- 4 Accretion disks
 - 4.1 Optically thick, geometrically thin accretion disks
 - 4.1.1 Basic disk parameters
 - 4.1.2 Luminosity emissivity and temperature
 - 4.1.3 Viscosity
 - 4.1.4 Important time scales
 - 4.1.5 Disk geometry
 - 4.1.6 The emitted spectrum
 - 4.1.7 Viewing angle dependences
 - 4.2 Real AGN disks
 - 4.2.1 Comptonization and the disk corona
 - 4.2.2 Irradiated disks
 - 4.3 Slim and thick accretion disks
 - 4.4 Radiatively inefficient accretion flows
 - 4.5 Further reading

Will not follow the subsubsections in the book exactly. Two additional key references:

* Accretion Power in Astrophysics, Frank, King, & Raine, Cambridge Univ. Press, 2
 * Hot Accretion Flows around Black Holes, Yuan & Narayan, 2014, ARA&A
 Video lectures given by Prof. Feng Yuan (SHAO)!



- What is Eddington luminosity? Can it be surpassed? If yes, how?
- What are the equations to be considered in the cases of HD and MHD accretion disks, respectively?
- Why is viscosity important in the accretion process? Which types of viscosities do you know about?
- What are the main features of the standard thin disk?
- What are the main features of the slim disk?
- What are the main differences between ADAF and LHAF?

Write your brief answers to these questions using your own words after this chapter is finished. http://mooc.chaoxing.com/course/2524589.html



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Formation and Co-Evolution of Galaxies and Supermassive Black Holes

Prof. Niel Brandt : An Observational Overview of Active Galactic Nuclei Prof. Luis C.Ho: The Galaxy Population (Properties, Origin, Evolution, Connection to SMBHs)

Prof. Houjun Mo : Cosmology and Galaxy Formation

Prof. Feng Yuan : Black hole accretion







Black hole accretion

Feng Yuan (袁峰)

Shanghai Astronomical Observatory Chinese Academy of Sciences



(courtesy of Feng Yuan)

4 Accretion disks

- Accretion disks (ADs):
 - very efficient accretion processes
 - fundamental and common physical processes in the universe
 - * protostars; planet formation
 - * various types of binary stars: LMXBs and HMXBs
 - * dwarf novae or cataclysmic variables; classical novae
 - * Gamma-ray bursts
 - * AGNs
- ADs in galactic centers:
 - naturally formed by infalling gas that sinks into the central plane of the galaxy while retaining most of its angular momentum
 - assumption: viscosity transfers gas angular momentum outward to allow it spiral into the center, losing a considerable % of grav. energy on the way
 - this lost grav. energy:
 - * convert into EM radiation (extremely high efficiency up to ~42%)
 - * convert into gas kinetic energy, gas blown away from the disk
 - * heat gas to very high T, causing much of energy to be advected into BH



daily-life "accretion" @ Hefei Sci. & Tech. Museum

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daily-life "accretion" @ Hefei Sci. & Tech. Museum

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• ADs: hydrodynamics (HD) --- simplest case

continuity equation:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \boldsymbol{v}) = 0$$

mass conservation

- momentum equation:

$$\rho \frac{d\boldsymbol{v}}{dt} = -\nabla P - \rho \nabla \Phi$$

mom. conservation

physical properties (ideal gas)

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where the Lagrangian derivative:

$$\frac{d}{dt} \equiv \frac{\partial}{\partial t} + v \cdot \nabla_{\text{going with the flow element}}$$

- energy equation:

$$ho rac{\mathrm{d}(e/
ho)}{\mathrm{d}t} = -P
abla \cdot oldsymbol{v}$$
 energy conservation

-kT

- equation of state:

- boundary conditions: differential --> algebra equations --> easier to solve

 μm_p

P

- ADs: magnetohydrodynamics (MHD) --- HD + magnetic field
 - HD + Lorentz force (← Maxwell equations)
 - need one additional equation to evolve the magnetic field
 - * Faraday's law (induction equation): $\partial oldsymbol{B}$

$$\frac{\mathbf{B}}{\partial t} = -c\nabla \times \mathbf{E}$$

- assume ideal MHD: gas is a perfect electric conductor (i.e., no resistance)
 - * the induction equation can be written as:

$$\frac{\partial \boldsymbol{B}}{\partial t} = \nabla \times (\boldsymbol{v} \times \boldsymbol{B})$$

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Strong field: matter move along field lines (beads on a wire).

Weak field: field lines are forced to move with the gas.



- ADs: viscosity holds the key
 - viscous flow (Navier-Stokes viscosity NS viscosity)
 - * Euler's equation and viscous stress tensor:

 $\frac{\partial(\rho \boldsymbol{v})}{\partial t} + \nabla \cdot (\rho \boldsymbol{v} \boldsymbol{v} + P \mathbf{I}) = \nabla \cdot \boldsymbol{\sigma} \quad \sigma_{ij} = \rho \nu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} - \frac{2}{3} \delta_{ij} \nabla \cdot \boldsymbol{v} \right)$

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- physical interpretation: diffusion of momentum momentum exchange across velocity gradient
- NS viscosity too small, so we need an 'anomalous' one: alpha-viscosity
- * assumed to be constant in the case of HD
 - * MHD simulations give diverse results on alpha
 - * alpha increases with the net magnetic flux, ranging from ~0.01-1
- disk properties that can affect viscosity:
 - * local microphysics (e.g., specific atomic or molecular processes)
 - * local or global turbulence
 - * magnetic field strength and structure

 results show that the higher the viscosity, the larger is the radial velocity of the inflowing gas; and the inward velocity is much less than the sound speed (i.e., the radial inflow is subsonic)

Corona-heated Accretion-disk Reprocessing: A Physical Model to Decipher the Melody of AGN UV/Optical Twinkling

Mouyuan Sun^{1,2,3}, Yongquan Xue^{2,3}, W. N. Brandt^{4,5,6}, Wei-Min Gu¹, Jonathan R. Trump⁷, Zhenyi Cai^{2,3}, Zhicheng He^{2,3}, Da-bin Lin⁸, Tong Liu¹, and Junxian Wang^{2,3}

