Some low luminosity hosts of active galactic nuclei (AGN) are known to boast short variability timescales, allowing practical quantitative analysis of the outer accretion region (a region at the very center of the AGN in which matter falls inward toward a black hole, liberating large amounts of energy). Specifically, observationally deriving wavelength-specific time lags via line reverberation mapping gives us clues as to the structure of the accretion region and allows us to constrain the mass of the central black hole (BH). Regardless, the processes driving brightness variability in AGN are difficult to describe quantitatively, and in the case of some low luminosity AGN (LLAGN), we find that rapid, dynamic physical processes must occur within the accretion region so as to drive the high amplitude, high frequency variability that is observed. Here we present a qualitative survey of several theoretical accretion region variability models, highlighted by experimental data and an observationally supported discussion of the quality of such models. In doing so, we hope to motivate a coupling between the known physical properties of LLAGN and the unification paradigm for generalized AGN, so that we may begin to quantitatively strengthen accretion region models for both.

The widely accepted unification paradigm of active galactic nuclei holds that the ultra-luminous cores of AGN host galaxies are powered by accretion onto a central supermassive black hole. In many cases, AGN exhibit intrinsic, sometimes highly aperiodic variability in continuum profiles, a property suggestive of a kinematically hot, dynamic accretion region. By “continuum variability”, we mean variations in AGN brightness over a period of time, (somewhat analogous to a flickering light bulb). Such variability is seen as the emission spectrum (continuum) of an AGN, especially when comparing two spectra of one object taken at different times (see Fig. 2 for a dramatic example). Unfortunately, studies of variability mechanisms in these active regions must be conducted indirectly, as the size scales for inner accretion environments are on the order of a few parsecs, mapping only to microarcsecond scales on the sky for AGN at high redshift (Z > 0.5, conservatively), where the majority are found (this makes sense, because AGN are widely regarded as young systems, so we expect them to be farther away). Despite these difficulties, spectral analysis yields several predominant, nearly universal features of the AGN accretion region, which while supportive of the unification paradigm, are not well understood.

In this paper we will discuss several predominant, theoretically generated models for driving AGN variability, which can often be quite rapid and dramatic. The majority of these models are constrained to the accretion region, extending to a radius of only a parsec, and so we must first discuss the structure of the AGN in terms of observationally derived findings, as well as the theoretical timescales of the region. We do this because, if AGN are observed to vary by orders of magnitude so rapidly (which they are, sometimes on the order of several days), then constraining physically based timescales in this region will provide a test for any theoretical model we present. Any violation of these timescales will suggest that the model being discussed may be physically unreasonable.

We then focus our discussion on the scientific value of extreme cases of AGN, specifically NGC 4395, the nearest and lowest luminosity Seyfert (AGN host galaxy) known. More importantly, NGC 4395 has been observed to vary in brightness by nearly 25% in only four days. Such properties make studies of this object not only practical, but rewarding as well. For, while extreme in both luminosity and variance, NGC 4395 still has a place within the unified model of AGN, and so it is reasonable to assume that its variability is powered by the same processes present in more common, less dramatic specimens. In exploring the properties of extreme objects, we learn more about the generalized model of AGN accretion regions, and the theory becomes all the more robust.

Observations and Theory

In this section, we will discuss in detail the unified model for AGN accretion region structure. Emission line studies reveal that, in many cases, AGN spectra reveal a heavy optical/ultraviolet (UV) component with a double-peaked Balmer line profile, suggesting a gaseous, optically thick Keplerian disk is present in the region surrounding the black hole. Also observed is a pseudo-spherically distributed, hard X-Ray emitting component overlapping the inner edge of the cool, UV disk. These components will be discussed individually in Narrow- and Broad-Line Region Properties sections, respectively, followed by a brief description on current research in coupling the two with a continuous, self consistent model, namely by
Narrow-Line Region Properties

