 99.92% confidence level.

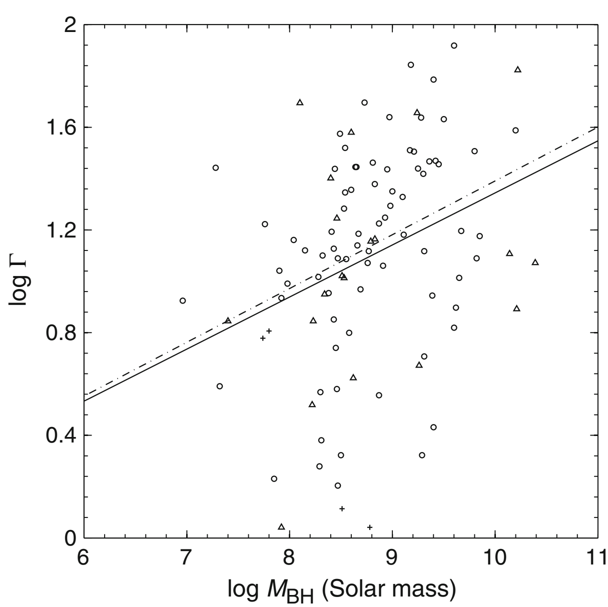

Figure 2. The relation between black hole mass and the bulk Lorentz factor of the jet components. The circles represent quasars, and triangles represent BL Lac objects, while the crosses represent radio galaxies. The solid line is the fitted line for the whole sample using the least-square method while the dotted-dashed line is the fitted for quasars only.

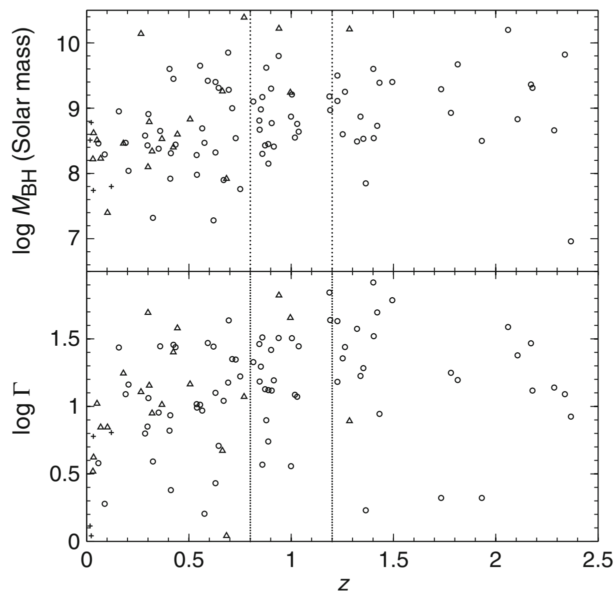

Figure 3. The relation between black hole mass and redshift z (the upper panel). The lower panel is the relation between the bulk Lorentz factor of the jet components and the redshift z. The two vertical dotted lines correspond to $z = 0.8$ and 1.2, respectively.

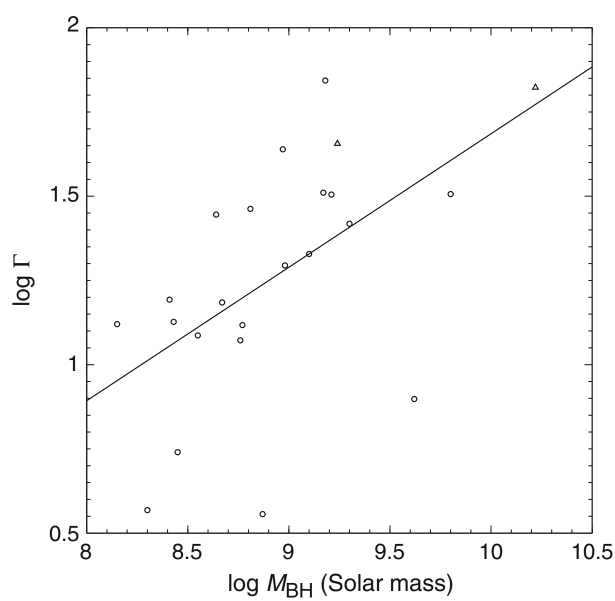

Figure 4. The relation between black hole mass and the bulk Lorentz factor of the jet components for the subsample of the sources with redshift $0.8 < z < 1.2$. The symbols are the same as in Figure 2.