THE ASTROPHYSICAL JOURNAL, 891:178 (21pp), 2020 March 10

Abstract

Active galactic nuclei (AGNs) have long been observed to "twinkle" (i.e., their brightness varies with time) on timescales from days to years in the UV/optical bands. Such AGN UV/optical variability is essential for probing the physics of supermassive black holes (SMBHs), the accretion disk, and the broad-line region. Here, we show that the temperature fluctuations of an AGN accretion disk, which is magnetically coupled with the corona, can account for observed high-quality AGN optical light curves. We calculate the temperature fluctuations by considering the gas physics of the accreted matter near the SMBH. We find that the resulting simulated AGN UV/optical light curves share the same statistical properties as the observed ones as long as the dimensionless viscosity parameter α , which is widely believed to be controlled by magnetohydrodynamic (MHD) turbulence in the accretion disk, is about 0.01–0.2. Moreover, our model can simultaneously explain the larger-than-expected accretion disk sizes and the dependence of UV/optical variability upon wavelength for NGC 5548. Our model also has the potential to explain some other observational facts of AGN UV/optical variability, including the timescale-dependent bluer-whenbrighter color variability and the dependence of UV/optical variability on AGN luminosity and black-hole mass. Our results also demonstrate a promising way to infer the black-hole mass, the accretion rate, and the radiative efficiency, thereby facilitating understanding of the gas physics and MHD turbulence near the SMBH and its cosmic mass growth history by fitting the AGN UV/optical light curves in the era of time-domain astronomy.



Figure 18. The SFs for the three *Kepler* AGNs. In each panel, the black thick curve represents the observed SF; the purple and orange thick curves correspond to our CHAR model with $\alpha = 0.2$ and $\alpha = 0.01$, respectively; the corresponding shaded regions indicate the 1σ uncertainties, which account for the photometric noise and sampling effects. The SFs show some dips or peaks at the long-timescale ends. This is simply because the light-curve durations are too short to constrain the long-timescale variability. For kplr 2694186, the observed SF has a dip feature around $\Delta t = 400$ days, which indicates periodicity in this source. However, this might be caused by instrumental effects (Smith et al. 2018a). Note that when generating the model light curves, our simulations include the same time-sampling issues and photometric errors as the SFs calculated from the real data.

- ADs: magneto-rotational instability (MRI)
 - MRI --> viscosity fluctuation --> accretion rate fluc. --> L fluc.
 - Rayleigh criteria for unmagnetized rotating disks:
 - * unstable if $d(\Omega R^2) < 0$, which is experimentally confirmed
 - * all astrophysical disks should be stable based on this criteria
 - include a vertical, well-coupled magnetic field and change the criteria qualitatively:
 - * unstable if

 $\frac{d\Omega}{dR} < 0$ * all astrophysical disks should be unstable! – MRI (B: not too strong/weak)

- resulted MHD turbulence: responsible for transport of angular momentum
- MRI can amplify magnetic field
- ADs: very complicated to find the exact solutions
- involve HD, MHD, viscosity, and MRI
 - * resort to numerical simulations, still extremely challenging
- consider some simplified cases
 - * e.g., no magnetic field

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Article Published: 30 June 2022

H_2O MegaMaser emission in NGC 4258 indicative of a periodic disc instability

Willem A. Baan 🖂, Tao An, Christian Henkel, Hiroshi Imai, Vladimir Kostenko & Andrej Sobolev

Nature Astronomy (2022) | Cite this article

2 Altmetric | Metrics

Abstract

H₂O MegaMaser emission may arise from thin gas discs surrounding the massive nuclei of galaxies such as NGC 4258, but the physical conditions responsible for the amplified emission are unclear. A detailed view of these regions is possible using the very high angular resolution afforded by space very long baseline interferometry (SVLBI). Here we report SVLBI experiments conducted using the orbiting RadioAstron Observatory that have resulted in detections of the H₂O 22 GHz emission in NGC 4258, with Earth-space baselines of 1.3, 9.5 and 19.5 Earth diameters. Observations at the highest angular resolutions of 11 and 23 µas show distinct and regularly spaced regions within the rotating disc, at an orbital radius of about 0.126 pc. These observations at three subsequent epochs also indicate a time evolution of the emission features, with a sudden rise in amplitude followed by a slow decay. The formation of these emission regions, their regular spacing and their time-dependent behaviour appear consistent with the occurrence of a periodic magneto-rotational instability in the disc. This type of shear-driven instability within the differentially rotating disc has been suggested to be the mechanism governing the radial momentum transfer and viscosity within a mass-accreting disc. The connection of the H₂O MegaMaser activity with the magneto-rotational instability activity would make it an indicator of the mass-accretion rate in the nuclear disc of the host galaxy.

安涛(上海天文台):

【科研进展】著名的漩涡星系 NGC4258,对,就是那个通过水脉泽精 确测量超大黑洞质量的明星星系,又有 了新发现!天文学家找到周期性吸积盘 不稳定性的观测证据。

由Willem Adrianus Baan教授领 导的一个国际团队利用最高分辨率的空 间VLBI对黑洞周围的吸积盘中的水超脉 泽进行了多次观测(水超脉泽存在于这 个气体盘中最致密的气体云中),成功 探测到多个随吸积盘旋转的致密云团, 这些云团在谏度上呈现出有规律的变化。 这些观测特征与吸积盘中发生的磁旋转 不稳定性相一致。长期以来,有理论研 究认为,吸积盘中的校差旋转会驱动产 生剪切不稳定性,吸积盘通过这种类型 的不稳定性调节径向动量传递和粘滞。 这不仅创造了VLBI最高分辨率的记录, 达到11微角秒,能够分辨出这个星系中 62个天文单位大小的天体的结构(这个 尺度相当于从太阳到海王星距离的两 ,而且还代表了空间VLBI在黑洞吸 倍) 积盘研究领域的一个突破,使人们能够 首次了解到吸积盘的最精细的动力学特 性。

