

Jets, Accretion and Spin in Supermassive Black Holes (Postprint)

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Abstract

The theoretical model suggests that relativistic jets of active galactic nuclei (AGNs) rely on the black hole spin and/or accretion. We study the relationship between jet, accretion, and spin using supermassive black hole samples with reliable spin of black holes. Our results are as follows: (1) There is a weak correlation between radio luminosity and the spin of the black hole for our sample, which may imply that the jet of the supermassive black hole in our sample depends on the other physical parameters besides black hole spins, such as accretion disk luminosity. (2) The jet power of a supermassive black hole can be explained by the hybrid model with magnetic field of corona. (3) There is a significant correlation between radio-loudness and black hole spin for our sample. These sources with high radio-loudness tend to have high black hole spins. These results provide observational evidence that the black hole spin may explain the bimodal phenomena of radio-loud and radio-quiet AGNs.

Full Text

Preamble

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Jets, Accretion and Spin in Supermassive Black Holes

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Abstract

Theoretical models suggest that relativistic jets in active galactic nuclei (AGNs) rely on black hole spin and/or accretion. We investigate the relationship between jets, accretion, and spin using a sample of supermassive black holes with reliably measured spins. Our results are as follows: (1) There is a weak correlation between radio luminosity and black hole spin in our sample, which may imply that the jets in these supermassive black holes depend on physical parameters besides black hole spin, such as accretion disk luminosity. (2) The jet power of supermassive black holes can be explained by a hybrid model incorporating the magnetic field of the corona. (3) There is a significant correlation between radio-loudness and black hole spin in our sample. Sources with high radio-loudness tend to have high black hole spins. These results provide observational evidence that black hole spin may explain the bimodal phenomena of radio-loud and radio-quiet AGNs.

Key words: galaxies: active – galaxies: general – galaxies: jets

1. Introduction

The origin of jets from active galactic nuclei (AGNs) has long remained unclear. It is generally believed that jet formation is primarily related to accretion and the spin of supermassive black holes (e.g., Blandford & Znajek 1977; Ghisellini 2006; Zamaninasab et al. 2014). Some authors have suggested that jet power is closely linked to accretion disk luminosity (e.g., Rawlings & Saunders 1991; Ghisellini et al. 2014; Sbarrato et al. 2014; Chen et al. 2015a, 2015b; Paliya et al. 2017; Chen et al. 2023a, 2023b, 2023c). Ghisellini et al. (2014) found that jet power exceeds accretion disk luminosity, implying that black hole spin may play an important role in jet formation in addition to accretion. Some authors

have found that jets from stellar-mass black holes in X-ray binaries are related to black hole spin (Narayan & McClintock 2012; Steiner et al. 2013). Recently, Cui et al. (2023) discovered a precessing jet nozzle connecting to a spinning black hole in M87, suggesting that jets are closely related to black hole spin. However, Fender et al. (2010) found no correlation between black hole spin and jets in X-ray binaries. Although some studies have examined the relationship between black hole spin and jets, whether black hole spin enhances relativistic jets has not been investigated using large samples with reliable black hole spin measurements.

The origin of the radio-quiet and radio-loud AGN dichotomy has been extensively discussed in the literature. Some authors suggest that accretion rate (Eddington ratios $\lambda = L_{\text{bol}}/L_{\text{Edd}}$, where L_{bol} is bolometric luminosity and L_{Edd} is Eddington luminosity) may explain this bimodal phenomenon (e.g., Ho et al. 2000; Sikora et al. 2007). Another possible explanation is that black hole spin leads to the dichotomy between radio-loud and radio-quiet AGNs. Sikora et al. (2007) discovered that radio-loud AGNs are hosted in elliptical galaxies, while radio-quiet AGNs are likely hosted in spiral galaxies. Volonteri et al. (2007) found that spiral galaxies have lower black hole spins than elliptical galaxies, indicating that the dichotomy of radio-loud and radio-quiet AGNs can be explained by supermassive black hole spin. However, there is currently a lack of observational evidence to support the correlation between black hole spin and radio-loudness.

In this paper, we primarily investigate the relationship between jets, black hole spin, and accretion using large samples. We also study the relationship between black hole spin and radio-loudness. The sample is presented in Section 2; the jet model is described in Section 3; Section 4 presents the results and discussion; Section 5 summarizes the conclusions. We adopt a Λ CDM cosmology with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$.

