

## AGN Variability

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**Abstract.** A number of monitoring observations of continuum emission from Active Galactic Nuclei (AGNs) have been made in optical–X-ray bands. The results obtained so far show (i) random up and down on timescales longer than decades, (ii) no typical timescales of variability on shorter timescales and (iii) decreasing amplitudes as timescales become shorter. The second feature indicates that any successful model must produce a wide variety of shot-amplitudes and -durations over a few orders in their light curves. In this sense, we conclude that the disk instability model is favored over the starburst model, since fluctuations on days are hard to produce by the latter model.

Inter-band correlations and time lags also impose great constraints on models. Thus, constructing wavelength and time dependent models remains as future work.

### 1. Introduction

Emission from Active Galactic Nuclei (AGNs) shows rapid and apparently random variability over wide wavelength ranges from radio to X ray or  $\gamma$  ray (for a review, see Ulrich, Maraschi & Urry 1997). In spite of numerous intensive, multi-wavelength monitoring projects, there still remain major questions; what causes the variability? Which parts of nuclei are emitting in various energy bands? One of the goals of variability studies is to identify and characterize the physical processes responsible for the observed variability.

Most AGN light curves exhibit neither apparent periodicity nor a typical timescale. In fact, the AGN light curves fluctuate over wide timescales (e.g. Fahlman & Ulrych 1975, for decades' light curve; Peterson et al. 1994, for years; Clavel et al. 1991, for months; Korista et al. 1995, for weeks; Edelson et al. 1996, for days). Figure 1 shows schematic light curves of AGNs on various timescales, from decades to days/hours. We point out the following three features;

1. The top panel, light curves on decades, is qualitatively different from the lower three. It seems to just fluctuate almost randomly, up and down.
2. There is no typical timescale in variability over less than years (see the lower three light curves). Flux variations over years to days/hours resemble each other; each light curve shows one or two bumps and small fluctuations superposed on them. In other words, the variations are self-similar or fractal.

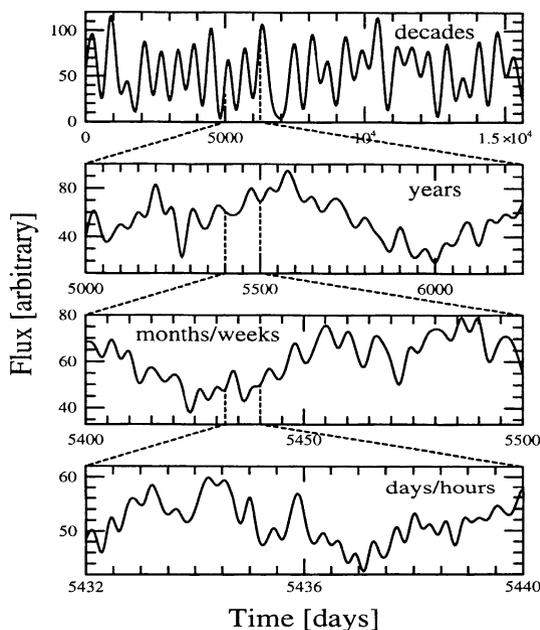


Figure 1. Schematic light curves of AGNs on different timescales.

3. Amplitudes of the variations over less than years decrease as the timescales become shorter.

To understand these features above in a statistical way, we often use the power-spectral density (PSD) and the structure function (SF). Observed PSD generally shows a power-law decline which is proportional to  $f^{-\alpha}$ . That corresponds to the fact that most AGN light curves show no typical timescale and the amplitudes of the variations decrease as the timescales become shorter. The power-law index ( $\alpha$ ) ranges from 1.5 to 2.0 (e.g. Leighly & O'Brien 1997; Hayashida et al. 1998). This index includes valuable information and is useful to discriminate among possible theoretical models. Generally, SF also has a power-law index,  $\beta$ , which is related to  $\alpha$  by  $\alpha = 1 + 2\beta$  (§2.1). On the other hand, when we analyze long light curves, we find one critical frequency ( $f_{\text{break}}$ ) under which PSD flattens and one timescale ( $\tau_{\text{var}}$ ) over which SF flattens. The frequency and timescale are related to each other [ $\tau_{\text{var}} \approx (2\pi f_{\text{break}})^{-1}$ ]. We often call  $\tau_{\text{var}}$  a (maximum) variability timescale, and typically it is around 2 - 3 years (e.g. Hook et al. 1994).