- Classification of AGN disks and ADs in general:
 - based on shape: thin, slim, and thick disks (depend on mass accretion rate)
 - * whether being optically thin or thick, depending on column density (or surface density) and level of ionization of the gas
 - * optical depth of AGN disks during fast accretion is very large
- Optically thick, geometrically thin ADs:
 - receive most attention
 - easier to treat analytically and numerically
 - a full solution can be used to calculate the emergent disk spectrum and to compare it with observations

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4.1 Optically thick, geometrically thin ADs

• Optically thick, geometrically thin ADs:

- likely to form over a large range of conditions in galactic nuclei during times when large amounts cold gas are falling toward the center
- properties governed by fundamental parameters:
 - * accretion rate, BH mass, and BH spin
 - * determine disk geometry, gas T everywhere, overall L, emitted spectrum

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Measure accretion rate in units of normalized accretion rate L/L_{Edd}

 not very accurate definition: accretion rate related to observed L via efficiency, so depending on BH spin; taking η ~ 0.1 for general discussion

H(r)

- Standard optically thick, geometrically thin AD:
 - approximated as a combination of multiple adjacent rings where all released grav. energy can be radiated locally as a perfect blackbody
 - characterized by $0.01 <^{\sim} L/L_{Edd} <^{\sim} 0.3$
 - * exact upper limit depends on disk shape and its deviation from a simple thin structure (definition of thin: thickness over radius well below 0.1)
 - * lower limit determined by disk viscosity and radiation efficiency
 - major assumptions:
 - * accreted gas moves inward slowly while retaining circular orbital motion
 - * the motion of a particle in the ring is coupled to the motion of gas particles just outside and just inside its location through some kind of friction or viscosity (friction between adjacent rings determined by viscosity)
 - viscous time scale (i.e., the radial drift time through the disk) t_{vis}:
 - * some typically assumed values give t_{vis} ~1e4 yr at r=100r_g
 - * faster AGN variability seen: other mechanisms affecting disk L needed

we write an expression for the viscous time scale, t_{vis} , which is the radial drift time through the disk, $r 2r^2$

$$t_{\rm vis} \simeq \frac{r}{v_r} \simeq \frac{2r^2}{3\nu}.$$
 (4.33)

The additional time scales that can provide some explanation to the optical–UV continuum variations are as follows:

The sound-crossing time scale:

$$t_s \simeq \frac{0.3M_8}{\sqrt{T/10^4}} \frac{r}{r_g} \,\mathrm{yr}$$
 (4.36)

The dynamical time scale:

("free fall")

$$t_{\rm dyn} \simeq 0.005 M_8 \left[\frac{r}{r_g}\right]^{2/3} \,\rm{yr} \tag{4.37}$$

The thermal time scale: ("fall with friction")

$$t_{\rm th} = t_{\rm dyn}/\alpha \tag{4.38}$$

The light-crossing time scale:

$$t_l \simeq 0.016 M_8 \frac{r}{r_g} \tag{4.39}$$

The light-crossing time scale is relevant to the case of an irradiated disk, which is discussed later. The other time scales are important in various cases involving instabilities in the disk.







Equations Mass conservation: $\dot{M} = 4\pi r H \rho v_r$ (P. gradient centrifugal gava. force Momentum: $\frac{1}{\rho} \frac{dP}{dr} - (\Omega^2 - \Omega_k^2)r + v_r \frac{dv_r}{dr} = 0$ Angular momentum: $\dot{M}(l - l_0) = 4\pi r^2 H\alpha P$ (2rd thermaldynamics law: TdS=dQ heat change viscous heating radiation Energy equation: $H\rho v_r T \frac{dS}{dr} = H\alpha Pr \frac{d\Omega}{dr} - F^-$ Here the vertical radiation flux is: $\frac{c}{k\rho}\frac{aT^4}{3H}$



Overview of the thin disk model

- Cool: ~10⁶ K → Geometrically thin & Keplerian rotation
- Slow radial velocity
- "Optically thick":
- Spectrum: black body spectrum
- Radiative efficiency is high, ~0.1



Momentum: $\frac{1}{\rho} \frac{d\rho}{dr}$ $-(\Omega^2 - \Omega_k^2)r + v_r$





Radiation We should have: $\sigma T^4(R) = D(R)$ [Compare with: $\frac{4\sigma}{3\pi}T_c^4 = D(R)$] (T: T at disk surface) $T(R) = \left\{ \frac{3GM\dot{M}}{8\pi R^3\sigma} \left[1 - \left(\frac{R_*}{R}\right)^{1/2} \right] \right\}^{1/4}$ Thus:

Emitted spectrum:

$$I_{\nu} = B_{\nu}[T(R)] = \frac{2h\nu^3}{c^2(e^{h\nu/kT(R)} - 1)} (\text{erg s}^{-1} \text{ cm}^{-2} \text{Hz}^{-1} \text{ sr}^{-1}$$

Integrate over radius,

$$F_{\nu} = \frac{4\pi h \cos i \,\nu^3}{c^2 D^2} \int_{R_*}^{R_{\text{out}}} \frac{R \,\mathrm{d}R}{e^{h\nu/kT(R)} - 1}$$







Note that within a radius, the main opacity mechanism is no longer Kramers' opacity, but electron scattering. Since it is no longer involves the microscopic inverse of the processes emitting the radiation (free-free and bound-free) the emergent radiation need not be precisely blackbody, even for quite large optical depth.

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Figure 4.3. A schematic of a combined disk-corona spectrum. The maximum temperature of the geometrically thin, optically thick accretion disk is $T_{\text{max}} = 10^5$ K, and its outer boundary temperature is determined by the conditions at the self-gravity radius. The disk is surrounded by an optically thin corona with $T_{\text{cor}} = 10^8$ K.



Figure 4.1. Definitions of basic disk parameters. The inner boundary of the disk is assumed to be the location of the ISCO. The outer boundary, r_{out} , is the self-gravity radius of the disk beyond which it breaks into self-gravitating blobs (courtesy of K. Sharon).

