THE CASE FOR STANDARD IRRADIATED ACCRETION DISKS IN ACTIVE GALACTIC NUCLEI

Doron Chelouche

Department of Physics, Faculty of Natural Sciences, University of Haifa, Haifa 31905, Israel; doron@sci.haifa.ac.il

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ABSTRACT

We analyze the broadband photometric light curves of Seyfert 1 galaxies from the Sergeev et al. sample and find that (1) perturbations propagating across the continuum emitting region are a general phenomenon securely detected in most cases, (2) it is possible to obtain reliable time delays between continuum emission in different wavebands, which are not biased by the contribution of broad emission lines to the signal, and (3) such lags are consistent with the predictions of standard irradiated accretion disk models, given the optical luminosity of the sources. These findings provide new and independent support for standard accretion disks being responsible for the bulk of the (rest) optical emission in low-luminosity active galactic nuclei (AGNs). We interpret our lag measurements in individual objects within the framework of this model and estimate the typical mass accretion rate to be $\lesssim 0.1 M_\odot$ yr$^{-1}$, with little dependence on the black hole mass. Assuming bolometric corrections typical of type I sources, we find tentative evidence for the radiative efficiency of accretion flows being a rising function of the black hole mass. With upcoming surveys that will regularly monitor the sky, we may be able to better quantify possible departures from standard self-similar models, and identify other modes of accretion in AGNs.

Key words: accretion, accretion disks – galaxies: active – methods: data analysis – quasars: general – techniques: photometric

Online-only material: color figures

1. INTRODUCTION

The current physical paradigm of accretion onto black holes (BHs) originates in the works of Salpeter (1964), Zel’dovich (1964), Lynden-Bell (1972), Novikov & Thorne (1973), and Shakura & Sunyaev (1973). In the standard model of accretion disks, matter gradually accretes onto the BH while losing angular momentum due to viscous shear. As the accreted gas becomes more tightly bound to the BH, its gravitational energy is locally dissipated and emitted as local blackbody radiation. The combined emission from a range of disk annuli around BHs typical of active galactic nuclei (AGNs) gives rise to a power-law emission in the optical band. The radiative efficiency of accretion processes through a thin disk depends largely on the gas ability to radiate close to the innermost stable orbit, which depends on the BH spin. Under favorable conditions, the total energy extracted is $\lesssim 30\%$ of the gas rest energy (Novikov & Thorne 1973; Noble et al. 2011), and most of it is emitted at extreme-UV (EUV) energies for the parameter range typical of AGNs.

We note that aside from thin accretion disks, a variety of additional accretion modes likely exist, such as advection-dominated accretion flows (Narayan & Yi 1994) and slim disk solutions (Abramowicz et al. 1988). Other configurations, such as ADIOS (Blandford & Begelman 1999) and CDAF (Quataert & Gruzinov 2000), where only a small fraction of the gas ultimately gets accreted by the BH, are also possible.

Qualitatively, the rapid time-varying flux level from AGNs is consistent with a compact source, which, by causality arguments, implies a BH-scale phenomenon. In particular, geometrically thin accretion disk models have been very successful in explaining the prominent continuum emission of AGNs over a broad range of wavelengths, from the optical to the soft X-ray bands. Quantitatively, however, very little is known with confidence about the physical properties of accretion flows, and many uncertainties remain about their nature. For example, the (wavelength-dependent) size of the continuum emitting region is rather loosely constrained by causality arguments, and some tension has recently risen between model predictions and microlensing-assisted measurements of the optically emitting region in a few lensed quasars (Blackburne et al. 2011, but see also Poinfexeter et al. 2008). Whether this tension is simply due to measurement systematics or whether it points to new, previously unrealized physics of accretion flows (Dexter & Agol 2011) is currently unclear. Providing reliable constraints on accretion disk models is therefore of considerable importance for shedding light on processes of gas accretion onto compact objects.

Reverberation mapping is a widely used technique for probing spatially unresolved regions in astrophysical systems; see, for example, Peterson et al. (2004) for a spectroscopic implementation of the technique for AGNs, and Chelouche & Daniel (2012) and Chelouche & Zucker (2013) for its photometric versions. This method, as applied to spectroscopic light curves of AGNs, proved to be essential for studying the broad emission-line region (BLR) in those objects, and for determining the masses of the BHs powering them (Peterson et al. 2004; Bentz et al. 2010). Similarly, by searching for, and studying, reverberating continuum signals over a range of wavelengths, one may be able to deduce the scale of accretion flow, thereby contrasting accretion disk model predictions with direct observables other than the shape of the spectral energy distribution (SED; Malkan 1983; Laor & Netzer 1989). Indeed, Collier et al. (1998, 2001) carried out the only intensive spectroscopic campaigns of two Seyfert 1 galaxies (NGC 7469 and the narrow-line object Akn 564) leading to wavelength-dependent time-delay maps, which are in qualitative agreement with thin accretion disk models. However, being the only objects for which such studies have been carried out to date (mainly due to the imposing requirements on high signal-to-noise ratios, S/Ns, and high-cadence observations), it remains to be established that this phenomenon is general, and to understand its manifestation in AGNs of different properties, such as BH mass and luminosity.
While several attempts have been made to use multi-band photometric data to constrain the physics of accretion processes in AGNs (Sergeev et al. 2005; Bachev 2009; Cackett et al. 2007), the scatter in the measured inter-band time delays was large and, as discussed in Chelouche & Zucker (2013), results were biased by the finite contribution of the broad emission lines to the signal. In particular, Chelouche & Zucker (2013) showed that the determination of continuum time delays and of line-to-continuum time delays must be done self-consistently when broadband photometric data are concerned. In this work, we apply their formalism to carry out reliable reverberation mapping analysis of the accretion disks in a sample of low-luminosity AGNs (Seyfert 1 galaxies) from Sergeev et al. (2005).