2.1. The Sample of Supermassive Black Holes

We select a large sample of supermassive black holes with reliable measurements of black hole spin, black hole mass, broad line region luminosity (BLR), and 1.4 GHz radio flux. Black hole spin is measured using the X-ray reflection spectroscopy method (Gallo et al. 2011; Brenneman 2013; Lohfink et al. 2013; Risaliti et al. 2013; Walton et al. 2013; Reis et al. 2014; Keck et al. 2015; Buisson et al. 2018; Parker et al. 2018; Sun et al. 2018; Jiang et al. 2019; Walton et al. 2019, 2020). We also require that these sources have measured broad emission line luminosities (Grupe et al. 2004; Sugai et al. 2007; Sulentic et al. 2007; Buttiglione et al. 2010; Assef et al. 2011; Koss et al. 2017; Malkan et al. 2017; Daniel & Wyse 2018; Afanasiev et al. 2019; Kim et al. 2021). Accretion disk luminosity is estimated using $L_{\text{disk}} = 10 \times L_{\text{BLR}}$, with an average uncertainty of a factor of 2 (Calderone et al. 2013; Ghisellini et al. 2014). We calculate radio-loudness using the ratio of 1.4 GHz flux to B-band flux, $R = S_{1.4}/S_B$ (e.g., Hao et al. 2014). The sample of supermassive black holes is

shown in Table 1 .

2.2. The Jet Power

The jet power of AGNs can be derived from the radio luminosity of the compact core (e.g., Merloni & Heinz 2007; Cavagnolo et al. 2010; Daly et al. 2012). Cavagnolo et al. (2010) obtained the relationship between radio luminosity and jet power using 21 giant elliptical galaxies:

$$\log P_{\text{jet}} = 0.14 \log L_{1.4} + 0.18$$

where $L_{1.4}$ is the 1.4 GHz radio power, estimated by $L_{1.4} = 4\pi d_L^2 S_\nu (1+z)^{\alpha-1}$. S_ν is the flux density at 1.4 GHz from the NASA/IPAC Extragalactic Database (NED), and the spectral index $\alpha = 0$ (e.g., Abdo et al. 2010; Komossa et al. 2018). P_{jet} is in units of 10^{42} erg s^{-1} and $L_{1.4}$ is in units of 10^{40} erg s^{-1} . The scatter for this relation is $\sigma_{1.4} = 0.78$ dex. In the sample of Cavagnolo et al. (2010), about 76% are radio-quiet AGNs (e.g., NGC 4636, NGC 5813, and NGC 5846). Therefore, Equation (1) can be used to calculate the jet power of radio-quiet AGNs. Some authors have also used this equation to estimate jet power for radio-quiet AGNs (e.g., Cheung et al. 2016; Mezcua et al. 2019; Chen et al. 2020; Singha et al. 2023; Igo et al. 2024). We use Equation (1) to estimate the jet power for our sample. We note that radio-quiet AGNs only show a compact radio core, and radio flux mainly originates from this core. Based on the 1.4 GHz radio luminosity (e.g., Fanaroff & Riley 1974), we find that almost all sources in our sample are FR I radio sources ($L_{1.4} \lesssim 10^{40.5}$ erg s^{-1}). This suggests our sample has bright cores, and the 1.4 GHz radio flux primarily comes from the core. Therefore, using 1.4 GHz radio flux to estimate jet power does not affect our main results. In the future, when core fluxes become available for these sources, we will test our results.

Table 1: The Sample of Supermassive Black Holes

Name	$S_{1.4}$ (mJy)	$\log L_{1.4}$ (erg s^{-1})	$\log M_{BH}$ (M_\odot)	Mass/Spin Ref- er- Spin- ence	$\log L_{BLR}$ (erg s^{-1})	BLR Ref- er- ence	S_B (mJy)	S_X (Jy)	S_X Er- ror (Jy)
Mrk0.02578	36 ± 2	44 ± 0.6	4.3	Pe04/W41307	S07	0.0054677	0.033	3440	
335	± 0.6		± 0.5				± 13	± 103	
IRAS03272.4	22.2 ± 1.3	0.00973	44.6	ZW05/W4033	M17	360	0.012884	3.1	
00521-	± 0.6		± 2			± 10.8	± 1.9	± 0.5	

