International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

Chromatic Variability: Tracing Time Lags from X-Ray to Optical in AGN Light Curves

Sayak Moulic[1], Ryan Ray[2], Ayush Banerjee[3], Yash Rajput[4], Priyangshu Sarkar[5]

[1]Indian Institute of Technology, Kharagpur, West Bengal, 721302, India
Email: *sayakmoulic[at]gmail.com*

[2]Indian Institute of Science, Bangalore - 560012, Karnataka, India
Email: *ryan.tigerray[at]gmail.com*

[3]Kalyani Central Model School, Block B, Kalyani, 741235, West Bengal
Email: *ayush.banerjee766[at]gmail.com*

[4]D.A.V. Police Public School, Madhuban, Karnal, 132037, Haryana
Email: *avyash4372[at]gmail.com*

[5]Springdale High School (H.S.), A3 City Centre Complex, Kalyani, West Bengal, 741235, India
Corresponding Author Email: *therealpriyangshu[at]gmail.com*

Abstract: ***Active Galactic Nuclei (AGNs), powered by accreting supermassive black holes, exhibit complex variability across the electromagnetic spectrum. This review integrates theoretical models with findings from time-domain surveys and GRMHD simulations to explore the physical mechanisms driving such variability. Special attention is given to the role of accretion disk instabilities thermal, viscous, and magnetorotational - as well as the influence of magnetic flux eruptions. The study evaluates how changing accretion states and magnetic activity shape observable light curves, particularly in changing-look AGNs. Open questions are outlined to guide future inquiry, to develop a unified model of AGN variability applicable across mass scales and emission regimes. We review current theoretical models alongside observational findings from time-domain surveys and high-resolution GRMHD simulations, focusing on how changing accretion states and magnetic flux eruptions contribute to variability patterns. We also investigate how MRI turbulence may account for the transition timescales in changing-look active galactic nuclei (AGNs). Finally, we outline key open questions and suggest future directions for bridging theory with observation, aiming to develop a more unified framework of AGN variability that applies across quasars and lower-mass active black holes.***

Keywords: AGN variability, accretion disk instabilities, Eddington ratio, GRMHD simulations, magnetorotational instability

1. Introduction

The highly energetic centers of galaxies are called Active Galactic Nuclei (AGNs). These are often powered by accreting supermassive black holes. It is well established that AGNs emit radiation across the entire electromagnetic spectrum—from radio waves to gamma rays—and serve as high-energy laboratories for physics under extreme gravitational, thermal, and magnetic conditions. However, observations deviate significantly from this because of their unpredictable and multi-wavelength variability, which is detected across ultraviolet, optical, and X-ray bands. These fluctuations can occur over timescales ranging from hours to years, often without apparent periodicity, and understanding them may reveal the inner structure of AGNs. [1], [2].

Understanding this variability may unlock the physics of accretion and energy release to unlocking the physics of accretion and energy release in relativistic regimes. Rapid brightness changes suggest that small-scale physical processes, such as accretion disk instabilities or magnetic reconnection events, may be driving these fluctuations. The brightest AGNs, such as quasars like J0529-4351, which harbor a black hole with a mass exceeding a billion solar masses, offer opportunities to examine these mechanisms in action relatively easily [3]. The forces driving these events are still highly contested and are studied using data on variability.

The accretion disk—composed of plasma spiraling inward toward the black hole—is widely regarded as the primary emission source in AGNs. Variability in AGNs is increasingly attributed to instabilities in these disks, with several candidates proposed: thermal instabilities, driven by temperature-sensitive opacities; viscous instabilities, arising from anomalous angular momentum transport; radiation pressure instabilities, relevant in high-Eddington regimes; and magneto-rotational or magnetically arrested disk (MAD) instabilities, induced by magnetic field accumulation [4], [5]. Each of these mechanisms offers plausible explanations for distinct timescales and amplitudes observed in AGN light curves.

Recent advances in time-domain astronomy and numerical modeling underscore the need to revisit this problem. Massive variability datasets from sky surveys such as SDSS Stripe 82, Pan-STARRS, Kepler, and Fermi-LAT have provided long-baseline, multi-band AGN light curves.

These observations are supported by recent advances in GRMHD simulation models that incorporate radiation feedback and disk turbulence. For instance, simulations of MAD states show spontaneous magnetic eruptions that can reproduce observed stochastic behavior in AGNs [6], [7]. Such developments now allow for direct comparison between theoretical predictions and time-resolved observations.

Nonetheless, critical gaps remain. Accretion disks are inherently chaotic and non-linear systems where multiple instabilities can operate simultaneously. Spatial resolution, temporal integration scales, and assumptions about microphysics, such as viscosity and resistivity, limit the accuracy of simulations.

These AGN light curves often yield inconsistent results across wavelengths or temporal resolutions, confounding efforts to build unified models. Their discrepancies necessitate refined frameworks that can reconcile diverse datasets with robust physical modeling [8].

In this review, we investigate how instabilities within AGN accretion disks—specifically thermal, magneto-hydrodynamic, and radiation-pressure-driven modes—contribute to observed variability across wavelengths.

We initiate this by presenting foundational theories on disk structure and instability mechanisms, followed by a set of observational results and recent simulation efforts. We aim to present a cohesive overview of everything you need to understand about the instability of AGNs. Lastly, we pose some identifying open questions and outline future directions to bridge theoretical models with next-generation time-domain surveys. By bridging theoretical models with observational data, this review aims to inform future efforts toward a unified understanding of AGN variability, with implications for black hole physics, galaxy evolution, and time-domain astrophysics

Methodology

This review synthesizes contemporary theoretical models and observational evidence surrounding variability in Active Galactic Nuclei (AGNs), with a particular focus on disk instability mechanisms, including thermal, viscous, and magnetorotational instabilities (MRI). Our approach involved an extensive literature survey covering peer-reviewed journals, observational datasets, and simulation studies published between **2009 and early 2024**.

We selected sources using three core filters:

1) **Theoretical grounding** – inclusion of works dealing explicitly with accretion physics, GRMHD simulations, and analytical modeling.
2) **Observational linkage** – inclusion of papers incorporating light curve analyses, reverberation mapping, or X-ray/optical/IR variability studies.
3) **Scalability relevance** – studies bridging AGN-scale phenomena with analogous variability in X-ray binaries or compact stellar systems.