This paper is organized as follows: the AGN sample is presented in Section 2, and the method of analysis briefly outlined in Section 3. The results are presented in Section 4, with their interpretation within the framework of irradiated thin accretion disk models given in Section 5. Section 6 discusses our findings in the context of AGN physics and the prospects for reverberation mapping of accretion disks using upcoming photometric surveys. The summary follows in Section 7.

2. SAMPLE

Here we restrict our analysis to objects in the Sergeev et al. (2005) sample of low-z Seyfert 1 galaxies for which the BLR size, hence also the BH mass, \( M_{\text{BH}} \), have been independently constrained by means of spectroscopic reverberation mapping (Bentz et al. 2009; Grier et al. 2012; Peterson et al. 2004). The reason for that will be further clarified below. Some properties of the sample are given in Table 1 (see also Sergeev et al. 2005 and Chelouche & Zucker 2013 for more details).

We estimate the monochromatic optical luminosity at 5100 Å \( L_{5100} \equiv \lambda L_{\lambda}(5100 \text{ Å}) \) for objects in the Sergeev et al. (2005) sample in several ways to bracket the relevant luminosity range under a plausible range of underlying assumptions. We note, however, that by using different data sets to estimate the AGN luminosity, some scatter in the luminosity may be expected on grounds of object variability as well as by the different starlight contribution admitted by the apertures used by different studies.

We first consider the results of Cackett et al. (2007), who quote V-band fluxes (we take the mean between their reported high and low states), and convert those to luminosity assuming concordance cosmology, while taking into account their reported Galactic and intrinsic reddening values (derived from the Balmer line ratio), and assuming \( R_V = 3.1 \). We also correct for the contribution of the host using their best-fit values. As an alternative estimate for the optical luminosity, we consider the results of Bentz et al. (2009), who were able to directly subtract the host’s contribution from the signal, but did not correct for intrinsic extinction. Unsurprisingly, their reported luminosities tend to be the lowest of all other estimates yet still larger than those reported by Bentz et al. (2006). As our third estimate, we take the absolute B-band magnitudes reported by Sergeev et al. (2005) and convert those to luminosities assuming the conversion factors appropriate for low-z quasars in Kaspi et al. (2000). Doing so we effectively neglect reddening effects as well as potential contribution from the host galaxy to the B-band flux. Lastly, we consider the luminosities previously reported by Kaspi et al. (2000) and Peterson et al. (2004) for some objects in our sample. The optical luminosities reported in Table 1 are the geometric means of all estimates. We note the especially large range of luminosities reported in the literature for Mrk 6, NGC 4151, and NGC 3516 (Bentz et al. 2009; Cackett et al. 2007).

In this work we use the published \( B, V, R, R_1 \), and \( J \) light curves from Sergeev et al. (2005) and note that, at the redshift of the sample, the \( B \) band includes high-order Balmer line emission, and the \( V \) band is relatively devoid of strong emission lines (Figure 1). The \( R \) band contains the prominent H\(\alpha \) emission line, with redder bands showing little contribution from strong emission lines. The best S/N for objects in this subsample is obtained for the \( V \) and \( R \) bands.

3. METHOD

We use the multivariate correlation function (MCF) method of Chelouche & Zucker (2013), which is able, under favorable conditions, to separate line-to-continuum and continuum-to-continuum time delays \( (\tau_c \text{ and } \tau_l \text{, respectively}) \) from the broadband photometric light curves of quasars. The reader is referred to Chelouche & Zucker (2013) for a complete description of the technique, and its implementation for a portion of the Sergeev et al. (2005) data set. In a nutshell, this technique eliminates the biases inherent to simple cross-correlation analyses that are encountered when several reverberating emission components, such as continuum and emission lines, contribute to the signal. Specifically, the algorithm seeks the best agreement between the (fluxed) light curve in one band, \( f_X(t) \), and its model, \( f_X^M(t) \), as a function of the model parameters. More specifically, \( f_X(t) \) is assumed to include at most two prominent echoed signals, with either positive or negative time delays, of a light curve in some other band, \( f_Y(t) \). An adequate first-order approximation for \( f_X(t) \) is then given by \( f_X^M(t; f_Y, \alpha, \tau_c, \tau_l) \equiv (1-\alpha)f_Y(t-\tau_c)+\alpha f_Y(t+\tau_l) \), where \( \alpha \) determines the relative contribution of the two signals to the broadband flux. Specifically, a parameter combination is sought in three-dimensional phase space, which maximizes the (linearly interpolated) Pearson correlation coefficient between the model and the data, \( R(f_X, f_X^M) \). As demonstrated in Chelouche & Zucker (2013), the use of priors on one or more parameter values, when available, may lead to improved constraints on the remaining parameters of the problem.

Table 1

| ID  | \( \zeta \) | \( L_{\text{opt}} \) | \( M_{\text{BH}} \) | \( \tau_c \) | \( M \) |
|-----|-------------|---------------------|-----------------|-------------|--------|
| 3C 390.3 | 0.056 | 43.9 | 8.46 | 1.2^{+0.4}_{-0.2}(1.5) | 0.02 |
| Akn 120 | 0.033 | 44.1 | 8.18 | 3.0^{+0.4}_{-0.4}(1.7) | 0.4 |
| Mrk 335 | 0.026 | 43.8 | 7.15 | 2.1^{+0.2}_{-0.2}(1.2) | 2.8 |
| Mrk 509 | 0.035 | 44.2 | 8.16 | 9.5^{+0.3}_{-0.3}(6) | 13 |
| Mrk 6 | 0.019 | 43.4 | 8.13 | 0.9^{+0.2}_{-0.2}(1.3) | 0.03 |
| Mrk 79 | 0.022 | 43.7 | 7.72 | 0.78^{+0.04}_{-0.04}(1.0) | 0.03 |
| NGC 3227 | 0.004 | 42.4 | 7.63 | 0.58^{+0.04}_{-0.04}(0.20) | 0.01 |
| NGC 3516 | 0.009 | 43.1 | 7.49 | 0.90^{+0.16}_{-0.16}(1.0) | 0.07 |
| NGC 4051 | 0.002 | 41.9 | 6.28 | 0.22^{+0.08}_{-0.10}(0.3) | 0.02 |
| NGC 4151 | 0.003 | 42.6 | 6.66 | 0.50 \pm 0.02(0.53) | 0.07 |
| NGC 5548 | 0.017 | 43.3 | 7.83 | \ldots | \ldots |
| NGC 7469 | 0.016 | 43.6 | 7.09 | 0.72^{+0.04}_{-0.04}(1.0) | 0.09 |

