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ACCRETION DISKS AND THE NATURE AND ORIGIN OF AGN CONTINUUM VARIABILITY

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RESUMEN

Se examinan la teoría y las observaciones de la emisión de continuo térmico de los AGN. Después de una corrección por enrojecimiento, las distribuciones espectrales de energía (SEDs) en reposo del óptico–UV tienen gran similitud. Las SEDs están dominadas energéticamente por el *big blue bump* (BBB), pero éste no muestra el espectro $\nu^{+1/3}$ predicho para un disco de acreción delgado con un gradiente radial térmico $r^{-0.75}$. En su lugar, la SED del óptico–UV muestra un gradiente térmico de $r^{-0.57}$ independiente del espesor del disco. Esto indicaría algo de flujo de calor hacia afuera del disco. El disco es grande y la región emisora del continuo óptico es tan grande como la región interna de líneas anchas (BLR). Como se observa variabilidad óptica en todos los AGN en el tiempo de cruce de la BLR, las variaciones deben propagarse con velocidad cercana a la de la luz, en lugar de tiempos dinámicos. Esto sostiene que el mecanismo de generación de energía sea electromagnético en lugar de hidrodinámico. Con velocidades casi lumínicas puede haber una anisotropía local significativa en la emisión. Las enormes variaciones rápidas del BBB implican que la generación de energía magnetohidrodinámica es fundamentalmente inestable. Debido al inevitable gradiente radial térmico en el material en acreción, *distintas regiones espectrales provienen predominantemente de distintos radios*, y variaciones en distintas zonas espectrales corresponden a variabilidad en diferentes radios. Esto explica la independencia observada frecuentemente entre variaciones ópticas y en rayos-X, casos de variabilidad a menores energías antecediendo la variabilidad a altas energías, y los cambios rápidos en la demora por reverberación en las líneas de emisión. Se proponen algunas pruebas observacionales de la hipótesis de variabilidad local.

ABSTRACT

Theory and observations of the dominant thermal continuum emission in AGN are examined. After correction for reddening, the steady state AGN optical–UV spectral energy distributions (SEDs) are very similar. The SEDs are dominated energetically by the "big blue bump" (BBB), but this bump never shows the $\nu^{+1/3}$ spectrum predicted for a standard thin accretion disk with a $r^{-0.75}$ radial temperature gradient. Instead, the observed optical–UV SED implies a temperature gradient of $r^{-0.57}$ independent of the thickness of the disk. This means that there is some flow of heat outwards in the disk. The disk is large and the region emitting the optical continuum is as large as the inner broad-line region (BLR). Because optical variability is seen in all AGN on the light-crossing time of the BLR, variations must propagate close to the speed of light, rather than on dynamical timescales. This argues that the energy-generation mechanism is electromagnetic rather that hydrodynamic. Since the velocities are near the speed of light, there can be significant local anisotropy in the emission. The large rapid variations of the BBB imply that the magnetohydrodynamic energy generation is fundamentally unstable. Because of the inevitable radial temperature gradient in the accreting material, *different spectral regions come predominantly from different radii*, and variations in different spectral regions correspond to variability at different radii. This explains the frequently observed independence of X-ray and optical variations, cases of variability at lower energies leading variability at higher energies, and rapid changes in emission-line reverberation lags. Some observational tests of the local variability hypothesis are proposed.

Key Words: accretion, accretion disks — black hole physics — galaxies: active — galaxies: Seyfert — quasars: general

1. INTRODUCTION

A symposium in honor of Deborah Dultzin's 50th birthday[2] is a good time to look at AGN variability because it is a major area of research in which Deborah has worked (see, for example, Dultzin-Hacyan et al. 1992; Crenshaw et al. 1996; Edelson et al. 1996; de Diego et al. 1998; Ramírez et al. 2003). There is much discussion elsewhere in these proceedings of

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[2]The "60th birthday" in the symposium title is clearly a mistake. Deborah can't really have turned 60 because that would have implications for my own age that I am not sure I am quite ready to face yet!

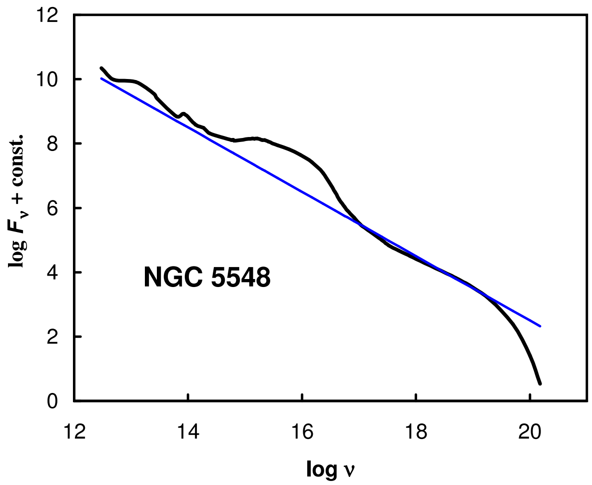

Fig. 1. The spectral energy distribution of NGC 5548 (thick curve) and a ν^{-1} power law (thin line). Compare this representation of the data with Figure 2 below. (Data from Gaskell, Klimek, & Nazarova 2007).

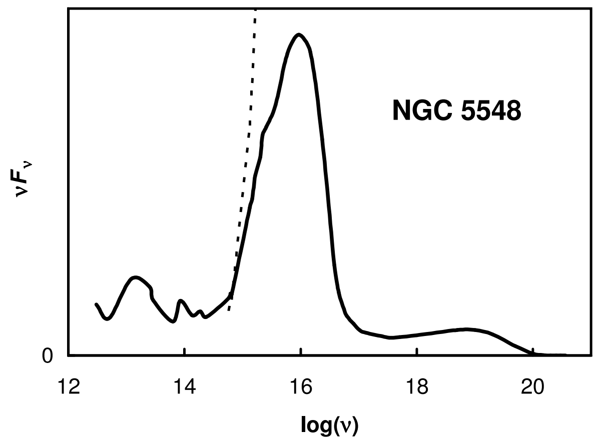

Fig. 2. The spectral energy distribution of NGC 5548 (solid line) and the spectrum of a $F_\nu \propto \nu^{+1/3}$ accretion disk (dotted line). Compare this representation of the observed SED with Figure 1 above. (SED from Gaskell, Klimek, & Nazarova 2007).

variability of the *blazar* component of AGN emission (an area of research in which Deborah and her collaborators have been particularly heavily involved), but in this paper I am just going to focus on what I think are some of the fundamental implications of *non*-blazar AGN continuum and continuum variability observations when confronted with simple accretion theory. For a more comprehensive overview of the state of our knowledge of AGN variability across the electromagnetic spectrum the reader see papers in Gaskell et al. (2006).