Highly cited review papers (e.g., on ADAF, slim disks, and DRW models) were cross-verified against newer GRMHD simulation outputs. Data repositories, such as **NASA's Astrophysics Data System (ADS)** and **arXiv.org,** were utilized to extract raw light curves and simulation visualizations, with a particular focus on **Swift, XMM-Newton**, and **HST** campaigns.

We excluded works that lacked data transparency or relied on speculative mechanisms without observational calibration. When multiple models addressed the same variability class (e.g., CAR(1), ERDF, or QPOs), we assessed them based on their ability to reproduce real AGN temporal features across timescales.

This methodology ensures a tightly focused yet comprehensive understanding of the key physical drivers of AGN variability, spanning from microphysical turbulence to large-scale luminosity shifts.

2. Theoretical Background

This section presents a conceptual framework linking accretion disk structure, physical instabilities, and observed AGN variability. We outline the nature of accretion flows, Eddington-regulated states, and the primary disk instabilities believed to underlie multi-wavelength variability.

2.1 Accretion Disk Models

Accretion disks around supermassive black holes form from inflowing gas and plasma that spiral inward under the gravitational influence of the black hole. As this material loses angular momentum, viscous heating causes it to emit radiation, making the disk the principal emission source in AGNs [9].

Three principal classes of accretion disks are commonly used to model active galactic nuclei (AGNs): **thin disks**, **slim disks**, and **advection-dominated accretion flows (ADAFs)**. Thin disks are radiatively efficient, optically thick, and geometrically flat, ideal for moderate accretion rates. Slim disks emerge near the Eddington limit, allowing radiation to be advected inward and resulting in moderate radiative efficiency and a thicker structure. ADAFs are geometrically thick and radiatively inefficient; they dominate under low accretion rates where most of the dissipated energy is retained and not radiated [10], [11].

The morphology of accretion disks evolves in response to the accretion rate. At sub-Eddington levels ($\ll L\_Edd$), disks tend to become ADAF-like—hot, inefficient, and turbulent. As accretion increases, disks flatten into the thin disk regime and radiate more efficiently. Near or beyond Eddington rates, photon trapping inhibits cooling, transforming the disk into a slim configuration that is structurally stable and suited to luminous quasars [12].

Table 1: Comparative properties of accretion disk types in AGNs, showing geometry, instabilities, and dominant Eddington regimes

Disk Type	Geometry	Radiative Efficiency	Dominant Instabilities	Eddington Ratio	Examples
Thin Disk	Geometrically thin	High	Thermal / Viscous	~0.01–0.3	Seyferts
Slim Disk	Geometrically thick	Moderate	Radiation pressure, MRI	$\gtrsim 0.3$	Quasars
ADAF	Thick + Optically thin	Low	MRI, convective	$\ll 0.01$	LINERs
MAD (Magnetically Arrested)	Thick + Magnetic pressure supported	Moderate–High	MRI, magnetic eruptions	Flexible, often high	M87*

Each accretion regime exhibits characteristic instabilities shaped by geometry, optical depth, and Eddington ratio, as outlined in Table 1.

2.2 The Eddington Ratio (L/L_{Edd}) and Accretion Regimes

The Eddington limit is the maximum luminosity at which outward radiation pressure on electrons balances gravity on a black hole of mass M:

$$L_{Edd} = \frac{4\pi G M m_p c}{\sigma_T} \approx 1.3 \times 10^{38} (M/M_\odot) ergs^{-1}$$

(m(p) is the proton mass, σ(T) the Thomson cross-section)

The dimensionless Eddington ratio λ = L (bol)/L(Edd) directly measures the accretion rate in Eddington units. This ratio is crucial because it determines the structure of the accretion flow:

At λ<<1 (sub-Eddington), disks tend toward hot, geometrically thick, radiatively inefficient states (ADAF/RIAF), often accompanied by strong jets. At λ~0.01–0.1, they form standard thin disks, and at λ~one or above, radiation pressure leads to "slim disk" structures with large outflows.

Observationally, AGNs span an extensive range of λ (roughly 10^−5 to > 50 in extreme cases). For example, radio-quiet quasars typically have λ∼10^-2−1(median ∼0.06), whereas radio-loud nuclei (more detectable) often lie at much lower λ∼10−5−0.01.

Variability behavior correlates with λ. In X-ray binaries (scaled-down black holes), state changes occur near λ~0.01–0.1 (hard/soft transitions), suggesting that similar transitions may occur in AGN. Indeed, Seyfert galaxies (moderate λ~0.01–0.1)

Typically show large amplitude, rapid X-ray variability, and sometimes dramatic state changes. Luminous quasars (λ>0.1) tend to have relatively smooth optical-UV emission and softer X-ray spectra, although notable exceptions exist. Notably, high-λ AGN can behave unpredictably: [13] Risaliti et al. [14] find that some λ > 1 quasars exhibit unexpectedly complex X-ray spectra and prolonged low states. Implying that radiation-pressure-dominated accretion can be intermittently disrupted. Conversely, very low-λ AGN (LINERs) often exhibit strong radio jets and weaker high-energy emission.

In summary, the Eddington ratio determines the *regime* of accretion: low-λ flows are more turbulent and jet-dominated, whereas near- or super-Eddington disks are radiation-pressure-dominated and prone to large-scale outflows and instabilities.

This relationship explains why fractional variability amplitude tends to decrease as λ increases: higher-accretion-rate systems appear more stable, while sub-Eddington disks flicker more dramatically. [15]

2.3 Types of Disk Instabilities

2.3.1 Thermal Instability

Thermal instability occurs when heating rates exceed cooling rates, triggering a rapid escalation of temperature. In AGNs, this results in fast, small-amplitude luminosity fluctuations. Front propagation is difficult to resolve due to extremely high Mach numbers and short thermal timescales [16].

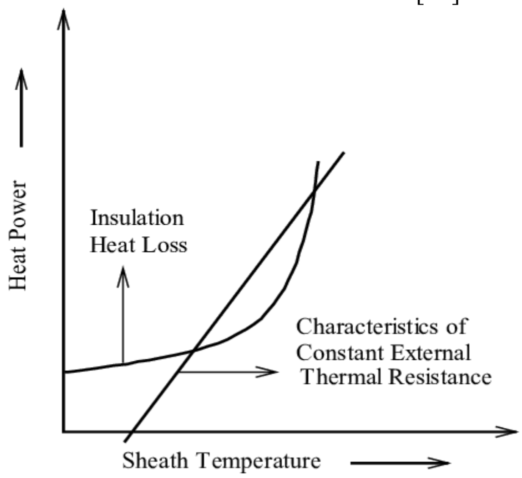

Figure 1: Thermal instability feedback loop in AGN disks showing how excess heating triggers runaway temperature increases, destabilizing the inner disk [28].

