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Multi-method Study of the Radiation Region Radius in AGN Accretion Disks: Postprint

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Abstract

By collecting data, we analyzed the accretion disk emission region radius of active galactic nuclei using the standard accretion disk method, short-timescale variability method, continuum reverberation lag method, and microlensing method, and conducted an analysis and discussion of the four methods. The results show that: (1) Comparing the parameters of blazars and quasars reveals no significant differences in central black hole mass, luminosity, and accretion disk emission region radius between the two subclasses. This study selected high-luminosity sources, which accounts for the lack of significant differences in the aforementioned parameters between the two subclasses; (2) The accretion disk emission region radius ratio obtained from the short-timescale variability method shows no significant correlation with black hole mass; (3) The accretion disk emission region radius ratio derived from the continuum reverberation lag method exhibits stronger dependence on black hole mass than the standard -disk model method; for sources where central black hole mass cannot be determined, the continuum reverberation lag method can be employed to obtain the accretion disk emission region radius; (4) The accretion disk emission region radius ratio obtained from the microlensing method shows no significant correlation with black hole mass, and this method is only applicable to quasars exhibiting microlensing effects, (5) These methods observationally demonstrate the existence of a correlation between accretion disk emission region radius and black hole mass, thereby validating the standard model. This provides theoretical guidance for future observational searches for sources suitable for these four methods. It holds significant importance for research on the accretion disk emission region radius of active galactic nuclei.

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Full Text

Multi-method Study on the Radius of the Radiation Zone of AGN Accretion Disks

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Abstract: We analyzed the radiation zone radius of active galactic nucleus (AGN) accretion disks using four distinct methods: the standard accretion disk model, short-timescale variability method, continuum reverberation lag method, and gravitational microlensing method. Our results demonstrate that: (1) No significant differences exist in central black hole mass, luminosity, or accretion disk radiation zone radius between blazars and quasars, likely due to our selection of high-luminosity sources; (2) The radiation zone radius derived from short-timescale variability shows no clear correlation with black hole mass; (3) The continuum reverberation lag method yields radiation zone radii that depend more strongly on black hole mass than the standard -disk model, making it particularly useful for sources where black hole mass cannot be determined; (4) The microlensing method shows no significant correlation between radiation zone radius and black hole mass, and its application is limited to quasars exhibiting microlensing effects; (5) Collectively, these methods observationally confirm the correlation between accretion disk radiation zone radius and black hole mass, validating the standard model. This work provides theoretical guidance for identifying suitable sources for these four methods and holds significant importance for AGN accretion disk radiation zone studies.

Keywords: accretion disk radiation zone radius; black hole mass; accretion disks; short-timescale variability; continuum reverberation lag; gravitational microlensing

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Active galactic nuclei (AGN) represent a special class of extragalactic sources characterized by extremely high luminosity, high polarization, and supermassive central black holes, with their host galaxies referred to as active galaxies [**?**]. The current consensus posits that a supermassive black hole (10 -10^{1} M) resides at the center of AGN, surrounded by diffuse gas that accretes onto the black hole under gravitational influence, forming a rotating accretion disk. Blazars constitute the most extreme AGN subclass, with their jets oriented toward the observer and exhibiting strong relativistic beaming effects, making them ideal laboratories for studying black hole accretion, electron acceleration mechanisms, and high-energy radiation processes. For instance, the luminosity cusp at the center of M87 can be explained by a supermassive black hole of approximately 3×10 M [**?**, **?**], a finding confirmed by Hubble Space Telescope observations. The asymmetric double-peaked Balmer line profiles in Arp 102B and 3C 390.3

can be interpreted through relativistic accretion disk radiation in the weak-field approximation [?, ?], while observational results reveal broad, double-peaked, or shoulder-shaped H emission lines in AGN [?]. These pieces of evidence collectively substantiate the existence of supermassive black holes and accretion disks in active galactic nuclei. Gravitational energy plays a crucial role in astrophysical energy production mechanisms, and thus the establishment of accretion disk models, parameter determination, and accretion processes enable researchers to investigate AGN in greater depth.

Due to differing observational characteristics among AGN subtypes (for example, BL Lac objects lack strong emission lines in their spectra), the methods for determining central black hole mass and accretion disk radiation radius vary accordingly. Through extensive literature review and collection of the latest data, this study employs several different methods to obtain central black hole masses and accretion disk radiation radii. By conducting comparative analyses of these calculations, we have obtained several important conclusions that provide crucial parameters for further investigation of AGN radiation mechanisms.

1. Calculation Methods for Accretion Disk Radiation Radius

Owing to current technological and observational limitations, even the nearest AGN accretion disks cannot be directly resolved with optical telescopes. Consequently, the accretion disk radiation radius can only be obtained through indirect methods such as the standard accretion disk model, short-timescale variability method, continuum reverberation lag method, and gravitational microlensing method. Each of these theoretical approaches has its own limitations and has not been systematically considered in unison.