Then, the main question in this paper arises;

- **What do the variability timescale ( $\tau_{\text{var}}$ ) and the power-law index of PSD ( $\alpha$ ) or that of SF ( $\beta$ ) tell us?**

In Section 2, we focus on the question above, presenting our time series analysis of the light curves. There, we introduce the two possible models for

AGN optical variability: the disk instability model and the starburst model, and show how we can interpret the observed fluctuation properties based on the two models. Other observed properties, such as wavelength-dependence of the AGN variability, are discussed in Section 3. Finally, we summarize the conclusion and address issues remaining as future work.

## 2. Comparison of Models

In this section, we analyze light curves obtained by the observation, disk instability (DI) model (Mineshige et al. 1994), and starburst (SB) model (Aretxaga et al. 1997). The main issues are the variability timescale and power-law index of SF of AGN light curves (Kawaguchi et al. 1998).

### 2.1. Observed Fluctuation Properties

Light curves ideal for our analysis are long-term observational data over years, which have high sampling rates and good photometric accuracy. According to these criteria, we chose the optical light curve of the double quasar 0957+561 monitored by Kundić et al. (1997).

One might think that the flux variation of this macro-lensed quasar may be largely affected by microlensing events. Fortunately, however, most of the variability in this quasar is intrinsic (see Figure 4 of Kundić et al. 1997). Then, we adopt these light curves for testing models of intrinsic variability of AGNs.

Instead of PSD, we use a structure function  $[V(\tau)]$  analysis, which is almost equivalent to PSD analysis but suitable for gapped data, as is often the case in AGN light curves. In short, SF expresses a curve of growth of variability with time-lag, and when a time series of magnitude  $[m(t_i), i = 1, 2, \dots; t_i < t_j]$  is given, it is defined as

$$V(\tau) \equiv \frac{1}{N(\tau)} \sum_{i < j} [m(t_i) - m(t_j)]^2, \quad (1)$$

where summation is made over all pairs in which  $t_j - t_i = \tau$ , and  $N(\tau)$  denotes a number of such pairs.

Usually, SF shows a power-law portion at smaller time-lags,

$$[V(\tau)]^{1/2} \propto \tau^\beta. \quad (2)$$

This index  $\beta$  also contains important information concerning the variability mechanism, like a power-law index of PSD. In fact, their indices are related to each other by  $\alpha = 1 + 2\beta$  in the limit of infinite and continuous data points.

We analyzed these light curves of Q0957+561 and showed that the power-law index  $\beta$  is about 0.35 (Kawaguchi et al. 1998), which is consistent with the value known for  $\alpha$  (1.5 - 2.0). Although we can not see the turn-off in the SF, which corresponds to the variability timescale, we expect to find it around 2 - 3 years, as observed in other quasars (Hook et al. 1994), if we obtain a longer light curve.

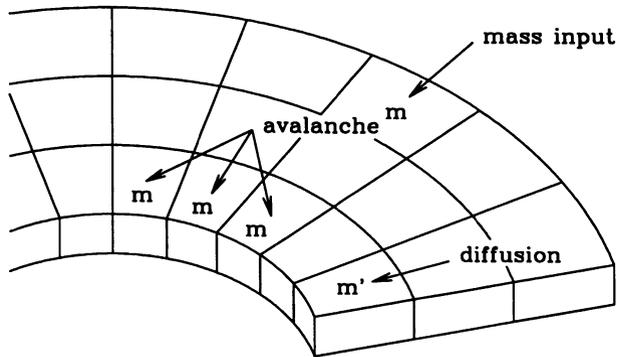


Figure 2. A schematic view of our cellular automaton model.

## 2.2. Disk-Instability Model

### *Procedure and Results*

The first model we are discussing is the disk instability model, whose original idea was proposed by Bak et al. (1988) as a sand-pile model to explain fluctuation properties of complex systems, such as earthquakes. They considered random input of sand grains onto a sand pile, and imposed a certain rule; when a slope at some site exceeds the critical value, an avalanche occurs, and the slope decreases below the critical value. Then, they found that such a system evolves to and stays at a self-organized critical (SOC) state, in which any size of avalanche flows can occur, thus producing  $1/f$ -like fluctuations.

In fact, this SOC model has been modified to the case of black-hole accretion flows and applied to X-ray variability of Cyg X-1 (Mineshige et al. 1994; Takeuchi et al. 1995). We get great success in reproducing the basic shapes of PSD and the smooth shot-size distribution.

Here, we propose that an accretion disk (or flow) of AGN also stays at an SOC state, and calculate flux variations expected by the model. There are two key assumptions. The first is that the disk is locally unstable. Probably, the local instability is of magnetic origin, leading to magnetic reconnection (Matsumoto et al. 1998). The second assumption is that each site of the disk interacts with each other via avalanche.