Notes. Column description: (1) object name, (2) redshift, (3) optical luminosity at 5100 Å in log \((\text{erg s}^{-1})\) units (see the text), (4) mass in log \((M_\odot)\), (5) time lag in days where the best-fit model is forced to go through zero lag at 5300 Å (values in parentheses correspond to fits that were not forced to go through zero lag, i.e., the dashed line models in Figure 5), (6) effective mass accretion rate in units of \(M_\odot\text{yr}^{-1}\).
As discussed in Section 2 (see also Figure 1), the $V$ band is relatively devoid of broad emission line contribution to its flux, and its light curve is typically characterized by high $S/N$ data. Specifically, a single power-law fit to the composite spectrum of Glikman et al. (2006) implies that the contribution of non-power-law continuum emission to this band is on the order of 5% or less, hence lower than that for the other bands (Figure 1). For these reasons, we consider the $V$-band light curves as our “pure” continuum light curve, hence $f_V(t)$ in the above notation, and use it to construct $f_X^m(t)$, where $X \in \{B, R, R1, I\}$. Upon maximizing $R(f_X, f_X^m(f_Y, \alpha, \tau, \tau_l))$, we find $\tau_c$, $\tau_l$, and $\alpha$ for each of the bands.

4. ANALYSIS

As discussed in Chelouche & Zucker (2013), determining $\tau_c$, which is a measure of the accretion disk size (see below), requires, in principle, the simultaneous determination of $\tau_l$ and $\alpha$. We first apply the full reverberation mapping analysis for a subsample of objects from Sergeev et al. (2005), and then, motivated by its results, extend the analysis to the full sample using spectroscopic priors on $\tau_l$.

4.1. A Subsample of Three AGNs from Sergeev et al. (2005)

We restrict the analysis in this section to objects in the Sergeev et al. (2005) sample, which gave high-confidence-level ($P > 90\%$) results in the Chelouche & Zucker (2013) analysis of the $V$ and $R$ data. For those objects, solutions for $\tau_c$, $\tau_l$, and $\alpha$ were most secure, and $\tau_l$ values showed good agreement with independent constraints from spectroscopic reverberation mapping studies (Peterson et al. 2004; Grier et al. 2012, and references therein). Our subsample of objects therefore includes NGC 5548, NGC 4151, and NGC 3516 (Chelouche & Zucker 2013, see their Table 1 for the relevant data). De-trending of the light curves by a first degree polynomial was used throughout.

Solutions for $\tau_c$, $\tau_l$, and $\alpha$ are shown in Figure 2 for the various bands. The quoted values reflect on the mode of the distribution functions obtained from Monte Carlo simulations that introduce Gaussian measurement noise in accordance with the reported measurement uncertainties (Sergeev et al. 2005). Reported error bars reflect on $\pm 68\%$ percentiles around the mode value (Chelouche & Zucker 2013).

Statistically significant $\tau_l$ values are detected in all three objects and in all bands but for the noisier $B$ band (not shown). In particular, for a given object, the deduced values are consistent for the different bands, as may be expected if emission from similar locations in the BLR contributes to their flux. As noted in Chelouche & Zucker (2013, see their Table 1), these lags are also consistent with the spectroscopically measured Balmer line delays. This is indeed expected given that hydrogen emission dominates the non-power-law emission in those bands either through Balmer line emission or via Paschen lines and continuum emission (Figure 1).

As far as results for the $B$ band are concerned, we note that higher-order Balmer line and iron blend emission are important contributors to the flux, and while the former originates from regions comparable to the Hα and Hβ emission regions (Bentz et al. 2010), the location of the latter is less secure with some studies placing it on scales comparable to or slightly larger than the Balmer line emission region (Bian et al. 2010; Hu et al. 2008); see also the new results of Barth et al. (2013) and Rafter et al. (2013), who find that the region is comparable in size to that which emits the Hα line (Bentz et al. 2010). For these reasons, in our analysis of the $B$-band data, we henceforth set $\tau_l$ to the spectroscopically measured Balmer line time delay (Chelouche & Zucker 2013, see their Table 1 and references therein), and determine $\tau_c$ and $\alpha$ for the $B$ band under this prior (see Section 4.1.1).

The deduced values for $\alpha$ for the redder bands are of order 20% (NGC 5548 results in $\alpha \sim 40\%$; see Figure 2). In comparison, the $B$-band data imply a smaller (5%–10%) relative contribution of a lagging emission component to the band. Indeed, a qualitative spectral decomposition of the Glikman et al. (2006) composite spectrum suggests that the contribution
of non-power-law emission to the bands is of the same order\footnote{It should be borne in mind that $\alpha$ measures the relative contribution of a non-power-law (lagging) emission component to the variable part of the light curve. In particular, in the presence of a constant additive flux to the redder bands (e.g., host galaxy contribution), the estimated $\alpha$ from the mean quasar template could be lower than its actual value.} (Figure 1).