1.1 Standard -Disk Model Method

Researchers have long investigated accretion disk characteristics and models. Due to the unknown nature of viscous processes in accretion disks, Shakura and Sunyaev (1973) introduced the parameter to describe viscosity, thereby establishing the famous geometrically thin, optically thick standard -disk model [?, ?, ?, ?]. The fundamental equations of this model are based on several key assumptions: gravitational potential is determined solely by the central black hole mass M_BH, with the disk' s self-gravity being negligible; the disk is stationary and axisymmetric; the disk is geometrically thin in the sense that H/r 1; rotation dominates (Keplerian) with |v_r| v_ ; vertical hydrostatic equilibrium is maintained; the disk is optically thick in the vertical direction; and a special viscosity law is adopted where the r component of the viscous stress tensor is proportional to pressure.

In the standard -disk model, the effective temperature depends on the disk' s radiation radius as T R , with higher temperatures occurring closer to the central black hole. The disk radiation is clearly blackbody radiation, where high-energy photons originate from the inner disk region while low-energy photons come from the outer region. According to this theoretical model, the accretion disk radiation radius at wavelength is given by [?]:

$$R = \left[\frac{45G\lambda^4 M_{BH}\dot{M}}{16\pi^6 h_p c^2}\right]^{1/3} = 9.7\times10^{15}\left(\frac{10^9 M_\odot}{M_{BH}}\right)^{2/3}\left(\frac{\lambda}{2500\text{Å}}\right)^{4/3}\left(\frac{L}{L_{Edd}}\right)^{1/3}\text{cm}$$

where $\dot{M}$ represents the accretion rate, h_p is the Planck constant, L denotes the luminosity in Eddington units, and $(\dot{M}c^2)$ represents the accretion efficiency. For our calculations, we adopt $\eta = 0.1$ [?, ?].

1.2 Short-timescale Variability Method

Variability represents an important observational characteristic of AGN [?, ?], reflecting the intensity of AGN activity and revealing information about radiation processes, radiative media, and the physical conditions and structural changes within and around the radiation region. Based on the timescale of variability, it can be classified into long-, intermediate-, and short-timescale variations. Short-timescale variability serves as an effective tool for calculating accretion disk radiation zone radii.

According to astrophysical stability theory, the vibration frequency and maximum rotation frequency of a celestial body are both of order:

$$\omega \sim \left(\frac{GM}{R^3}\right)^{1/2}$$

Assuming the variability period of a celestial body is , we obtain:

$$\tau \sim \left(\frac{R^3}{GM}\right)^{1/2}$$

Through simple transformation, $R \sim (GM\tau^2)^{1/3}$. For a black hole of mass M, $2GM \approx 1$, giving $R \sim c\tau$. However, matter near black holes is unstable. According to accretion disk theory, we typically adopt $10R_s$ as the observable radius (i.e., the inner radius of the radiation zone), where R_s is the Schwarzschild radius of the galactic nucleus, $R_s \equiv 2GM/c^2 = 2.96 \times (M/M_\odot)$ km. Therefore, the inner radius of the accretion disk radiation zone can be obtained as:

$$R_{in} = 10R_s = \frac{20GM}{c^2} = \frac{c\tau_{obs}}{\sigma(1+z)}$$

where c is the speed of light (we adopt $c = 3 \times 10^{10}$ cm s ¹ in our calculations), σ is the Doppler factor, z is the source redshift, and τ_{obs} is the observed minimum variability timescale. Due to the stochastic nature of short-timescale variability in observations, obtaining accretion disk radiation zone radii for sample sources becomes relatively challenging.

1.3 Continuum Reverberation Lag Method

The physical models and variability mechanisms of AGN can be investigated through light curves. Variability curves characterize the intensity of celestial activity, and time lags exist between continuum emission and broad emission lines. Assuming these lags correspond to the light travel time from the central black hole to the broad-line region, we can determine the size of the broad-line region and the central black hole mass [?, ?]. In principle, time lags between different continuum bands can be used to determine accretion disk structure, including the radiation zone radius [?, ?].

The cross-correlation function (CCF) represents a traditional method for calculating time delays between two light curves [?, ?], but this method imposes stringent requirements on sampling conditions and observational time intervals. Consequently, the JAVELIN method [?, ?] is generally employed to obtain time lags between different continuum bands. Jiang Feiyan et al. used the JAVELIN method to detect that time lags increase with luminosity, with values 2–3 times larger than those estimated from the standard -disk model [?]. Mudd et al. [?] developed the JAVELIN thin-disk model based on this method, yielding results consistent with microlensing measurements. For example, Mitsuru Kokubo [?] studied the light curves of quasar PG 2308+098 in five bands (u, g, r, i, and z), finding that longer wavelengths exhibit larger lags and using equation (6) to determine the inner radius of PG 2308+098’ s accretion disk:

$$R = c\tau_{rest,2500} = c\tau_{rest,u} \left(\frac{\lambda_{rest,2500}}{\lambda_{rest,u}} \right)^{4/3}$$

where $\tau_{obs,u}$ represents the observed lag from the u-band light curve. When $\lambda_{rest,u} = 3551$ Å, the accretion disk radiation zone size of PG 2308+098 is determined to be $9.46^{+0.29}_{-3.12}$ light-days. The continuum reverberation lag method proves highly practical for applying observational data to calculate accretion disk radiation zone radii and central black hole masses [?, ?].

