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Research on Changing-Look Events in Active Galactic Nuclei

Liu Zhongshu

International Department, The Affiliated High School of SCNU, Guangzhou, Guangdong, China, 510635

Abstract: *Changing-look active galactic nuclei (CL-AGNs) are a unique class of AGNs that exhibit rapid and dramatic transitions in their spectra, including the appearance or disappearance of broad emission lines. In this study, we analyze a sample of 26 CL-AGNs using spectroscopic data, focusing on the relationships between their variability timescales, Eddington ratios, black hole masses, and broad-line region (BLR) properties. Our results show an inverse correlation between the Eddington ratio and the timescale of changes, indicating that AGNs with higher accretion rates undergo faster transitions. Additionally, we find that the full width at half maximum (FWHM) of the BLR emission lines correlates positively with both black hole mass and Eddington ratio, suggesting stronger gravitational forces and radiation pressure drive faster gas velocities in the BLR. The flux received by the BLR is also positively correlated with the Eddington ratio, emphasizing the close connection between the accretion disk and the BLR. We discuss several models, including accretion disk instabilities, obscuration, and disk winds, to explain these transitions. While accretion rate changes likely play a significant role, the exact mechanisms behind the rapid variability remain debated. Our findings underscore the importance of both the black hole mass and accretion dynamics in shaping the spectral properties and variability of CL-AGNs, contributing to the broader understanding of AGN evolution and the complex interaction between the accretion disk and BLR.*

Keywords: *Changing-look, active galactic nuclei, supermassive black holes (SMBHs)*

1. Introduction

Active Galactic Nuclei (AGNs) are powered by the accretion of matter onto supermassive black holes (SMBHs) at galactic centers. Traditionally, AGNs are classified into two main types: Type I AGNs, which exhibit both broad and narrow emission lines, and Type II AGNs, which show only narrow lines. This distinction is explained by the orientation of an obscuring torus relative to our line of sight. In this unification model, an AGN's classification is expected to remain stable over short timescales [1]. However, the discovery of Changing-Look AGNs (CL-AGNs) has challenged this model, revealing objects that rapidly transition between Type I and Type II states, sometimes over just months to years, which cannot be attributed to changes in the viewing angle alone [2][3].

CL-AGNs are categorized based on the direction of their spectral transitions. "Turn-off" CL-AGNs exhibit the disappearance of broad emission lines characteristic of Type I AGNs, often accompanied by a decline in optical and ultraviolet (UV) continuum emission. This is thought to reflect a significant drop in the accretion rate, causing the broad-line region (BLR) to fade due to insufficient ionizing radiation [4][5]. In contrast, "turn-on" CL-AGNs transition from Type II to Type I, showing a sudden appearance of broad emission lines and a sharp increase in optical/UV luminosity. This transition is likely driven by an increase in the accretion rate, reactivating the AGN's central engine and leading to BLR formation [6][7]. Recent studies suggest that such transitions may also be triggered by transient events, such as tidal disruption events (TDEs), where a star is disrupted by the SMBH's tidal forces, resulting in a sudden influx of material [8][9].

Many CL-AGNs display significant variability in the X-ray regime, with fluctuations in X-ray flux often accompanying spectral changes [3][10]. Some CL-AGNs undergo sharp declines in X-ray luminosity and softening of the X-ray spectrum during transitions. This suggests that CL-AGN transitions are not purely driven by obscuration but may involve intrinsic changes in accretion processes close to the SMBH. Proposed mechanisms include variations in accretion rates, changes in the corona's structure, and interactions between disk winds and the central engine. Failed winds—highly ionized outflows that do not escape the SMBH's gravitational influence—have also been suggested as a potential cause for the observed X-ray variability in many CL-AGNs [7][11][12].

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The discovery of CL-AGNs highlights the dynamic and complex nature of AGN accretion processes. Traditional unification models, which rely on obscuration and orientation, are insufficient to account for the rapid and drastic transitions observed in these objects. The study of CL-AGNs, particularly those exhibiting "turn-on" and "turn-off" behaviors, provides valuable insights into the relationship between SMBH accretion processes, BLR formation, and AGN evolution over short timescale [13]. Continued multi-wavelength observations are crucial for unraveling the physical mechanisms driving these transitions and enhancing our understanding of AGN variability [14][15][16].

