The SDSS-RM Project: UV/Optical Accretion Disk Measurements for Supermassive Black Holes with Hubble Space Telescope

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The SDSS-RM Project: UV/Optical Accretion Disk Measurements for Supermassive Black Holes with Hubble Space Telescope

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May 2021

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Abstract

We report accretion-disk structure measurements for eight rapidly accreting supermassive black holes selected from the Sloan Digital Sky Survey Reverberation Mapping project sample. Reverberation mapping uses light echoes to measure disk size from the time lag between variability in the inner/hotter and outer/cooler disk emission. We use Hubble Space Telescope ultraviolet observations coordinated with optical monitoring from the Liverpool Telescope and Las Cumbres Observatory. We find ten significant UV/optical lags for five out of the eight total targets. Through these time lags, we study the accretion disk as a function of disk size, temperature profile and radiative efficiency. We find that the best-fit color profile for our sample matches the classic analytic model for a disk around a compact object. We find slightly larger disk sizes than expected, providing evidence for diffuse nebular emission from Balmer and FeII lines over discrete wavelength ranges. Our results overall are broadly consistent with the classic model but also support various theories pointing towards larger disk sizes in a subset of black holes. In the near future with new large time-domain surveys, the techniques we use in this work can be used on a larger scale to clearly determine the accuracy and reliability of this analytical model.
1 Supermassive Black Holes

Supermassive black holes (SMBH) are fascinating and yet ubiquitous objects living in the center of every massive galaxy. These black holes are rips in spacetime, containing up to billions of times the mass of our sun, operating under extreme gravity, growing by feeding on the nearby mass and glowing by converting that mass to light as it falls into the black hole. SMBHs are important in many different areas of astronomy. Their mass is observed to be correlated with the mass of their host galaxy, indicating coevolution between the two. Despite being small compared to their host galaxy, the two interact significantly with each other and grow together. Additionally, merging black holes are one of the main sources of gravitational waves in our universe. Since they are so massive and so compact, merging black holes, each drastically bending spacetime, can spiral in extremely close to each other and produce gravitational waves detectable here on earth.

1.1 The Accretion Disk

Black holes are named for their inescapable event horizon, below which gravity is so strong that even light cannot escape its pull. This means it is impossible to directly observe the interior of a black hole. Fortunately, techniques have been developed to measure properties of black holes by observing their gravitational influence on nearby matter, including the accretion disk. Due to angular momentum, rapidly circulating matter spiraling into the event horizon collapses down into a disk, known as the accretion disk. As matter rotates around the black hole, different parts of the disk slide together and, through friction, lose energy in the gravitational potential of the black hole. Consequently, this less energetic matter can no longer maintain its original orbit and eventually falls into the black hole. This process is known as the accretion onto black holes. A quasar is a rapidly accreting SMBH which, due to the enormous energy loss during material infall, can exhibit such high luminosity that it outshines entire galaxies.

The accretion disk around a compact object like a SMBH is commonly described by the standard “thin-disk” model proposed by Shakura & Sunyaev (1973, hereafter SS73):

\[
ct = \left(\frac{45G}{16\pi^6hc^2}\right)^{1/3} \lambda^{4/3} \dot{M}_{\text{BH}}^{1/3} \dot{M}_{\text{BH}}^{1/3}
\] (1)

Here \(ct = R\) is the disk size at rest-frame wavelength \(\lambda\), \(M_{\text{BH}}\) is the black hole mass and \(\dot{M}_{\text{BH}}\) is the accretion rate.

Despite being widely used, various observations find disk sizes that are not fully described by the SS73 prescription. Many observations report disk sizes that are larger by a factor of \(\sim 3-4\) compared to SS73 expectation (Morgan et al., 2010; Fausnaugh et al., 2016). However, these studies are limited to narrow range of \(M_{\text{BH}}\) and luminosity. In contrast, other works (Mudd et al., 2018; Homayouni et al., 2019; Yu et al., 2020) found that the model is a good average description but there is a lot of intrinsic scatter and many disks are significantly smaller or larger than the model. Together these observations hint at missing physics in SMBH accretion disks beyond the basic SS73 model.

1.2 Echo Mapping Black Hole Disks

Mass, accretion disk structure, and spin are the three fundamental properties of black holes. However, since the matter infalling onto black holes extends only to \(\sim 1\) pc, their inner environment cannot be spatially resolved in the distant universe (\(>100\) Mpc) and reverberation mapping is the only available technique used to make measurements of these black hole properties (Blandford & McKee, 1982).