2. THE STEADY-STATE SPECTRUM OF THE NON-BLAZAR EMISSION

Unfortunately, one cannot see what the SED of an AGN is like simply by adding up flux-calibrated spectra from one's favorite satellites because solid-state and atomic absorption features caused by dust and gas along the line of sight modify the SED. The average properties of dust in AGN are modified by the AGN environment so the extinction curve of AGN differs somewhat from that of dust in the solar neighborhood (see Gaskell et al. 2004; Czerny et al. 2004; Gaskell & Benker 2007). The *observed* SEDs of AGN show considerable variety, especially in the optical to UV, but we have argued (see Gaskell et al. 2004) that this is predominantly due to differing amounts of extinction. Once AGN SEDs are corrected for extinction, the SEDs in the optical to UV are very similar. A mean AGN extinction curve can be found in Gaskell & Benker (2007).

Sometimes history and conventions get in the way of understanding what is really going on in a subject. I believe the way AGN continua have commonly been graphed is an example of this. It was recognized over half a century ago that the spectra of strong radio sources were non-thermal and could be approximated by a $F_\nu \propto \nu^\alpha$ power law in frequency, ν, where F_ν is the energy per unit frequency, and α is a power-law index. $F_\nu \propto \nu^{-1}$ is also not a bad approximation of the overall spectrum from the radio region to the optical in many radio-loud AGN. Since α is, of course, the slope of a line in a log–log plot, it was only natural to make $\log F_\nu$ vs. $\log \nu$ plots of the the overall SEDs of AGN. An example of this is Figure 2 of Shields (1978), the first paper to point out that there are clear signs of thermal emission in AGN. The unmistakable impression one gets from such plots (see Figure 1) is that the dominant thing is the power law and that there is a modest bump (the "big blue bump", BBB) superimposed on top of it.

With increased interest in the significance of various spectral components it has now become standard practice to make $\log \nu F_\nu$ vs. $\log \nu$ plots since these emphasize deviations from a $F_\nu \propto \nu^{-1}$ power law more clearly. What was formerly a downwards sloping line in the earlier plots now becomes deviations from a horizontal line. This makes various wiggles in the overall SED clearer, but the impression is still that the dominant thing is the $F_\nu \propto \nu^{-1}$ power law which has now been transformed into a horizontal line. A much more informative way of plotting things is to make a log–*linear* plot of νF_ν (rather than $\log \nu F_\nu$ vs. $\log \nu$). As Carleton et al. (1987) point out, such a plot "is particularly useful in that an area under the plotted spectrum between two values of $\log \nu$ represents the power actually radiated in that frequency band".

Figures 1 and 2 respectively show $\log F_\nu$ vs. $\log \nu$ and νF_ν vs. $\log \nu$ plots of our best estimate of the SED of the well-observed AGN NGC 5548 at a single epoch. The SED has had the host galaxy emission removed and has been corrected for reddening both by dust in both the host galaxy and the Milky Way. Details can be found in Gaskell, Klimek, & Nazarova (2007). Note the strikingly different impressions Figures 1 and 2 create! Since areas under the curve in the $\log \nu F_\nu$ vs. $\log \nu$ plot represent the power per decade, it can be seen clearly from Figure 2 that, rather than being dominated by a $F_\nu \propto \nu^{-1}$ power law, the spectrum is instead dominated by a broad peak in the far UV. The remaining emission is primarily the result of reprocessing the radiation of the broad far UV peak. The smaller bump at $\log \nu \sim 13$ is caused by thermal emission from hot dust in the torus, and the X-ray emission at frequencies higher than 10^{17} Hz is believed to be due to Comptonization of lower-energy radiation.

3. THEORY OF AGN ENERGY GENERATION

Once the nature of the compact sources of energy in AGN became apparent it was quickly recognized that the most likely source of energy was accretion onto supermassive black holes (Zel'dovich & Novikov 1964; Salpeter 1964). The theory of this is straight forward. As matter falls in from infinity the gravitational potential energy (PE) is converted into bulk kinetic energy (KE) of motion. For a bound system in equilibrium the virial theorem tells us that $KE = -PE/2$. So one half of the potential energy must be lost. This energy is lost mechanically (as mass outflow) and via radiation. Since the infalling matter will have non-zero angular momentum, the virialization will take place in a disc (Lynden-Bell 1969). This disk was at first thought to be geometrically thin (Pringle & Rees 1971; Shakura & Sunyaev 1972), and such disks have been widely studied, but more detailed consideration of the processes going on in disks (see Blandford & Begelman 2004) shows that convection and mass loss cause a substantial thickening of the disk. This is seen in detailed simulations of accretion (see, for example, Stone, Pringle, & Begelman 1999; Hawley & Krolik 2001). The resulting outflows are well established observationally (see Crenshaw, Kraemer, & George 2002) and there is abundant evidence that the accretion structures in AGN have a substantial covering factor (see Gaskell, Klimek, & Nazarova 2007), and are hence geometrically thick.

To find the overall SED of an accretion disk one integrates the emission over radius. Since in AGN we expect the disk to be optically thick everywhere,[3] for our present purposes we can approximate the local spectrum at each radius as a black body depending only on the temperature at that radius. With this approximation, the shape of the overall SED then depends only on the radial dependence of the temperature. We will assume that the luminosity, L, at a given radius, R, is proportional to the energy production rate at that radius. This energy production rate per square centimeter in a ring of thickness dR at radius R is proportional to the PE released per gram of material going from $R + dr$ to R and the mass accretion rate, dM/dt, divided by the area of the ring of thickness dR. If we put all this together we get

$$L \propto \frac{GM}{R^2} dR \frac{dM}{dt} \frac{1}{\pi r dR} \propto \frac{1}{R^3}. \tag{1}$$

Since we are assuming a black-body spectrum, $L \propto T^4$,

$$T \propto L^{1/4} \propto (R^3)^{1/4} \propto R^{-3/4}. \tag{2}$$

and because the wavelength, λ_{max}, of the peak of a black body spectrum, is proportional to T^{-1}, most of the radiation at a given wavelength, λ, comes from near a radius:

$$R \propto \lambda^{4/3}. \tag{3}$$

To get the integrated spectrum from the disk one adds up all the Planck curves from each radius. It can be shown that if $T \propto R^p$ then

$$F_\nu \propto \nu^{(3-2/p)} \tag{4}$$

(see Pringle & Rees 1971 or Shakura & Sunyaev 1972). If $p = 3/4$ we get

$$F_\nu \propto \nu^{+1/3}. \tag{5}$$

Note that this result arises in a straight forward way solely from considerations of energetics and mass conservation; one does not need to worry about the much more vexing issues of how angular momentum is transported outwards. It also does not depend on the thickness of the disk. The high-energy end of the spectrum is a Wien exponential cutoff corresponding to the temperature of the inner radius of

[3]AGN differ from X-ray binaries in this regard because the disks in AGN are many orders of magnitude larger.