Broad band spectra of Seyfert cores reveal heavy AGN contribution to short-optical/UV wavelengths. Because of its nearly universal appearance in AGN spectral energy distributions (SEDs), it has been coined the "big blue bump" (BBB), a spectral feature which can extend into soft X-Rays in some Seyfert specimens. Also notable is the presence of a Balmer edge, seen near ~4000 angstroms in Fig. 1. This strongly suggests that the continuum source is made up of a gaseous, optically thick material. Furthermore, there is strong, albeit circumstantial evidence that this gaseous component roughly assumes the form of a Keplerian disk. This argument is supported by the existence of a small sub-class of AGN whose spectra contain double-peaked emission lines, a feature produced by a spatially thin, optically thick gaseous disk.\(^{2}\) (As stellar matter spirals inward towards a BH, it settles into a thin accretion disk so as to conserve angular momentum). Also evidence of disk-like structure is the fact that similar features appear in soft X-Ray novae.\(^{3}\) The most dramatic evidence for an accretion disk, however, is the presence of polar jets in AGN, always perpendicular to the plane of the galactic disk. These jets must be produced by gravitational scattering off the black hole, and their 'polar' structure suggests that they originate from an axisymmetric accretion disk, also lying within the galactic plane. These jets are the mechanisms by which excess angular momentum from the accretion disk is carried away from the black hole, (because the angular velocity of the BH cannot exceed the speed of light). The BBB region of AGN spectra is produced by the inner edge of the disk (which makes sense, as we expect relatively hot material to be radiating in the UV). As thermal excitement increases as an inverse function of radius from the BH, we expect gradual cooling of the accretion disk at further distances, so much so that infrared (IR) emission becomes prominent at the disk's outer edge. IR observations of AGN reveal this to be the case. Furthermore, constraints on the radius of the accretion disk can be derived via line reverberation mapping, in which arrival time lags observed in UV/IR comparisons are coupled with reprocessing timescales for optical/UV light absorbed at the inner edge of the accretion disk and thermally reradiated in the infrared at the opposite end. For a more detailed description of this numerical process, we refer you to Brad Peterson, namely Peterson & Horne (2004). The outer accretion disk and a surrounding molecular halo make up the narrow-line region (NLR) of the AGN, named so for the low velocity dispersions of its constituent particles (e.g. the effect of Doppler broadening in emission lines from this region is very small). This is in contrast to the counterpart of the NLR, the broad-line region (BLR), which will be discussed in the following section.

Accretion Region Dynamics

Here we briefly discuss some of the details related to the processes by which mass accretes onto the BH from the gaseous/
dusty torus, in a manner consistent with the work of Czerny et al. (2004). While not directly related to our discussion, the most observationally consistent model of AGN variability (discussed in Self-Organized Criticality section) depends directly on accretion disk dynamics, so a qualitative review of some of the physics of mass flow in this region will be helpful.

Especially near the BBB, thermal excitement produced by proximity to the black hole leads to ionization of some of the constituent particles of the accretion disk. A non-negligible ionization in the disk implies that any truly accurate model of AGN variability must include, or at least acknowledge, contribution of magnetohydrodynamics (MHD) to the overall physics of the region, as it turns out that MHD (specifically, magnetic field interactions brought about by ionized plasma near the inner edge of the disk) can play a very dramatic role in both the structure and kinematics of an accretion disk.

The unification paradigm of AGN includes a minor stipulation for MHD-produced effects. Much like the work done by Czerny et al. (2004), it allows for magnetic flares (loops), running along the radius of the disk, perpendicularly to the plane. At some transition radius, usually at several Schwarzschild radii, these field lines open and give rise to the BLR corona. Furthermore, matter evaporation in the disk is prevented by magnetic field confinement, especially at long distances from this transition radius. As such, the toroidal structure of the cold disk is magnetically self-reinforced. Near the transition radius, however, open field lines produce the spheroidal (spherical?) distribution of the ionized gas stripped from the edge of the accretion disk. (This is, of course, an oversimplified generalization of a complicated system, so we refer you to Czerny et al. (2004) for a more detailed description).