Our $\tau_c$ measurements relative to the $V$ band show a qualitative trend whereby $\tau_c$ increases with wavelength from negative values for the $B$ band to positive lags for the redder bands. This is most notable for NGC 4151 and less so for NGC 3516. Results for NGC 5548, while formally negative, are consistent with a zero lag in all bands, with only the upper uncertainty envelope hinting on a possible increase of $\tau_c$ with wavelength.

4.1.1. Setting Priors on $\tau_l$

The consistency between the $\tau_l$ values deduced for the different bands, the agreement between those and the spectroscopic time-lag measurements for the Balmer emitting region (Figure 2 and Chelouche & Zucker 2013), and the reasonable results for $\tau_c$ and $\alpha$ obtained for the $B$ band when using priors motivate us to consider a refined analysis approach, where the number of degrees of freedom is reduced. In particular, we henceforth set $\tau_c$ to the spectroscopically measured Balmer emission line lag (Chelouche & Zucker 2013, see their Table 1 for the adopted values, and note that we neglect the measurement uncertainty on $\tau_l$, as well as the weak inverse trend between the time delay and the increasing line order; Bentz et al. 2010), and constrain the values for $\tau_c$ and $\alpha$ under this prior in the remaining two-dimensional phase space for all bands. The results are shown in Figures 3 and 4 for the three objects in our subsample.

Figure 3. Solutions for $\tau_c$ using a spectroscopic prior on $\tau_l$ for three AGNs (see the legend and compare to the upper panel of Figure 2). Also shown, for comparison, are the spectroscopic results for NGC 7469 by Collier et al. (1998). Overplotted are $\tau_c = 0.1 \times 2^n[(\lambda/5500 \text{ Å})^{3/2} - 1]$ models with $n$ indicated next to each curve. Best-fit models, in the least squares sense, appear as colored curves, where the fit is forced to go through $\tau_c(5500 \text{ Å}) = 0$ days (solid lines), and when it is not (colored dashed lines). Light shaded symbols denote the inter-band time delays of Cackett et al. (2007, those for NGC 5548 are $\gtrsim 5$ days and are marked here as lower limits). Small wavelength shifts were applied for clarity.

(A color version of this figure is available in the online journal.)
lines to the flux (more accurately, flux variance) compared to NGC 3516, but that which monotonically rises toward the redder parts of the spectrum. There are various possible reasons for that, among which a BLR that varies less on the relevant timescales, and/or continuum emission that varies less in the redder parts of the spectrum, or is suppressed altogether due to disk truncation (it is not possible to robustly test either of these scenarios using the present data set). Lastly, we note the case of NGC 5548 that exhibits $\alpha$ values that are in excess of what is expected from spectral decomposition, and in addition leads for formally negative (yet consistent with zero) lags for the redder bands. Together, these facts lead us to doubt the validity of the $\tau_c$ and $\alpha$ solution in this case, and we exclude this object from further analysis.

4.2. The Full Sergeev et al. (2005) Sample

We next analyze the remaining nine objects in the Sergeev et al. (2005) sample using spectroscopic priors on $\tau_l$ (Table 1 in Chelouche & Zucker 2013). Results for most objects are consistent with $\tau_l$ rising monotonically with wavelength from negative values for the $B$ band to positive values for the redder bands (Figure 5). In particular, results for NGC 7469 are in good agreement with the spectroscopic lag measurements of Collier et al. (1998). NGC 3227 and Akn 120 are exceptions as $\tau_l$ for the $B$ band is marginally positive, in contrast to naive model expectations where the bluer bands should lead the redder ones. The reason for that is currently unclear, and may have to do with the particular light-curve behavior observed, sampling, or residual signal from emission lines. Results for the $R1$ and $I$ bands are largely consistent as the centroid wavelengths of both bands are quite similar (Figure 1).

2 Note that the wavelength which actually characterizes the bands is a (filter) response-weighted average over the light-curve variance at each wavelength. This, however, is not known, and centroid values, assuming a flat quasar spectrum, are used instead.

Considering the statistical properties of the entire sample (Figure 6), we note that the median $\tau_l$ is consistent with being monotonically rising with wavelength, i.e., with geometrically thin accretion disk model predictions where $\tau_l(\lambda) \sim \lambda^{4/3}$ (Collier et al. 1998). In comparison, the best-fit curve obtained using the median results of Cackett et al. (2007) is much steeper, with an effective linear slope that is $\sim 2$ times greater than the one found here. As discussed above, this is likely because of

3 Note, however, that the limited wavelength range probed here does not allow us to provide physically meaningful constraints on the power-law index.
BLR emission contamination of the signal in cross-correlation analyses (Chelouche & Zucker 2013).

Turning our attention to $\alpha$, we note that it is, typically, smallest for the $B$ band, peaks in the $R$ band, and somewhat declines, yet remains finite also for the $R1$ and $I$ bands (Figure 5). This behavior is expected from a naive spectral decomposition of the Glikman et al. (2006) composite into power-law and non-power-law emission components (Figure 4). Particular objects (e.g., NGC 3227) show, however, a more monotonic increase of $\alpha$ with wavelength, as discussed in Section 4.1.1. Further investigation into the different $\alpha$ behavior observed in different objects is outside the scope of this work.