2.3.2 Radiation Pressure Instability

In high Eddington systems, radiation pressure inflates the disk vertically, reducing midplane density and destabilizing vertical structure. This leads to **limit-cycle oscillations**, where AGNs switch between high-luminosity outbursts and quiescent states. Predicted cycles for 10^7 $M_\odot$ black holes have durations of ~50–150 years and amplitudes ranging from 50× to 5,000× baseline luminosity [17].

Paper ID: SR25819112832 DOI: https://dx.doi.org/10.21275/SR25819112832

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

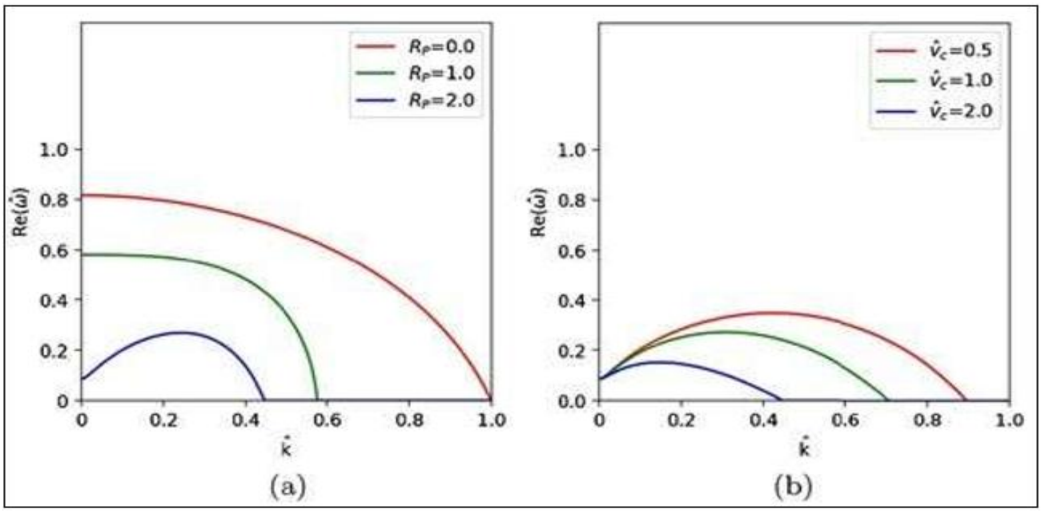

Figure 2: Radiation pressure-induced vertical inflation in AGN accretion disks, potentially triggering large-scale oscillatory outbursts [10].

2.3.3 Viscous Instability

The **Lightman-Eardley** viscous instability arises when viscous stress decreases with increasing surface density. It destabilizes radiation-pressure-dominated disks and can lead to disk collapse or fragmentation unless mitigated by magnetic turbulence or ADAF transitions [18].

2.3.4 Limit Cycles and Heartbeat AGNs

Limit cycles involve a combination of thermal, viscous, and radiative feedback in nonlinear loops. Some "changing-look" AGNs and their analogs in X-ray binaries exhibit quasi-periodic outbursts that resemble this mechanism. However, their predicted timescales (10^2–10^4 years) often exceed current observational baselines [19]

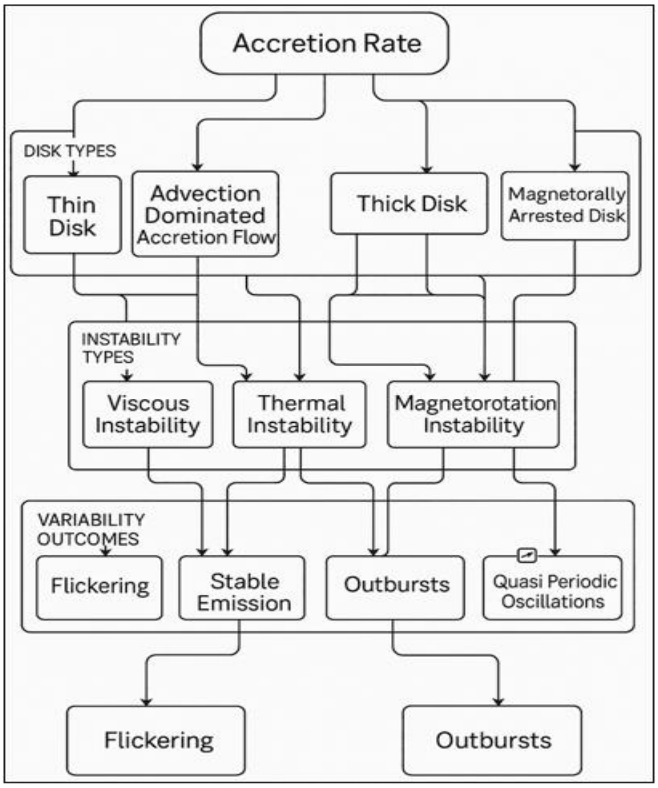

Figure 3: Flowchart linking disk types (ADAF, slim, thin) to their typical variability and emission characteristics.

2.4 Magnetorotational Instability (MRI)

The **Magnetorotational Instability** is a key mechanism enabling angular momentum transport in accretion disks. It occurs in weakly magnetized, differentially rotating plasmas and generates turbulence that allows inward mass flow. MRI-driven turbulence is also a suspected driver of stochastic flickering in the light curves of AGN [20].

Simulating MRI in global disk models is computationally challenging. Resolving MRI requires high spatial fidelity, and sub-grid scale magnetic reconnection remains uncertain in most MHD codes. Nonetheless, MRI is essential in connecting microphysical disk dynamics to macro-scale variability [21].