- r_{ISCO} (r_{ms}) provides a good approximation for r_{in} and its exact value depends on BH spin as mentioned before
- r_{out} is more difficult to define and is a function of the pressure and gravity at large distances
 - fate of outward-going angular momentum
 - * result in expansion of the outer parts of the disk
 - * some of this momentum may be transferred to gas and stars in regions far away from the BH
 - * the inner torus in AGNs may be influenced by this process

- Assumption that all released grav. energy can be radiated locally as a perfect blackbody must break down at some point:
 - e.g., the disk density may be too low to radiate away all locally released energy on local dynamical time
 - * local T increases and the assumption of a thin, gas-pressure-dominated disk no longer holds, resulting in radiation-inefficient flows
- Self-gravity becomes important (i.e., >BH gravity) far enough from BH:
 the disk breaks into small fragments at corresponding radii (i.e., r_{out})
- r_{in}, H(r), and r_{out} completely specify the thin-disk geometry:
 - typical disk mass ~3e5 Msun for M_{BH} =1e8 Msun
 - * typical time for such an entire disk to be accreted ~1e6 yr (efficiency~0.1, $L/L_{Edd}=0.1$) \rightarrow "accretion episode"
 - * need several hundreds accretion episodes lasting about 1e6 yr each to double the mass of such a BH (though real situation being more complex)
 - * important implications regarding growth times and modes of SMBHs Viewing angle dependences need to be considered when, e.g., attempting to derive total disk L from a single line-of-sight SED measurement (anisotropic disk emission)

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Article Published: 05 October 2023

A universal average spectral energy distribution for quasars from the optical to the extreme ultraviolet

Zhen-Yi Cai 🗠 & Jun-Xian Wang 🗠

Nature Astronomy (2023) Cite this article

Quasars feature gas swirling towards a supermassive black hole inhabiting a galactic centre. The disk accretion produces enormous amounts of radiation from optical to ultraviolet (UV) wavelengths. Extreme UV (EUV) emission, stemming from the energetic innermost disk regions, has critical implications for the production of broad emission lines in quasars, the origin of the correlation between linewidth and luminosity (or the Baldwin effect) and cosmic reionization. Spectroscopic and photometric analyses have claimed that brighter quasars have on average redder EUV spectral energy distributions (SEDs), which may, however, have been affected by a severe EUV detection incompleteness bias. Here, after controlling for this bias, we reveal a luminosity-independent universal average SED down to a rest frame of ~500 Å for redshift $z \approx 2$ quasars over nearly two orders of magnitude in luminosity, contrary to the standard thin disk prediction and the Baldwin effect, which persists even after controlling for the bias. Furthermore, we show that the intrinsic bias-free mean SED is redder in the EUV than previous mean quasar composite spectra, while the intrinsic bias-free median SED is even redder and is unexpectedly consistent with the simply truncated wind model prediction, suggesting prevalent winds in quasars and altered black hole growth. A microscopic atomic origin is probably responsible for both the universality and redness of the average SED.

AGN Accretion Disk Sizes

Winds can 'blow up' AGN accretion disc sizes

Mass outflows from accretion disks

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Stellar Black Holes Can "Stretch" Supermassive Black Hole Accretion Disks

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⁶ School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People's Republic of China Received 2024 February 7; revised 2024 April 5; accepted 2024 April 8; published 2024 April 24

Abstract

Stellar black holes (sBHs) are widely believed to exist in the accretion disks of active galactic nuclei (AGNs). Previous studies often focus on the transient emission produced by embedded sBHs. Here, we explore the possible observational consequences of an AGN accretion disk that contains a population of accreting sBHs. Embedded accreting sBHs change the effective temperature distribution of the AGN accretion disk by heating gas in the outer regions. Two possible observational consequences are presented. First, the spectral energy distribution has a turnover feature at ~4700 Å when the supermassive black hole mass is ~10⁸ M_{\odot} , which can help explain the observed shallow spectral shape at wavelengths >5000 Å for the Sloan Digital Sky Survey quasar composite spectrum. Second, the half-light radius of a given relatively long wavelength is significantly larger than for an AGN disk without sBHs, which can be tested by microlensing observations. With appropriate sBH distributions, the model can be reconciled with quasar microlensing disk sizes. We propose that the half-light radius–wavelength relation can be utilized to investigate the distributions of embedded sBHs in AGN accretion disks.



4.2 Real AGN disks

- Real AGN disks could be quite diff. from the simple standard thin ADs:
 - strong magnetic fields:
 - * affect physics and structure of the systems
 - * provide an important source of viscosity and may drive massive winds from disk surface
 - very hot coronae (>1e7 K):
 - * give rise to strong X-ray radiation that hits disk surface and changes local energy balance
 - disk-corona models: used extensively but details still not well understood



Figure 4.4. Complex magnetic disks may include a nonuniform geometry like the one shown schematically in this diagram. Winds and cool blobs can flow from the surface of the disk along the magnetic field lines. Such gas is exposed to the central radiation field at some height above the disk surface and can be driven in the radial direction by radiation pressure force (courtesy of K. Sharon).



4.2.1 Comptonization and the disk corona

- More realistic calculations of disk atmospheres include several processes that affect the emergent spectrum:
 - consider T gradient across disk and T increase in atmosphere
 - * T increase + large Compton depth lead to Comptonization of softeremitted photons and a considerable hardening of emitted spectrum (fig.)
 - hot, dilute gas/corona around thin ADs:
 - * needed to explain AGN X-ray radiation
 - * where soft disk-emitted photons are IC upscattered to X-rays
 - * conditions for hot corona formation still unknown
 - one possibility: large vertical density gradient → some accretion proceeds via lower-density, outer layers of disk → large energy dissipation and sharp T rise → expansion of outer layers and creation of hot corona
 - * even <1% of total accretion power released in corona \rightarrow T~1e8K
 - * such coronae radiate through free-free processes, dominating hard
 X-ray emission
 - * explain X-ray obs. (E index~1, i.e., Gamma~2) of many AGNs, but not all



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Figure 4.5. Calculated spectra of three accretion disks around BHs with $M_{\rm BH} = 10^6$, 10^7 , and $10^8 M_{\odot}$, all with $L/L_{\rm Edd} = 0.3$. The viewing angle of the disk is 60 degrees. The dotted lines show the much softer simple spectra obtained by assuming a combination of blackbodies without Comptonization (from Hubeny et al., 2001, reproduced by permission of the AAS).