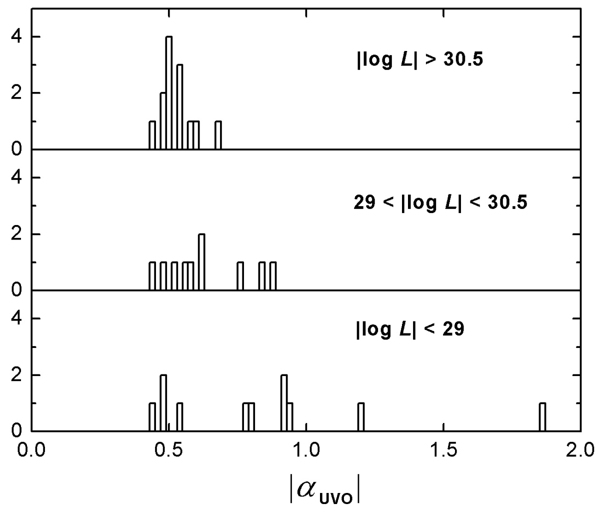

Fig. 3. The distribution of optical to UV spectral indices in AGN. Note that this figure, taken from Gaskell et al. (2004), uses the opposite sign convention for α from this paper.

the disk, and the low-energy limit of the spectrum is a Rayleigh-Jeans tail of the emission from outermost part of the disk.

Equation (5) is a well-known result, and there have been many attempts to model the BBB in AGN SEDs with a $\nu^{+1/3}$ disk spectrum and with additional refinements such as more realistic local emergent spectra, the addition of Componizing coronae, and consideration of inclination effects (see Bonning et al. 2007 for a recent example). These additional refinements mostly affect only the high energy shape of the SED, and extend the BBB to somewhat higher energies (see, for example, Czerny & Elvis 1987; Laor & Netzer 1989; Hubeny et al. 2001).

Despite the considerable effort expended on them, I believe that *one should not be obsessed with the $\nu^{+1/3}$ spectra!* First, despite impressions one might get from the literature, a $\nu^{+1/3}$ spectra is *not* a good fit to an AGN SED. We simply *never* observe rising $\nu^{+1/3}$ spectra. The only way to get a $\nu^{+1/3}$ spectrum to fit a real AGN SED is to arbitrarily add in a substantial power-law contribution (see, for example, Figure 2 of Malkan 1983) or to fit a limited region of the observed SED with the high-energy turnover in the theoretical spectrum.[4] In doing this, fine-tuning of parameters is needed and this approach gives a fundamental problem: how does an AGN manage to convert most of its energy into a mysterious non-thermal power law? The difficulty of fitting $\nu^{+1/3}$ to any part of an SED is illustrated in Figure 2 where the steep dotted line is $\nu^{+1/3}$.

The second reason one should not get obsessed with a $\nu^{+1/3}$ spectrum is that it is easy to get a different slope from an accretion disk because the slope of the emergent spectrum depends strongly on the radial temperature index, p. Even a small deviation of p from 0.75 will have a big effect on the slope of the spectrum. The important assumption in our derivation of equation (4) is that the energy at a given radius is generated locally at that radius by the accretion. In reality this will not be the case. The inner part of the disk is much hotter than the outer part of the disk (equation 2), heat flows from hot to cold, and the effect of any radial transfer of heat will therefore be to soften the radial temperature gradient. The limiting case of this is to make the opposite assumption from above, and to assume that the heating at a given radius is not the result of local energy generation from accretion, but comes instead from heat flow from hotter material at smaller radii. If we assume a single central energy source then the flux falls off as R^{-2} and the effective equilibrium temperature falls off as

$$T \propto R^{-1/2} \tag{6}$$

This give $p = -0.5$ and from equation (3) we get a radically different spectrum of $F_\nu \propto \nu^{-1}$. An example of a model giving a ν^{-1} spectrum is the so-called "slim disk" of Abramowicz et al. (1988).

Since the theory of accretion disks is still at a rudimentary stage, I believe that it is better to turn the problem around and derive the radial temperature distribution empirically from the observed spectral slope rather than trying to force a theoretical spectrum coming from a preconceived idea of the temperature structure to fit the observations. Figure 3 shows the distribution of UV to optical spectral indices, α_{UVO}, for a sample of AGN. Note, after allowing for the opposite sign convention for α in the Gaskell et al. (2004), that nowhere in this figure do we see anything remotely approaching $F_\nu \propto \nu^{+0.33}$! Instead, it can be seen that for high luminosities there is a sharp peak in the distribution at $\alpha_{UVO} = -0.5$. The narrowness of this distribution is all the more striking since the UV and optical observations (see Malkan 1984) were non-simultaneous. As one goes to lower luminosities it can be seen that $\alpha_{UVO} = -0.5$ represents the limit of the bluest spectra. Gaskell et al. (2004) interpret $\alpha_{UVO} = -0.5$ as the intrinsic unreddened slope of the spectrum, and interpret steeper values of α_{UVO} as the result

[4]Note that the inner disk temperatures in the fits of Malkan (1983) are more than an order of magnitude too low to explain the extreme-UV to soft X-ray SED.