Name	$S_{1.4}$ (mJy)	$\log L_{1.4}$ (erg s ⁻¹)	$\log M_{BH}$ (M)	Mass/Spin Ref- er- Spinence	$\log L_{BLR}$ (erg s ⁻¹)	BLR Ref- er- ence	S_B (mJy)	S_X (Jy)	S_X Er- ror (Jy)
Mrk20 359	29.1 ± 1 0.8	0.00608	355 ± 10	Be11/Wa13	15 ± 0	7.15 ± 0.11	0.83	0.1377 ± 0.09	
Mrk0.98038 1018	38.62 ± 0.04	8.18 ± 0.06	0.64	0.11 Fa19/Ri33	3.52	K17	7.72 ± 0.12	0.7 0.10	38.11
NGC7.47 1365	0.92 ± 0.08	0.04	38.08	Pe04/L713	0.94	0.05	7.76	0.930.02	8.3 ± 0.09
3C120.045 1213	0.16 ± 0.173	0.16	6.50E-07	6.90E-09	Ca11 0.467 ± 0.0495	1.89	1.66E-07	0.00E+00 ± 0.727	0.81
Ark1200E-07 08	2.07E-1.2	8.12 ± 1.2	-0.28	5.59E-07	Br13 7.59E-08	39.8 ± 0.79	0.98	4.55E-07 ± 0.41	2.23
Mrk3.19 79	3.05E-06	1.53E-07	11.5 ± 0.46	On10/O3e15	1.89E-06	1.88E-07	5.13 ± 0.12	0.641.79E-06	1.79E-07
NGC7.7 3783	0.76 ± 0.24	3.55E-06	1.76E-07	Be03/Bu18	0.98	1.39E-05	6.90E-07	1.41 2.07E-06	0.00E+00
NGC1.58 4151	2.24 ± 0	0.14	1.75E-07	ZW05/OE130	0.63	2.48E-07	0.00E+00	0.67 ± 0	1.38E-06
Mrk0.00E-270 766	6.270 ± 1.48	1.26	5.78E-06	Ni09/SOE+019	0.7 ± 2.1	0.03	5.86E-07	0.00E+00 ± 0	1.33
PG1226E-200E+00 07	0.694 ± 0	0.694	Wa20/Wa20	Si12/Re14		-	-	-	-

Note: The table data appears corrupted in the original manuscript. Column values may not correspond to their intended headings.

3. The Jet Model

Currently, the main jet formation mechanisms include the Blandford-Znajek (BZ) mechanism (Blandford & Znajek 1977), the Blandford-Payne (BP) mechanism (Blandford & Payne 1982), and the hybrid jet model (e.g., Meier 2001; Garofalo et al. 2010), which combines BZ and BP processes. It is generally believed that jets and/or outflows can be accelerated and collimated by large-scale

magnetic fields (e.g., Pudritz et al. 2007). Spruit & Uzdensky (2005) suggested that the large-scale magnetic field that accelerates the jet or outflow is formed by the advection of a weak external field. However, Lubow et al. (1994) found that advection of the external field caused by the small radial velocity of geometrically thin accretion disks ($H/R = 1$) is quite ineffective. The coronal mechanism was proposed to alleviate this problem of weak external field advection in thin disks (e.g., Spruit & Uzdensky 2005; Cao & Spruit 2013). Beckwith et al. (2009) found that the hot corona above the accretion disk can effectively drag the external magnetic field inward.

Some authors have found that the magnetic field of the corona can enhance relativistic jets (e.g., Cao 2018). Our sample has high relativistic jet power. Therefore, in this work we use the magnetic field of the corona above the thin accretion disk to estimate jet power in our model. We then compare the model jet power with the observed jet power.

3.1. Magnetic Field of Corona

The corona above the accretion disk can be described by the corona thickness H_c and optical depth τ_c (Cao 2018). Cao (2018) estimated the magnetic field strength of the corona using the following formula:

$$B_c \approx \sqrt{\frac{2L_{\text{disk}}}{r_c^2 c} \frac{\tilde{H}_c}{\tau_c}}$$

where \tilde{H}_c is the relative thickness (Cao 2018). To estimate the maximum jet power, we adopt $\omega_F = 1/2$ (Ghosh & Abramowicz 1997), $\beta = 1$, $\xi_f = 1$, $\tilde{H}_c = 0.5$, $\tau_c = 0.5$, and $L_* = L_K(r_{\text{ms}})$ (Cao 2018).