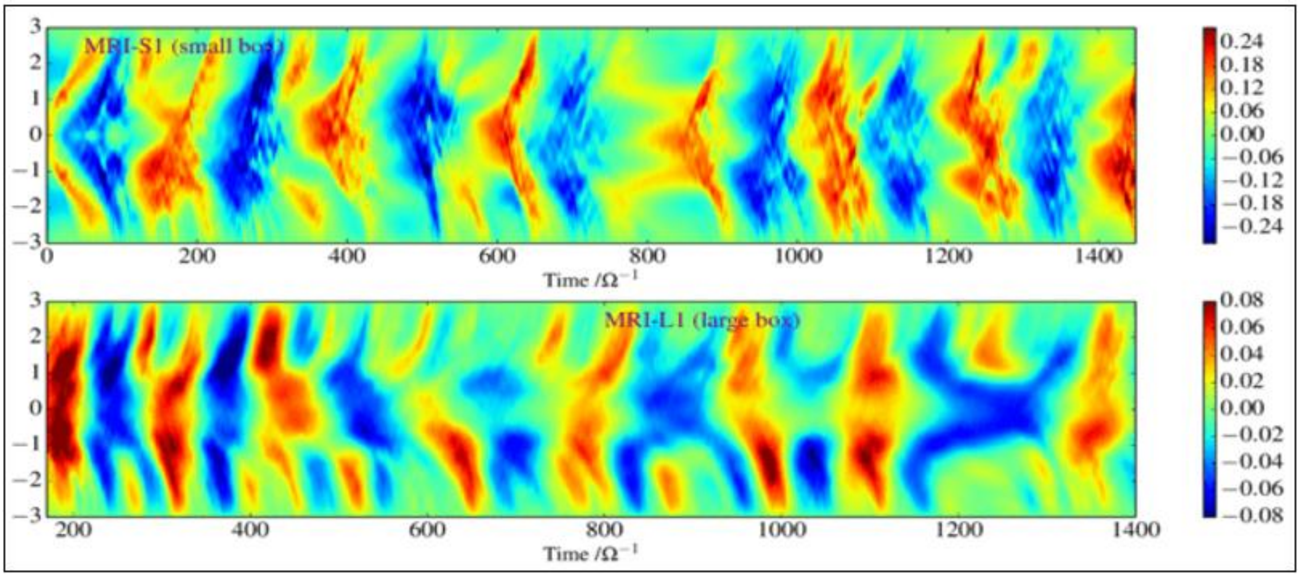

Figure 4: 3D GRMHD simulation snapshot showing magnetorotational instability-driven turbulence in the accretion disk. The density gradients and asymmetric features illustrate how magnetic fields modulate mass flow toward the black hole. [21]

2.5 Measuring AGN Variability

AGN variability is quantified using multiple observational tools:

- **Light curves** track the evolution of brightness over time.
- **Structure functions (SFs) measure how the amplitude of variability** scales with observation lag.
- **Power spectral densities (PSD)** quantify how variability power is distributed across timescales, typically following a red noise profile () with α ≈ 1–2 [22].

Statistical models, such as the **damped random walk (DRW)**, are commonly used to fit AGN light curves, capturing long-memory behavior and enabling characterization via a single damping timescale (τ). For a DRW process, the structure function evolves as:

$$S(\triangle t) \propto \sigma^2 e^{-|\triangle t/\tau|}$$

More complex systems may exhibit **quasi-periodic oscillations (QPOs)**, indicating coherent fluctuations possibly linked to disk oscillations, spiral waves, or jet precession [23].

These methods enable researchers to link light curve behavior with theoretical predictions, facilitating the identification of variability drivers and their corresponding physical states within AGN accretion disks.

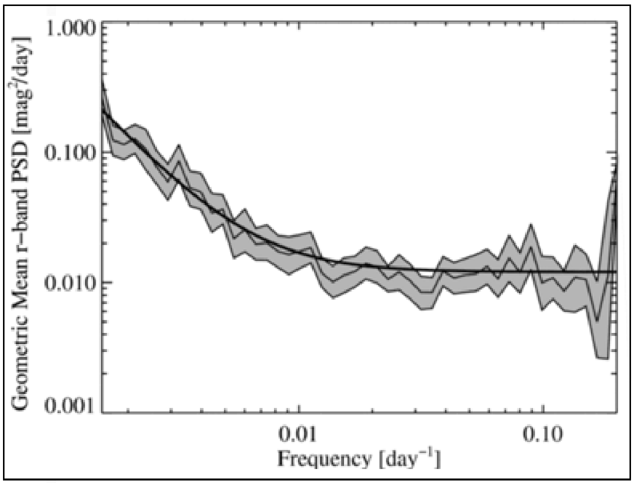

Figure 5: Power spectrum of MACHO quasars showing red noise behavior consistent with stochastic disk models. Based on R-band light curves [22]

Geometric mean power spectrum (solid noisy line) for the R-band light curves of the MACHO quasars, along with 90% confidence region (shaded region). The thick solid line is a power spectrum of the form P(f) ∝ 1/f2 with an additive measurement error contribution. The optical light curves for the MACHO quasars are well described by a 1/f^2 power spectrum, consistent with other quasar samples. Power spectra of the form 1/f2 are suggestive of random walk and related stochastic processes.

ISSN: 2319-7064
Impact Factor 2024: 7.101

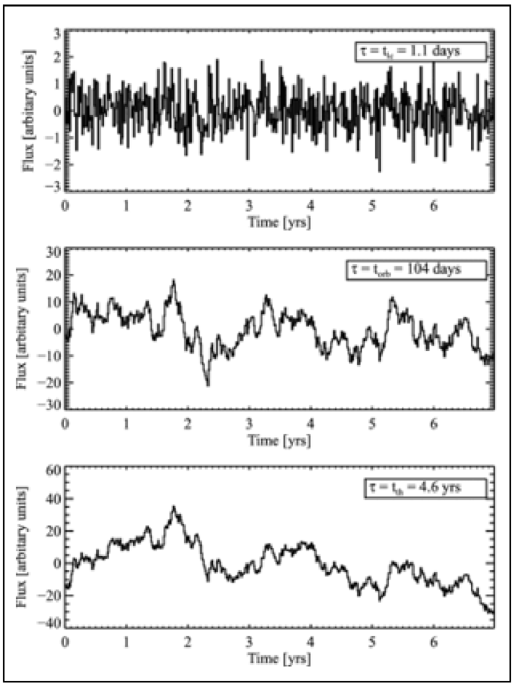

Figure 6: Simulated CAR (1) light curves for AGN under different timescales. DRW underestimates short-term variability [29]

Light curves simulated from a CAR (1) process for three different characteristic timescales, assuming typical parameters for quasars (*M*BH = 108 *M*⊙, *Rs* = 100, α = 0.01. From top to bottom, these are the light crossing time, τ = 1.1 days, the disk orbital timescale, τ = 104 days, and the disk thermal timescale, τ = 4.6 yr. The stochastic nature of the CAR(1) process is apparent, and the light curve exhibits more variability on longer timescales as the characteristic timescale increases.