Comptonization: hardening, but still not enough --> corona





variability: corona size << disk size

Figure 4.6. Two schematic disk-corona structures showing possible locations of the corona and the scattering geometry of the disk-produced and corona-produced photons.

Disc-corona model

Motivation

- To explain X-ray radiation
 Analogy with solar corona
 Formation mechanism of corona
 - Emergence of magnetic field from disk to corona
 - Magnetic reconnection heating (mag. E → thermal E, heating)
- MHD simulation to Corona:
 - Magnetically supported
 - High temperature



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X-ray Image of the Sun from Yokoh





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X-ray Emission from Active Galactic Nuclei

Nearly universal from luminous AGNs. From immediate vicinity of black hole.

Compton reflection or Fe Ka emission

X-ray

Solar Coronal Loops Seen in EUV with TRACE X-ray

UV

Compton up-scattering of photons by ~ 10⁹ K accretion-disk "corona"

Tr'Ehnl & Brandt (2017)

UV to X-ray image





4.2.2 Irradiated disks

- External radiation sources can illuminate the disk and change the local energy balance
- Important examples are illumination by an X-ray-emitting corona and the irradiation of the outer areas of a flaring disk by its inner part
- Calculation of the spectrum of irradiated disks:
 - complicated due to unknown geometry and the combination of external sources of energy and locally dissipated energy
 - the simplest case: external point source of radiation is located along BH rotational axis at a height H*
 - * when H_{*}>>H(r), have the same SED as the standard thin AD (some part shows disk SED with L_ν ∝ ν^{1/3}) under numerous assumptions
 * when H_{*}<<H(r), reprocessing is important at the outskirt of the system;
 - can produce an SED with a typically observed slope in opt.-UV spectrum

- Most important cases of irradiated AGN disks: illumination of optically emitting ADs by an external X-ray source such as a disk corona
 - alter significantly disk structure, local level of ionization, local T, and consequently, local emitted spectrum
 - * hard corona photons can escape or be absorbed by cool AD
 - * soft disk photons can be absorbed by corona or escape freely



Figure 4.7. Various models illustrating the spectra of X-ray-illuminated accretion disks under different conditions (Rozanska and Madej, 2008; reproduced by permission of John Wiley & Sons Ltd.).



Figure 1: Illustration of our corona-driven temperature-fluctuation model. The accretion disc (gray) and the corona (light blue) are tightly coupled by the magnetic fields (orange curves). Note that the disc might extend to the innermost stable radius; these inner regions have negligible contribution to the UV/optical variability discussed here. MHD flares in the corona can affect MHD turbulence and alter the heating rate in the accretion disc. As a result, the disc temperature fluctuates in response to the variable heating rate. The temperature fluctuations can be determined by solving the equation for thermal-energy conservation.

(Sun, Xue et al. 2020)

- Nomenclature adopted in the field of X-ray astronomy:
 - reflection: radiation whose origin is outside the disk, being either scattered or else absorbed and reemitted by the gas in the disk

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- disk emission: radiation from the disk material itself, with the energy source being the external radiation field, but the emission frequency depends on the specific atomic processes
 - * the absorption and emission frequencies can be very different
 - * X-ray fluorescence lines belong to this category

4.3 Slim and thick accretion disks

- Larger accretion rates can result in large optical depths and inefficient emission since the accretion (inflow) timescale can be shorter than the time it takes for the radiation to diffuse to the disk surface
 - photons created in radiation-pressure-dominated regions of such disks are trapped in the accretion flow and advected onto the BH

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- higher T leads to slim or thick ADs
- low radiation efficiency with $\epsilon_r < \eta_r$

Some slim-disk models give the relation between total L and normalized accretion rate: $L = a(1 + b \ln \dot{m})M_{BH}$ (where $\dot{m} = \dot{M}/\dot{M}_{Edd}$)



One-dimensional Dynamics: energy advection

Recall energy eq: $H\rho v_r T \frac{dS}{dr} = H\alpha Pr \frac{d\Omega}{dr} - F^-$ When accretion rate is above Eddington, advection becomes dominant ("photon trapping" effect). This is because viscous heating increases faster than radiative cooling. Thus T is much higher and the disk is slim



Self-similar solution

Wang & Zhou 1999; Belodorodov 2003 (not accurate solutions)

$$P = \left(\frac{\xi f}{n}\right)^{1/2} \frac{\dot{M}\Omega_{\rm K}}{4\pi\alpha r} \propto \underline{r^{-5/2}},$$

$$\rho = \frac{\gamma_0^2}{4\pi\alpha} \left(\frac{\xi^3}{n^3 f}\right)^{1/2} \frac{\dot{M}}{\Omega_{\rm K} r^3} \propto \underline{r^{-3/2}}$$

$$v_r = \frac{n\alpha}{\xi\gamma_0} r\Omega_{\rm K} \propto \underline{r^{-1/2}},$$

$$\frac{H}{r} = \frac{1}{\gamma_0} \left(\frac{nf}{\xi}\right)^{1/2} = \text{constant},$$

 $\Omega = \frac{\Omega_{\rm K}}{\gamma_0} \propto \underline{r^{-3/2}},$

$$c_s = \left(\frac{nf}{\xi}\right)^{1/2} \frac{r\Omega_{\rm K}}{\gamma_0} \propto \underline{r^{-1/2}},$$

Strong advection assumption $H\rho v_r T \frac{dS}{dr} = H\alpha Pr \frac{d\Omega}{dr} - F^2$



Global solution

(solve diff. equ. for accurate solutions)

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Three boundary conditions to be satisfied
 Outer boundary condition (temperature, density, radial velocity); (starting status of accretion at outer radius)
 sonic point condition (singularity: dv/dr=0/0); r dΩ/dr
 inner boundary condition (horizon of the BH)
 Solving two-point boundary value problem: difficult