1.4 Gravitational Microlensing Method

In lensed high-redshift quasars, the observed UV-optical microlensing effects arise from the lensing magnification of the quasar accretion disk by foreground stars in the lensing galaxy. The microlensing variability rate can be used to study the mass of the lensing system and the structure of the quasar continuum emission region.

Utilizing gravitational microlensing effects, Pooley et al. [?] investigated the size of X-ray emission regions for both thermal and non-thermal radiation, while Morgan et al. [?] studied the correlation between radiation zone inner radius and black hole mass.

2. Data and Analysis

Through extensive literature review, we calculated accretion disk radiation zone radii using four distinct methods. Table 1 presents data obtained via the short-timescale variability method [?], including source name, short timescale, redshift, Doppler factor, radiation zone radius ratio from the short-timescale method (R), luminosity, Eddington luminosity, black hole mass, and radiation zone radius ratio from the standard accretion disk method (R). Table 2 contains continuum reverberation lag data, including source name, reverberation lag time, luminosity, Eddington luminosity, black hole mass, radiation zone radius ratio from the reverberation lag method (R), and radiation zone radius ratio from the standard accretion disk method (R). Table 3 comprises gravitational microlensing data, including source name, black hole mass, radiation zone radius ratio from the microlensing method (R), and radiation zone radius ratio from the standard accretion disk method (R).

Sources in Table 1 belong to the blazar class, while those in Tables 2 and 3 are quasars. Since they represent different AGN subclasses, we conducted comparative correlation analyses of their parameters. Figures 1-3 reveal no significant differences in black hole mass, luminosity, or accretion disk radiation zone radius between blazars and quasars. This outcome likely stems from the constraints of the standard -disk model, as our study specifically selected high-luminosity sources. According to the standard -disk model, the accretion disk radiation zone radius depends on black hole mass following the relation log R 0.667 log(M_BH/10 M) from equation (1). Since the Schwarzschild radius is proportional to black hole mass, we performed linear fitting and comparative correlation analyses using the radiation zone radius ratios Y = log(R/R_s) from three methods against black hole mass X = log(M_BH/10 M). The linear correlation plots are shown in Figures 4 [Figure 4: see original paper], 5, 6, and 7, with correlation analysis results presented in Table 4, which lists slope A, intercept B, correlation coefficient r, confidence probability p, and number of objects N.

Based on the linear correlation plots and Table 4, we find that except for the short-timescale variability and microlensing methods, the other methods show strong correlations between the accretion disk radiation zone radius ratio Y = log(R/R_s) and black hole mass log(M_BH/10 M). Linear fitting of radiation zone radius ratios from two methods in Tables 1 and 2 against Eddington luminosity reveals no significant correlation for the short-timescale variability method, but a strong correlation for the continuum reverberation lag method (Figure 7 [Figure 7: see original paper]: R : r = 0.153, p = 0.558, N = 17; R : r = -0.857, p = 6.713×10^{12}, N = 38). Due to the limited sample size, we will expand our sample for further analysis and discussion in future work.

[Figure 1: see original paper]
[Figure 2: see original paper]
[Figure 3: see original paper]
[Figure 4: see original paper]
[Figure 5: see original paper]
[Figure 6: see original paper]
[Figure 7: see original paper]

3. Discussion and Conclusions

Based on the above data analysis, we draw the following conclusions:

(1) In active galactic nuclei, comparing parameters between blazars and quasars reveals no significant differences in central black hole mass, luminosity, or accretion disk radiation zone radius. Since standard -disk accretion corresponds to high-luminosity AGN typically above 0.01 times the Eddington luminosity, our selection of high-luminosity sources likely accounts for the lack of significant differences between these subclasses.

(2) The radiation zone radius ratio obtained from the short-timescale variability method shows no clear correlation with black hole mass. This result may be attributed to several factors: the short-timescale variability calculation does not account for black hole spin, the formula for calculating radiation zone radius lacks mass parameters, and the sample size is insufficient. In our future work, we will enhance observational efforts to increase the number of samples exhibiting short-timescale variability.

(3) The continuum reverberation lag method yields radiation zone radius ratios that depend more strongly on black hole mass than the standard -disk model method, yet the radiation zone radii from both methods show no significant differences. Therefore, for sources where central black hole mass cannot be determined, the continuum reverberation lag method can be employed to obtain accretion disk radiation zone radii.

(4) The microlensing method shows no significant correlation between radiation zone radius ratio and black hole mass, and its application is restricted to quasars exhibiting microlensing effects, imposing certain limitations on source selection. However, due to the limited data available for each method, these conclusions require further verification with expanded samples or by incorporating central black hole spin into short-timescale variability studies.

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