TESTS FOR STANDARD ACCRETION DISK MODELS BY VARIABILITY IN ACTIVE GALACTIC NUCLEI

H. T. Liu, J. M. Bai, X. H. Zhao, and L. Ma

ABSTRACT

In this paper, standard accretion disk models of active galactic nuclei (AGNs) are tested using light curves of 26 objects that have been well observed using reverberation mapping. Timescales of variations are estimated by the most common definition of the variability timescale and the zero-crossing time of the autocorrelation function of the optical light curves for each source. The timescales of variations measured by the two methods are consistent with each other. If the typical value of the viscosity parameter $\alpha \sim 0.1$ is adopted, the measured optical variability timescales are closest to the thermal timescales of the standard disks. If $\alpha$ is allowed to range from $\sim 0.03$ to $\sim 0.2$, the measured timescales are consistent with the thermal timescales of the standard disks. There is a linear relation between the measured variability timescales and black hole masses; this linear relation is qualitatively consistent with expectation of the standard accretion disk models. The time lags measured by the $z$-transformed discrete correlation function (ZDCF) between different bands are on the order of days. The measured time lags of NGC 4151 and NGC 7469 are marginally consistent with the time lags estimated in the case of continuum thermal reprocessing for the standard accretion disk models. However, the measured time lags of NGC 5548 and Fairall 9 are unlikely to be the case of continuum thermal reprocessing. Our results are unlikely to be inconsistent with, or are likely to be conditionally in favor of, the standard accretion disk models of AGNs.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: Seyfert — quasars: general

1. INTRODUCTION

Large flux variations on timescales from hours to years are common in active galactic nuclei (AGNs), and longer timescale variations of the order of months to years may be related to the propagation of the shorter timescale variations (e.g., Ulrich et al. 1997). The combination of high flux variability and short variability timescales implies that the energy conversion in AGNs is more efficient than the ordinary stellar processes. Accretion of matter onto a black hole can have high energy release efficiency (Rees et al. 1982; Rees 1984). The evidence that AGNs such as quasars and Seyfert galaxies are powered by gravitational accretion of matter onto supermassive black holes is now quite convincing. Certainly there has been no definitive detection of the relativistic effects that would be required for unambiguous identification of a singularity, although studies of the iron K $\alpha$ emission line in the X-ray spectra of AGNs currently provides some promise (e.g., Reynolds & Nowak 2003).

In general optical-UV radiations of most non-blazar-type sources are within the so-called big blue bump. The optical variability is characterized as poorly understood, but it is nevertheless recognized as a means of probing physical scales that cannot be resolved spatially by any telescope or instrument (e.g., Netzer & Peterson 1997; Peterson et al. 2004; Wold et al. 2007). A number of models have been proposed to explain optical-UV quasar variability. One way of attempting to help constrain the proposed models is to find relationships between variability and other parameters of AGNs, such as black hole mass. The black hole mass is a fundamental parameter of AGNs, and the discovery of such a relationship—or lack thereof—may provide useful clues to the physical mechanisms behind the variability (e.g., Wold et al. 2007). Processes intrinsic to the central engine itself could dominate. Wold et al. (2007) investigated the dependence of quasar variability on black hole mass and found that black hole mass correlates with the measured variability amplitude. A number of models for quasar optical variability exist, but there are no clear predictions relating black hole mass and variability amplitude. Different sources of optical variations could be associated with different characteristic timescales, and many of these timescales depend on black hole mass. Collier & Peterson (2001) attempted to define a relationship between black hole mass and characteristic variability timescale. After studying 10 well-monitored AGNs, they reported evidence of black hole mass correlating with characteristic optical variability timescales that are roughly consistent with accretion disk thermal timescales.

The standard accretion disk is the basic model for a radiatively efficient, geometrically thin, optically thick disk (Shakura & Sunyaev 1973). In the standard picture this accretion disk radiates thermally mainly in the optical-UV bands for AGNs with black hole masses of $\sim 10^8 - 10^9 M_{\odot}$. AGNs with black hole masses of $\sim 10^7 - 10^9 M_{\odot}$ would be expected to have accretion disk thermal characteristic timescales of the order of months to years. Many investigations based on central radiations from thin accretion disks have been done (e.g., Ebisawa et al. 1991; Hanawa 1989; Li et al. 2005; Pereyra et al. 2006; Zimmerman et al. 2005). Connections between jets and disks, a very important aspect of AGN research, have been investigated on the basis of standard accretion disks (e.g., Meier 2001, 2002). Although many investigations are based on standard disks, only a few investigations aim at testing standard accretion disk models with observations. Collier et al. (1998) briefly discussed the relation of time delays between the UV and optical continuum variations with the accretion disk in NGC 7469. It is believed that for non-blazar-type AGNs the optical-UV emissions are produced thermally from accretion disks. The radiation energies of thermal emissions from accretion disks are from two possible contributions. One well-known origin is the local viscous dissipation in accretion disks. This local viscous dissipation can produce the local thermal
equilibrium, and then the local blackbody emissions (e.g., Krolik 1999). Another origin is the reprocessed X-rays. The X-rays are commonly attributed to Compton upscattering of the thermal UV photons produced by the viscous dissipation (e.g., Sunyaev & Titarchuk 1980; Haardt & Maraschi 1991). In the case of thermal emissions from viscous dissipation, the accretion flow fluctuations traveling inward across the emitting regions affect first the optical-emitting region at outer radii and then the UV-emitting region at inner radii. Thus, the longer wavelength variations are likely to lead the shorter wavelength ones. If the radial temperature profiles of accretion disks are not set primarily by viscous effects but by irradiation from the central X-ray sources, the longer wavelength variations are likely to lag the shorter wavelength ones for thermal emissions from continuum thermal reprocessing. The flux variability must occur on a physical timescale that is consistent with the chosen model. The timescales of interest are the light crossing, dynamical, thermal, and sound crossing timescales that are set by the black hole mass (Frank et al. 2002), and the order-of-magnitude scales are