Slim disks: Radiation

Because of advection, we have

$$T_{\rm eff}^4 \propto \frac{T_{\rm c}^4}{\tau} \propto \frac{p}{\rho H} \propto r^{-2}$$

different from the thin disk.
Thus spectrum also changes
Radiative efficiency lower than thin disk

Luminosity: can be much higher than Eddington! (disk vs. spherical accretion)







Possible Applications

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Narrow line Seyfert 1 (Mineshige et al. 2000)
Ultraluminous X-ray sources (Watarai et al. 2001)
SS433

Some AGNs (very large mass, luminous, high-z quasars)



Super-Eddington Accreting Massive Black Holes as Long-Lived Cosmological Standards

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Super-Eddington accreting massive black holes (SEAMBHs) reach saturated luminosities above a certain accretion rate due to photon trapping and advection in slim accretion disks. We show that these SEAMBHs could provide a new tool for estimating cosmological distances if they are properly identified by hard x-ray observations, in particular by the slope of their 2–10 keV continuum. To verify this idea we obtained black hole mass estimates and x-ray data for a sample of 60 narrow line Seyfert 1 galaxies that we consider to be the most promising SEAMBH candidates. We demonstrate that the distances derived by the new method for the objects in the sample get closer to the standard luminosity distances as the hard x-ray continuum gets steeper. The results allow us to analyze the requirements for using the method in future samples of active black holes and to demonstrate that the expected uncertainty, given large enough samples, can make them into a useful, new cosmological ruler.

$$L_{\bullet} = \ell_0 (1 + a \ln \dot{m}_{15}) M_{\bullet},$$

(1)

where $\ell_0 \approx 5.29 \times 10^{38} \text{ erg s}^{-1} M_{\odot}^{-1}$, and $a \approx 0.476$ [7]. For reference, at $\dot{m} = 15$ the saturated luminosity is $\sim 4.20 L_{\text{Edd}}$. Thus, at a given black hole mass, SEAMBHs are radiating basically at a constant luminosity which, as shown below, can therefore be used to deduce cosmological distances.



- Spectra of thick ADs can differ substantially
- Such thick ADs:
 - may have narrow funnels, along BH rotational axis, and geometrically thick, optically thick structure
 - gas T along walls of funnel can be very high, resulting in a hard X-raydominated spectrum in the general direction of BH axis
 - * larger viewing angle spectrum is much softer, with most of radiation emitted in optical part of spectrum
 - * such disks may look very different for observers at diff. viewing angles
 gas surrounding such disks may also be exposed to different radiation fields in different directions, which would affect its T and level of ionization in a geometrically dependent fashion

4.4 Radiatively inefficient accretion flows

- Optically thick, geometrically thin ADs: cooling-dominated flows
 - cooling mostly due to high-E electrons with high radiative efficiency
 - * cooling efficiency in most cases ~ electron density squared
 - * SSD: high enough densities \rightarrow cooling very efficient (< inflow timescale)
- ADs with very low accretion rates:
 - much lower densities \rightarrow cooling timescale >= or >> inflow timescale
 - extremes cases of very low density:
 - * cooling very inefficient
 - * particles retain dissipated grav. energy for a long time
 - * T rises to virial T (1e12K/r) and advected into BH without releasing E
 - * called ADAFs: advection-dominated accretion flows
 - a more general term: radiatively inefficient accretion flows (RIAFs)
 - * ions and electrons can have very different T (T_ion >> T_e by ~2 orders)
 - low density \rightarrow less Coulomb collisions that share kinetic E
 - electrons are more efficient coolants

Additional RIAFs: ADIOS (advection-dominated inflow outflow solution) and CDAF (convection-dominated accretion flow)



truncated

disks

Figure 4.8. Two-temperature disks are similar to the standard optically thick, geometrically thin accretion disks far from the BH. Their very low accretion rate results in low densities and inefficient cooling in the inner parts. The gas in these regions cannot radiate away the released gravitation energy. It heats to very high temperatures, which results in a significant increase in the thickness of the disk. A large fraction of the released energy is advected to the center, and the mass-to-radiation conversion efficiency drops significantly.

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An energetic hot wind from the low-luminosity active galactic nucleus M81*

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For most of their lifetime, super-massive black holes (SMBHs) commonly found in galactic nuclei obtain mass from the ambient medium at a rate well below the Eddington limit¹, which is mediated by a radiatively inefficient, hot accretion flow². Both theory and numerical simulations predict that a strong wind must exist in such hot accretion flows³⁻⁶. The wind is of special interest not only because it is an indispensable ingredient of accretion but also, perhaps more importantly, because it is believed to play a crucial role. in the evolution of the host galaxy via the so-called kinetic mode active galactic nucleus feedback^{7,8}. Observational evidence for this wind, however, remains scarce and indirect⁹⁻¹². Here we report the detection of a hot outflow from the low-luminosity active galactic nucleus in M81, based on Chandra high-resolution X-ray spectroscopy. The outflow is evidenced by a pair of Fexxy Ly α lines redshifted and blueshifted at a bulk line-of-sight velocity of $\pm 2.8 \times 10^3$ km s⁻¹ and a high line ratio of FexxvI Ly α to Fexxv K α implying a plasma temperature of 1.3×10^8 K. This high-velocity, hot plasma cannot be produced by stellar activity or the accretion inflow onto the SMBH. Our magnetohydrodynamical simulations show that, instead, it is naturally explained by a wind from the hot accretion flow, propagating out to $\geq 10^6$ times the gravitational radius of the SMBH. The kinetic energy and momentum of this wind can significantly affect the evolution of the circumnuclear environment and beyond.