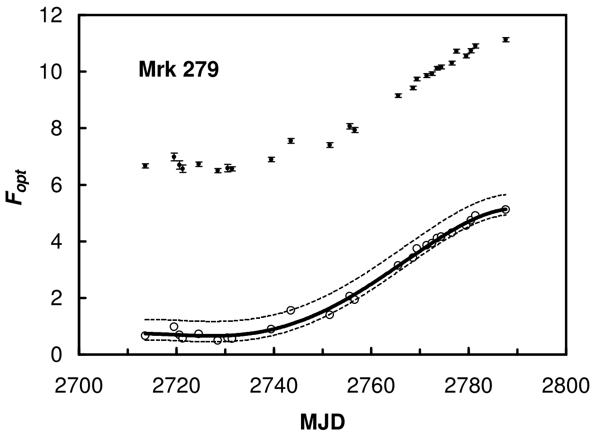

Fig. 4. The V-band light curve of Mrk 279. Top points (filled circles with error bars) are the observed relative fluxes observed through an 8-arcsecond photometric aperture. Bottom points (open circles) show the fluxes after correction for host galaxy light. The solid two lighter lines on either side of the solid curve show the effects of the upper limits in the uncertainty in the host galaxy light correction. From Gaskell et al. (in preparation); see also Costantini et al. (2006).

of increasing reddening as one goes to less luminous objects. Support from this picture comes from emission-line ratios. If we accept the interpretation that $\alpha_{UVO} = -0.5$ is the true slope of the spectrum in the optical and UV, then from equation (3) this implies that $p = 0.57$.

$p = 0.57$ falls comfortably between our limiting cases of $p = 0.75$ for local energy generation (e.g., the standard thin disk) and $p = 0.5$ for non-local central energy generation. $p = 0.57$ explains the rise of the spectrum in Figure 2 as one goes from the optical to the UV. Looking at the areas under the solid curve in Figure 2 shows that there we can put strong limits on any power-law contribution. The main energy unaccounted for is the energy in the IR, and this is easy to explain by thermal reprocessing in the torus. In the thermal dust emission model the ratio of areas under the IR portion of the curve to the area under the curve from the optical region to higher frequencies gives the covering factor of the dusty torus. IR variability strongly supports the correctness of this dust-reprocessing picture.

4. VARIABILITY FUNDAMENTALS

Variability is the change in some quantity with time. The first two basic questions one ought to ask about anything varying are, "how much does it change?" and "how rapidly does it change?" If one looks at the extensive astronomical literature on time variability of anything one finds that the overwhelming focus is on the temporal aspect. One will find innumerable papers determining periods of things or searching for periods, and there are discussions of exponential decay times, duty cycles, power spectra, chaotic behavior, and so on. What gets far less attention is the first question of *how much* something changes,[5] yet this is really the more fundamental question. It is the *amplitude* which tells us how *important* variability really is. A couple of examples should make this very clear. The bolometric amplitudes of pulsating variable stars are very small. This tells us that this variability is unimportant in the sense that it is not the main energy mechanism of the star which is varying. The variability of pulsating stars is in fact a minor consequence of changing opacity in the outer envelope of the star. Likewise with the sun, the solar cycle has a very low amplitude. It too has nothing to do with the main energy generation in the core of the sun, but is a consequence of small secondary effects to do with magnetic fields in the outer regions of the sun. At the other extreme, the variability amplitude of supernovae is enormous. This is no minor secondary phenomena; the mechanism causing the variability in a supernova is the mechanism causing the supernova. What about AGN variability? Is it a minor phenomenon like pulsations of variable stars, or is it the fundamental energy generation mechanism of the AGN turning off and on?

If one routinely monitors AGN in the optical one finds that, for a typical AGN light curve, the amplitude during the course of a year will probably be only a couple of tenths of a magnitude or so. Since this is less than the amplitude of a typical Cepheid variable star, one might conclude, therefore, that, as is the case with pulsating variable stars, variability of AGN is just some minor phenomenon unrelated to the main energy production I have outlined in the previous section. However, the way observations are almost always presented is misleading, because AGN light curves are almost invariably shown including the star light from the nucleus of the host galaxy. Figure 4 shows the effect of removing host galaxy light. If one ignores the host-galaxy contamination, the variability shown in Figure 4 is $\sim \pm 15\%$. However, after appropriate subtraction of the host-galaxy light, it can be seen that the amplitude of

[5] As an illustration of this, as of this writing, a search on the ADS for the word "time" in abstracts brings up almost 200,000 hits, and "timescale" brings up 125,000 hits. The combination of the words "amplitude" and "variability" only generates 8000 hits.

TABLE 1

DISK CHARACTERISTICS FOR NGC 5548

R/R_g	v_{orb} (km s^{-1})	Region	R (lt-d)	t_{orb} (days)	t_{orb} (yrs)	$T_{0.72}$ (K)	$T_{0.57}$ (K)	$\lambda_{0.72}$ (Åetc.)	$\lambda_{0.57}$ (Åetc.)
3	120,000		0.02	0.4		155000	149000	200	210
10	70,000	Kα	0.08	2		65000	75000	500	430
30	40,000	Kα	0.25	11		29000	40000	1100	800
100	20,000		0.8	70		12300	20000	2600	1600
300	12,000	BLR	2	360	1	5600	10800	6000	3000
1000	7,000	BLR	8		6	2400	5400	1.3 μm	5900
3000	4,000	BLR	23		30	1100	2900	2.9 μm	1.1 μm
10000	2,000	dust	80		200	400	1500	8 μm	2.1 μm

variability is almost an order of magnitude over a six-week period.

5. SIZES AND TIMESCALES

We have seen in § 3 that a modest modification of the radial temperature distribution of a accretion flow enables us to explain the single-epoch (or steady-state) main power-producing part of the AGN spectrum. What predictions can we make for the *variability* of this main component of the spectrum? Physically, a timescale comes from a length scale and a relevant velocity. I have attempted in Table 1 to give a reasonably observer-friendly compilation of relevant sizes, velocities, timescales, and temperatures for a disk with the characteristics of NGC 5548 where we believe that there is a $6.7 \times 10^8 M_\odot$ black hole accreting at $L/L_{Edd} \sim 0.06$ (Koratkar & Gaskell 1991a,b; Peterson et al. 2004). Two sets of temperatures are shown. The first, $T_{0.72}$, has been scaled from the temperatures of the Hubeny et al. (2001) disk models (where $p = 0.72$) using the standard $T \propto M^{-1/4}(L/L_{Edd})^{1/4}$ scaling. The second set of temperatures, $T_{0.57}$, uses the $T \propto r^{-0.57}$ dependency deduced above from the optical–UV spectrum, and has been scaled to produce approximately the same L_{bol} as the Hubeny et al. (2001) disk. The derivations of the remaining quantities should be obvious.