\[ \tau_l = 6M(B)\xi, \quad \text{days}, \]  
\[ \tau_{\text{dyn}} = 6M(B)\xi^{3/2}, \quad \text{months}, \]  
\[ \tau_h = \frac{\tau_{\text{dyn}}}{\alpha} = 5M(B)\xi^{3/2}, \quad \text{yr}, \]  
\[ \tau_r = 70M(B)\xi^{3}T^{-1/2}, \quad \text{yr}, \]

where \( M(B) = M(B)/10^8 M_\odot, \alpha \approx 0.1 \) is the Shakura-Sunyaev viscosity parameter (Shakura & Sunyaev 1973), \( T = T/10^8 \) K, and \( \xi = r_g/10^2 r_d \) (where \( r_d \) is the disk radius, \( r_g = GM/Bc^2 \) the gravitational radius). In order to determine which physical mechanism is responsible for the variability and to test standard accretion disk models, it is necessary to connect the observed variability timescales with one of the above physical timescales and to search the correlation of black hole masses with characteristic optical variability timescales, and it is important to compare the observed time lags between different bands with the theoretical values predicted by the standard accretion disk models.

The structure of this paper is as follows. The sample and data are in § 2. The calculations of the temperature profiles are described in § 3. Section 4 presents variability timescales and time lags. Section 4.1 is an analysis of variability timescale, § 4.2 an analysis of time lag, and § 4.3 a comparison to models. Section 5 presents discussions and conclusions. Throughout this paper, we use a flat cosmology with a deceleration factor \( q_0 = 0.5 \) and a Hubble constant \( H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1} \).

### 2. The Sample and Data

The objects listed in Table 1 are based on the samples analyzed by Kaspi et al. (2000) and Peterson et al. (2004), but the light-curve data come from a variety of sources. The rest-frame wavelengths and references for the light curves are listed in columns (3) and (4) of Table 1, respectively. The optical variability timescales are estimated by the light curves around 5100 Å. There are four objects, Fairall 9, NGC 4151, NGC 5548, and NGC 7469, that have multicomponent light curves well observed at the optical-UV bands. The multicomponent light curves are used to estimate time lags for the four objects.

The black hole masses for AGNs have been well estimated by the reverberation mapping technique (e.g., Kaspi et al. 2000, 2005; Peterson et al. 2004, 2005; Vestergaard & Peterson 2006). The masses of the central black holes of quasars span a large range of \( 10^7 M_\odot \leq M_{BH} \leq 3 \times 10^9 M_\odot \) and have an upper limit of \( M_{BH} < 10^{10} M_\odot \) (McLure & Dunlop 2004; Vestergaard 2004). The black hole masses used in this paper are taken from Peterson et al. (2004) and are listed in column (5) of Table 1. The bolometric luminosity \( L_{bol} \) of all objects except for Mrk 279 are taken from Woo & Urry (2002), and are listed in column (6) of Table 1. The bolometric luminosity of Mrk 279 is estimated by \( L_{bol} \approx 9L_\nu (5100 \text{ Å}) \) (Kaspi et al. 2000), with \( \nu L_\nu (5100 \text{ Å}) \) taken from Peterson et al. (2004).

| Table 1 | Sample and Data |
|---------|-----------------|
| Object (1) | z (2) | \( \lambda \) (Å) | Refs. (3) | \( M_{BH} \) (10^8 M_\odot) | \( L_{bol} \) (ergs s\(^{-1}\)) |
| ---------- | ----- | ------ | ------ | ----- | ------ |
| PG 0026+129 | 0.142 | 5100 | 1, 2 | 3.93 | 45.39 |
| PG 0052+251 | 0.155 | 5100 | 1, 2 | 3.69 | 45.93 |
| Fairall 9 | 0.047 | 5340 | 3 | 2.55 | 45.23 |
| 1880 | 4 |
| 1300 | 4 |
| PG 0804+761 | 0.100 | 5100 | 1, 2 | 6.93 | 45.93 |
| PG 0844+349 | 0.064 | 5100 | 1, 2 | 9.24 | 45.36 |
| PG 0953+414 | 0.239 | 5100 | 1, 2 | 2.76 | 46.16 |
| NGC 3783 | 0.010 | 5150 | 5 | 0.30 | 44.41 |
| NGC 4051 | 0.002 | 5100 | 6 | 0.02 | 43.56 |
| NGC 4151 | 0.003 | 5125 | 7 | 0.13 | 43.73 |
| 2688 | 8 |
| 1440 | 8 |
| 1275 | 8 |
| PG 1211+143 | 0.085 | 5100 | 1, 2 | 1.46 | 45.81 |
| PG 1226+023 | 0.158 | 5100 | 1, 2 | 8.86 | 47.35 |
| PG 1229+204 | 0.064 | 5100 | 1, 2 | 0.73 | 45.01 |
| PG 1307+085 | 0.155 | 5100 | 1, 2 | 4.40 | 45.83 |
| Mrk 279 | 0.030 | 5100 | 9 | 0.35 | 44.83 |
| PG 1351+640 | 0.087 | 5100 | 1, 2 | 0.46 | 45.50 |
| PG 1411+442 | 0.089 | 5100 | 1, 2 | 4.43 | 45.58 |
| NGC 5548 | 0.017 | 5150 | 10 | 0.67 | 44.83 |
| 2787 | 11 |
| 2441 | 11 |
| 2237 | 11 |
| 1841 | 11 |
| 1749 | 11 |
| 1378 | 11 |
| PG 1426+015 | 0.086 | 5100 | 1, 2 | 12.98 | 45.19 |
| PG 1613+658 | 0.129 | 5100 | 1, 2 | 2.79 | 45.66 |
| PG 1617+175 | 0.114 | 5100 | 1, 2 | 5.94 | 45.22 |
| PG 1700+518 | 0.292 | 5100 | 1, 2 | 7.81 | 46.56 |
| PG 1704+608 | 0.371 | 5100 | 1, 2 | 0.37 | 46.33 |
| 3C 390.3 | 0.056 | 5177 | 12 | 2.87 | 44.88 |
| Mrk 509 | 0.034 | 5100 | 13 | 1.43 | 45.03 |
| PG 2130+099 | 0.061 | 5100 | 1, 2 | 4.57 | 45.47 |
| NGC 7469 | 0.016 | 4845 | 14 | 0.12 | 45.28 |
| 6962 | 14 |
| 1825 | 15 |
| 1740 | 15 |
| 1485 | 15 |
| 1315 | 15 |