2. Data

We compiled a comprehensive collection of CL-AGNs reported in the literature. These sources were then carefully screened based on the following criteria.

We require that the turn-off spectra for the objects in our sample be sourced from the Sloan Digital Sky Survey (SDSS). Since spectra from different telescopes may introduce flux calibration offsets and add uncertainties to the analysis, we ensure all turn-off spectra come from the same instrument, with SDSS being our preferred choice. SDSS utilizes a 2.5-meter wide-field telescope [17] at Apache Point Observatory, and observations are conducted using fiber-fed dual spectrographs with 3″ diameter fibers, which capture more emission from the host galaxies. The resulting reduced one-dimensional spectra cover a wavelength range of 3800–9200Å with a spectral resolution of R □ 1500–2500. This wavelength range and spectral resolution are well-suited for analyzing the stellar populations of host galaxies. For these reasons, we focus on CL-AGNs with SDSS turn-off spectra in our sample. Our sample consists of a total of 26 objects.

We limit the redshift to 0.35 or lower for the following reason: this redshift range ensures that key absorption lines necessary for spectral analysis are covered, while avoiding MgII emission lines, which could interfere with the analysis when they shift into the optical band.

The turn-on spectra primarily utilize data from the SDSS and LAMOST surveys. LAMOST, a quasi-meridian reflecting Schmidt telescope, features an aperture with an effective light-collecting area ranging from 3.6 to 4.9 meters. It is equipped with 4000 fibers and a 5° field of view [18][19]. Each fiber has a diameter of 3″, and the telescope covers wavelengths from 3700 to 9000 Å, divided into two arms: a blue arm (3700–5900 Å) and a red arm (5700–9000 Å) [20]. The spectral resolution of LAMOST is approximately R □ 1800 across the full wavelength range. The data we used are processed by the LAMOST pipelines [21] and are included in the LAMOST Quasar Catalog [22][23].

A total of 23 turn-on spectra were flux-calibrated. However, the spectral resolution of ZTF18aasszwr is insufficient to resolve narrow emission line features. Additionally, for ZTF18aasuray, the scaling of the [OIII] λ5007 line resulted in an unphysical outcome, showing a significant flux decrease in the longer wavelength range after flux cross-calibration. For these two cases, we used the originally observed spectra instead.

3. Results

Based on the obtained data, we analyzed the relationships between key parameters of different changing-look AGNs, including the timescale of the change, Eddington ratio, black hole mass, and the full width at half maximum (FWHM) of the emission lines.

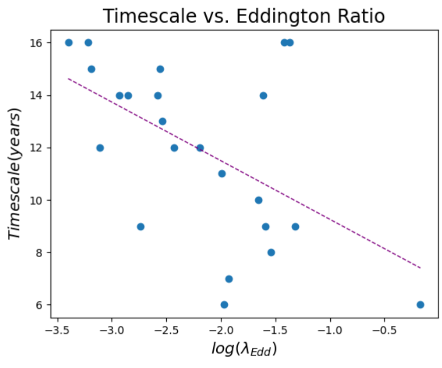

Figure 1. Relationship between timescale and Eddington ratio

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As shown in Figure 1, the changing timescale and Eddington ratio exhibit an inverse relationship, where a higher Eddington ratio corresponds to a shorter timescale. This is due to the faster propagation of changes within the accretion disk. With a higher accretion rate, material moves toward the black hole at greater velocities, resulting in a more rapid timescale for these changes.

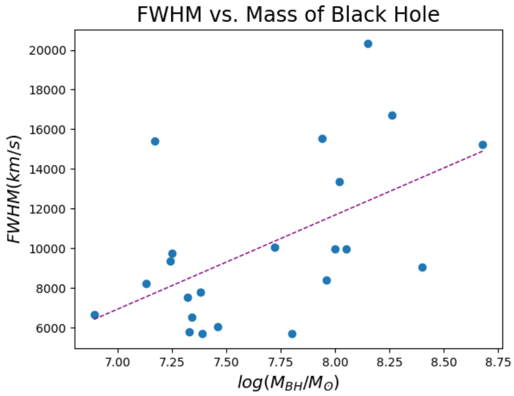

Figure 2. Relationship between FWHM and mass of black hole

As illustrated in Figure 2, the FWHM, which reflects the velocity of gas in the broad-line region (BLR), shows a positive correlation with black hole mass. This is expected, as a more massive black hole exerts stronger gravitational forces on the surrounding gas, causing it to move at higher velocities in order to maintain its orbit around the black hole.

