The role of accretion disk instabilities in driving AGN X-ray variability

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Introduction

At the centre of every massive galaxy, there is thought to reside a super-massive black hole (SMBH; [1]). As material falls into the centre of the galaxy, it forms a co-rotating accretion disk which fuels the SMBH, precipitating the formation of a so-called Active Galactic Nucleus (AGN). AGN are nature's most powerful sustained engines, and the energy they liberate can exceed the binding energy of the host galaxy by a factor of ~ 80, meaning that the role of the SMBH in galaxy evolution may be profound if even a small fraction of this energy is distributed through the bulge and disk. As such, they are crucial to our understanding of the Universe through cosmic time [2].

In order for material to move inwards and accrete it must transfer its angular momentum outwards, disrupting the disk. As such, the accretion disk is subject to a host of instabilities, and it is these instabilities which subsequently drive turbulent motions. These turbulent motions cause turbulent accretion, which is observed as variability in the AGN lightcurve. Such chaotic behaviours are consistently difficult to model as they occur over distinct length scales: thermal instabilities reign king in the inner radiation-dominated regions of the disk, whilst gravitational instabilities impact the disk in the outermost regions. Low resolution simulations – both temporally and spatially – may act to dampen the effects of these instabilities beyond what is realistically expected, but high-resolution simulations across the entirety of the disk are computationally intractable.

It is this compromise between the computational load and the complexity of the physics that leads to the wealth of opportunity in this field, which promises to lead to great advances in our understanding as our technology improves. Beyond its applications to the SMBH accretion disk, these studies interface with fundamental open problems in fluid dynamics, such as the nature of MHD turbulence at very high Reynolds numbers and for magnetic Prandtl numbers away from unity, demonstrating the wider applicability of this work.

X-ray variability

More AGN are discovered in the $2-10$ keV band than at any other energy, making X-ray emission a defining characteristic of these objects [3]. This X-ray emission also varies faster than that at any other wavelength, strongly suggesting that it originates near to the central engine and within the accretion disk. If X-rays were produced at higher radii than the accretion disk then the timescale of variability would be significantly longer [4]. AGN X-ray spectra can be broadly categorised as hard or soft, representing the high and low energy portions, respectively, of the X-ray regime. Sources are additionally categorised by their X-ray luminosity, with high luminosity sources often corresponding to soft X-ray states (the soft-high state, e.g. Seyfert galaxies and quasars; [5]), and low luminosity AGN being associated with hard X-rays (the hard-low state, e.g LLAGN; [6]). It is important to note that these two grouping are not distinct, however, and a number of sources exhibit intermediate characteristics such as a high luminosity and hard X-ray spectrum.

The difference between these states is thought to be caused by a transition within the disk from a geometrically-thick, radiatively-inefficient inner region to a geometrically-thin, radiatively-efficient outer region [7], which are additionally correlated with hot and cold modes of accretion and differing degrees of disk truncation [8]. In a radiatively-inefficient disk, the gas thermal energy cannot be efficiently radiated away and so the flow becomes hot and inflates an optically thin, geometrically thick disk. Within this disk, the hot accretion flow may be advection or convection dominated (ADAF [9] or CDAF [10] respectively). Alternatively, thermal energy can be easily liberated from a radiatively-efficient disk, leading to an optically thick, geometrically thin disk characterised by cold gas flows (e.g. the classical α-disk of Shakura & Sunyaev 1973; [11], [12]). Whilst cold flows in thin disks and hot flows in thick disks have been independently modelled, the combination of these disk types is more difficult to model due to sharp changes in physical properties across the thick-thin boundary (i.e. the point of disk truncation), and has a strong dependence on the magnetohydrodynamic (MHD) properties within the disk.

As the low-hard state is often associated with the presence of radio jets, the duty cycles of these jets may additionally lead to variation in the X-ray spectra. X-ray transient behaviour and state changes may also occur when the black hole accretes material within a binary system, as in stellar-mass black hole binaries (BHBs), although direct comparisons are fraught with uncertainty as the timescale over which AGN change state is too long for direct observation [5].

Accretion disk instabilities

The viscosity of the material in the accretion disk has been long-held to be an important property [11] and may be measured by the Reynolds number Re, the ratio of inertial forces to viscous forces within a fluid. Angular momentum is then transported by the stress this causes, with Reynolds stress $R_{R\phi} = \rho v_R \delta v_\phi$ for density ρ and radial and azimuthal flow velocities v_R and v_ϕ, respectively [13]. However, viscous disturbances propagate to a distance l through the disk on timescales of the order of l^2/v_k for kinematic viscosity v_k [14], which is far too slow to account for the observed time variability.

More accurate models of an accretion disk require the inclusion of magnetic fields, represented by the associated Maxwell stress $M_{R\phi} = -B_R B_\phi / 4\pi$ [13] for radial and azimuthal field strengths of B_R and B_ϕ, respectively. These magnetic stresses lead to a dominant form of instability in accretion disks: the so-called *magnetorotational instability* (MRI; [15]). Models including the MRI can be investigated numerically on reasonable grid resolutions whilst also capturing the rapid changes in turbulence expected within the accretion disk, making it a focus for current numerical simulations [15].

Additional effects on turbulence may be caused by thermal and gravitational instabilities within the disk. Hot accretion flows in particular may be vulnerable to thermal instabilities, however a globally non-viable solution can be avoided if the gas accretes faster than these instabilities can grow, which is expected to be the case for ADAFs for most perturbation wavelengths [6]. For thin disks, if the cooling time of the gas is much shorter than the disk rotational period, it may fragment at intermediate-to-large radii and become locally gravitationally unstable [16]. However, in general, the accretion disks of luminous AGN are MHD stable at large radii, and is only MHD and gravitationally unstable at intermediate ranges. The radii at which these transitions occur depend both on the local temperature and the accretion rate of the disk, and for LLAGNs with accretion rates $\dot{M} \lesssim 10^{-3} M_\odot \text{ yr}^{-1}$, sections of the disk may be locally gravitationally stable, globally gravitationally stable, and MHD stable, leading to no or low accretion and a build-up of mass [17], which may then lead to observed X-ray transient behaviour.

Method

My project will focus on generating self-consistent models for black hole accretion disks to investigate instabilities and to assess their importance for driving observed AGN behaviour. It will build upon the work of Hogg & Reynolds (2018) [5], in which the authors simulate a 3-dimensional, semi-global, MHD accretion disk with thermal instabilities modelled through a bistable cooling function; however, I will improve upon this work by including models of more complex radiative physics as given by the adaptive mesh refinement (AMR) code ATHENA++ [18]. By working at large radii where disk truncation is expected to occur, general relativistic (GR) effects can be ignored, reducing the computational load of the work.

Simulations of these models will likely be carried out on the high-performance supercomputer *Peta 4*, which is hosted by the Cambridge Service for Data Driven Discovery (CSD3), led by the University of Cambridge. In utilising the computing power of one of the fastest supercomputers in the United Kingdom, this project aims to unite the new advances in both MHD disk simulations and models of radiative transfer. Using our findings from these simulations, we will consequently seek to construct semi-analytic models of reduced complexity which can be compared to AGN X-ray variability as observed by the Advanced Telescope for High Energy Astrophysics (*Athena*; [19]), planned for launch in 2028. The implementation of multiple state-of-the-art theoretical models, combined with national infrastructure and large-scale survey data, creates the potential for significant national and international collaborations, helping to further the research profile of the University of Cambridge.

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