The foremost thing to notice from Table 1 is how *big* the disk is! The inner and outer disk temperatures and radii are in good agreement with the cutoff of the BBB and the dust radius respectively for NGC 5548 (see Gaskell, Klimek, & Nazarova 2007), but notice how *the disk regions contributing to the photoionization of the BLR come right up to and into the inner BLR*! Notice also that the region dominating the visible light is at the same radius as the inner BLR. The idea of the BLR overlapping with the energy-producing region has already long been considered by Suzy Collin-Souffrin and collaborators (see for example Collin-Souffrin, Hameury, & Joly 1988). The approximate correctness of the radii in Table 1 is supported by the disk temperature falling below the dust sublimation temperature just where the hottest dust is indeed observed in NGC 5548 (see Gaskell et al. 2007).

Table 1 also gives sizes in light-travel units, and orbital timescales for the proposed NGC 5548 disk. It is important to note that the *each spectral region is predominantly emitted at the radius given.* This radius comes from equation 3. Taking the optical as an example, while there is some emission from the Rayleigh-Jeans tail of the inner disk, the bulk of the emission comes from material at a temperature of ~ 6000 K.

Czerny (2006) has given a good summary of the timescales of standard thin accretion disks. In Table 1 I have given just the two shortest timescales. The corollary of the large radii in Table 1 is that even these timescales are long. Additional timescales, such as the sound-crossing times (see Czerny 2006) are so long for regions producing the optical and UV radiation, that they are clearly irrelevant for observed AGN variability and do not need to be considered further. The dynamical (orbital) timescale, however, is important since this is the fastest one can move large amounts of matter into an AGN at a given radius. From Table 1 it can be seen that it is quite long (year to decades) for the regions producing the optical continuum. AGN vary considerably faster than this (on a timescale of days for NGC 5548), so we can say that, contrary to popular opinion, *normal optical variability is not the re-*

sult of variations in the accretion rate on dynamical timescales.

The only remaining relevant timescale is the light-crossing time, and this is indeed the shortest timescale on which AGN show strong variability. This simple but important fact tells us that *whatever causes AGN variability propagates at the speed of light, or close to it.*

6. THE WAVELENGTH-DEPENDENCE OF AGN VARIABILITY

At least in the steady-state approximation we have been considering so far, different spectral regions of the SED are emitted at different radii. Connections between wavebands therefore tell us how energy is propagating radially, and an enormous amount of observational effort has justifiably been put, and continues to be put, into multi-wavelength observing. The two most common goals of these multi-wavelength observing campaigns are (i) to search for correlations between the variability in different wavebands, and (ii) to search for time lags between bands. Correlations indicate possible causal relationships, and since effects follow causes, time lags can help us understand what causes what.

One of the most commonly investigated hypotheses is *reprocessing* of radiation. The three main ways reprocessing can happen are (i) heating and thermal re-radiation, (ii) reprocessing through atomic processes (emission lines and bound-free continua), and (iii) Compton scattering. Of these the first two produce lower-energy photons, while Compton upscattering will produce higher energy photons. The best understood AGN variabilty is IR variability. There is excellent evidence that this is the result of reprocessing of higher energy radiation. It has long been observed that the IR emission follows variability at shorter wavelengths (Clavel, Wamsteker, & Glass 1989; Oknyanskii et al. 1999; Glass 2004; Suganuma et al. 2006) and that the lags are consistent with thermal reprocessing in the dusty torus (Barvainis 1992; Gaskell, Klimek, & Nazarova 2007).

It is believed that the hard X-ray emission ($> 1-2$ keV is produced by Compton upscattering of lower-energy photons. Recent overviews of X-ray variability and its connection with variability at other wavelengths can be found elsewhere (e.g., Gaskell & Klimek 2003; McHardy et al. 2006; Gaskell 2006; Uttley 2006).

It is often suggested in both the literature and in observing proposals that *optical* variability is a consequence of re-processing of X-ray emission, but it can be seen from Figure 2 that this cannot be because there is more energy in the optical/UV than in the X-ray region. The small lags that are sometimes seen between hard X-ray emission and the optical are probably the result of both lagging behind the EUV/soft X-ray variability.

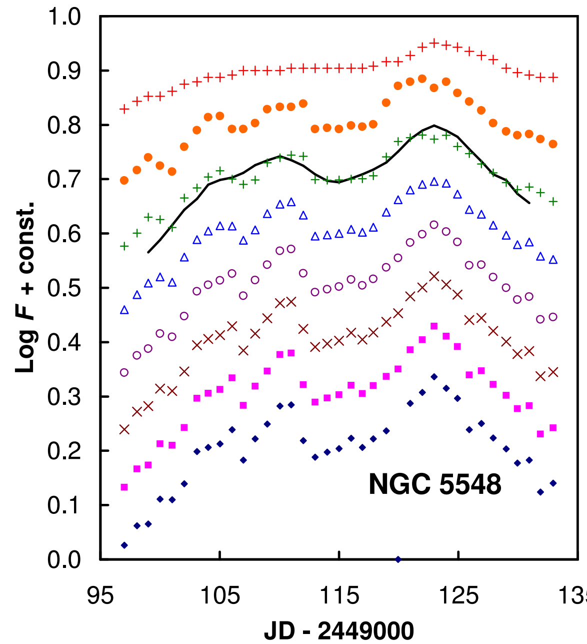

Fig. 5. Light curves for NGC 5548. Data from Korista et al. (1995). The light curves, starting from the bottom are, at $\lambda\lambda$ 912 (extrapolated), 1145, 1350, 1460, 1790, 2030, 2195, and 5100. Notice the decreasing amplitudes and greater smoothness of the light curves as one goes to to longer wavelengths. The smooth curve through the λ2030 curve is the λ912 light curve smoothed with a boxcar function running from -3 to $+3$ days.