The procedure of our cellular-automaton simulation is as follows (Figure 2).

(i) First, we divide the disk into numerous cells. Then, we assume each cell behaves as a reservoir, which is quiescent until the mass density exceeds the critical value. In a word, even when mass input is steady, output will be episodic.

(ii) We put one mass particle ( $m$ ) at the outermost ring, which represents a mass supply to the disk.

(iii) Then, for unstable cells, where mass density exceeds a critical value, we set an avalanche flow. In other words, we move three mass ( $3m$ ) particles into inner adjacent cells.

(iv) Aside from such critical behavior, we take account of viscous diffusion ( $m'$  at each annulus). In general, effect of the diffusion is much less than avalanche flow.

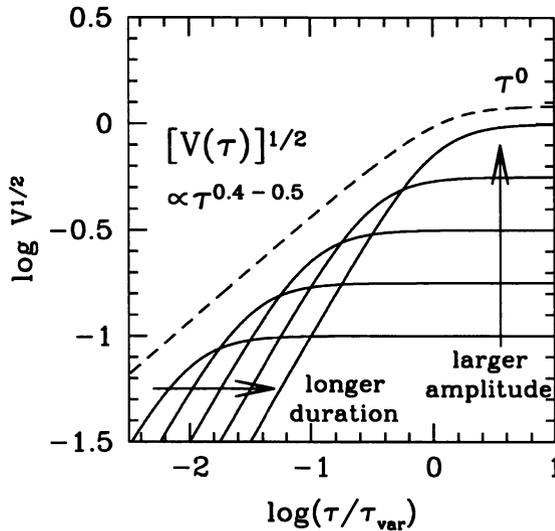


Figure 3. Typical structure function expected by the DI model (dashed line) and structure functions of individual flares (solid lines).

(v) We repeat the above procedures and we can draw the resultant light curve, assuming that the radiative energy is proportional to the potential energy released.

We calculated models for some parameter sets, finding that the resultant SFs exhibit power-law indices ( $\beta$ ) of 0.4 - 0.5, which are close to the observed value ( $\sim 0.35$ ). Here, we should remark on the robustness of the cellular-automaton rule. The results are quite insensitive to the detailed rules, such as the number of cells, number of fallen particles, and prescription of the critical mass etc. The only influential parameters are the ratio of the diffusion flow over avalanche flow,  $m'/m$ , and the size of the disk.

#### *What Determines the Power-Law Index and Variability Timescale?*

Figure 3 illustrates what determines the power-law index and variability timescale in the DI model. The dashed line represents a typical SF; a gradual ( $\beta \sim 0.4 - 0.5$ ) power-law increase at smaller time lags and a plateau over a variability timescale ( $\tau_{var}$ ). The solid lines show SFs of individual flares. In general, smooth time-symmetric flares produce steeper SFs than  $\tau^{0.5}$ , as displayed by those solid lines. Thus, in order to explain the observed gradual slope, 0.35, there must be numerous shots with a wide variety of shot-amplitude and -duration. Moreover, smaller-amplitude and shorter-duration flares should occur more frequently than larger and longer ones.

Thus, the index does not sensitively depend on the shot profile. Instead, the distribution of shot-amplitude and -duration is more important. Therefore, the index will not be largely changed even when the light curves of individual flares are modified.

According to this picture, the variability timescale is determined by the duration of the largest flare. If the fluctuating part of the disk is advection-

dominated, that duration will be of order of the free-fall timescale from the outer rim. Then, variability timescales of several hundred days roughly correspond to the size of 100 Schwarzschild radii ( $r_g$ ) for a black hole mass of  $10^8 M_\odot$ ;

$$\tau_{\text{var}} \approx \frac{r}{v_r} = 160 \left( \frac{v_r}{0.1 v_{\text{ff}}} \right)^{-1} \left( \frac{r}{10^2 r_g} \right)^{3/2} \left( \frac{M}{10^8 M_\odot} \right) \text{ day}, \quad (3)$$

where  $v_r$  and  $v_{\text{ff}}$  are radial velocity and free fall velocity, respectively.

### 2.3. Starburst Model

#### *Procedure and Results*

As an alternative model for radio-quiet AGNs, the starburst model has been investigated by Prof. Terlevich and his collaborators (e.g. Terlevich et al. 1992). According to the starburst model, optical variability is explained as superposition of supernova (SN) explosions. In the superposition, the released energy and duration of each SN explosion are varied within a factor of 2 in a Gaussian way around the mean values given a priori. As the supernova rate increases, resultant light curves are less variable in magnitude. In other words, luminous AGNs must be less variable, which roughly agrees with the observed trend (Cristiani et al. 1996; see also Paltani & Courvoisier 1997).