Notes.—Col. (1): Name. Col. (2): Redshift. Col. (3): Rest-frame wavelengths of the light curves. Col. (4): References for the light curves. Col. (5): Black hole mass. Col. (6): Log of the bolometric luminosity.
3. CALCULATIONS OF TEMPERATURE PROFILES

The local effective temperatures of accretion disks are functions of radii $r_g$, black hole mass $M_{BH}$, spin $a_\ast$, and mass accretion rate $M$ (e.g., Ebisawa 1991; Hanawa 1989; Kubota et al. 2005; Li et al. 2005; Pereyra et al. 2006; Shakura & Sunyaev 1973; Zimmerman et al. 2005). The standard accretion disk is the basic model for a radiatively efficient, geometrically thin disk. If the central black holes are Kerr ones, the local effective temperature of the standard disk is given in the Kerr metric as (Krolik 1999)

$$T_{\text{eff}}(X_d) = \left[ \frac{3GM_{BH}M}{8\pi \sigma_{SB} r_g^2 X_d} \right]^{1/4} ,$$

where $\sigma_{SB}$ is the Stefan-Boltzmann constant, $G$ is the gravitational constant, $M$ is the mass accretion rate of the central black hole, $M_{BH}$ is the central black hole mass, and $X_d = r_d/r_g$ is the disk radius in units of the gravitational radius $r_g$. The function $R_g(X_d)$ in equation (5) is defined as

$$R_g(X_d) = \frac{C(X_d)}{B(X_d)} ,$$

where the functions $B(X_d)$ and $C(X_d)$ are, respectively, (Krolik 1999)

$$B(X_d) = 1 - \frac{3}{X_d} + \frac{2a_\ast}{X_d^{3/2}} ,$$

$$C(X_d) = 1 - \frac{y_{ms}}{y} - \frac{3a_\ast}{2y_{ms}} \ln \left( \frac{y_{ms}}{y} \right)$$

$$- \frac{3(y_1 - a_\ast)^2}{yy_1 (y_1 - y_2)(y_1 - y_3)} \ln \left( \frac{y_{ms} - y_1}{y_{ms} - y} \right)$$

$$- \frac{3(y_2 - a_\ast)^2}{yy_2 (y_2 - y_1)(y_2 - y_3)} \ln \left( \frac{y_{ms} - y_2}{y_{ms} - y} \right)$$

$$- \frac{3(y_3 - a_\ast)^2}{yy_3 (y_3 - y_1)(y_3 - y_2)} \ln \left( \frac{y_{ms} - y_3}{y_{ms} - y} \right) ,$$

where $y = (X_d)^{1/2}, a_\ast = cJ/GM_{BH}^2$ is the dimensionless spin parameter of the central black hole with spin angular momentum $J$, $y_{ms} = (X_{ms})^{1/2}$ is the value of $y$ at the marginally stable orbit, and $y_1,2,3$ are the three roots of $y^3 - 3y + 2a_\ast = 0$ (e.g., Krolik 1999; Reynolds & Nowak 2003).

Assuming prograde orbits, the radii of the marginally stable orbits in the equatorial plane of a Kerr black hole are (Bardeen et al. 1972)

$$X_{ms} = 3 + Z_2 - [(3 - Z_1)(3 + Z_1 + 2Z_2)]^{1/2} ,$$

where

$$Z_1 = 1 + (1 - a_\ast^2)^{1/3} \left[ (1 + a_\ast)^{1/3} + (1 - a_\ast)^{1/3} \right] ,$$

$$Z_2 = (3a_\ast^2 + Z_1^{1/2})^{1/2} .$$

The marginally stable orbits in the equatorial plane correspond to the maximum efficiency of energy release as a result of accretion, assuming prograde orbits (Kembhavi & Narlikar 1999, p. 107):

$$\eta_{\text{max}} = 1 - \frac{X_{ms} - 2 + a_\ast X_{ms}^{-1/2}}{\sqrt{X_{ms} (X_{ms} - 3 + 2a_\ast X_{ms}^{-1/2})}} .$$

According to the definition of the efficiency $\eta$ with which various types of black holes convert rest-mass energy into outgoing radiation (Thorne 1974), the mass accretion rate of the central black hole can be estimated by the formula

$$\dot{M} = \frac{L_{\text{bol}}}{\eta_{\text{max}} C^2} .$$

The dimensionless spin parameter of a black hole can take on any value in the range $-1 \leq a_\ast \leq 1$, where negative values of $a_\ast$ correspond to a black hole that retrogrades relative to its accretion disk. For simplicity we consider only prograde spins up to the Thorne spin equilibrium limit, i.e., $0 \leq a_\ast \leq 0.989$ (Thorne 1974). The limiting value of $a_\ast = 0.998$ for black hole spins was first discussed in Thorne (1974). Recent work on magnetohydrodynamic accretion disks suggests a rather lower equilibrium spin (e.g., Gammie et al. 2004; Krolik et al. 2005). It has been suggested that spin equilibrium is reached at $a_\ast \approx 0.9$ through accretion of gases onto the central black holes, and mergers of black holes with comparable mass can result in a final spin of $a_\ast \approx 0.8-0.9$ (Gammie et al. 2004). Krolik et al. (2005) suggested that equilibrium spins as low as $a_\ast < 0.9$ are within the realm of possibility. Brenneman & Reynolds (2006) obtained a formal constraint on the dimensionless black hole spin parameter $a_\ast = 0.989_{-0.002}^{+0.009}$ at 90% confidence for the Seyfert galaxy MCG –06-30-15. A value of $a_\ast = 0.9939_{-0.0072}^{+0.0026}$ for the Galactic center black hole is obtained by Aschenbach et al. (2004). Considering the probable ranges of spin parameter $a_\ast$, suggested above, we take four values of $a_\ast = 0.5, 0.8, 0.9, \text{and } 0.998$ in the Kerr metric to calculate the temperature profiles. By combining equations (5)–(13) and the parameters of $M_{BH}$, $L_{\text{bol}}$, and $a_\ast$, we can calculate the surface effective temperature profiles.