As shown in Figure 3, the FWHM also correlates with the Eddington ratio of the accretion disk. This is because a higher accretion rate results in stronger radiation pressure from the central engine, pushing the BLR further away from the black hole and causing the gas to accelerate.

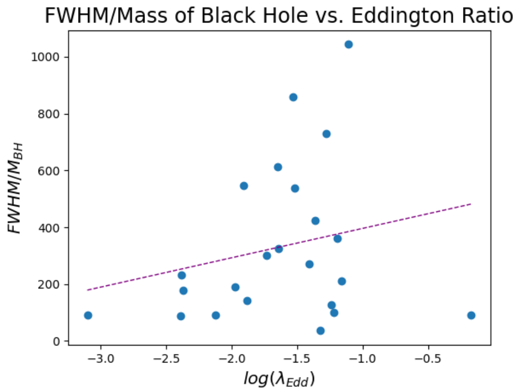

Figure 3. Relationship between FWHM and Eddington ratio

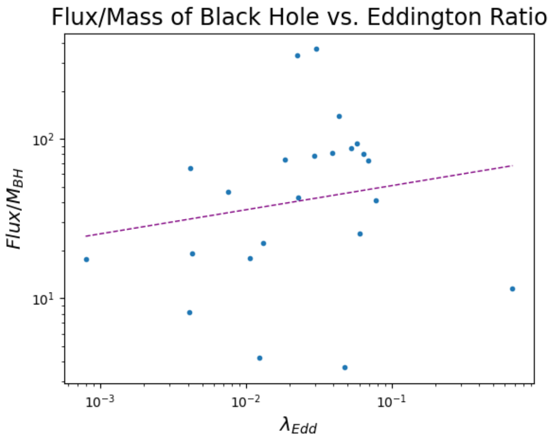

Figure 4. Relationship between flux and Eddington ratio

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As shown in Figure 4, the flux (the energy received by the BLR from the accretion disk) shows a positive correlation with the Eddington ratio. A higher accretion rate results in stronger radiation from the disk, providing the BLR gases with more energy. This relationship between the BLR spectrum and the accretion rate indicates a close connection between the accretion disk and the BLR.

4. Discussion

The results presented in Figures 1 through 4 provide key insights into the dynamics of changing-look AGNs (CL-AGNs) and the relationship between the accretion disk, black hole mass, and the broad-line region (BLR). As indicated in Figure 1, the inverse correlation between the changing timescale and Eddington ratio suggests that CL-AGNs with more powerful accretion disks undergo variations over shorter periods. This behavior points to a strong connection between the state of the accretion disk and the observed spectral changes, potentially classifying these CL-AGNs as "changing-state" AGNs, where variations in the disk state drive the transitions [24][6].

Figures 2 and 3 further reinforce this idea by showing how the full width at half maximum (FWHM) of the BLR emission lines correlates with both black hole mass and Eddington ratio. The positive relationship between FWHM and black hole mass in Figure 2 is consistent with the expectation that larger black holes exert stronger gravitational forces on the surrounding gas, accelerating it to higher velocities [25]. Figure 3 extends this by demonstrating that a higher Eddington ratio, indicative of a larger accretion rate, also leads to faster gas velocities in the BLR, driven by increased radiation pressure from the central engine.

Finally, Figure 4 shows a direct relationship between the flux received by the BLR and the Eddington ratio, further emphasizing the strong coupling between the accretion disk and the BLR. As the accretion rate increases, more energy is emitted by the disk, and the BLR gases absorb this additional energy, influencing the spectral properties. This suggests a close connection between the accretion disk and the BLR, supporting the idea that spectral variations in CL-AGNs are fundamentally linked to changes in the accretion process around the black hole.

Taken together, these results highlight that both black hole mass and accretion dynamics play pivotal roles in shaping the spectral properties and variability timescales of CL-AGNs. The rapid changes seen in these objects likely stem from alterations in the accretion disk, with larger black holes and higher accretion rates driving more energetic and faster BLR gas motions. These findings underscore the importance of the accretion disk-BLR interaction in understanding the spectral evolution of CL-AGNs and provide further evidence that the observed variability originates from the central engine and its surrounding environment [14].