To close this section, let us briefly review some of the quantitative timescales intrinsic in the NLR and BLR.

Assuming generally Keplerian accretion flow, we know from Czerny et al. (2004) that the dynamical timescale of gas and dust within the disk will be given by

\[ t_{\text{dyn}} = \sqrt{\frac{GM}{r^3}} \]

where \( M = M_{\text{BH}} \) and \( r = r_{\text{BH}} \). This is the Keplerian frequency, equivalent to the orbital period of an object in orbit of the BH. From this, we may obtain a generalized timescale for the radial propagation of sonic fronts with respect to the BH, namely

\[ t_{\text{sound}} = t_{\text{dyn}} \left( \frac{r}{h_{\text{disk}}} \right) \]

where \( h_{\text{disk}} \) is the thickness of the accretion disk through which the front is passing.

Thermal timescales are important as well, especially given our reliance on AGN spectra. Quantitative understandings of disk temperatures require familiarity with the thermal timescale of the region, which we define as

\[ t_{\text{therm}} = \alpha^{-1} t_{\text{dyn}} \]

where \( \alpha \) is related to the viscosity in the disk and is \( \sim 0.1 \). The viscous timescale, then, strongly resembles (3) and (4), in that it is directly proportional to another timescale, specifically

\[ t_{\text{visc}} = t_{\text{therm}} \left( \frac{r}{h_{\text{disk}}} \right)^2 \]

Despite our brevity in this section, the timescales surveyed above play a vitally important role in testing theoretically generated variability models, some of which are described in the following section.

**AGN Variability Models**

The majority of AGN exhibit at least some degree of wavelength-specific flux variability, particularly in the optical/UV (See Figs. 2 and 3). By this virtue alone, it becomes apparent that a solid, well supported variability model would eventually become a part of the AGN unification paradigm, making our understanding of AGN structure and dynamics all the more complete.

Furthermore, if extreme cases of AGN nonetheless remain consistent with this paradigm, then the extreme variability mechanisms present in these objects must also be consistent with the lower-energy processes in more common AGN. SDSS J124602.54+011318.8, for example, has such high variability that it was once mistaken for a gamma ray burst afterglow. Regardless, it must still be explained by a model capable of
explaining less dramatic examples. In light of this, we now present a discussion of several such models for AGN variability, and briefly comment on the physical rationality behind the theories.

**Self-Organized Criticality**

One of the most promising AGN variability models in the field today is based upon the principle of self-organized criticality (SOC), an idea so elegant in its universality and powerful in its simplicity that it can explain something as complex as AGN luminosity fluctuations, as well as something as simple as the shape of a pile of sand.7

Quantitatively, AGN power spectral densities (PSDs) mimic declines well modeled by power laws in bluer ends of the spectrum. Specifically, these declines follow the trend

\[
\frac{1}{f^\beta}
\]

where \( f \) is frequency and \( \beta \) is a constant of order unity, between -1 and -2. Amazingly, this type of variation is widespread in nature, and can be observed in Earth’s weather patterns, the behavior of flowing water, and even Mozart’s orchestral compositions.7 Unsurprisingly, then, this power law fluctuation also appears in X-Ray binary spectra, such that they share two properties in common with AGN (the other being the BBB). However, it is known that X-Ray binaries and AGN vary in different ways, so similarities between the two end here. X-Ray binary variability arises from abrupt, dramatic events called flares (or “shots”). AGN lightcurves, on the other hand, vary with smooth, continuous dips and inclines. (Note the near symmetry of the two spectra in the top panel of Fig. 2). Explaining this seemingly contradictory observation is a valuable beginning to modeling AGN variability mechanisms.

It turns out that SOC is inherently connected with \( 1/f^\beta \) variation, so much so that an avalanche of snow on a mountain will liberate energy with \( 1/f^\beta \) fluctuations, once a certain critical slope is met, (dependent on the physical properties of the snow).