The local effective temperature in equation (5) is arrived by assuming local thermal equilibrium (LTE) in the disk. A consequence of the LTE radiation assumption is that a specific photon frequency $\nu$ maps to a specific radius $r_{\nu}$ in the disk. According to the discussion in Krolik (1999, see eq. [7.53] on p. 155), most of the light at frequency $\nu$ is emitted near the radius $r_{\nu}$ for the local blackbody. Thus, the optical spectrum can still be dominated by emission from the outer radii, and the UV spectrum can be dominated by emission from the inner radii. So variations in the outer disk might manifest themselves significantly in the observed spectrum.

4. VARIABILITY TIMESCALE AND TIME LAG

Two methods are applied to analysis of the variability timescale. One is the most common definition of the variability timescale (e.g., Wagner & Witzel 1995). Another is a well-defined quantity, the zero-crossing time of the autocorrelation function of the light curves. Time lags are analyzed by the z-transformed discrete correlation function (ZDCF; Alexander 1997). Then the analysis results are compared to predctions of accretion disk models.

4.1. Analysis of Variability Timescale

The variability timescales have been defined in different ways. The most common definition of the variability timescale, $\tau = F/|\Delta F/\Delta t|$, and the more conservative approach, $\tau = |\Delta t/\Delta \ln F|$, have the advantage of weighting fluctuations by their amplitudes, where $F$ is the flux, and $\Delta F$ is the variability amplitude in the timescale $\Delta t$ (e.g., Wagner & Witzel 1995). Here we use the most common definition of the variability timescale, $\tau = F/|\Delta F/\Delta t|$, where $F$ is taken as the flux at the minimum. In this paper, we refer to the interval between subsequent local minima and maxima at
| Object          | $\tau_{(1+z)}$ (days) | $\tau_{h(1+z)}$ (days) | $\tau_{f}$ (days) | $\tau_{df}$ (days) | $\tau_{d}$ (days) | $\tau_{f}$ (days) | $\tau_{s}$ (days) |
|----------------|-----------------------|------------------------|------------------|-------------------|-----------------|-----------------|-----------------|
| PG 0026        | 343.6 ± 1.6           | 182.7^{+9.2}_{-5.5}   | 1.20             | 8.22              | 84.01           | 2.14 x 10^4     |
| PG 0052        | 242.5 ± 1.8           | 326.4^{+10.5}_{-6.4}  | 1.85             | 16.44             | 164.36          | 3.31 x 10^4     |
| Fairall 9      | 160.8 ± 0.3           | 110.6^{+8.8}_{-2.6}   | 1.00             | 7.91              | 76.70           | 1.83 x 10^4     |
| PG 0804        | 385.5 ± 0.7           | 497.0^{+7.2}_{-5.2}   | 2.20             | 15.52             | 153.41          | 3.93 x 10^4     |
| NGC 3783       | 38.2 ± 2.8            | 29.5^{+0.20}_{-0.14}  | 0.26             | 3.04              | 29.22           | 4.69 x 10^3     |
| NGC 4051       | 120.3 ± 0.05          | 165.4^{+0.30}_{-0.40} | 0.06             | 1.22              | 10.96           | 1.02 x 10^4     |
| NGC 4151       | 70.4 ± 0.6            | 45.0^{+0.13}_{-0.20}  | 0.12             | 1.52              | 14.61           | 2.10 x 10^3     |
| PG 1211        | 237.1 ± 0.8           | 533.4^{+11.9}_{-3.8}  | 1.28             | 14.91             | 149.75          | 2.29 x 10^4     |
| PG 1226        | 314.4 ± 5.7           | 401.2^{+5.5}_{-2.6}   | 7.61             | 87.66             | 876.60          | 1.36 x 10^5     |
| PG 1229        | 124.5 ± 4.3           | 143.0^{+1.8}_{-2.2}   | 0.55             | 5.78              | 58.44           | 9.76 x 10^3     |
| PG 1307        | 234.2 ± 7.7           | 294.8^{+4.3}_{-3.6}   | 1.79             | 14.31             | 142.45          | 3.20 x 10^4     |
| Mrk 279        | 86.5 ± 2.9            | 76.5^{+0.91}_{-0.15}  | 0.38             | 4.87              | 47.48           | 8.62 x 10^3     |
| PG 1351        | 423.6 ± 1.7           | 476.4^{+1.9}_{-2.8}   | 0.70             | 10.96             | 109.58          | 1.26 x 10^4     |
| PG 1411        | 317.4 ± 1.4           | 356.6^{+4.1}_{-2.5}   | 1.45             | 10.35             | 102.27          | 2.60 x 10^4     |
the adjacent valleys and peaks in the entire light curve. First, we select a valley and subsequent peak that are sufficiently dense sampled in one light curve. Second, we require variations of $\Delta F/F \geq 30\%$ between the subsequent minimum and maximum within the timescale $\Delta \tau$. The estimated values of $\tau$ are listed in column (2) of Table 2. The uncertainty on the values of $\tau$ are estimated by the relation

$$
\sigma_\tau = \Delta\tau (\sigma_{\Delta F} | \Delta F | - F_{\text{min}} | \sigma_{\Delta F} - \sigma_{\text{F_{min}}}| | \Delta F |^{-2},
$$

where $\Delta F = F_{\text{max}} - F_{\text{min}}$, $\sigma_{\Delta F}$ is the observed error of $F_{\text{max}}$, and $\sigma_{\text{F_{min}}}$ is the observed error of $F_{\text{min}}$.