7. REPROCESSING IN THE BIG BLUE BUMPS

It has long been known that variability of what we now recognize as BBB emission gets smoother and of lower amplitude as one goes to lower energies. This is illustrated in Figure 5. The smoothing due to reprocessing of higher-energy radiation is a natural explanation of this, but a long-standing problem for processing within the BBB (as opposed to IR and X-ray reprocessing) has been that the observed delays between the optical and the UV have been very short and were not detected in the first *International AGN Watch* monitoring campaigns (Clavel et al. 1991; Peterson et al. 1991; Edelson et al. 1996). In fact, we only have one clear cut case of an optical–UV delay, NGC 7469 (Wanders et al. 1997; Collier et al. 1998). In Figure 6 I have rescaled and replotted the optical and UV light curves from these two papers to show the lag. A little further consideration shows

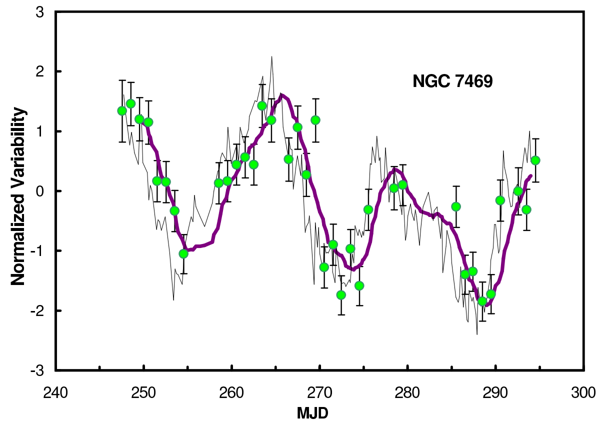

Fig. 6. The relative UV, $\lambda1315$, variability of NGC 7469 (thin line) compared with the optical, $\lambda4845$, variability (circles with error bars). The thick solid curve is the UV variability smoothed with a boxcar function extending from 0 to 5 days. The variations are shown on a linear scale normalized to the same variance (data from Wanders et al. 1997; Collier et al. 1998; Kriss et al. 2000).

that reprocessing appears to work very well in this case. As can be seen in Figure 6, the optical light curve is fit very well with the average of the previous five days (to give a total delay of 2.5 days). This boxcar smoothing of the UV light curve also reproduces the UV-optical cross-correlation function (see Gaskell & Sparke 1986) well from the UV autocorrelation function. I have shown normalized variability in Figure 6 because there are uncertainties over the corrections for host galaxy light and reddening, but the amplitude of the optical variations in energy units probably does not exceed the amplitude of the UV variability.

For NGC 7469 we found that the wavelength-dependent lags, $\tau(\lambda)$, in NGC 7469 could be fit well by

$$\tau(\lambda) \propto \lambda^{4/3} \tag{7}$$

(see Wanders et al. 1997; Collier et al. 1998; Kriss et al. 2000). This is consistent with equation (3) if $\tau(\lambda) \propto R$.

Although reprocessing looks convincing in this case, the shortness of the delay, which is on the order of the light crossing-time, is problematic. We therefore interpreted the lags as a consequence of light-travel time in the external illumination of a disk with a $T \propto R^{-3/4}$ radial temperature structure (see Wanders et al. 1997; Collier et al. 1998; Kriss et al. 2000). From broad-band optical photometry going out to the near IR (0.9 μm), Sergeev et al. (2005) have found many more wavelength-dependent lags and also shown that the lags at a given wavelength

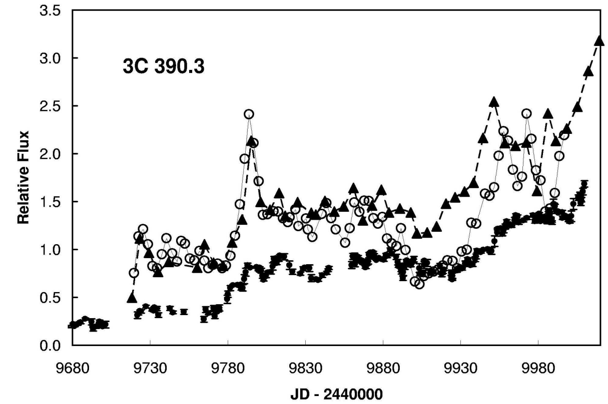

Fig. 7. Soft X-ray, UV, and optical fluxes of 3C 390.3. The open circles are 0.1–2 keV *ROSAT* HRI fluxes; the black triangles are *IUE* $\lambda1370$ UV fluxes, and the small black circles with error bars are V-band fluxes. The *ROSAT* fluxes are from Leighly et al. (1997), the UV fluxes are based on O'Brien et al. (1998), and V-band fluxes have been derived with scalings and corrections from Dietrich et al. (1998). Scale factors have been chosen for plotting convenience, and an arbitrary constant has been subtracted from the V-band fluxes. Figure reproduced from Gaskell (2006).

are proportional to $L^{1/2}$ where L is the optical luminosity of the AGN. To explain this they also suggest an external illumination source and postulate that the height of this external illumination source depends on the square-root of the luminosity.

As discussed in Gaskell (2007) there are many problems with the external illumination model. Foremost among these are that the external illumination source is never seen from the earth, and because the amplitude of the variability can be large (see, for example, Figure 4), this mysterious energy source, rather than the disk itself, must be the main energy source. Instead I have proposed (see Gaskell 2007) that the general increase in lag, Sergeev et al. (2005) find towards the near IR comes naturally as a result of increasing contamination from re-emitted light from the very hot dust in the torus.

The nice reprocessing picture I have shown for NGC 7469 in Figures 6 and 7 is shattered when we go back to looking at the variability of NGC 5548 (Figure 5). The variability does indeed get smoother as one goes to longer wavelengths and the amplitude decreases as expected in the reprocessing model. Again there is good quantitative agreement illustrated both by the fit of a smoothed short wavelength curve to one of the longer UV wavelengths in Figure 5 and to the optical continuum autocorrelation function. But there is a *huge problem with causality* – the ±3 day boxcar function used in Figure 5 and the wider ($\pm$4.5 day) one needed to explain the optical continuum autocorrelation function extend to both positive and negative times! In other words, we need to reprocess photons that will not be emitted until several days in the future!

The simple reprocessing picture continues to collapse when we consider an AGN for which we have good long-term soft X-ray, UV, and optical monitoring. In Figure 7 I shown the soft X-ray, UV, and optical light curves of 3C 390.3. Since 3C 390.3 has a substantial (and as yet undetermined) host galaxy contribution. I have subtracted an arbitrary constant flux to emphasize the optical variations.