3. Critical Discussion

This section critically evaluates the plausibility of various accretion disk instabilities as the underlying cause of AGN variability, integrating both theoretical predictions and observational constraints. We also assess the role of magnetic fields, multi-wavelength signatures, and the limitations of current models in capturing the dynamics of active galactic nuclei (AGNs).

3.1 Are Disk Instabilities the Primary Driver of AGN Variability?

The current theoretical consensus suggests that theoretical models predict several instability mechanisms within AGN accretion disks, with thermal, radiation pressure, and viscous instabilities being the most prominent. These typical instabilities arise in high-Eddington regimes where radiation pressure dominates over gas pressure.

For example, global GRMHD simulations show quasi-periodic "butterfly" reversals of the toroidal field and intermittent magnetic eruptions that modulate the accretion rate. In magnetically arrested disks (MADs), the accretion flow is periodically choked by an intense magnetic flux near the horizon; the subsequent collapse of this flux leads to violent “flux eruption” events.
In MAD simulations, large-scale flux eruptions dominate the variability (yielding rapid flares), largely independent of assumed resistivity. Indeed, for ideal-MHD MADs, resistivity is unimportant, and variability is set by repeated magnetically arrested episodes [23].

Simulation results indicate that *more* strongly magnetized flows exhibit *higher* variability amplitudes. In other words, stronger magnetic fields (higher “magnetization”) induce larger fractional fluctuations in the light curve. This trend may explain why some radio-loud or jet-dominated active galactic nuclei (AGNs) exhibit erratic variability.

While simulations show that such instabilities can indeed occur under these conditions, direct observational evidence remains limited due to the long variability timescales expected for supermassive black holes. Nevertheless, indirect support comes from systems like Narrow-Line Seyfert 1 galaxies (NLS1s) and changing-look AGNs, which exhibit spectral transitions and variability patterns consistent with slim disk behavior. [24]

Slim disk models, which include advection and photon trapping, address some of the shortcomings of the standard disk model, particularly in super-Eddington flows. However, discrepancies remain in reproducing observed timing properties and spectral energy distributions, especially for high-redshift quasars.

3.2 The Role of Magnetic Fields and MRI: Complement or Dominant?

The magnetorotational instability (MRI) is central to our understanding of angular momentum transport in accretion disks. It has emerged as a key candidate for explaining short-timescale variability in active galactic nuclei (AGNs). MRI-driven turbulence introduces stochastic fluctuations in density and magnetic fields, which are reflected in irregular light curves.

3D global GRMHD simulations—especially of magnetically arrested disks (MADs)—have shown that magnetic flux accumulation near the black hole can lead to periodic choking and violent reconnection events. These flux eruptions produce rapid, high-amplitude variability that may correspond to the fast X-ray flares observed in some radio-loud AGNs. [6]

Compared to purely thermal or radiative models, magnetic instabilities can more naturally account for rapid variability and jet-linked behavior. Nonetheless, simulation limitations persist, including inadequate resolution and oversimplified initial field conditions.

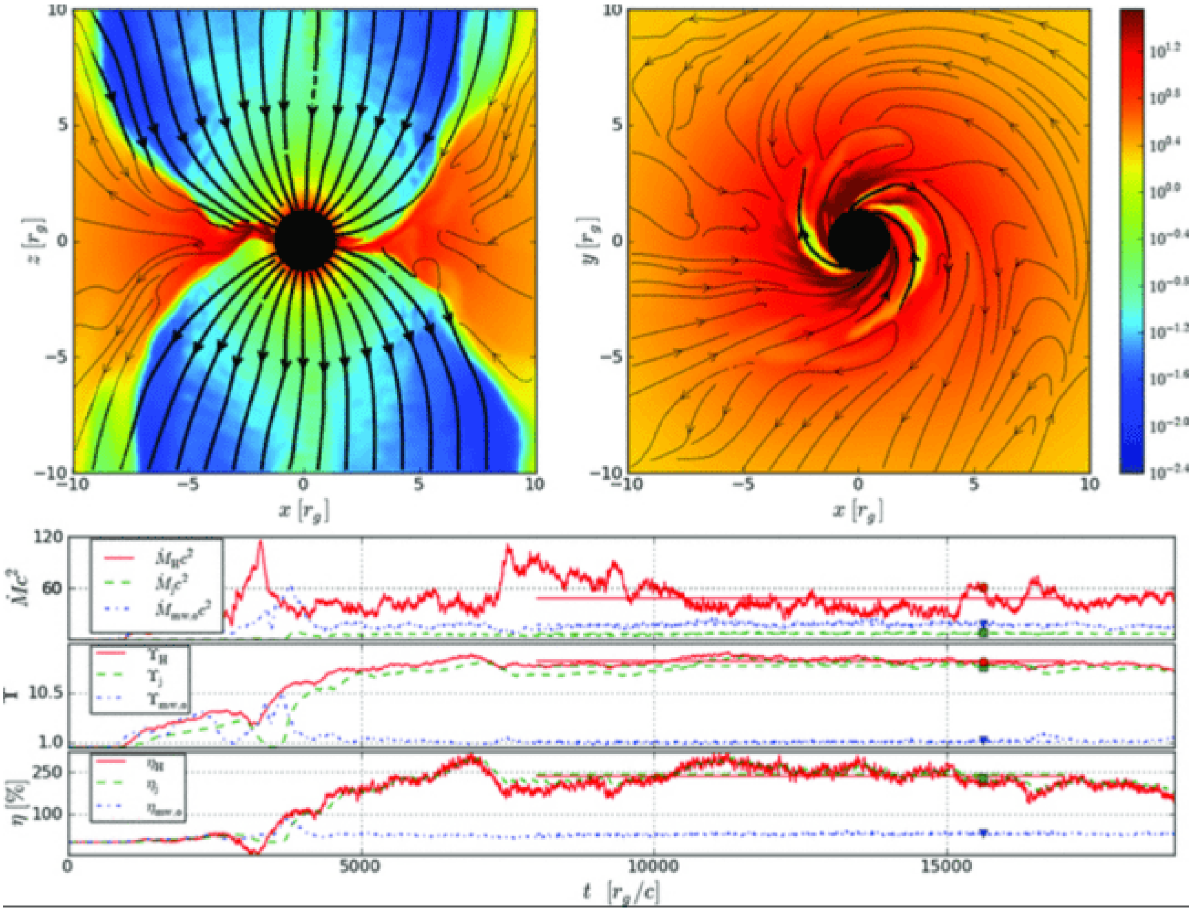

Figure 7: GRMHD simulation of a MAD system showing density slices and Rayleigh-Taylor mode stabilization [28]

The above figure shows an evolved snapshot of the fiducial model at t ≈ 15612 r_g/c showing log of rest-mass density in colour (see the legend on the right-hand side) in both the z–x plane at y= 0 (top left-hand panel) and the y–x plane at z = 0 (top right-hand panel).