5. THE CASE FOR STANDARD ACCRETION DISKS

Motivated by the fact that $\tau_c(\lambda)$ behavior is consistent, at least on average, with the model expectations (Figure 6), and that reasonable values are obtained for both the continuum lags and the relative contribution of line and continuum processes, for all bands, we shall now interpret our findings for individual objects within the framework of the irradiated geometrically thin accretion disk model (Collier et al. 1998; Cackett et al. 2007, see also the Appendix). Specifically, we turn to Figures 3 and 5, where the measured $\tau_c(\lambda)$ values are fitted, in the least squares sense, by a model for a self-similar geometrically thin accretion disk that is illuminated by a point source, for which

$$\tau_c(\lambda) = \tau_c^0 \left( \frac{\lambda}{5500 \, \text{Å}} \right)^{4/3} - 1 ,$$

where $\lambda$ is the centroid wavelength of band $\lambda$ obtained by assuming a flat quasar continuum and the filter’s throughput curves (Figure 1). For example, we find $\tau_c^0 = 0.5 \pm 0.02$ days for NGC 4151, and $\tau_c^0 = 0.90^{+0.16}_{-0.01}$ days for NGC 3516. For comparison, we also experimented with less physical models, which were not restricted to pass through $\tau_c(5500 \, \text{Å}) = 0$ days (effectively it allows for deviations of the centroid broadband wavelengths from the assumed values), and find consistent results for most objects (see Table 1). Objects for which significant differences are encountered between the two fitting methods include Mrk 509, Akn 120, and NGC 3227, with the latter two having their blue continua formally leading the $V$ band, yet still consistent with a zero lag.

5.1. The Lag–Luminosity Relation

We first consider the relation between the lag and the object luminosity, both of which are independent observables in our study. Figure 7 shows the best-fit relation to the data, $\tau_c^0 \propto L_{\text{opt}}^{0.53 \pm 0.10}$ (error bars were obtained by means of Monte Carlo simulations that take into account the errors on individual $\tau_c^0$ measurements, but do not consider the uncertainty on the luminosity). In the standard theory of accretion disks, as applies to AGNs (Shakura & Sunyaev 1973; Davis & Laor 2011), the optical spectrum is self-similar ($L_v \sim v^{1/3}$, where $v$ is the frequency), and hence results in $L_{\text{opt}} \sim (M_{\text{BH}}M)^{2/3}$, where $M$
is the effective mass accretion rate (allowing for irradiation; see the Appendix). The light crossing time of the optical emitting region in such a disk is \( \tau_c^0 \sim (M_{\text{BH}} M)^{1/3} \) (Collier et al. 1998). This implies that for a thin irradiated self-similar accretion disk one expects \( \tau_c^0 \sim L_{\text{opt}}^{1/2} \), which agrees well with the observed relation.

One may wonder whether our \( \tau_c^0 \) measurements on sub-sampling times, \( \tau_* \), are at all meaningful (e.g., NGC 4051 has a formal lag of \( \sim 0.2 \pm 0.1 \) while the minimum visit interval is \( \sim 0.8 \) days). The answer depends on (1) the number of data points and (2) the power density spectrum of the quasar. In particular, high power density spectra, which have little power at high frequencies (e.g., \( > 1/\tau^2_0 > 1/\tau_* \)), may result in robust continuum lags measurements provided enough data with good S/N exist.

In fact, this justifies the use of linear interpolation schemes for evaluating correlation functions in the general context of AGN reverberation mapping (Cackett et al. 2007; Kaspi et al. 2000; Sergeev et al. 2005). Nevertheless, sampling is known to affect time-lag measurements (Grier et al. 2008), and it will be of importance to repeat this experiment with better-sampled data, especially for the lower luminosity objects, considering the typical values for \( \tau_c^0 \) determined here.

We note that while the minimum cadence of the observations is similar for all objects in the Sergeev et al. (2005) sample, the median sampling, which may be a more meaningful quantity as far as time-lag measurements are concerned, does show a weak trend with luminosity (Figure 7). Nevertheless, were our time-lag measurements merely reflecting on the slightly different sampling used, \( \tau_c^0 \) would have shown a mere factor of \( < 2 \) in range, in contrast to our findings. With that being said, it will be of importance to repeat this analysis for a sample of objects having a range of luminosities with luminosity-independent sampling, to verify that residual biases are indeed eliminated.

We note that Mrk 509 is consistently an outlier in our sample; whether this is due to extreme inclination (see below) or, more likely in our opinion, due to an erroneous lag measurement (note the poor fit in Figure 5) is yet to be determined.

\[ 5.2. \text{The Source of Optical Emission} \]

The fact that \( \tau_c^0 \propto L_{\text{opt}}^{1/2} \) does not necessarily imply that viscous heating (perhaps with some irradiation) is primarily responsible for the bulk of the optical emission. For example, the light intensity of a varying point source that scatters off a uniform extended surface could result in a similar size–luminosity relation. To show that the irradiated thin accretion disk physics indeed provides a viable interpretation of the data, we will next relate the measured time delays to the optical luminosity of the source within the framework of a Shakura & Sunyaev (1973) accretion disk model.

Note that for low-amplitude radiative perturbations of a disk carrying an effective mass accretion rate, \( \dot{M} \) (Collier et al. 1998, and the Appendix),

\[ \tau_c^0 \simeq 0.7 \left( \frac{M_{\text{BH}} \dot{M}}{10^6 M_\odot \text{yr}^{-1}} \right)^{1/3} \text{days,} \]

(2)

where the exact normalization depends on which property of the continuum transfer function is being traced (for reverberation mapping algorithms that effectively measure the centroid of the transfer function, the above normalization holds irrespectively of the disk inclination\(^7\)). Our normalization of Equation (2) is smaller by a factor \( \approx 2 \) than the one used by Collier et al. (1998, allowing for the different definitions used in each work), and is supported by numerical calculations outlined in the Appendix. It is also in better agreement with the revised values adopted in Collier (2001).

The optical flux in some AGNs has been known to vary significantly over long, \( \sim 1 \) day, timescales ( Uttley et al. 2003), which are, nevertheless, shorter than dynamical timescales associated with the optically emitting region. If due to variations in the irradiation level, then the disk would effectively “breath” during the time series, increasing/decreasing its size in high/low flux states, as \( M \) varies (Equation (2) and the Appendix).