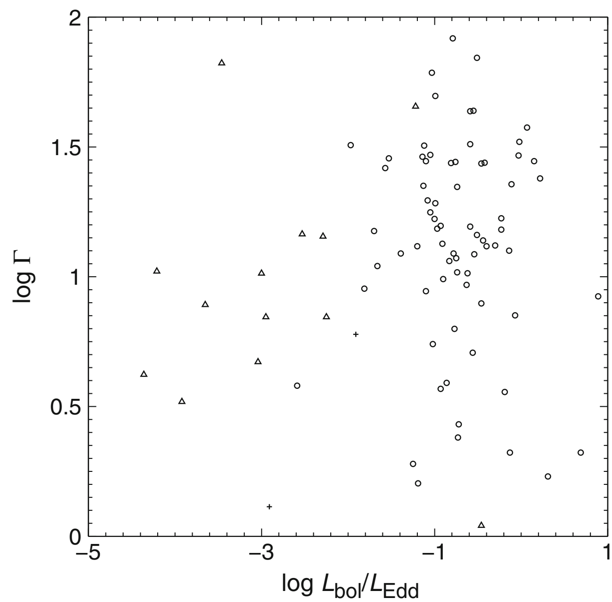

Figure 5. The relation between the Eddington ratio and the bulk Lorentz factor of the jet. The symbols are the same as in Fig. 2.

In Figure 3, we plot the relation between black hole mass and redshift z, and the relation between the bulk Lorentz factor and redshift z. It is found that both the black hole mass and the Lorentz factor are strongly correlated with redshift z, which implies that the correlation between black hole mass and the Lorentz factor may be caused by the common dependence of redshift. We therefore, choose a subsample of the sources in a restricted range of redshift $0.8 < z < 1.2$ (see the sources between two vertical dotted lines in Figure 3). No significant correlations were present between $M_{\rm BH}$ and z, or Γ and z, while a significant correlation between $M_{\rm BH}$ and Γ is still present for the sources in this subsample (see Figure 4a). Therefore, we conclude that significant correlation between black hole mass and the bulk Lorentz factor might be intrinsic, at least for our present sample, which is confirmed by the partial correlation analyses (see detailed results in Chai *et al.* 2012).

The relation between the Eddington ratio and the bulk Lorentz factor of the jet components is plotted in Figure 5. The correlation analysis shows that no significant correlation is found between $L_{\rm bol}/L_{\rm Edd}$ and Γ with a correlation coefficient $r = 0.099$ at 63.94% confidence level.

3. Discussion

As massive black holes acquire mass and angular momentum simultaneously through accretion, the black holes will be spun up with mass growth. Volonteri *et al.* (2007) investigated how accretion from a warped disk influences the evolution of black hole spins, in which the effects of accretion and merger are considered. They concluded that within the cosmological framework, most super-massive black holes in elliptical galaxies have on average higher spins than black holes in spiral galaxies, where random, small accretion episodes (e.g., tidally disrupted stars, accretion of molecular clouds) might have played a more important role. Cao & Li (2008) calculated the black hole mass function of AGN relics with the observed Eddington ratio distribution of AGNs and compared it with the measured mass function of the massive black holes in galaxies. They found that the radiative efficiencies of the most massive accreting black holes are higher than those of the less massive black holes.

The correlation between the black hole mass and the Lorentz factor of the jet components implies that the motion velocity of the jet components is probably governed by the black hole spin. No correlation is present between the Eddington ratio and the Lorentz factor, which implies the acceleration of the jets is not directly linked to the accretion disks. The results imply that BZ mechanism may dominate over BP mechanism for the jet acceleration. The faster moving jets are magnetically accelerated by the magnetic fields threading the horizon of more rapidly rotating black holes.

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References

Blandford, R. D., Königl, A. 1979, *ApJ*, **232**, 34.
Blandford, R. D., Payne, D. G. 1982, *MNRAS*, **199**, 883.
Blandford, R. D., Znajek, R. L. 1977, *MNRAS*, **179**, 433.
Cao, X., Jiang, D. R. 1999, *MNRAS*, **307**, 802.
Cao, X., Jiang, D. R. 2001, *MNRAS*, **320**, 347.
Cao, X., Li, F. 2008, *MNRAS*, **390**, 561.
Celotti, A., Padovani, P., Ghisellini, G. 1997, *MNRAS*, **286**, 415.
Chai, B., Cao, X., Gu, M. 2012. *ApJ*, **759**, 114.
Gu, M., Cao, X., Jiang, D. R. 2009, *MNRAS*, **396**, 984.
Jiang, D. R., Cao, X., Hong, X. 1998, *ApJ*, **494**, 139.
Kellermann, K. I., Lister, M. L., Homan, D. C. *et al.* 2004, *ApJ*, **609**, 539.
Königl, A. 1981, *ApJ*, **243**, 700.
Rawlings, S., Saunders, R., Eales, S. A., Mackay, C. D. 1989, *MNRAS*, **240**, 701.
Volonteri, M., Sikora, M., Lasota, J.-P. 2007, *ApJ*, **667**, 704.
Zhou, M., Cao, X.-W. 2009, *Res. Astron. Astrophys.*, **9**, 293.