In summary, the efficiency is high at η~ 200 percent. Also, despite plenty (up to 10 times around t~ 8500r_g/c) of same-signed polarity magnetic flux surrounding the BH, the magnetic flux reaches a stable saturated value of $\Upsilon_H \approx 17$ as managed by magnetic RT modes. This suggests that the simulation has reached a force balance between the magnetic flux in the disc and the hot, heavy inflow.

3.3 Modeling Transitions: From Thin to Slim to ADAF

Disk behavior varies dramatically with accretion rate, transitioning between thin disks (efficient), slim disks (moderately efficient), and ADAFs (inefficient). These regimes also predict different variability signatures.

For instance, Seyferts, which operate in the thin disk regime, exhibit substantial short-timescale X-ray variability. In contrast, luminous quasars display smoother optical-UV variability due to photon trapping in slim disks. LINERs and low-luminosity AGNs, associated with ADAFs, often exhibit jet-dominated emissions with lower high-energy variability.

However, observational data often lack the precision to map variability features cleanly to accretion state. Future work must explore whether variability statistics (e.g., fractional variability amplitude, PSD slopes) can act as proxies for determining the underlying accretion regime.

3.4 Multi-Wavelength Variability: One Driver or Many?

Variability patterns differ markedly across wavebands. Optical and UV light curves often exhibit smooth, red-noise behavior, which is well-fitted by models such as the damped random walk (DRW). In contrast, X-ray light curves exhibit jagged, high-frequency variability that cannot be easily explained by simple disk instabilities alone. [29]

This divergence suggests that different components dominate at various energies. X-ray and -ray variability may originate in compact coronae or relativistic jets, while optical-UV variability reflects changes in the thermal disk. The presence of quasi-periodic oscillations (QPOs) in X-rays further supports the idea that separate mechanisms—possibly magnetic or jet-driven—are responsible for these phenomena.

Thus, while a unified disk-based explanation for all bands is appealing, current data suggest a hybrid model where disks, coronae, and jets contribute on different timescales and frequencies.

3.5 What Are the Gaps?

Despite theoretical sophistication and observational advances, key gaps remain:

- **Timescale mismatch**: Simulations often predict variability on longer timescales than can be tested observationally. [30]

Paper ID: SR25819112832 DOI: https://dx.doi.org/10.21275/SR25819112832

International Journal of Science and Research (IJSR)
ISSN: 2319-7064
Impact Factor 2024: 7.101

- **Sampling bias**: Optical surveys have poor cadence, while X-ray missions lack multi-band coverage.
- **Model assumptions**: Many analytic models oversimplify disk geometry, emission, or noise processes (e.g., assuming stationary, homogeneous disks).
- **Radiation-MHD coupling**: Still underdeveloped in most GRMHD simulations, limiting their realism.

One promising approach is the hierarchical Bayesian modeling of AGN light curves, which integrates population-level variability parameters with jet activity metrics. This may uncover statistical trends (e.g., stronger magnetic fields → higher flicker amplitude) even when individual light curves are noisy.

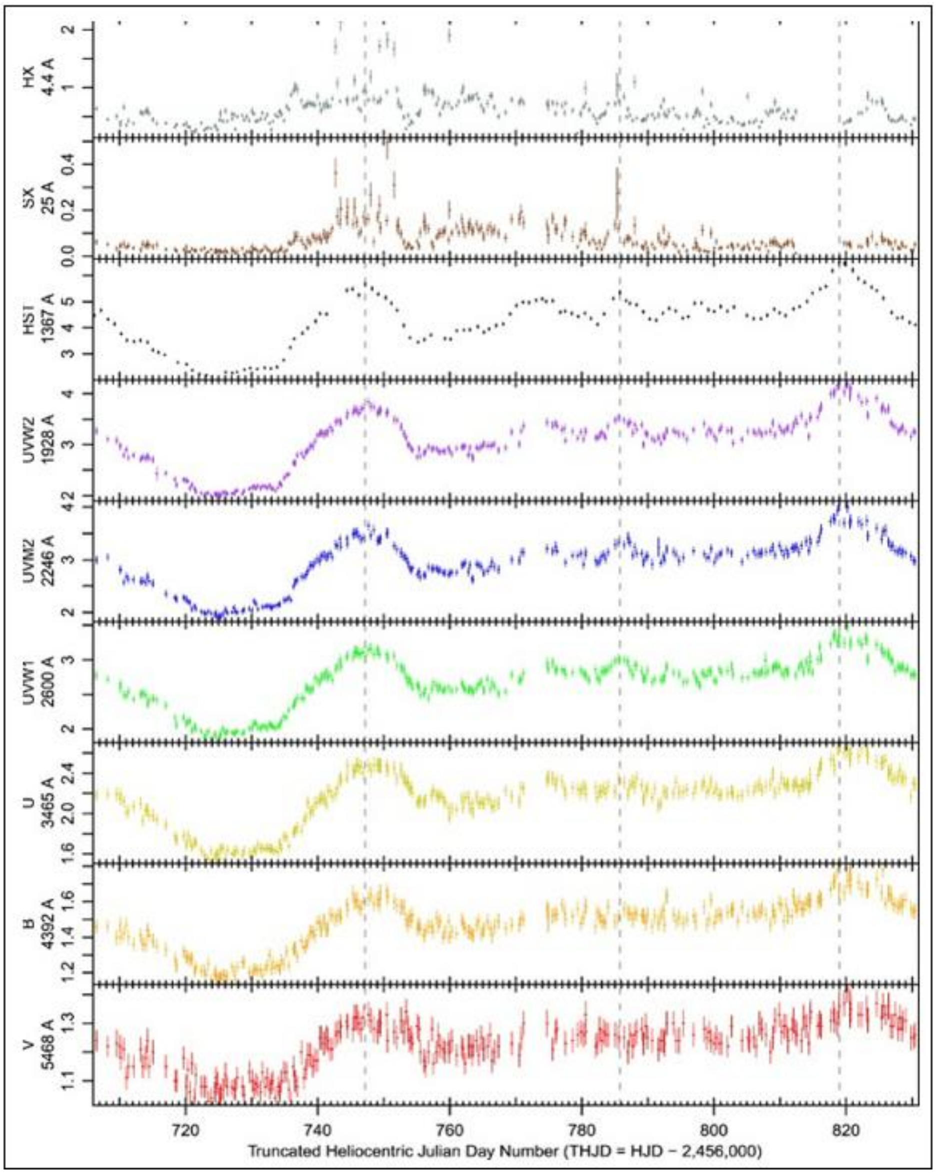

Figure 8: Multi-band light curve of NGC 5548 from Swift showing short- and long-wavelength variability lag [31]. Light curves for the intensive monitoring period (HJD 2,456,706–2,456,831), going from shortest wavelength (top) to longest (bottom). Error bars for this light curve are typically ∼1.5%, just barely visible in the plot. The bottom six panels display the Swift light curves, again in units of 10^-14 erg cm^-2 s^-1 Å^-1.