For most AGNs, it is difficult to define a single characteristic variability timescale. One approach to a single timescale is described by Giveon et al. (1999). Their definition is given as the zero-crossing time of the autocorrelation function (ACF). If there is an underlying signal with a typical variability timescale in the light curve, the width of the ACF peak near zero time lag will be proportional to this variability timescale (e.g., Giveon et al. 1999; Netzer et al. 1996). This zero-crossing time of the ACF, $\tau_0$, is a well-defined quantity and is used as a characteristic variability timescale (e.g., Alexander 1997; Giveon et al. 1999; Netzer et al. 1996). Another function used in variability studies to estimate the variability timescale is the first-order structure function (SF; e.g., Trevese et al. 1994). There is a simple relation between the ACF and the SF (see eq. [8] in Giveon et al. 1999). Therefore, only an ACF analysis is performed on our light curves. Comparison of $\tau$ with $\tau_0$ is performed to test the reliability of the variability timescale listed in column (2) of Table 2. The ACF is estimated by the ZDCF (Alexander 1997). It has been shown that this method

| Object        | $\tau(1+z)$ (days) | $\tau_0(1+z)$ (days) | $\tau_1$ (days) | $\tau_{\text{dyn}}$ (days) | $\tau_{\text{th}}$ (days) | $\tau_0$ (days) |
|---------------|--------------------|----------------------|----------------|---------------------------|---------------------------|----------------|
| NGC 5548      | 45.1 ± 1.1         | 141.5 ± 7.1          | 0.96           | 5.48                      | 54.79                     | 1.71 × 10^4     |
| PG 1426       | 638.7 ± 1.9        | 852.0 ± 20.2         | 0.38           | 3.35                      | 36.53                     | 6.86 × 10^3     |
| PG 1613       | 309.5 ± 1.2        | 232.1 ± 7.5          | 1.22           | 4.57                      | 47.48                     | 2.17 × 10^4     |
| PG 1617       | 277.9 ± 3.6        | 187.9 ± 6.1          | 1.12           | 8.83                      | 87.66                     | 2.01 × 10^4     |
| PG 1700       | 470.4 ± 87.4       | 419.3 ± 12.2         | 3.85           | 33.48                     | 336.03                    | 6.88 × 10^3     |
| PG 1704       | 286.7 ± 5.9        | 389.1 ± 8.8          | 1.27           | 29.22                     | 292.20                    | 2.27 × 10^4     |
| 3C 390.3      | 143.8 ± 0.6        | 50.6 ± 0.3           | 0.73           | 4.57                      | 47.48                     | 1.32 × 10^4     |
| Mrk 509       | 258.7 ± 1.0        | 181.0 ± 2.2          | 0.67           | 5.78                      | 58.44                     | 1.20 × 10^4     |
| PG 2130       | 319.0 ± 12.3       | 332.9 ± 11.0         | 1.28           | 8.52                      | 84.01                     | 2.28 × 10^4     |
| NGC 7469      | 74.9 ± 0.8         | 4.5 ± 0.02           | 0.36           | 7.91                      | 80.36                     | 6.33 × 10^3     |

Notes.—Col. (1): Name. Col. (2): Variability timescale at the optical band. Col. (3): Variability timescale obtained by the zero-crossing time of the ACF estimated by the ZDCF. Col. (4): Light crossing timescales. Col. (5): Dynamical timescales. Col. (6): Thermal timescales. Col. (7): Sound crossing timescales. For each object, the first, second, third, and forth values listed in columns (4)–(7) are calculated from the standard accretion disks under the Kerr metric with spin parameter $a_r = 0.5, 0.8, 0.9, and 0.998$, respectively.
is statistically robust even when applied to very sparsely and irregularly sampled light curves (Alexander 1997). The ZDCF was calculated for all of the light curves used to estimate $\tau$. Following Giveon et al. (1999), a least-squares procedure is used to fit a fifth-order polynomial to the ZDCF, and the ZDCF fit is used to evaluate the zero-crossing time in the observer’s frame. The evaluated results are listed in column (3) of Table 2. For one light curve, the ZDCF code of Alexander (1997) can automatically set how many bins are given and used to calculate the one light curve, the ZDCF code of Alexander (1997) can automatically set how many bins are given and used to calculate the ACF. However, this code cannot estimate the ACF. Thus, the time lag and its uncertainty are immediately given.

For comparison, we plotted $\tau$ versus $\tau_0$ in Figure 1. It can be seen in Figure 1 that the data points are basically shared by two sides of the line $\tau_0 = \tau$. The linear regression analysis shows that there is a correlation between $\tau$ and $\tau_0$ with Pearson correlation coefficient $r = 0.766$ at the chance probability $P = 5.1 \times 10^{-6}$. The regression line fit by the ordinary least-squares bisector regression analysis (Isobe et al. 1990) is

$$\frac{\tau}{1 + z} = -\left(96.1 \pm 33.8\right) + \left(1.5 \pm 0.3\right)\frac{\tau}{1 + z}, \quad (14)$$

where $z$ is the redshift, and $\tau$ and $\tau_0$ are in units of days. This suggests that $\tau$ and $\tau_0$ are acceptable for characterizing the typical variability timescale, and that the estimated results for $\tau$ listed in column (2) of Table 2 are reliable.