Around MJDs 9725 and 9790 we see what we would expect from reprocessing. A strong soft X-ray "flare" with an almost simultaneous UV flare, and a much less obvious optical event. But that is where the agreement with reprocessing expectations ends. Right after the MJD 9790 event there is a follow-on event in the optical *of comparable magnitude to the optical event at MJD 9790*, but there are at best only very weak corresponding UV and soft X-ray events. A soft X-ray "anti-flare" (dip) at MJD 9855 has no corresponding event in the UV or optical. Then the X-rays go into a "low state" around MJD 9900 and the optical follows suit about 10 days later (this is more obvious in the smoothed curves – see Gaskell 2006). But then look at what happens – there is a *major* flare in the UV. This has no counterpart in the optical, but a major flare in the soft X-rays *follows* the UV flare! Another soft X-ray major flare, fast on the heels of the first, has no obvious counterparts in the UV and the optical.

8. A MODEL FOR MULTI-WAVELENGTH VARIABILITY OF AGN

Clearly the behavior of 3C 390.3 and NGC 5548 rules out the widely considered simple reprocessing picture. Instead it points to *different spectral regions varying relatively independently*, which is just what we expect from the temperature structure of the accretion flow. Variability at one radius produces UV variability; variability at another produces optical variability. This is energetically quite feasible. If the effective temperature of just a quarter of the surface area of what I will loosely call the "optical" region of the disk doubles, this will increase the energy output of the region varying 16 fold and the quadruple the energy output of the whole optical region of the disk. The variability at this radius will propagate inwards and outwards to hotter and cooler regions. Given perfect multi-wavelength, monitoring the radius varying can be identified from the part of the SED which varies most strongly.

If the AGN is not face on but has a significant inclination angle the lags between events at different frequencies will also depend on whether the driving event is into or out of the plane of the sky. The lag will be less when the disturbance in propagating towards the observer.

This model makes quite a number of predictions that are testable at least in practice:

(1) The closer regions of the SED are to each other in energy, the more correlated their variability will be. This does indeed seem to be the case.

(2) When a disturbance originates in a cooler region giving a low-energy event and this disturbance propagates inwards, the higher energy event will *follow* the lower energy event. This should be testable. As one moves away from the spectral region of maximum variability (identified by the maximum variability) both lower energy *and the higher energy* variability will lag behind the driving variability.

(3) The timescale of driving events of comparable relative amplitude in different spectral regions will vary as λ^{β} where $\beta = 1/p$.

(4) Secondary events will be smoothed relative to driving events, although this might not always be detectable.

(5) Because individual variations in the ionizing continuum are no longer axially symmetric, light echoes in emission lines and polarized flux (see Gaskell et al. 2007) will be different for different events, even though there is insufficient time for the mean distance of the emission-line regions or polarizing electrons to change their distance from the central black hole. Although somewhat bad news for reverberation mappers, this is quite a powerful test, and hitherto puzzling changes in lags for separate consecutive events have already been noticed (Maoz 1994).

(6) Changes in line lags and color-dependent lags will be greater for AGN with higher inclination angles because the azimuthal location matters more.

9. WHERE NEXT?

I believe that there are a couple of clear directions we need to be going in. First, we need more data. A lot of effort has gone into AGN monitoring, but it has been concentrated on only a few objects. Astrophysicists, along with vertebrate paleontologists are probably the world leaders in building theories on the observations of a single object! I hope it is clear from my discussion of the contrasting multi-wavelength behavior of NGC 5548, NGC 7469, and 3C 390.3 that one can get *very* misleading impressions from just a single short-duration observing campaign looking at only one object. Yet this is where a lot of our ideas of AGN variability have come from. We need comparable or better monitoring of quite a few objects, and preferably ultimately of well chosen samples.

The second direction I believe we need to be going in is in making more detailed 3D-magnetohydrodynamic simulations of accretion onto compact objects. I find the results obtained so far by Hawley & Krolik (2001) and others to be very encouraging, and this sort of thing is only going to get easier as increases in computing power shows no signs of tapering off. Although treatment of all relevant radiative processes is not yet included in these simulations, Hawley & Krolik (2001) find that fluctuations in the volume-integrated Maxwell stress and accretion rate at the inner edge of the disk (both of which are probably related to the luminosity) fluctuate wildly (i.e., the energy generation is indeed fundamentally unstable) and that the Fourier power spectrum of the variability, $P(f)$, has a "red" $P(f) \propto f^{-1.8}$ shape similar to what is observed in AGN. NGC 5548, for example, has indices of -3 and -2.5 at different epochs (Koratkar & Gaskell 1991a; Krolik et al. 1991), and the Reichert et al. (1994) observations of NGC 3783 give an index of -1.8 (White & Peterson 1994). It remains to be seen, however, how well such simulations will be able to reproduce the rapidity of flux variations and the small lags.

Finally, although they differ from AGN in many ways, it is possible that observations of accreting binaries could offer useful insights into what is going on with AGN. For example, eclipse "flicker mapping" of the dwarf nova V2051 Oph (Baptista & Bortoletto 2004) shows that there is high-frequency flickering all over the disk with a constant relative amplitude independent of disk radius and accretion rate. This is consistent with the model of AGN variability I have suggested, although the amplitude of the dwarf nova flickering is lower (3% rms) for V2051 Oph.

10. CONCLUSIONS

Variability rules out the standard popular geometrically-thin "α-disk" paradigm of Pringle & Rees (1971) and Shakura & Sunyaev (1972). Variability in the UV and optical is simply too fast and much too simultaneous to be due to fluctuations in the accretion rate in a standard thin disk. The rapidity and simultaneity instead require that the variability mechanism propagates close to the speed of light. Since the amplitude of AGN variability is enormous the variability mechanism is the main energy generating mechanism of AGN. Both theory and observations strongly point to variability being *localized* in the disk, and there are tests that can be made of this hypothesis.

