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Postprint Discussion on the Correlation Between Black Hole Accretion Rate and Jet Energy

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Date: 2017-10-20T00:00:00+00:00

Abstract

The formation of jets has long been intimately connected with black hole accretion. Analyzing the correlation between black hole accretion rate and jet energy is of considerable significance for investigating the internal structure of black holes and the specific mechanisms of jet formation. Twenty-four data sources were collected from the literature, comprising 13 radio-selected BL Lac objects (RBL) and 11 flat-spectrum radio quasars (FSRQs). The sample data were used to investigate the correlations among black hole accretion rate, jet energy, and gamma-ray flux density. The results indicate: (1) a significant correlation exists between accretion rate and jet energy for the 24 active galactic nuclei, consistent with the findings of Allen et al.; (2) there exist certain differences in the jet energy distributions between radio-selected BL Lac objects and flat-spectrum radio quasars; (3) the correlation between accretion rate and gamma-ray flux density for radio-selected BL Lac objects is not significant, but there exists a certain correlation between accretion rate and gamma-ray flux density for flat-spectrum radio quasars; (4) the results further demonstrate that jet energy is not only related to black hole mass, but is also likely associated with black hole accretion. The formation of black hole jets is likely the result of the combined effects of black hole mass and accretion. These results are consistent with those obtained by other methods.

Full Text

Discussion on the Correlation Between Black Hole Accretion Rate and Jet Energy

Abstract

The formation of relativistic jets and black hole accretion are intrinsically linked phenomena. Analyzing the correlation between black hole accretion rate and jet energy is crucial for understanding the internal structure of black holes and the physical mechanisms underlying jet formation. This study compiled sample data from the literature comprising active galactic nuclei (AGN) sources, including both BL Lac objects and flat-spectrum radio quasars. Our results demonstrate a significant correlation between black hole accretion rate and jet power, consistent with findings by Allen and collaborators. The jet energy distributions exhibit notable differences between BL Lac objects and flat-spectrum radio quasars. While the correlation between accretion rate and gamma-ray flux density is relatively weak for BL Lac objects, flat-spectrum radio quasars show a substantial correlation between these quantities. These findings further demonstrate that jet energy depends not only on black hole mass but also likely on the accretion process, suggesting that black hole jet formation results from the combined influence of both black hole mass and accretion rate. Our results are consistent with those obtained through other independent methods.

1. Introduction

Supermassive black holes at the centers of active galaxies commonly produce powerful relativistic jets [1-2]. The strength of black hole accretion directly influences both jet formation and the efficiency of energy conversion. Jets typically originate in the vicinity of the black hole’ s event horizon [3], where accretion processes enable energy extraction that can power the observed outflows. The bending of magnetic field lines near the accretion disk due to frame-dragging effects provides a viable mechanism for jet launching, a scenario now supported by numerical simulations. In this framework, radiative energy generated at larger accretion radii is converted into jet energy as matter flows toward the black hole, ultimately producing collimated outflows on smaller scales. Although certain aspects of this mechanism remain debated, the theory provides an important foundation for understanding accretion physics and the growth of supermassive black holes [5].

Observational studies using *Chandra* and *XMM-Newton* have revealed that central black holes significantly influence their surrounding environments [5]. The accretion process can create pronounced cavities in the X-ray emitting gas and drive shock waves through the ambient medium [7], making the X-ray gas temperature a valuable diagnostic for estimating black hole accretion rates [8]. Previous investigations of the accretion rate-jet power correlation yielded positive results but were limited by small sample sizes, potentially introducing statistical biases. This work expands the sample significantly and employs alternative jet energy calculation methods to re-examine this fundamental relationship. Additionally, we investigate the correlation between accretion rate and gamma-ray flux density to assess whether accretion processes influence high-energy emission.

2. Methodology

2.1 Black Hole Accretion Rate Calculation We calculate the black hole accretion rate using the ratio of bolometric luminosity to Eddington luminosity [9]:

$$\dot{m} = \frac{L_{\mathrm{bol}}}{L_{\mathrm{Edd}}}$$

where the Eddington luminosity is given by:

$$L_{\mathrm{Edd}} = 1.3 \times 10^{38} \left(\frac{M}{M_{\odot}}\right) \mathrm{erg\ s^{-1}}$$

and the bolometric luminosity is approximated as:

$$L_{\mathrm{bol}} = 10 L_{\mathrm{BLR}}$$

with L_{BLR} representing the broad-line region luminosity.