Therefore, as one extracts the disk size from the full light curves, one actually measures some average value over the time series (cf. the corresponding effect for the BLR; Peterson et al. 2002). This average is, however, difficult to define, and hence to accurately interpret, since it depends on how the signal is accumulated by the correlation function and therefore on the light-curve properties. Specifically, the particular variability pattern of the AGN, the sampling used, and the S/N of the data are all relevant factors in determining the exact value of the average lag. For the Sergeev et al. (2005) sample, we find that flux variations could affect the effective disk size at the \( \sim 10\% \) level for most objects (with the most pronounced effect being at the \( \sim 17\% \) level for 3C 390.3). Such uncertainties should be borne in mind when quantitatively interpreting the data, and better data sets are required to shed light on their potential importance.

Inverting Equation (2), one can use the measured lags to determine the product \( M_{\text{BH}} \dot{M} \), which, in turn, sets the optical luminosity for AGNs (Bian & Zhao 2003; Collin et al. 2002; Laor & Davis 2011, and the Appendix). This leads to the total optical disk luminosity being

\[ L_{\text{opt}} \simeq 3 \times 10^{43} \left( \frac{\tau_c^0}{\text{days}} \right)^2 \text{erg s}^{-1}. \]

(3)

To be able to compare model predictions to observations, whose reported values assume isotropic emission of the source, we note that \( L_{\text{opt}} \sin i \simeq 2 L_{\text{opt}} \cos(i) \), where \( i \) is the inclination angle. This means that for sources observed with inclinations \( i > 60^\circ \), the implied isotropic luminosity will be lower than the true luminosity of the source. Nevertheless, for type I sources, whose continuum emission is not obscured by the putative torus, it is believed that, generally, \( i < 60^\circ \), which is also consistent with the findings of microlensing studies (Poindexter & Kochanek 2010).

Figure 8 shows model predictions for the isotropic optical luminosity \( (i = 0^\circ \) is assumed) versus the measured value. It is important to re-emphasize that, a priori, it is not clear that Equation (3) should predict a luminosity similar to the observed one as our time-lag measurements are independent of the object luminosity (so long as the AGN is not too faint to be observed). The fact that a 1:1 relation between the measured and predicted quantities is roughly obtained (note the different 1:1 relations plotted for various object inclinations in Figure 8) provides strong evidence for the prevalence of standard thin irradiated accretion disks in AGNs, at least as far as their optical emission properties are concerned. Furthermore, it implies that our time-lag measurements are probably in the right ballpark, and that type I AGNs are not highly inclined sources, as expected by theory. For example, had our time-lag measurements been a factor \( \sim 2 \) larger than observed (cf. Cackett et al. 2007 and
that the size of their rest-UV emitting regions is, on average, a factor \( \sim 4 \) larger than predicted by theory for plausible values of the radiative efficiency, object inclination, and BH mass. Crudely, had the same effects been present here, our predicted luminosities would have been \( \sim 16 \) times greater than observed (Equation (3)), which is, generally, not the case.\(^8\) Whether this indicates a departure from self-similarity in the inner disk regions of AGNs, a genuine difference between quasars and AGNs, or systematic effects (and/or inadequate interpretation of the signal) in either of the methods requires further investigation. In what follows, we shall assume that geometrically thin accretion disks provide a viable physical explanation for the bulk of the optical emission in AGNs, and consider the physical implications of our results.

6.2. Effective Mass Accretion Rates and Radiative Efficiencies

Our time-lag measurements, as interpreted by standard thin (infinite) accretion disk models, may be used to measure the effective mass accretion rate, \( \dot{M} \), independently of the luminosity, in objects for which \( M_{BH} \) is known (Equation (2)).\(^9\) Typical \( \dot{M} \) values for objects in the Sergeev et al. (2005) sample are shown in Figure 9, where the results hover around 0.01–0.1 \( M_\odot \) yr\(^{-1}\). When contrasted with the accretion rates of the Palomar–Green (PG) objects (Davis & Laor 2011), Seyfert 1 galaxies tend to have \( \dot{M} \) values that are smaller by about 1–2 orders of magnitude, which is consistent with their luminosities being similarly lower than bona fide quasars. Comparing our results for the mass accretion rate to those of other Seyfert 1 galaxies from Raimundo et al. (2012), based on optical luminosity considerations (Bechtold et al. 1987), we find qualitative agreement with their findings. We note, however, that the true mass accretion rate is somewhat lower than deduced here, as \( \dot{M} \) includes the effects of irradiation; this is also true for the Davis & Laor (2011, see also Raimundo et al. 2012) results (see the Appendix).

An interesting property of our results is that the deduced \( \dot{M} \) values (apart from three objects, including Mrk 509) span only about a factor of \( \sim 5 \) in range, and could even be similar given the measurement uncertainties (mainly on \( M_{BH} \)). In contrast, the AGNs in our sample span almost two orders of magnitude in luminosity. Whether this implies a common triggering mechanism for low-luminosity type I AGNs, which sets a rather uniform mass accretion rate across a broad range of BH masses, or whether this result vanishes as better data and more statistics are accumulated remains to be determined. It is, however, interesting to note that a similar non-dependence of the (median) mass accretion rate on \( M_{BH} \) has been previously reported by Davis & Laor (2011, see our Figure 9), for the PG quasars, over a similar range of BH masses.

It is furthermore possible to estimate the radiative efficiency of Seyfert galaxies, \( \eta \equiv L_{bol}/\dot{M}c^2 \), provided the bolometric

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\(^8\) For such a discrepancy to be accommodated by our rest-frame optical data would require that our time-lag measurements are systematically underestimated and/or our luminosities systematically overestimated, and that all objects are, in fact, lying on a relation whose normalization is set by our brightest object, Mrk 509; see Figure 8.