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REFERENCES

Abramowicz, M. A., Czerny, B., Lasota, J. P., & Szuszkiewicz, E. 1988, ApJ, 332, 646
Baptista, R., & Bortoletto, A. 2004, AJ, 128, 411
Barvainis, R. 1992, ApJ, 400, 502
Blandford, R. D., & Begelman, M. C. 2004, MNRAS, 349, 68
Bonning, E. W., Cheng, L., Shields, G. A., Salviander, S., & Gebhardt, K. 2007, ApJ, 659, 211
Carleton, N. P., Elvis, M., Fabbiano, G., Willner, S. P., Lawrence, A., & Ward, M. 1987, ApJ, 318, 595
Clavel, J., Wamsteker, W., & Glass, I. S. 1989, ApJ, 337, 236
Clavel, J., et al. 1991, ApJ, 366, 64
Collier, S. J., et al. 1998, ApJ, 500, 162
Collin-Souffrin, S., Hameury, J.-M., & Joly, M. 1988, A&A, 205, 19
Costantini, E., et al. 2007, A&A, 461, 121
Crenshaw, D. M., Kraemer, S. B., & George, I. M., 2002, ASP. Conf. Ser. 255, Mass Outflow in Active Galactic Nuclei: New Perspectives (San Francisco: ASP)
Crenshaw, D. M., et al. 1996, ApJ, 470, 322
Czerny, B. 2006, ASP Conf. Ser. 360, AGN Variability from X-Rays to Radio Waves, ed. C. M. Gaskell, I. M. McHardy, B. M. Peterson, & S. G. Sergeev (San Francisco: ASP), 265
Czerny, B., & Elvis, M. 1987, ApJ, 321, 305
Czerny, B., Li, J., Loska, Z., & Szczerba, R. 2004, MNRAS, 348, L54
de Diego, J. A., Dultzin-Hacyan, D., Ramirez, A., & Benitez, E. 1998, ApJ, 501, 69
Dietrich, M., et al. 1998, ApJS, 115, 185
Dultzin-Hacyan, D., Schuster, W. J., Parrao, L., Peña, J. H., Peniche, R., Benitez, E., & Costero, R. 1992, AJ, 103, 1769
Edelson, R. A., et al. 1996, ApJ, 470, 364
Gaskell, C. M. 2006, ASP Conf. Ser. 360, AGN Variability from X-Rays to Radio Waves, ed. C. M. Gaskell, I. M. McHardy, B. M. Peterson, & S. G. Sergeev (San Francisco: ASP), 111

———. 2007, ASP Conf. Ser. 373, The Central Engine of Active Galactic Nuclei, ed. L. C. Ho & J.-M. Wang (San Francisco: ASP), 596
Gaskell, C. M., & Benker, A. J. 2007, ApJ, submitted (astro-ph/0711.1013)
Gaskell, C. M., Goosmann, R. W., Antonucci, R. R. J., & Whysong, D. H. 2004, ApJ, 616, 147
Gaskell, C. M., Goosmann, R. W., Merkulova, N. I., Shakhovskoy, N. M., & Shoji, M. 2007, ApJ, submitted (astro-ph/0711.1019)
Gaskell, C. M., & Klimek, E. S. 2003, Astron. Astrophys. Trans., 22, 661
Gaskell, C. M., Klimek, E. S., & Nazarova, L. S. 2007, ApJ, submitted (astro-ph/0711.1025)
Gaskell, C. M., McHardy, I. M., Peterson, B. M., & Sergeev, S. G. 2006, ASP Conf. Ser. 360, Variability from X-Rays to Radio Waves (San Francisco: ASP)
Gaskell, C. M., & Sparke, L. S. 1986, ApJ, 305, 175
Glass, I. S. 2004, MNRAS, 350, 1049
Hawley, J. F., & Krolik, J. H. 2001, ApJ, 548, 348
Hubeny, I., Blaes, O., Krolik, J. H., & Agol, E. 2001, ApJ, 559, 680
Koratkar, A. P., & Gaskell, C. M. 1991a, ApJ, 370, L61
Koratkar, A. P., & Gaskell, C. M. 1991b, ApJ, 375, 85
Korista, K. T., et al. 1995, ApJS, 97, 285
Kriss, G. A., Peterson, B. M., Crenshaw, D. M., & Zheng, W. 2000, ApJ, 535, 58
Krolik, J. H., Horne, K., Kallman, T. R., Malkan, M. A., Edelson, R. A., & Kriss, G. A. 1991, ApJ, 371, 541
Laor, A., & Netzer, H. 1989, MNRAS, 238, 897
Leighly, K. M., et al. 1997, ApJ, 483, 767
Lynden-Bell, D. 1969, Nature, 223, 690
Malkan, M. A. 1983, ApJ, 268, 582
Malkan, M. A. 1984, Max-Planck Inst. Reports 184, X-Ray and UV Emission from Active Galactic Nuclei, 121
Maoz, D. 1994, ASP Conf. Ser. 69, Reverberation Mapping of the Broad-Line Region in Active Galactic Nuclei, ed. P. M. Gondhalekar, K. Horne, & B. M. Peterson (San Francisco: ASP), 95
Marscher, A. P., Jorstad, S. G., Gómez, J.-L., Aller, M. F., Teräsranta, H., Lister, M. L., & Stirling, A. M. 2002, Nature, 417, 625
McHardy, I., Uttley, P., Taylor, R., & Papadakis, I. 2006, ASP Conf. Ser. 360, AGN Variability from X-Rays to Radio Waves, ed. C. M. Gaskell, I. M. McHardy, B. M. Peterson, & S. G. Sergeev (San Francisco: ASP), 85
O'Brien, P. T., et al. 1998, ApJ, 509, 163
Oknyanskij, V. L., Lyuty, V. M., Taranova, O. G., & Shenavrin, V. I. 1999, Astron. Lett., 25, 483
Peterson, B. M., et al. 1991, ApJ, 368, 119
———. 2004, ApJ, 613, 682
Pringle, J. E., & Rees, M. J. 1972, A&A, 21, 1
Ramírez, A., de Diego, J. A., Dultzin-Hacyan, D., & Benítez, E. 2003, RevMexAA (SC), 17, 106
Reichert, G. A., et al. 1994, ApJ, 425, 582
Salpeter, E. E. 1964, ApJ, 140, 796
Sergeev, S. G., Doroshenko, V. T., Golubinskiy, Yu. V., Merkulova, N. I, & Sergeeva, E. A., ApJ, 622, 129
Shakura, N. I., & Syunyaev, R. A. 1973, A&A, 24, 337
Shields, G. A. 1978, Nature, 272, 706
Suganuma, M., et al. 2006, ApJ, 639, 46
Stone, J. M., Pringle, J. E., & Begelman, M. C. 1999, MNRAS, 310, 1002
Uttley, P. 2006, ASP Conf. Ser. 360, AGN Variability from X-Rays to Radio Waves, ed. C. M. Gaskell, I. M. McHardy, B. M. Peterson, & S. G. Sergeev (San Francisco: ASP), 101
Wanders, I., et al. 1997, ApJS, 113, 69
White, R. J., & Peterson, B. M. 1994, PASP, 106, 879
Zel'Dovich, Y. B., & Novikov, I. D. 1964, Sov. Phys. Dokl., 9, 246