2.2 Jet Energy Calculation Our jet power estimation follows the methodology described in the literature, relating synchrotron radiation from radio lobes to the underlying particle energy distribution. For a homogeneous source of volume V with a power-law distribution of relativistic electrons (and possibly positrons) characterized by Lorentz factors, the synchrotron radiation between frequencies ν and $\nu + d\nu$ can be expressed as:

$$L_{\mathrm{syn}} \approx 1.58 \times 10^{12} B^{-3/2} \nu^{1/2} V$$

where B is the magnetic field strength. The jet power can be derived by considering the timescale for energy transfer from the jet to the radio lobes and the synchrotron cooling time of the relativistic particles. Accounting for spectral curvature at low frequencies due to lobe plasma, we correct the spectral index α based on observational constraints, yielding the final expression for jet power:

$$Q_{\mathrm{jet}} \approx 5.7 \times 10^{44} (1+z)^2 F_{151}^{1} \mathrm{erg\ s^{-1}}$$

where F_{151} is the flux density at 151 MHz in Jy and z is the redshift.

2.3 Data Sample We compiled a sample of 24 AGN sources with accurate broad-line region luminosities and black hole mass measurements from the NASA/IPAC Extragalactic Database (NED) and published literature. The sample comprises 13 radio-selected BL Lac objects (RBLs) and 11 flat-spectrum radio quasars (FSRQs). For each source, we extracted redshift, black hole mass, 151 MHz flux density, and gamma-ray flux density from *Fermi* observations where available. Table 1 presents the complete dataset.

3. Results

[Figure 1: see original paper] shows the jet power distributions for RBLs and FSRQs, revealing distinct patterns: FSRQs exhibit a relatively uniform distribution across multiple decades, while BL Lac objects concentrate at lower jet power values.

[Figure 2: see original paper] demonstrates a strong positive correlation between black hole accretion rate and jet power ($Q_{\rm jet}$) for the combined sample, with a correlation coefficient $R = 0.65$ and statistical significance $P < 0.001$ (Table 2). This indicates that systems with higher accretion rates produce more powerful jets, supporting a direct link between accretion processes and jet energetics.

[Figure 3: see original paper] and [Figure 4: see original paper] examine the relationship between accretion rate and gamma-ray flux density (L_γ). We find that BL Lac objects show only a weak correlation ($R = 0.22$), suggesting that gamma-ray emission in these sources is largely independent of the current accretion rate. In contrast, FSRQs display a significant correlation ($R = 0.59$), indicating that their gamma-ray output is substantially influenced by accretion processes.

provides the individual source measurements, including redshift, black hole mass in units of $M_\odot$, accretion rate, jet power, and gamma-ray luminosity.

summarizes the correlation statistics for different sub-samples, including intercepts, slopes, and their respective errors for the linear regression analyses.

4. Discussion

Our results confirm a robust correlation between black hole accretion rate and jet power, consistent with theoretical expectations and previous observational studies. The correlation holds across both BL Lac objects and FSRQs, though the distributions of jet power differ between these populations. This suggests that while accretion provides a fundamental energy source, other factors such as black hole spin and magnetic field configuration may also play important roles.

The differing correlations between accretion rate and gamma-ray flux density for RBLs versus FSRQs imply distinct high-energy emission mechanisms. In FSRQs, where accretion rates are generally higher, the gamma-ray emission appears to be directly linked to the accretion process, possibly through inverse Compton scattering of accretion-disk photons by relativistic electrons in the jet.

For BL Lac objects, the weaker correlation suggests that gamma-ray emission may originate primarily from synchrotron self-Compton processes or external photon fields less directly tied to the current accretion rate.

These findings support scenarios where jet energy extraction involves both black hole spin and accretion, such as hybrid models combining Blandford-Znajek and Blandford-Payne mechanisms. However, we cannot yet definitively establish whether jet power derives entirely from accretion or if black hole spin provides a substantial contribution.

5. Conclusions

This study demonstrates a clear correlation between black hole accretion rate and jet power in AGN, reinforcing the fundamental connection between accretion processes and relativistic outflows. Key findings include:

1. A strong, statistically significant correlation between accretion rate and jet power across our expanded sample.
2. Systematic differences in jet power distributions between BL Lac objects and flat-spectrum radio quasars.
3. Divergent relationships between accretion rate and gamma-ray flux density for different AGN classes.
4. Support for models where jet formation results from combined effects of black hole mass and accretion.

Further detailed investigation of the accretion-jet connection, particularly the role of black hole spin, requires larger, high-quality samples with multi-wavelength coverage and more precise measurements of black hole properties.

Acknowledgments

We gratefully acknowledge the NASA/IPAC Extragalactic Database (NED), operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with NASA, for providing essential data for this study. The 178 MHz flux densities used in our analysis were also obtained from NED.

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