### 4.2. Analysis of Time Lag

Cross-correlation function (CCF) analysis is a standard technique in time series analysis for finding time lags between light curves at different wavelengths, and the definition of the CCF assumes that the light curves are uniformly sampled. However, in most cases the sampling is not uniform. The interpolated cross-correlation function (ICCF) method of Gaskell & Peterson (1987) uses a linear interpolation scheme to determine the missing data in the light curves. On the other hand, the discrete correlation function (DCF; Edelson & Krolik 1988) can utilize a binning scheme to approximate the missing data. Apart from the ICCF and DCF, there is another method of estimating the CCF in the case of non-uniformly sampled light curves, the $z$-transformed discrete correlation function (Alexander 1997). The ZDCF was used as an estimation of the ACF in $\S$ 4.1; here it is used as an estimation of the CCF. The ZDCF is a binning type of method as an improvement of the DCF technique, but it has a notable feature in that the data are binned by equal population rather than equal bin width $\Delta \tau$ as in the DCF. It has been shown in practice that the calculation of the ZDCF is more robust than that of the ICCF and the DCF when applied to sparsely and unequally sampled light curves (e.g., Edelson et al. 1996; Giveon et al. 1999; Roy et al. 2000). The ZDCF is calculated in this paper.

In general, it seems to be true that the time lag is better characterized by the centroid $\tau_{cent}$ of the DCF and the ICCF than by the peak $\tau_{peak}$, namely, the time lag where the linear correlation coefficient has its maximum value $r_{max}$ (e.g., Peterson et al. 2004, 2005). In both the DCF and the ICCF $\tau_{peak}$ is much less stable than $\tau_{cent}$, but $\tau_{peak}$ is much more stable in the DCF than in the ICCF (Peterson et al. 2005). Thus, we prefer the time lag estimated from the ZDCF method to be characterized by the centroid $\tau_{cent}$ of the ZDCF, for the ZDCF is an improvement of the DCF method. The centroid time lags $\tau_{cent}$ are computed using all points with correlation coefficients $r \geq 0.8 r_{max}$, and the uncertainties in the time lags of data points in the ZDCF are computed with a large number (1000) of Monte Carlo realizations. The ZDCFs of four objects are presented in Figures 2–5, and the measured time lags are listed in column (4) of Table 3.

### 4.3. Comparison to Models

There is a correlation between the black hole mass $M_B$ and the measured characteristic variability timescale $\tau$ with Pearson correlation coefficient $r = 0.760$ at the chance probability $P = 6.6 \times 10^{-6}$ (see Fig. 6). The regression lines fit by the bisector regression analysis are

$$\frac{\tau}{1 + z} = \left(0.27 \pm 0.04\right) + \left(0.12 \pm 0.02\right)M_B \text{ yr}. \quad (15)$$

If $r_\alpha \sim 100 r_\alpha$ in equation (3) with viscosity parameter $\alpha = 0.1$, there is a relation of $\tau_{\alpha} \sim 0.15 M_B$. Although the intercept in equation (15) differs from the intercept predicted by equation (3), this predicted slope of $\sim 0.15$ is consistent with that in equation (15). This indicates that the linear correlation between black hole mass and characteristic variability timescale is qualitatively consistent with the expectation of equation (3) that the thermal
Fig. 3.—ZDCF for NGC 4151, (a) between the 2688 and 1440 Å light curves, and (b) between 2688 and 1275 Å.

Fig. 4.—ZDCF for NGC 5548, between (a) 2441 and 1749 Å, (b) 2441 and 1378 Å, (c) 2787 and 1378 Å, (d) 2787 and 1841 Å, (e) 2441 and 1841 Å, (f) 2237 and 1749 Å, (g) 1841 and 1378 Å, (h) 2237 and 1378 Å, (i) 2237 and 1841 Å, and (j) 2787 and 1749 Å.
timescale is essentially linearly related with the black hole mass. Thus, equation (15) is qualitatively consistent with the expectations of the standard accretion disk models.

According to the standard accretion disk models, the optical-UV emissions are produced thermally in accretion disks. The standard accretion disk models are used to estimate the radii of maximum optical-UV emissions. We consider the accretion disk to be composed of rings with approximately uniform temperature radiating locally as a blackbody, and estimate the radii of maximum flux emission at different wavelengths using a disk radial temperature profile given by equation (5). Then the light crossing, dynamical, thermal, and sound crossing timescales are estimated by equations (1)–(4), respectively, assuming viscosity parameter \( \alpha = 0.1 \). The calculated results are presented in columns (4)–(7) of Table 2, respectively. It can be seen from columns (2)–(7) of Table 2 that the thermal timescales are closest to the optical variability timescales, but the light crossing and dynamical timescales are much smaller than the measured timescales. This might indicate that the optical variations result from the thermal instability in accretion disks or a mechanism related to it. Although, it cannot be affirmed that the optical variations result from the accretion disk thermal instability, the linear relation presented in equation (15) is qualitatively consistent with the expectation of equation (3) that the thermal timescale is essentially linearly related with the black hole mass. These above results are obtained by adopting the viscosity parameter \( \alpha = 0.1 \) for each source in our sample. In practice, various values of \( \alpha \) are suggested and used in investigations (e.g., Afshordi & Paczynski 2003; Khajenabi & Shadmehri 2007; Merloni 2003; Merloni & Nayakshin 2006; Pariev et al. 2003). If the viscosity parameter \( \alpha \) is allowed to range from \( \alpha \sim 0.03 \) to \( \sim 0.2 \) (e.g., Afshordi & Paczynski 2003), calculations show that the combinations of \( \alpha \sim 0.03–0.2 \) and \( a_\ast = 0.5–0.998 \) can result in the thermal timescales that are in good agreement with the optical variability timescales presented in Table 2. Thus, it is likely that the optical variations result from the accretion disk thermal instability.