3.2. The Jet Model

(1) The BZ Jet Model. The formula for calculating jet power in the BZ mechanism is (e.g., MacDonald & Thorne 1982; Thorne et al. 1986; Ghosh & Abramowicz 1997; Livio et al. 1999; Nemmen et al. 2007):

$$P_{\text{jet}}^{\text{BZ}} = \frac{\omega_F}{8\pi} B_{\perp}^2 r_H^2 c$$

where B_{\perp} is the magnetic field strength at the black hole horizon ($B_{\perp} \approx B_c$) and r_H indicates the horizon radius. The parameter ω_F is estimated using the angular velocity of field lines Ω_F and the black hole Ω_H . To obtain the maximal jet power from the BZ mechanism, we use $\omega_F = 1/2$ (MacDonald & Thorne 1982).

(2) The BP Jet Model. We calculate jet power in the BP model using the following formula (Livio et al. 1999; Cao 2018):

$$P_{\text{jet}}^{\text{BP}} = \frac{1}{8\pi} B_s^2 R_j^2 \Omega^2$$

where B_s indicates the azimuthal component of the magnetic field on the corona surface. The ratio $\xi_f \lesssim 1$ is required (Livio et al. 1999). R_j indicates the radius of the jet formation region in the corona, and Ω is the angular velocity of gas in the corona. According to Equations (2) and (5), the jet power from the BP mechanism can be estimated as:

$$P_{\text{jet}}^{\text{BP}} \approx 2 \times 10^{44} \xi_f \beta^2 \tilde{H}_c^{-2} \tau_c^{-2} \left(\frac{L_{\text{disk}}}{10^{45} \text{erg s}^{-1}} \right) \text{erg s}^{-1}$$

Since most of the released gravitational power is located in the inner region of the accretion disk with radius $\sim 2R_{\text{ms}}$ (Shakura & Sunyaev 1973), we use $R_j = 2R_{\text{ms}}$ to estimate the jet power of the BP model. R_{ms} can be derived from:

$$R_{\text{ms}} = \frac{GM}{c^2} \left(3 + Z_2 \mp \sqrt{(3 - Z_1)(3 + Z_1 + 2Z_2)} \right)$$

where $Z_1 = 1 + (1 - a^2)^{1/3}((1 + a)^{1/3} + (1 - a)^{1/3})$ and $Z_2 = \sqrt{3a^2 + Z_1^2}$.

(3) The Hybrid Jet Model. The hybrid model combines BZ and BP mechanisms. Garofalo et al. (2010) used the following formula to obtain jet power for the hybrid model in the case of a thin accretion disk:

$$P_{\text{jet}}^{\text{Hybrid}} = \alpha P_{\text{jet}}^{\text{BZ}} + (1 - \alpha) P_{\text{jet}}^{\text{BP}}$$

where α and f are parameters that combine the BZ and BP mechanisms. These are respectively given by (Garofalo 2009):

$$\alpha = \frac{a^2}{a^2 + f^2(1 - a^2)}$$

$$f = \delta(1 - a)^{1/2}$$

The conservative value of δ is about 2.5 (Garofalo et al. 2010). The parameter α represents the effectiveness of the BP jet as a function of black hole spin, while f reflects the enhancing effect of the disk-threaded field on the black hole.

4.1. The Formation Mechanism of Jets

Currently, three popular jet formation mechanisms exist: the BZ mechanism (Blandford & Znajek 1977), the BP mechanism (Blandford & Payne 1982), and the hybrid model (Meier 2001; Garofalo et al. 2010). The BZ mechanism primarily extracts rotational energy from the black hole, while the BP mechanism extracts rotational energy from the accretion disk. The hybrid model combines both BZ and BP mechanisms. In both BZ and BP mechanisms, matter accretion onto the black hole leads to an expected relationship between jet power and accretion disk properties (Maraschi & Tavecchio 2003).

Figure 1 [Figure 1: see original paper] shows the relationship between black hole spin (left panel), accretion disk luminosity (right panel), and radio luminosity for our sample. From the left panel of Figure 1, we find a weak correlation between radio luminosity and black hole spin ($r = 0.27$). We further tested the correlation between jet power and black hole spin at an 84% confidence level and found a correlation coefficient of 0.42, showing a moderately strong correlation. The best-fit equation between radio luminosity and spin for our sample is:

$$\log L_{\text{radio}} = 39.3 + 0.42a$$

This result suggests that jet power depends on black hole spin. Some authors have found a close connection between jets and accretion (e.g., Rawlings & Saunders 1991; Ghisellini et al. 2014; Sbarrato et al. 2014; Chen et al. 2015a, 2015b; Paliya et al. 2017; Mukherjee et al. 2019; Chen et al. 2023a, 2023b, 2023c). We test this correlation in the right panel of Figure 1, which shows the relation between radio luminosity and accretion disk luminosity. We find a significant correlation between radio and accretion disk luminosity for our sample ($r = 0.51$, $p = 0.04$). This further demonstrates a close connection between jets and accretion. The best-fit equation is:

$$\log L_{\text{radio}} = 0.18 \log L_{\text{disk}} + 18.2$$

These results may imply that both black hole spin and accretion enhance relativistic jets, suggesting our sample's jet model may be a hybrid one. We test this speculation in Figure 2 [Figure 2: see original paper], which shows jet power in Eddington units as a function of black hole spin. The orange dashed line indicates BP mechanism jet power, the green dashed line indicates BZ mechanism jet power, and the red dashed line indicates the hybrid model. The right-hand axis shows jet efficiency.

From Figure 2, we find that jet power from the BZ mechanism and hybrid model varies with black hole spin, while BP mechanism jet power does not change with spin. The greater the black hole spin, the higher the jet efficiency, consistent with GRMHD simulations (Tchekhovskoy et al. 2012). The jet efficiency reaches 1% for the BZ model and 300% for the hybrid model when black hole spin is 0.99,

implying the hybrid model plays a more important role than the BZ mechanism. We find that almost all sources in our sample lie below the red and orange dashed lines except Mrk 359, indicating the hybrid model can explain the jet power of nearly our entire sample. We note that Mrk 359 has a relatively low black hole mass, resulting in a high $\log P_{\text{jet}}$.

The properties of a corona are usually closely related to hard X-ray emission. If the coronal jet model indeed operates in these supermassive black holes, we might expect a correlation between radio and hard X-ray luminosity. Figure 3 [Figure 3: see original paper] shows this relation, revealing a significant correlation ($r = 0.75$, $p = 0.0009$) between radio luminosity and hard X-ray luminosity.

4.2. Relation Between Black Hole Spin and Radio-Loudness

AGNs are divided into radio-loud and radio-quiet types based on radio-loudness. The origin of radio-loudness remains unclear. Some studies have found an inverse correlation between radio-loudness and accretion (e.g., Sikora et al. 2007). In addition to accretion rate, a second physical parameter determining AGN radio-loudness may naturally be related to central black hole properties, such as black hole spin. We test this correlation in Figure 4 [Figure 4: see original paper], which shows the relation between radio-loudness and black hole spin.

We find a significant correlation between radio-loudness and black hole spin for our sample ($r = 0.48$, $p = 0.04$). The best-fit equation is:

$$\log R = 2.60 + 0.48a$$

Sources with high radio-loudness tend to have high black hole spin, suggesting that black hole spin may explain the dichotomy between radio-quiet and radio-loud AGNs. Tchekhovskoy et al. (2010) investigated whether the bimodality of radio-loud and radio-quiet AGNs could result from differences in black hole spin using numerical simulations. They suggested this dichotomy could be explained by two different populations of galaxies with modestly different black hole spins. Radio-loud and radio-quiet AGNs may have different merger and accretion histories, leading to different black hole spins. Radio-loud AGNs are hosted in elliptical galaxies, whereas radio-quiet AGNs are likely hosted in spiral galaxies (Sikora et al. 2007). Volonteri et al. (2007) found that the average spin of supermassive black holes in elliptical galaxies is higher than in spiral galaxies, suggesting radio-loud AGNs may have higher black hole spins than radio-quiet AGNs. However, we find the parameter space for black hole spin is quite narrow (e.g., a from -0.3 to 0), with most sources having very high spin parameters and only four sources with $a \sim 0.6$ –0.7. This correlation may be strongly affected by sample selection, and our results should be tested with larger samples in the future.

5. Conclusions

In this work, we study the relationship between jets, accretion, and black hole spin, as well as the relationship between radio-loudness and black hole spin. Our main results are:

1. We find a weak correlation between radio luminosity and black hole spin in our sample. We further test the correlation between jet power and black hole spin at an 84% confidence level, finding a correlation coefficient of 0.42. These results imply that jets in the supermassive black holes of our sample depend on parameters besides black hole spin.
2. We investigate jet power from the BZ mechanism, BP mechanism, and hybrid mechanism based on thin disks surrounding Kerr black holes. From the diagram of jet power in Eddington units versus black hole spin, we find that the hybrid model can explain the jet power of almost all sources.
3. We find a significant correlation between radio-loudness and black hole spin in our sample. This result may provide observational evidence for explaining the radio-quiet and radio-loud dichotomy.

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