We followed Aretxaga et al. (1997) and calculated light curves, finding that the power-law indices  $\beta$  expected from the model are around 0.7 - 0.9, which is significantly larger than the observed value, 0.35. Although the quasar we used here for the comparison is a radio-loud object and this may not be a fair test for the starburst model, we assume that optical variability of radio-loud objects is not very different from that of radio-quiet ones.

#### *What Determines the Power-Law Index and Variability Timescale?*

Then, why are the results so different between the two models? In both models, something like shots or flare-like events are superposed almost randomly in the light curves. The critical point is that in the SB model there will not be large variation in the shot-amplitude and -duration over many orders of magnitude; timescales and released energies of each explosion can vary only by some factor. This is the substantial difference from the disk instability model.

As a result, both the timescale and power-law index of SF are determined by a typical light curve of SN explosions, as shown in Figure 4.

To produce the gradual index in the SF, we need much shorter events; for instance, SN explosions decaying over days. This is probably not the case in the actual situation. It is possible that a thermal instability within SN remnants may change the typical light curve to fluctuate more over short timescales (Cid Fernandes et al. 1996), so that the resultant power-law index will be consistent with the observed one.

### 3. Other Issues

We have focused on the AGN light curve itself, with structure function analysis. In this section, we will discuss several related issues, especially the wavelength dependency of the variability.

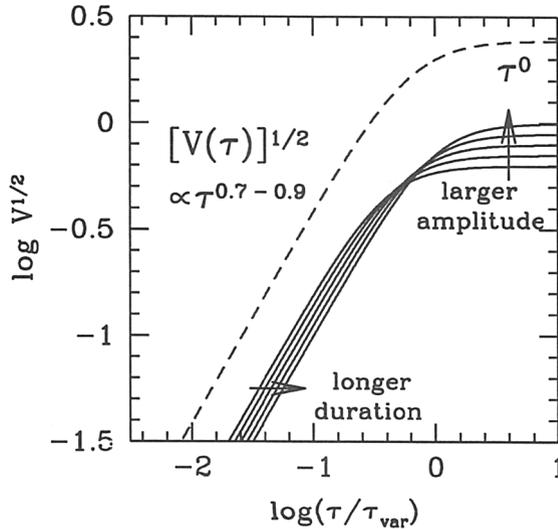


Figure 4. Typical structure function expected by the SB model (dashed line) and structure functions of individual explosions (solid lines).

First, there is a clear anti-correlation between fractional amplitudes and observed wavelength (e.g. Di Clemente et al. 1996). In other words, flux at shorter wavelength varies with larger amplitudes, compared to that at longer wavelength. It is also known that optical/UV continuum becomes “harder” as it gets brighter (Maoz et al. 1993; Peterson et al. 1994; Trèvese 1998). These properties should contain important clues to the understanding of the physics and site of variability generation. However in dealing with the spectral variability, we must be careful about the mixture of numerous emission lines and Balmer continuum, and also contaminations of other components.

Next, the flux variations at different wave-bands are almost simultaneous (e.g. Edelson et al. 1996), but recently it is reported that there seem to exist some lags by several days or less than a day; (i) Optical variations tend to lag behind UV variations by  $\sim 1$  day (Peterson et al. 1998; Courvoisier 1998) (ii) Flux variations of NGC 7469 in UV band sometimes lead X-ray ones by  $\sim 4$  days and sometimes they are simultaneous (Nandra et al. 1998).

In tentative pictures for central engines of AGNs, such as a cold accretion disk with hot corona or cold clouds within a hot corona, we had expected that X-ray variations lead Opt./UV variations, if we could detect such small lags. The new results of Nandra et al. (1998) are challenging to the tentative pictures. Thus, it is a good time to construct a wavelength-dependent model of AGN variability including an anti-correlation of wavelength – variation amplitude and spectral variability.

#### 4. Summary

(1) As far as the power-law index in structure functions is concerned, the disk instability model is favored, since this model can produce a wide variety of shot-amplitudes and -durations, as found in observed light curves.

(2) Observed variability timescales and power-law indices are the key properties to testing models.

(3) Constructing a wavelength and time dependent model of AGNs remains as future work.

**Acknowledgments.** One of the authors (TK) is grateful to Prof. Edward Khachikian for the invitation to this stimulating conference. He also thanks the Yamada Science Foundation for financial support.

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