Reverberation mapping uses the time delay between variations of hotter emission from the inner disk compared to cooler emission from the outer edges of the disk due to material infall. The entire disk is directly illuminated by the X-ray emission from an ionizing source above/below the disk (Galeev et al., 1979; Krolik...
et al., 1991; Reynolds & Nowak, 2003). The X-ray radiation is reprocessed by the disk from the inner edge to the outer edge, (known as the “lamp-post” model), allowing for continuum variation at different radii (Cackett et al., 2007). Consequently, flux variations in the X-ray emitting corona will drive the ultraviolet (UV) and optical variation.

In other words, matter infall causes fluctuations in the glow of the accretion disk and the same fluctuations seen at the inner edge are also observed at the outer edge. However, the regions of the accretion disk closer to the black hole vary first while the outer regions vary after some time delay that corresponds to the extent of the disk, like a “light echo” where variability at the inner edge of the disk is “echoed” at the outer edge. These correlated fluctuations enable cross-correlation between variability across interband UV/optical continuum emission to measure the accretion disk size and structure by estimating the light travel time (i.e., lag \( \tau \)) between UV and optical emitting regions (Blandford & McKee, 1982; Peterson, 1993, 2004). This technique is depicted in Figure 1.

## 2 The Quasar Sample

### 2.1 The SDSS-RM Project

The Sloan Digital Sky Survey Reverberation Mapping Project (SDSS-RM) is a pioneering multi-object campaign targeting 850 rapidly accreting SMBH (quasars) each year from January-June with spectroscopic and photometric monitoring from 2014-2020. The SDSS-RM quasar sample spans a broad range of mass, luminosity, and redshift and is more representative of the entire quasar population. Our set of eight targets is drawn from the SDSS-RM quasar sample (see Table 1).
### Table 1. Quasar Sample Information

<table>
<thead>
<tr>
<th>RMID</th>
<th>RA (deg)</th>
<th>Dec (deg)</th>
<th>z</th>
<th>$i$ mag</th>
<th>Var (%)</th>
<th>log $\lambda L_{3000}$ (erg s$^{-1}$)</th>
<th>log $M_{BH}$ ($M_\odot$)</th>
<th>log($L/L_{Edd}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>267</td>
<td>212.80299</td>
<td>53.75199</td>
<td>0.588</td>
<td>19.6</td>
<td>19.4</td>
<td>44.41</td>
<td>7.42$^{+0.17}_{-0.17}$</td>
<td>-0.39</td>
</tr>
<tr>
<td>300</td>
<td>214.92128</td>
<td>53.61379</td>
<td>0.646</td>
<td>19.5</td>
<td>18.2</td>
<td>44.87</td>
<td>7.6$^{+0.15}_{-0.12}$</td>
<td>-1.09</td>
</tr>
<tr>
<td>399</td>
<td>212.63053</td>
<td>52.25938</td>
<td>0.608</td>
<td>20.1</td>
<td>23.6</td>
<td>44.22</td>
<td>7.91$^{+0.16}_{-0.2}$</td>
<td>-0.01</td>
</tr>
<tr>
<td>551</td>
<td>212.9461</td>
<td>51.93883</td>
<td>0.681</td>
<td>21.5</td>
<td>10.3</td>
<td>44.33</td>
<td>6.95$^{+0.19}_{-0.19}$</td>
<td>-0.83</td>
</tr>
<tr>
<td>622</td>
<td>212.81328</td>
<td>51.86916</td>
<td>0.572</td>
<td>19.6</td>
<td>17.2</td>
<td>44.5</td>
<td>7.94$^{+0.19}_{-0.16}$</td>
<td>-0.88</td>
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<tr>
<td>634</td>
<td>212.89953</td>
<td>51.83459</td>
<td>0.651</td>
<td>20.8</td>
<td>13.2</td>
<td>44.06</td>
<td>7.56$^{+0.24}_{-0.26}$</td>
<td>-1.82</td>
</tr>
<tr>
<td>824</td>
<td>212.65879</td>
<td>52.00913</td>
<td>0.846</td>
<td>21.5</td>
<td>36.6</td>
<td>44.2</td>
<td>8.63$^{+0.45}_{-0.45}$</td>
<td>-1.82</td>
</tr>
<tr>
<td>840</td>
<td>214.18813</td>
<td>54.42799</td>
<td>0.244</td>
<td>18.6</td>
<td>50.0</td>
<td>43.49</td>
<td>7.93$^{+0.21}_{-0.2}$</td>
<td>-1.83</td>
</tr>
</tbody>
</table>

#### 2.2 Selection Criteria

Our targets were selected to be significantly variable, exhibiting root mean square (RMS) variability of 10%-50% at rest-frame $\lambda L_{3000}$ continuum. Using highly variable quasars maximizes the potential of detecting their fluctuations over our period of observation. Additionally, these targets do not have substantial flux from broad-line emitting region (BLR) in the UV filter. Typically, BLRs have longer timescales of variability and could bias the continuum light curves’ underlying shorter lags, so we ensure that our targets have < 10% BLR contamination. Lastly, most of our targets have reliable masses from H$\beta$ reverberation mapping (Grier et al., 2017).