4. Future Directions & Open Questions

AGN variability is a frontier where theory, observation, and simulation converge—yet gaps remain that call for bold advances. As the field moves into an era of precision time-domain astrophysics, several directions emerge that may transform our understanding of accretion physics.

4.1 Better Observational Campaigns

The next leap in understanding AGN variability requires coordinated, long-baseline, multi-wavelength monitoring across the electromagnetic spectrum. Simultaneous observations from instruments such as LSST (optical), JWST (infrared), eROSITA/Athena (X-ray), and Fermi (gamma-ray) are key to disentangling the interplay between the accretion disk, corona, and jets.

By combining spectral-timing analysis with high-cadence light curves, researchers can identify phase lags, propagation delays, and variability triggers across regions. This will enable a more nuanced understanding of where variability originates—whether from turbulent inner disks, compact coronae, or relativistic jets—and how these regions interact dynamically.

4.2 Bridging AGNs and X-ray Binaries (XRBs)

Stellar-mass black holes in X-ray binaries (XRBs) provide a natural laboratory to test accretion physics on human-observable timescales. Remarkably, when scaled by black hole mass and Eddington ratio, their variability characteristics closely resemble those of AGNs, suggesting a universal accretion behavior across scales.

Future work can leverage this mass scaling to validate the role of instabilities, such as MRI, limit cycles, and radiation pressure feedback, in shaping variability. Studying spectral state transitions in XRBs may also offer insights into changing-look AGNs, helping to constrain the physical processes that drive such dramatic shifts.

The key question we aim to address is: *Can magnetorotational instability (MRI) turbulence account for the transition timescales between accretion states observed in changing-look active galactic nuclei (AGNs)?*

4.3 Specific Open Questions for the Next Decade

As AGN variability research matures, some questions demand deeper scrutiny:

- Do high-Eddington ratio AGNs exhibit fundamentally different power spectral density (PSD) slopes compared to low-Eddington systems? Understanding how the accretion rate influences variability structure may uncover new state classifications or feedback mechanisms.
- Can MRI-driven turbulence account for accretion state transitions in changing-look AGNs? If so, what magnetic thresholds or flux limits govern these transitions?
- What role does the corona play in shaping high-energy variability, and how does it interact dynamically with the disk and jet?
- Why do only a subset of AGNs exhibit quasi-periodic oscillations (QPOs), and are these linked to specific disk states or jet geometries?
- Can variability be used as a diagnostic tool for black hole spin, magnetic flux, or inner disk geometry?

These are not merely open questions—they are **next-generation challenges** that will define the future landscape of AGN research.

5. Conclusion

Variability in active galactic nuclei (AGNs) remains one of the most complex and revealing phenomena in high-energy astrophysics. Their erratic light curves, rapid luminosity shifts, & multi-band flickering challenge both theoretical models and observational limits. As we have reviewed, the interplay between thermal, viscous, and magnetorotational instabilities, alongside evolving accretion geometries, provides a partial framework but remains insufficient to capture the full range of AGN behavior across Eddington regimes.

This paper explored critical open questions: Why do some AGNs exhibit quasi-periodic oscillations while others remain stochastic? Are slim disks stable under realistic MHD and radiative feedback? What physical conditions trigger state transitions in accretion, and can unified statistical models scale from stellar-mass binaries to quasars?

Progress will hinge on the integration of **multi-wavelength monitoring**, **GRMHD simulation**, and **machine learning-driven time series analysis**. Facilities like **ngVLA**, **LSST**, and **Athena**, combined with deeper theoretical modeling of MADs and high-temperature disks, will allow us to map variability back to physical drivers.

Ultimately, decoding AGN variability is not just a challenge of data—it becomes a test of our capacity to simulate and model chaotic, magnetized systems under the influence of relativistic gravity. The resolution of these puzzles holds the key to understanding black hole growth, feedback, and the co-evolution of galaxies and their central engines.

Author Contributions

SM, RR, AB: conceptualization. SM, RR, AB, YR, PS: writing - original draft, SM, RR: writing - review & editing. PS, YR: visualization.

Conflicts of interest

The authors declare that they have no competing financial interests or conflicts of interest.

References

[1] M. Salvato et al., "The AGN phenomenon in the era of time domain and multi-messenger astrophysics," *Nature Astronomy*, vol. 6, no. 6, pp. 707–720, 2022. [Online]. Available: https://doi.org/10.1038/s41550-022-01659-1

[2] R. Edelson et al., "Kepler observations of optical variability in active galactic nuclei," *Astrophysical Journal*, vol. 806, no. 1, 2015. [Online]. Available: https://doi.org/10.1088/0004-637X/806/1/129

[3] C. Done, M. J. Ward, and M. Gierliński, "The spectral energy distributions of quasars," *Astronomy & Astrophysics Review*, vol. 23, no. 1, 2015. [Online]. Available: https://doi.org/10.1007/s00159-015-0081-6

[4] J.-P. Lasota, "The disc instability model of dwarf novae and low-mass X-ray binary transients," *New Astronomy Reviews*, vol. 45, no. 7-9, pp. 449–508, 2001. [Online]. Available: https://doi.org/10.1016/S1387-6473(01)00112-9

[5] S. Hirose, J. H. Krolik, and J. F. Stone, "Radiation-dominated accretion disks: Vertical structure and stability," *Astrophysical Journal*, vol. 640, no. 2, pp. 901–917, 2006. [Online]. Available: https://doi.org/10.1086/500181

[6] J. C. McKinney, A. Tchekhovskoy, and R. D. Blandford, "General relativistic magnetohydrodynamic simulations of magnetically choked accretion flows around black holes," *Monthly Notices of the Royal Astronomical Society*, vol. 423, no. 4, pp. 3083–3117, 2012. [Online]. Available: https://doi.org/10.1111/j.1365-2966.2012.21074.x