\(^9\) While the results of the previous section imply that whether one uses \( r_o \) to measure \( M \) or the optical luminosity is immaterial, using time-lag measurements has the advantage of being less affected by systematics such as extinction and reddening in the AGN host, and to the latter’s contribution to the flux (this may be a non-negligible source for uncertainty given the relatively large apertures used by Sergeev et al. 2005). Also, mass accretion rates estimated from the centroid lags are unaffected by accretion disk inclination, in contrast to luminosity-based estimates (Davis & Laor 2011; Raimundo et al. 2012).
luminosity of the source, $L_{\text{bol}}$, may be reasonably estimated from the limited spectral range probed. To this end, we first assume that $L_{\text{bol}}/L_{\text{opt}} \simeq 9$, and is independent of $M_{\text{BH}}$, as was assumed for the PG sample of quasars (Davis & Laor 2011). Alternatively, we assume that $L_{\text{bol}}/L_{\text{opt}} \sim 9(M_{\text{BH}}/10^{8} M_{\odot})^{-0.5}$, which is consistent with the findings of Raimundo et al. (2012, see also Scott et al. 2004) for their sample of AGNs. We plot $\eta(M_{\text{BH}})$ in Figure 9 using the above bolometric corrections, and conclude that the radiative efficiency is indeed consistent with the typical efficiencies from geometrically thin accretion disk models (Narayan & Quataert 2005). The results for a constant bolometric correction trace well the findings of Davis & Laor (2011) for the PG sample of quasars. This means that, under the same assumptions, the radiative efficiency, $\eta$, for PG quasars and for Seyfert 1 galaxies behaves in a similar manner with the BH mass, and is independent of the mass accretion rate.\footnote{Note that both the method applied here and the one used by Davis & Laor (2011) measure $\dot{M}$ rather than $\dot{M}$; see the Appendix.} Using a mass-dependent bolometric correction does not appreciably alter the above conclusions.

Our findings provide tentative evidence for $\eta$ being a rising function of BH mass, as previously reported by Davis & Laor (2011) based on SED arguments. With that being said, better bolometric corrections for individual objects, as well as better time-delay measurements for the least massive AGNs, are required to firmly establish such a trend, and, if real, its origin.

### 6.3. Reverberation Mapping of Accretion Disks

In this study we were able to measure, for the first time in a non-biased way and with a high success rate, continuum-to-continuum time delays in 11/12 low-luminosity AGNs. To securely determine the time delays associated with an irradiated accretion disk, high-cadence, good-S/N observations are required, and prior knowledge of the BLR size could be advantageous in narrowing down the parameter space, thereby leading to higher-confidence results.

Evidently, minimal benchmarks for a successful reverberation campaign are provided by the Sergeev et al. (2005) sample. Nevertheless, given the shorter delays deduced here compared to the Sergeev et al. (2005) findings, higher-cadence observations, especially for low-luminosity objects, are preferred. With upcoming photometric surveys, such as the Large Synoptic Survey Telescope (especially their deep-drilling fields), it may be possible to obtain much higher quality data for many more (bright) objects, potentially transforming the field.

In the long term, it may be possible to look for deviations from simple infinite self-similar disk models, which could shed light on the role of outflows in those systems, as well as on the accretion rate in the inner disk regions, which ultimately feeds the BH. Further, it may be possible to probe the far outskirts of the disk, where it becomes self-gravitating, and may join with other components of the AGN, such as the BLR. In addition, it may be possible to determine the inclinations of accretion disks by comparing their apparent luminosities to their predicted ones. Lastly, reverberation mapping of the accretion flows in numerous AGNs could reveal the different modes of accretion prevailing in those systems (e.g., slim versus thin disk accretion) with implications for BH growth rates.

Once accretion disk models are quantitatively tested and verified and reddening corrections and the host contribution to the flux adequately estimated, it may be possible to use quasars as standard candles, as envisioned by Collier (2001) and Cackett et al. (2007, and references therein). Interestingly, as our deduced lags are a factor $\sim$2 smaller than those considered by Cackett et al. (2007), with all other quantities held fixed at the values adopted by these authors, our deduced value for $H_0$ based on their formalism (see their Equation (15)) would...
To this end, we resort to semi-analytic models and consider a Shakura & Sunyaev (1973) accretion disk solution around a BH of mass $M_{\text{BH}}$ with a mass accretion rate $\dot{M}$. We solve for the emitted SED assuming local dissipation of gravitational energy and blackbody emission from each annulus in the disk.

We neglect general relativistic effects near the BH, which is justified in the optical band.

Consider next a case where the above disk is further illuminated by central EUV point sources located at an elevation $h_{\text{EUV}}$ above the disk surfaces.\(^{11}\) For an EUV source luminosity given by $L_{\text{EUV}}(t)$, the local irradiated disk temperature, assuming instantaneous reprocessing, is set by (Cackett et al. 2007, and references therein)

$$T(r, t) = \left[ \frac{3G M_{\text{BH}} \dot{M}(t) (1 - r/c)}{8\pi \sigma r^3} \right]^{1/4}, \quad (A1)$$

where the effective mass accretion rate

$$\dot{M}(t) \equiv M \left[ 1 + \frac{8\pi}{3} \left( \frac{\dot{m}}{\dot{M}} \right) \frac{L_{\text{EUV}}(t)}{L_{\text{Edd}}} \right] \geq \dot{M}, \quad (A2)$$

and $\dot{m} \equiv m_p c/r_g(h_{\text{EUV}}/r_g)^2 (r_g/\sigma_T)$ ($r_g \equiv GM_{\text{BH}}/c^2$, $\sigma_T$ is the Thomson cross-section, $L_{\text{Edd}}$ is the Eddington luminosity, and $m_p$ is the proton mass). Interestingly, for slow perturbations (i.e., with appreciable flux variations over timescales longer than the light crossing times of the disk), the optical luminosity satisfies $L_{\text{opt}} \propto \dot{M}_{\text{opt}}^{2/3} \propto (L_{\text{EUV}} + \text{const})^{2/3}$ (Section 6.2), which could explain the fact that quasars become bluer as they brighten (Schmidt et al. 2012), provided that some residual EUV emission leaks into the near-UV band.