One-dimensional equations



Self-similar solution

Narayan & Yi 1994;1995; Yuan, Bu & Wu (2012)

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Assuming power-law scaling with radius for physical quantities:

$$\begin{split} v \simeq -1.1 \times 10^{10} \, \alpha r^{-1/2} & \mathrm{cm} \ \mathrm{s}^{-1}, \\ \Omega \simeq 2.9 \times 10^4 \ m^{-1} r^{-3/2} & \mathrm{s}, \\ c_s^2 \simeq 1.4 \times 10^{20} \ r^{-1} \ \mathrm{cm}^2 \ \mathrm{s}^{-2}, \\ n_e \simeq 6.3 \times 10^{19} \ \alpha^{-1} \ m^{-1} \dot{m} \ r^{-3/2} \ \mathrm{cm}^{-3}, \\ B \simeq 7.8 \times 10^8 \ \alpha^{-1/2} \ m^{-1/2} \dot{m}^{1/2} \ r^{-5/4} \ \mathrm{G}, \\ p \simeq 1.7 \times 10^{16} \ \alpha^{-1} \ m^{-1} \dot{m} \ r^{-5/2} \ \mathrm{g} \ \mathrm{cm}^{-1} \ \mathrm{s}^{-2} \\ q^+ \simeq 5.0 \times 10^{21} \ m^{-2} \dot{m} \ r^{-4} \ \mathrm{ergs} \ \mathrm{cm}^{-3} \ \mathrm{s}^{-1}, \\ \tau_{\mathrm{es}} \simeq 24 \ \alpha^{-1} \dot{m} \ r^{-1/2}, \end{split}$$



Main features

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- Large radial velocity:
- $v_r \sim \frac{\alpha c_s H}{P}$ C_s~(P/rou)^0.5 Sub-Keplerian rotation: pressure-gradient support • High temperature: $T \sim \frac{GMm_p}{6kR} \sim \frac{10^{12}}{r}$ (Virial) • Geometrically thick: $(H = \frac{c_s}{\Omega_k} \sim R)$ ~spherical Optically thin (because of large radial velocity) Two-temperature: $T_i \gg T_e$ coupling between ions and electrons not strong enough plasma collective behavior also too weak

Radiative efficiency is low when *M* is small

outflow

The energy equation of the accretion flow:

$$\rho \upsilon T \frac{ds}{dr} = q_{adv} = q^+ - q^-$$

For the standard thin disk, we have,

$$q^+ \approx q^- >> q_{adv}$$

For ADAFs, we have,

$$q^+ \approx q_{adv} >> q^-$$

physics:

- the density of the accretion flow is very low so: radiation timescale >> accretion timescale.
- So most of the viscously dissipated energy is stored in the accretion flow and advected in to the black hole rather than radiated away.

The critical accretion rate of ADAF

With the increasing of *M*, cooling increases faster than the viscous dissipation and advection
So there exists a critical accretion rate of ADAF, determined by

 $q^+ = q^- \rightarrow \dot{M}_{crit,ADAF} \sim \alpha^2 \dot{M}_{Edd}$

What will happen when $\dot{M} > \dot{M}_{crit,ADAF}$?





Global Solutions of hot accretion flow



Yuan 2001

α=0.3; M_{BH} = 10M.
 Accretion rates are: 0.05(solid; ADAF); 0.1 (dotted; critical ADAF); 0.3 (dashed; type-I LHAF) 0.5 (long-dashed; type-II LHAF)


Radiative processes

(optically thin, no longer BB)

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Synchrotron emission: relativistic electrons & B field (described by a parameter _e); (beta: gas pressure/B pressure) Maxwell distribution Self-absorption of synchrotron emission Bremsstrahlung radiation Comptonization seed photons are synchrotron & Brem. photons Misc: Gamma-ray emission by the decay of neutral pions created in proton-proton collisions







Sgr A* as an example: SSD vs. ADAF



Narayan, Yi & Mahadeven 1995, Nature



Total emission 37 Sgr A^{*} 36 Synchrotron emission (from thermal electrons) 35 og[vLv(erg s 34 33 35 35 synchrotron emission (from power-law electrons) Comptonization (from thermal electrons) 31 30 10 12 $log[v(Hz)]^{14}$ 18 20 8 Bremsstrahlung

more advanced ADAF models

- Stability analyses for hot ADs:
 - viscous stability: all hot ADs are viscously stable
 - convective stability:
 - * without B field, unstable, convective instability drives winds
 - * with B field, more realistic, stable, as MRI changes dynamics of hot ADs
 - thermal stability:
 - * stable for long-wavelength perturbations
 - * debates on short-wavelength perturbations: stable vs. unstable
 - * consequence of thermal instability:

When M < 0.2αM_{Edd}, no problem (growth timescale > accretion timescale)
 When M > 0.2αM_{Edd}, growth timescale < accretion timescale,
 Two-phase accretion flow! (cold dense clumps within hot dilute gas)





- Various complicated numerical simulations for hot ADs being carried out:
 HD & MHD simulations:
 - * mass accretion rate decreases inward
 - * radial profiles of physical quantities are described by a powerlaw, consistent with self-similar solutions
 - * viscosity~0.05-0.2, actually being quite diverse





now: GRRMHD!

- Various complicated numerical simulations for hot ADs being carried out:
 - GRMHD simulations: B field configuration and strength in three regions:
 - * jet: B strongest, quite ordered, large-scale poloidal B field
 - magnetic energy density > gas rest (mass) energy
 - * corona: no significant difference btw corona T and disk T (unlike SSD)
 - B strong; less ordered, turbulent, toroidal B field
 - magnetic pressure ~ gas pressure
 - * main disk body: B weak, very turbulent

- magnetic pressure ~ 0.1*gas pressure



- When RIAFs involve mass loss through winds/outflows:
 - a large fraction of grav. E of inflowing gas converted to kinetic E of wind
 - such wind can leave BH on a short timescale, and move through galactic ISM or perhaps even IGM in a cluster of galaxies, delivering much of its kinetic E to the surrounding gas
 - * sometimes this surrounding gas heated to emit X-rays, so can measure
 - L_X to estimate the kinetic E of the outflow
 - some well-documented cases: $dE_K/dt > L_{bol}$
- AGN modes: cold and hot modes --- another classification
 - radiative/AGN/QSO mode: radiation-dominated processes, high L/L_{Edd}
 - radio/jet/kinetic/maintenance mode:
 - most of the released E is kinetic E, low L/L_{Edd} , observations show that such flows often associated with powerful radio jets



Figure 4.9. Schematic of the two modes of accretion in AGNs. The radiation power, L_{bol} , and the kinetic energy power, dE_K/dt , are plotted against the normalized accretion rate, $\dot{m} = \dot{M}/M_{Edd}$. The transition from the radiative (AGN) mode to the kinetic energy (radio) mode is at $\dot{m} = \dot{m}_{cr}$, which, in this example, corresponds to $\dot{m} \approx 0.01$. The mass-to-radiation conversion efficiency ϵ_r (Equation 4.64) approaches at high accretion rates the radiation conversion efficiency η .