The radiation energies emitted in accretion disks are probably from the continuum thermal reprocessing and/or the local viscosity dissipation (e.g., Ulrich et al. 1997). If the X-rays illuminating optically thick material in a thin disk produce the optical-UV emissions through thermal reprocessing, the optical and UV variations following the X-ray variations are probably correlated with the UV variations leading the optical ones. The time lags in the case of continuum thermal reprocessing are estimated for the standard accretion disks with black hole spin parameter \( a_\ast = 0.5, 0.8, 0.9, \) and \( 0.998 \). The relevant time lags are listed in columns (5)–(8) of Table 3. The positive values in columns (5)–(8) mean that the variations at longer wavelengths lag the variations at shorter wavelengths. It can be seen from columns (4) and (5)–(8) of Table 3 that the measured time lags are marginally consistent with those predicted by the standard accretion disks for NGC 4151 and NGC 7469. This implies that the optical and UV emissions are likely to be the reprocessed X-rays for NGC 4151 and NGC 7469. In addition, the time lags decrease slightly as spin...
and 200 dash-dotted, and solid lines are the theoretical lines of eq. (3) for parameter \(a\). The first at outer radii and then in the inner region, this may result in variations in the accretion flow affect the flux of the measured time lags. This indicates that the optical-UV continuum thermal reprocessing time lags are opposite those of Table 3. The negative values in column (9) mean that the variations at outer radii lead the variations at inner radii. It can be seen from columns (4) and (9) of Table 3 that the measured time lags are much smaller than those predicted by the standard accretion disks in the case of accretion flow fluctuations traveling inward.

5. DISCUSSIONS AND CONCLUSIONS

One way of testing the standard accretion disk models is to find relationships between variability and fundamental parameters of AGNs, such as black hole mass. The discovery of such a relationship—or lack thereof—may provide useful clues to the physical mechanisms behind the variability. Different sources of optical variations can be associated with different characteristic timescales, and many of these timescales depend on black hole mass. Wold et al. (2007) investigated the dependence of quasar variability on black hole mass and found that the measured variability amplitude correlates with black hole mass. Collier & Peterson (2001) attempted to define a relationship between black hole mass and characteristic variability timescale. They reported evidence of black hole masses correlating with characteristic optical variability timescales for a sample of 10 well-monitored AGNs. In this paper, a linear correlation between the measured timescales of optical variations and the black hole masses is found for a sample of 26 well-monitored AGNs using reverberation mapping. This linear correlation supports the suggestion of Collier & Peterson (2001). The slope of this correlation in equation (15) is \(\sim 0.12\), which is consistent with the slope of \(\sim 0.15\) predicted by equation (3) with viscosity parameter \(\alpha = 0.1\) and the emitting radius is estimated for Fairall 9 and NGC 5548 by adopting \(a = 0.998\). The estimated results are listed in column (9) of Table 3. The negative values in column (9) mean that the variations at outer radii lead the variations at inner radii. It can be seen from columns (4) and (9) of Table 3 that the measured time lags are much smaller than those predicted by the standard accretion disks in the case of accretion flow fluctuations traveling inward.

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- parameter \(a\), increases. For Fairall 9 and NGC 5548, the signs of the continuum thermal reprocessing time lags are opposite those of the measured time lags. This indicates that the optical-UV emissions are unlikely to be the reprocessed X-rays for Fairall 9 and NGC 5548. If variations in the accretion flow affect the flux first at outer radii and then in the inner region, this may result in correlated optical-UV light curves with longer wavelength variations leading shorter wavelength variations. As a reference timescale, the sound crossing time in a standard accretion disk between these radii is estimated for Fairall 9 and NGC 5548 by adopting \(a = 0.998\). The estimated results are listed in column (9) of Table 3. The negative values in column (9) mean that the variations at outer radii lead the variations at inner radii. It can be seen from columns (4) and (9) of Table 3 that the measured time lags are much smaller than those predicted by the standard accretion disks in the case of accretion flow fluctuations traveling inward.

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One way of testing the standard accretion disk models is to find relationships between variability and fundamental parameters of AGNs, such as black hole mass. The discovery of such a relationship—or lack thereof—may provide useful clues to the physical mechanisms behind the variability. Different sources of optical variations can be associated with different characteristic timescales, and many of these timescales depend on black hole mass. Wold et al. (2007) investigated the dependence of quasar variability on black hole mass and found that the measured variability amplitude correlates with black hole mass. Collier & Peterson (2001) attempted to define a relationship between black hole mass and characteristic variability timescale. They reported evidence of black hole masses correlating with characteristic optical variability timescales for a sample of 10 well-monitored AGNs. In this paper, a linear correlation between the measured timescales of optical variations and the black hole masses is found for a sample of 26 well-monitored AGNs using reverberation mapping. This linear correlation supports the suggestion of Collier & Peterson (2001). The slope of this correlation in equation (15) is \(\sim 0.12\), which is consistent with the slope of \(\sim 0.15\) predicted by equation (3) with viscosity parameter \(\alpha = 0.1\) and the emitting

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radius $r_d = 100r_g$. The slopes between the thermal timescale and the black hole mass are estimated for another two emitting radii of $r_d = 50r_g$ and $200r_g$ in equation (3) with $\alpha = 0.1$. The three theoretical lines between timescales and black hole masses are presented in Figure 6. It can be seen in Figure 6 that the theoretical line of $r_d = 100r_g$ matches the observed data points and the best-fit line better than the other two lines do. This means that the measured characteristic timescales of optical variations are likely to be from the accretion disk thermal instability. Thus, the standard accretion disk models are likely to be conditionally favored by observations.

Another way of testing the standard accretion disk models is to connect the observed variability timescale with one of the physical timescales in equations (1)–(4). Among the four physical timescales, the thermal timescale is closest to the measured optical variability timescale as $\alpha = 0.1$. The viscosity parameter $\alpha$ has the typical value of $\sim 0.1$ for the standard accretion disks (Shakura & Sunyaev 1973). A value of $\alpha \approx \frac{1}{2}$ is implied by the condition that the turbulence should be subsonic in standard disks (Merloni 2003). A lower value of $\alpha < 0.14$ is suggested by numerical investigations for thin accretion disks with a constant effective sound speed (Afshordi & Paczyński 2003). Merloni & Nayakshin (2006) also limited a similar range of $\alpha \leq 0.15$ by studying the limit-cycle instability in magnetized accretion disks. Khajenabi & Shadmehri (2007) adopted $\alpha \sim 0.03$–0.3 to study the dynamical structure of a self-gravitating disk. Thus, the viscosity parameter $\alpha$ in standard disks possibly has a wide range including the typical value of $\alpha \sim 0.1$. If the viscosity parameter $\alpha$ is allowed to range from ~0.03 to ~0.2, the timescales of optical variations are consistent with the thermal timescales predicted by the standard accretion disk models. This implies that the measured characteristic timescales of optical variations are likely to be produced by the accretion disk thermal instability.