To give some numbers, for a Seyfert 1 galaxy emitting at $0.1L_{\text{Edd}}$, we shall assume $L_{\text{EUV}}/L_{\text{Edd}} \approx 0.03$. Now, EUV emission originates close to the BH, at $< 10 r_g$, and so, for a thin accretion disk, where the outer-disk viscosity parameter $\alpha \approx 0.01$ (Penna et al. 2013), it is reasonable to assume $h_{\text{EUV}} \approx r_g$. Taking $M_{\text{BH}} \sim 10^8 M_\odot$ and $\dot{M} \sim 10^{-2} M_\odot\,\text{yr}^{-1}$, we get $\dot{M}/\dot{M} \approx 1.5$. As the optical luminosity $L_{\text{opt}} \propto \dot{M}_{\text{opt}}^{2/3}$, typical brightening levels over timescales greater than the light crossing times of the disk can reach the 30% level, which is of the order of the observed values in AGNs (note that we do not claim here that irradiation is the only cause for optical AGN variability, on all timescales). Further, as $\dot{M}/\dot{M} \sim 1 \propto L_{\text{EUV}}$, and irradiation may have a constant flux component, as well as a varying one, our ability to accurately measure the mass accretion rate, $\dot{M}$, is limited, as a constant irradiation level can always masquerade as a higher effective accretion rate, $\dot{M}$. However, if accretion rather than irradiation is primarily responsible for the optical emission in AGNs, then $\dot{M} \gtrsim \dot{M}$, and irradiation may be considered as a small perturbation.

To calculate the normalization of Equation (2), we evaluate the continuum transfer functions, $\psi(t)$, at 5500 Å and at 9250 Å (the time delay between continuum light curves in those two bands corresponds to $r_g$), for a short pulse, with respect to the light crossing time of the disk, of irradiating flux that peaks at a

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\(^{11}\) The source need not be elevated above the disk and can, in fact, be part of the inner disk. For example, if the effective disk thickness is $\alpha$, $\psi(\alpha)$ being the viscosity parameter), then, as recent magnetohydrodynamic simulations suggest (Penna et al. 2013, and references therein), the rise of $\alpha$ near the BH may provide a natural elevated continuum source illuminating the outer disk. Also, a modest flaring of the outer disk could make the inner region radiate its outskirt. Lastly, a compact (ionized) reflector covering a fair fraction of the sky around the inner accretion disk may also result in illumination of the outer disk parts.
luminosity $L_{\text{EUV}}$, and show the results in Figure 10. Clearly, higher levels of irradiating flux result in more considerable departures from the non-irradiated case, where $\mathcal{M}/M - 1 = 0$. The centroid time delay (i.e., $\tau_0^c$) between the bands is given by the centroid of $\psi = \psi_{5500\text{Å}} \ast \psi_{9250\text{Å}}$ (“$\ast$” denotes convolution). Results for a non-irradiated disk with $M_{\text{BH}} M = 10^6 M_\odot^2$ yr$^{-1}$ are shown in Figure 10 for various levels of irradiation. As expected, for low levels of irradiation ($\mathcal{M}/M - 1 < 0.1$), $\tau_0^c \sim 0.7(M_{\text{BH}} M/10^6 M_\odot^2$ yr$^{-1})^{1/3}$ to a good approximation (see Section 5.2 and Equation (2)). For higher levels of irradiation, the measured disk size reflects on the irradiated structure rather than on the non-perturbed state; hence, asymptotically, $\tau_0^c \propto (M_{\text{BH}} L_{\text{EUV}})^{1/3}$ (see the right panel of Figure 10 and its caption, as well as Section 5.2).

Note that, on accounts of our assumption of azimuthal symmetry, inclination does not affect the centroid lag. For comparison, we also show the time difference between the peaks of the correlation functions in each band, which is shifted to symmetry, inclination does not affect the centroid lag. For higher levels of irradiation, the measured lag corresponds to its size had the perturbation acted for times longer than its light crossing time. Specifically, the curve corresponding to the peak of the transfer functions, for two disk inclinations; see the legend) and the amplitude of the perturbation. For low-amplitude perturbations, $\tau_0^c$ is constant as the disk temperature structure does not deviate considerably from its non-perturbed state. For higher-amplitude perturbations, the optically emitting region increases in size, and the measured lag corresponds to its size had the perturbation acted for times longer than its light crossing time. 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Poindexter, S., Morgan, N., & Kochanek, C. S. 2008, ApJ, 673, 34
Quataert, E., & Gruzinov, A. 2000, ApJ, 545, 842
Rafter, S. B., Kaspi, S., Chelouche, D., et al. 2013, ApJ, in press
Raimundo, S. I., Fabian, A. C., Vasudevan, R. V., Gandhi, P., & Wu, J. 2012, MNRAS, 419, 2529
Salpeter, E. E. 1964, ApJ, 140, 796
Schmidt, K. B., Rix, H.-W., Shields, J. C., et al. 2012, ApJ, 744, 147
Scott, J. E., Kriss, G. A., Brotherton, M., et al. 2004, ApJ, 615, 135
Sergeev, S. G., Doroshenko, V. T., Golubinskiy, Y. V., Merkulova, N. I., & Sergeeva, E. A. 2005, ApJ, 622, 129
Shakura, N. I. 1972, AZh, 49, 921
Shakura, N. I., & Sunyaev, R. A. 1973, A&A, 24, 337
Uttley, P., Edelson, R., McHardy, I. M., Peterson, B. M., & Markowitz, A. 2003, ApJL, 584, L53
Zel’dovich, Y. B. 1964, SPhD, 9, 195