However, there are several ongoing debates and challenges in modeling CL-AGNs. One of the leading models suggests that changes in the accretion rate are the primary driver behind the CL-AGN phenomena [4]. According to this model, fluctuations in the accretion flow toward the supermassive black hole (SMBH) can lead to transitions between AGN states. The inverse relationship between the Eddington ratio and the timescale of spectral changes, as seen in Figure 1, supports this idea. When the accretion rate increases, the accretion disk becomes more luminous, and the AGN transitions to a more active state over a shorter timescale. Conversely, a drop in the accretion rate can cause the AGN to "turn off."

However, this model faces some challenges. While it successfully explains the rapid timescale of changes in CL-AGNs with high accretion rates, it is less clear how it accounts for the cases where no obvious changes in the accretion rate are detected, yet spectral transitions still occur. Additionally, the precise mechanism by which the accretion rate fluctuates so dramatically remains a topic of debate. Some suggest that tidal disruption events or instabilities within the disk itself could trigger these fluctuations, but these explanations lack direct observational support in many cases.

Another model attributes the variability in CL-AGNs to obscuration by clouds of gas and dust that pass through our line of sight [26]. According to this view, changes in the observed spectrum, particularly the appearance or disappearance of broad emission lines, are due to moving clouds temporarily blocking the BLR. This model can explain some of the observed transitions, especially cases where the change occurs without a corresponding change in the accretion rate.

However, obscuration models face limitations as well. For instance, the correlation between the Eddington ratio and FWHM in Figures 3 and 4 suggests that the changes are intrinsic to the AGN, rather than simply the result of a change in the line of sight. If obscuration were the primary driver, we would not expect such strong correlations between the internal properties of the AGN, such as the accretion rate,

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and the spectral changes. Additionally, while obscuration can explain changes in the BLR visibility, it does not adequately account for the overall variability in the AGN's luminosity, which is often seen in CL-AGNs [5].

A more complex explanation involves the interplay between the accretion disk and a powerful wind driven by radiation pressure from the central engine. As suggested by the positive correlation between the FWHM of the BLR and the Eddington ratio (Figure 3), radiation pressure may play a significant role in shaping the BLR [27]. In high-Eddington ratio systems, the stronger radiation pressure could drive outflows or winds, pushing the BLR gas outward and causing it to move faster. Disk-wind models propose that changes in the wind's strength or geometry could lead to the observed transitions in CL-AGNs. A powerful wind might disrupt the BLR, leading to the disappearance of broad emission lines, while a weaker wind could allow the BLR to reform.

Yet, while the disk-wind model offers a compelling explanation for some CL-AGN behavior, it is still underdeveloped in terms of specific predictions. For instance, what triggers the changes in the wind, and how does it correlate with variations in the accretion disk? Furthermore, not all CL-AGNs show the expected signatures of outflows or winds, suggesting that this may be only one piece of a more complex puzzle [13].

Another layer to the discussion involves the role of black hole mass in CL-AGN behavior. Figures 2 and 3 indicate that larger black holes with higher accretion rates produce higher velocities in BLR gases and undergo more rapid changes. This raises questions about the evolution of AGNs across different mass regimes. Some studies suggest that CL-AGNs are more common in lower-mass black holes, where the accretion process may be more variable [28]. Others propose that CL-AGNs could represent an evolutionary stage in AGN lifecycles, with some AGNs transitioning between active and quiescent phases over time. Understanding the connection between black hole mass, accretion rate, and CL-AGN variability could provide valuable insights into the broader process of black hole growth and AGN evolution.

5. Conclusions

In summary, the models discussed here—accretion disk instabilities, obscuration, and disk winds—each provide useful frameworks for understanding CL-AGNs but come with significant caveats and limitations. The relationship between black hole mass, accretion rate, and spectral variability, as highlighted by Figures 1 through 4, suggests that a combination of these models may be necessary to fully explain CL-AGN behavior. Future observations and long-term monitoring, especially with high-resolution spectroscopic and multi-wavelength surveys, will be crucial to refining these models and providing a more unified understanding of CL-AGNs [29].

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