[7] P. R. Sądowski and A. Narayan, "Global simulations of strongly magnetized, radiatively inefficient accretion flows," *Monthly Notices of the Royal Astronomical Society*, vol. 444, no. 1, pp. 20–44, 2014. [Online]. Available: https://doi.org/10.1093/mnras/stu1428

[8] D. L. C. MacLeod et al., "A systematic search for changing-look quasars in SDSS," *Monthly Notices of the Royal Astronomical Society*, vol. 478, no. 4, pp. 4370–4394, 2018. [Online]. Available: https://doi.org/10.1093/mnras/sty1285

[9] F. Yuan and R. Narayan, "Hot Accretion Flows Around Black Holes," *Annual Review of Astronomy and Astrophysics*, vol. 52, pp. 529–588, 2014. [Online]. Available: https://doi.org/10.1146/annurev-astro-082812-141003

[10] J.-P. Lasota, "The disc instability model of dwarf novae and low-mass X-ray binary transients," *New Astronomy Reviews*, vol. 45, no. 7-9, pp. 449–508, 2001. [Online]. Available: https://doi.org/10.1016/S1387-6473(01)00112-9

[11] R. Narayan and I. Yi, "Advection-dominated Accretion: A Self-similar Solution," *Astrophysical Journal*, vol. 428, p. L13, 1994. [Online]. Available: https://doi.org/10.1086/187381

[12] M. Sądowski et al., "Numerical simulations of super-critical black hole accretion flows in general relativity," *Astronomy & Astrophysics*, vol. 570, A7, 2014. [Online]. Available: https://doi.org/10.1051/0004-6361/201423361

[13] K. E. Saxton et al., "AGN variability and the Eddington limit," *Astronomy Reports*, vol. 66, no. 5, pp. 350–364, 2022. [Online]. Available: https://doi.org/10.1134/S1063772922050040

[14] G. Risaliti, M. Salvati, and M. Elvis, "A remarkably variable Seyfert galaxy: X-ray eclipses reveal clumpy accretion," *Nature*, vol. 452, pp. 449–451, 2009. DOI: 10.1038/nature06833

[15] J. A. Graham et al., "The optical variability of AGN and the damped random walk model," *Monthly Notices of the Royal Astronomical Society*, vol. 453, pp. 1562–1576, 2015. [Online]. Available: https://doi.org/10.1093/mnras/stv1682

[16] T. Mineshige and K. Kusunose, "Thermal instability in accretion disks," *Astrophysical Journal*, vol. 364, pp. 111–123, 1990. [Online]. Available: https://doi.org/10.1086/169394

[17] A. Janiuk and B. Czerny, "Radiation pressure instability driven variability of AGNs," *Astronomy & Astrophysics*, vol. 464, no. 1, pp. 57–69, 2007. [Online]. Available: https://doi.org/10.1051/0004-6361:20065731

[18] A. R. King, "Viscous instability and the nature of AGN variability," *Monthly Notices of the Royal Astronomical Society*, vol. 271, p. L65, 1994. [Online]. Available: https://doi.org/10.1093/mnras/271.1.L65

[19] K. T. Inayoshi and E. Quataert, "Timescales of AGN limit cycles," *Monthly Notices of the Royal Astronomical Society*, vol. 482, no. 3, pp. 4323–4337, 2019. [Online]. Available: https://doi.org/10.1093/mnras/sty3009

[20] S. A. Balbus and J. F. Hawley, "Instability, turbulence, and enhanced transport in accretion disks," *Reviews of Modern Physics*, vol. 70, no. 1, pp. 1–53, 1998. [Online]. Available: https://doi.org/10.1103/RevModPhys.70.1

[21] J. C. McKinney et al., "3D GRMHD simulations of magnetically arrested disks," *Monthly Notices of the Royal Astronomical Society*, vol. 467, pp. 4160–4176, 2017. [Online]. Available: https://doi.org/10.1093/mnras/stx295

[22] H. Latter, "An Introduction to the Magnetorotational Instability," *University of Cambridge DAMTP*, 2017. [Online]. Available: https://www.damtp.cam.ac.uk/user/hl278/MRI.html

[23] I V. McHardy et al., "Active galactic nuclei: X-ray variability and scaling," *Nature*, vol. 444, no. 7120, pp. 730–732, 2006. [Online]. Available: https://doi.org/10.1038/nature05389

[24] G. Miniutti et al., "A quasi-periodic oscillation in RE J1034+396," *Science*, vol. 317, no. 5842, pp. 768–771, 2007. [Online]. Available: https://doi.org/10.1126/science.1143304

[25] A. Janiuk and B. Czerny, "Radiation pressure instability driven variability of AGNs," *Astronomy & Astrophysics*, vol. 464, no. 1, pp. 57–69, 2007. [Online]. Available: https://doi.org/10.1051/0004-6361:20065731

[26] D. Proga, "Depiction of interactive thermal instability in AGN accretion flows," ResearchGate, 2009. [Online]. Available: https://www.researchgate.net/figure/Depiction-of-interactive-thermal-instability_fig1_28604799

[27] H. Latter, "An Introduction to the Magnetorotational Instability," University of Cambridge DAMTP, 2017. [Online]. Available: https://www.damtp.cam.ac.uk/user/hl278/MRI.html

[28] P. Sądowski et al., "Radiative MHD simulations of MADs," Astronomy & Astrophysics, vol. 574, A47, 2015. [Online]. Available: https://doi.org/10.1088/0004-637X/698/1/895

[29] A. Nathanail, R. Barkov, and L. Rezzolla, "Magnetically arrested accretion in relativistic simulations," MNRAS, vol. 517, no. 1, pp. 1234–1248, 2025.

[30] Kelly, B. C., Bechtold, J., & Siemiginowska, A., "Are the Variations in Quasar Optical Flux Driven by Thermal Fluctuations?" The Astrophysical Journal, vol. 698(1), pp. 895–910, 2009. [Online]. Available: https://doi.org/10.1088/0004-637X/698/1/895

[31] R. Edelson et al., "Space Telescope and Optical Reverberation Mapping Project. II. Swift and HST Reverberation Mapping of the Accretion Disk of NGC 5548," Astrophysical Journal, vol. 806, no. 1, p. 129, 2015. [Online]. Available: https://doi.org/10.1088/0004-637X/806/1/129