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- Brief summary:
 - Accretion rate: Slim>SSD>LHAF>ADAF (holds the key)
 - Temperature: ADAF~LHAF>>Slim>SSD (hot: virial T 1e12K/r; cold: 1e6-7 K)
 - Thickness: ADAF (like spherical)~LHAF>Slim>SSD
 - Surface density: Slim>SSD>LHAF>ADAF
 - Optical depth: Slim>SSD>LHAF>ADAF
 - Radiation efficiency: SSD>Slim>LHAF>ADAF



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The Accretion Flow in M87 is Really MAD

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Abstract

The supermassive black holes in most galaxies in the universe are powered by hot accretion flows. Both theoretical analysis and numerical simulations have indicated that, depending on the degree of magnetization, black hole hot accretion flow is divided into two modes, namely SANE (standard and normal evolution) and MAD (magnetically arrested disk). It has been an important question which mode the hot accretion flows in individual sources should belong to in reality, SANE or MAD. This issue has been investigated in some previous works but they all suffer from various uncertainties. By using the measured rotation measure (RM) values in the prototype low-luminosity active galactic nuclei in M87 at 2, 5, and 8 GHz along the jet at various distances from the black hole, combined with three-dimensional general relativity magnetohydrodynamical numerical simulations of SANE and MAD, we show in this paper that the RM values predicted by MAD are well consistent with observations, while the SANE model overestimates the RM by over two orders of magnitude and thus is ruled out.







"疯狂"的黑洞磁囚禁吸积盘

Science

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RESEARCH ARTICLE

BLACK HOLES

Observations of a black hole x-ray binary indicate formation of a magnetically arrested disk

Bei You¹*, Xinwu Cao²*, Zhen Yan³*, Jean-Marie Hameury⁴, Bozena Czerny⁵, Yue Wu^{1,6,7}, Tianyu Xia^{1,8,9}, Marek Sikora¹⁰, Shuang-Nan Zhang^{11,12} Pu Du¹¹, Piotr T. Zycki¹⁰

Accretion of material onto a black hole drags any magnetic fields present inwards, increasing their strength. Theory predicts that sufficiently strong magnetic fields can halt the accretion flow, producing a magnetically arrested disk (MAD). We analyzed archival multiwavelength observations of an outburst from the black hole x-ray binary MAXI J1820+070 in 2018. The radio and optical fluxes were delayed compared with the x-ray flux by about 8 and 17 days, respectively. We interpret this as evidence for the formation of a MAD. In this scenario, the magnetic field is amplified by an expanding corona, forming a MAD around the time of the radio peak. We propose that the optical delay is due to thermal viscous instability in the outer disk.

- 武汉大学的研究人员领衔的国际研究团队
 - 利用"慧眼"卫星等数据,发现一个黑洞X射线双星在爆发过程中, 射电和光学辐射相对于硬X射线辐射存在罕见的长时标(~8天和17天)时延,首次揭示了黑洞吸积流中磁场输运过程及黑洞磁囚禁盘的完整形成过程,给出磁囚禁盘模型的最直接观测证据
- 成果于2023年9月1日发表于国际
 科学期刊《科学》



Neutrino-dominated accretion flows as the central engine of gamma-ray bursts

Tong Liu^{a,b}, Wei-Min Gu^a, Bing Zhang^{b,c,d}

Abstract

Neutrino-dominated accretion flows (NDAFs) around rotating stellar-mass black holes (BHs) are plausible candidates for the central engines of gamma-ray bursts (GRBs). NDAFs are hyperaccretion disks with accretion rates in the range of around 0.001-10 M_{\odot} s⁻¹, which have high density and temperature and therefore are extremely optically thick and geometrically slim or even thick. We review the theoretical progresses in studying the properties of NDAFs as well as their applications to the GRB phenomenology. The topics include: the steady radial and vertical structure of NDAFs and the implications for calculating neutrino luminosity and annihilation luminosity, jet power due to neutrino-antineutrino annihilation and Blandford-Znajek mechanism and their dependences on parameters such as BH mass, spin, and accretion rate, time evolution of NDAFs, effect of magnetic fields, applications of NDAF theories to the GRB phenomenology such as lightcurve variability, extended emission, X-ray flares, kilonovae, etc., as well as probing NDAFs using multi-messenger signals such as MeV neutrinos and gravitational waves.



4.5. Further reading

Standard α -disks: The seminal paper on the physics of α -disks is Shakura and Sunyaev (1973). Optically thick, geometrically thin disks are discussed in numerous books and articles. The treatment adopted here is similar to the one discussed in greater detail in Frank et al. (1985). A useful comprehensive review is given in Blaes (2007). State-of-the-art calculations of thin-disk spectra can be found in Blaes et al. (2001), Hubeny et al. (2001), Davis et al. (2007), and references therein. Davis and Laor (2011) describe the method to estimate a BH accretion rate regardless of its spin.

Comptonization and disk corona: See Reynolds and Nowak (2003), and references therein.

X-ray emission from irradiated disks: For the general geometry, see Blaes (2007). For X-ray features, see Reynolds and Nowak (2003), Ross and Fabian (2005), Dovčiak et al. (2004), Rozanska and Madej (2008), Cao (2009), and references therein.

Slim and thick accretion disks: There are relatively few calculations of such disks and their spectra; see, for example, Madau (1988), Kawaguchi et al. (2001), and Wang and Netzer (2003). For super-Eddington accretion, and the connection to NLS1s, see Collin and Kawaguchi (2004), and references therein.

RIAFs: The physics of various advection-dominated flows is discussed in numerous papers, including many that are not related to accretion onto massive BHs. Useful comprehensive descriptions with many additional references are Narayan and McClintock (2008) and Cao (2010).

Find newer further reading by yourself!