The analysis shows that the wavelength differences $\Delta \lambda$ are correlated with the relevant time lags between different bands for NGC 7469, but there is no correlation between the two quantities for NGC 5548. If the flux variations are caused by the accretion flow fluctuations traveling inward across the emitting regions, it is likely that the shorter wavelength variations lag the longer wavelength variations. However, the longer wavelength variations lag the shorter wavelength variations for NGC 4151 and NGC 7469. The shorter wavelength variations lag the longer wavelength variations for NGC 5548 except that the variations at 2787 Å lag those at 1841 Å. The variations at 1390 Å lag those at 1880 Å for Fairall 9. If the optical-UV fluxes are the reprocessed continuum with harder photons from the center of the accretion disk and softer ones from radii farther out, the longer wavelength variations are expected to lag the shorter wavelength variations. However, the longer wavelength variations lead the shorter wavelength variations for NGC 5548 and Fairall 9, which is inconsistent with the expectation in the case of continuum reprocessing. The calculations for NGC 7469 and NGC 4151 show that the time lags estimated in the case of continuum reprocessing are marginally consistent with the measured time lags. In addition, Fairall 9 and NGC 5548 have the black hole mass $M_{BH} > 5 \times 10^7 M_\odot$ with the longer wavelength variations leading the shorter wavelength variations, but NGC 4151 and NGC 7469 have $M_{BH} < 5 \times 10^7 M_\odot$ with the shorter wavelength variations leading the longer wavelength variations (see Table 3). There seems to be a trend between black hole mass and time lag. If the black hole mass is above some value, the longer wavelength variations might lead the shorter wavelength variations, but if black hole mass is below this value, the shorter wavelength variations might lead the longer wavelength variations.

The origin of the radiation energies emitted in an accretion disk is key to the issue of whether the harder photons lead or lag the softer ones. For non-blazar-type objects, if the optical-UV radiations are the reprocessed X-rays that are commonly attributed to Compton upscattering of thermal UV seed photons by hot electrons in a corona (e.g., Sunyaev & Titarchuk 1980; Haardt & Maraschi 1991), the optical-UV and X-ray light curves are expected to be correlated with the X-rays leading the optical-UV radiation, and then the harder and softer photons in the optical-UV regime are correlated with the harder photons leading the softer ones. The optical-UV emissions in NGC 7469 and NGC 4151 probably belong to this case. If the bulk of the observed optical-UV continuum arises from the viscous dissipation in the accretion disk, the resulting light curves would be correlated but the UV radiations should lead the X-rays. This scenario is supported by observations of the Seyfert galaxy MCG −6-30-15 (Arevalo et al. 2005). In this scenario, the observed UV and the seed-photon-emitting regions are connected by perturbations of the accretion flow traveling inward through the accretion disk, affecting first the main UV-emitting radii and then the innermost region where the bulk of the seed photons are expected to be produced (e.g., Arevalo et al. 2005). We analyzed the flux variations in 1–2 keV (Leighly et al. 1997) and 1855 Å (O’Brien et al. 1998) for 3C 390.3 and found behavior similar to that of MCG −6-30-15. The time lag estimated by the ZDCF centroid for 3C 390.3 is $\tau_{cent}^\alpha = -4.01_{-1.28}^{+1.28}$ days with the X-rays lagging the UV radiation. The UV radiation emitted by NGC 5548 and Fairall 9 might belong to the thermal radiation from the viscous dissipation, and perturbations of the accretion flow traveling inward through the accretion disk result in the softer photons leading the harder ones. Our results may support the observation that the signs of the time lags differ from case to case (e.g., Maoz et al. 2002). The existences of negative as well as positive time lags imply that different processes could be dominating the emissions in different cases, and generally do not indicate any simple relation between the energy bands.

In this paper, a sample of 26 objects that were well observed with reverberation mapping is used to test the widely accepted standard accretion disk models by comparing the theoretical expectations to the measured timescales of optical variations, the observed relation of the black hole masses with the measured timescales, and the measured time lags between the optical-UV bands. The timescales measured by both the most common definition of the variability timescale and the zero-crossing time of the ACF are consistent with each other (see Fig. 1). The observed variability timescales are linearly correlated with the black hole masses (see Fig. 6), and this linear relation is conditionally consistent with expectation for the thermal timescales and the black hole masses in equation (3). When we adopt a typical viscosity parameter of $\alpha \sim 0.1$ (Shakura & Sunyaev 1973), the thermal timescales are closest to the measured timescales of optical variations. The combinations of $\alpha \sim 0.03$–0.2 and $a_* = 0.5$–0.998 could result in thermal timescales that are in good agreement with the optical variability timescales presented in Table 2. Thus, it is likely that the optical variations result from the accretion disk thermal instability. The time lags are measured by the ZDCF method for four of these 26 objects. The analyzed results show that the harder and softer photons at the optical-UV bands are correlated with the harder photons leading the softer ones for NGC 4151 and NGC 7469, and with the harder photons lagging the softer ones for NGC 5548 and Fairall 9 (see Table 3). For NGC 7469 and NGC 4151, the measured time lags are marginally consistent with the time lags estimated in the case of continuum thermal reprocessing. It is possible that the optical-UV emissions
of NGC 4151 and NGC 7469 are the reprocessed X-rays that are commonly attributed to Compton upscattering of thermal UV seed photons by hot electrons. For NGC 5548 and Fairall 9, the UV photons are unlikely to be from the continuum thermal reprocessing in the accretion disk. Our investigations on the variability timescales, the relation of the variability timescales with the black hole masses, and the time lags between different bands are unlikely to be inconsistent with, or are likely to be conditionally in favor of, the standard accretion disk models of AGNs.

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