In a qualitative sense, describing an AGN accretion disk as snow on a mountainside appears to be a physically reasonable comparison. Both disk and snow are under the influence of a gravitational potential – whether that potential is generated by a black hole or the gravitational pull of the Earth is inconsequential. Both are governed by SOC, in that they spontaneously reorganize their structure to attain progressively lower energy and higher entropy.

In this model, then, AGN variability is produced by a series of self-reorganizations (“avalanches”) within the accretion disk. The amount of matter accreting on the black hole is thus time dependent, and increases for a short period of time after a disk reorganization. Because this model is based on the principle of SOC, the resulting luminosity fluctuations predicted by the model follow \( 1/f^\beta \) variation, consistent with observed data. Furthermore, the model is consistent with the timescales discussed in Accretion Region Dynamics section as, for an unstable disk, reorganizations can occur at a relatively rapid-fire pace, enough so that the model can almost satisfactorily produce the short, large amplitude variability profiles of extreme-case AGN like NGC 4395. Conveniently, the SOC model can also be adapted to explain observed variability in X-Ray binaries, and we refer you to Mineshige & Yonehara (2001) for an excellent discussion of the model’s interplay between these two systems.

Of the multiple paradigms of AGN variability, those based upon simple, physically consistent ideas are always the most attractive. As SOC is a predominant process in nature, we are inclined to consider this model as the best start toward accurately describing the processes occurring within the accretion disk. As with all nascent models, however, this is a gross oversimplification of the actual system, as it ignores any effect of MHD, which must be an important part of any “hot accretion disk” theory (discussed in Accretion Region Dynamics section).

Though we have paid most attention to what appears to be the best candidate for an AGN variability mechanism, we now present a brief discussion of other recently developed models.

**Other Models**

The majority of variability models are based upon some connection to a time-dependent parameter in the accretion region. This makes sense, because a discontinuous accretion rate is the simplest, most physically reasonable method by which to drive luminosity fluctuations in the region surrounding a black hole. This is the principle surrounding the theory of X-Ray irradiation. This model is dependent upon response times in disk layers, as well as time lags in reflected versus direct X-Ray emission from the BLR, a parameter dependent upon extinction in the foreground and observation angle. As with the SOC model, this theory is sound and well-supported by observation, so much so that it probably plays a somewhat substantial role in AGN variability. Unlike SOC, however, it is not stand-alone in that it cannot produce extreme variability patterns, like those observed in NGC 4395 and hundreds of other objects, like SDSS J124602.54+011318.8.

Of course, one must ask whether variability in AGN is an intrinsic process at all, or merely a trick of the eye; an artifact of observation angle and foreground obscuration. The question is legitimate, and these effects most likely play at least a non-
negligible role, but by no means can they hold up to the wide range of observed AGN spectra.

In reality, the most accurate model would probably be a combination of the above three paradigms, and would probably be based upon physically simple theory, much like SOC.

Discussion

In fields as young and vibrant as AGN physics, qualitative survey papers such as this discussion are most useful when they provide scientific motivation for further research. In this paper, we surveyed the unified model of AGN in terms of its theoretical structure, observed properties, and quantitative timescales. Having described this environment, we then presented several AGN variability models, consistent with the unification paradigm, which must exist in this environment in order to produce the sometimes dramatic luminosity fluctuations observed in nearly all AGN.

Models like these are difficult to generate, because AGN are very far away, and so we cannot observe their inner structures. If, however, we are able to constrain at least a few parameters of AGN physics, our variability models improve along with the unification paradigm as a whole. Currently, the best way to do this is to study extreme cases of AGN, like NGC 4395, the uniqueness of which allows us access to quantitative data hitherto out of reach in more common specimens.

It is the hope of the author that research will continue along these lines.


Grant Tremblay will graduate with a B.S. in Physics and Astronomy in May, 2006. He has worked with Dr. Alice Quillen for three years and plans to continue the collaboration through graduate school, where he intends to complete a Ph.D. in Astrophysics. He plans for a career in research.


Table 1: Near-IR fluxes over a 258 day period

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