This selection results in a sample of targets that probe a broad range of quasar parameter space in redshift, $\lambda L_{3000}$ continuum luminosity, and Eddington ratio. Our sample represents the most diverse set of quasars, and the first beyond the local Universe ($z > 0.1$), for UV/optical echo mapping of black hole accretion disks. Figures 2 illustrates this diversity.

#### 2.3 Observations

We used coordinated UV and optical monitoring from multiple telescopes in order to probe the different regions of the accretion disk. A summary of our observations is provided in Table 2.

We used HST UVIS Wide Field Camera 3 (WFC3) with the UV filter F275W (centered at 2704 Å) to observe 8 quasars every other day over 72 orbits (5 targets for 32 orbits in Cycle 25 and 3 targets for 40 orbits in Cycle 26). The monitoring duration maximizes the probability of observing a period of strong variability and accounts for the full range of predicted time lags. The HST UV observations probe the inner edge of the accretion disk which contains high energy particles that emit photons in the UV. A space-based observatory is required since most UV rays cannot penetrate the earth’s atmosphere to be detected at the ground.

During Cycle 25, we adopted the “drift and shift” (DASH) observing mode, which maximizes observing time by using unguided, gyro-controlled exposures. Normally, the telescope must spend time acquiring a guide star to maintain accurate pointing before beginning to record data. However, due to our targets proximity in the sky, HST can turn off guiding between targets, i.e. it only to has to find one target and then “drift-and-shift” to observe the others. This method allows many targets to be observed during each orbit and makes it an unusually efficient program. However, due to the lack of guidance sensor corrections, the telescope drift was reported to result in a smeared image by 0.001 - 0.002 per second (Momcheva et al., 2017). The DASH observing method has been successful in other IR wide-field studies such as COSMOS-DASH (Mowla et al., 2019). This observing method had not been tested in the UV range until the current
Figure 2 The SDSS-RM parent sample of 849 quasars (gray points) and the set of eight quasars from the UV monitoring campaign (colored points). Our targets probe a wide range of quasar parameter space in $\lambda L_{3000}$ continuum luminosity, and Eddington ratio, as reported in Shen et al. (2019).

<table>
<thead>
<tr>
<th>Observatory Name</th>
<th>Observing Window</th>
<th>Filters</th>
<th>Epochs</th>
<th>Target ID</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>HST UV Monitoring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hubble Cycle 25</td>
<td>March - May (2018)</td>
<td>F275W</td>
<td>32</td>
<td>399, 551, 622, 634, 824</td>
</tr>
<tr>
<td>Hubble Cycle 26</td>
<td>March - June (2019)</td>
<td>F275W</td>
<td>40</td>
<td>267, 399, 840*</td>
</tr>
<tr>
<td><strong>Ground-based Optical Monitoring</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Las Cumbres (McDonald)</td>
<td>Feb-May (2018)</td>
<td>r</td>
<td>54</td>
<td>551, 622, 824</td>
</tr>
<tr>
<td>Las Cumbres (Haleakala)</td>
<td>Feb-May (2018)</td>
<td>z</td>
<td>104</td>
<td>551, 622</td>
</tr>
<tr>
<td>Liverpool Telescope</td>
<td>March-June (2018)</td>
<td>r</td>
<td>80</td>
<td>399, 551, 622, 634, 824</td>
</tr>
<tr>
<td>Las Cumbres (McDonald)</td>
<td>Jan-May (2019)</td>
<td>g</td>
<td>57-66</td>
<td>267, 300, 840</td>
</tr>
<tr>
<td>Las Cumbres (McDonald)</td>
<td>Jan-May (2019)</td>
<td>i</td>
<td>58-65</td>
<td>267, 300, 840</td>
</tr>
<tr>
<td>Liverpool Telescope</td>
<td>March-June (2019)</td>
<td>r, z</td>
<td>80</td>
<td>267, 300, 840</td>
</tr>
</tbody>
</table>

*During Cycle 26, RM840 was observed for 33 orbits due to limitation of available guide star and rolling angle.
Figure 3 Each of four images during one orbit for one target. The red ovals describe the moving target area, in which the target drifts during the DASH observations. Other white spots are cosmic rays, making target identification difficult among the noise.

study. We found that our UV monitoring experiment displayed drifting $\gtrsim 0.005''$/sec (Homayouni et al., 2021, in prep.) which is much larger than the prediction. This is depicted in Figure 3.

Along with the UV observations we used coordinated ground-based observations with a daily cadence from the Liverpool Telescope (LT) and Las Cumbres Observatory Global Telescope Network (LCOGT). Using two different telescopes fills weather gaps and provides sufficient cadence to generate well-sampled light curves over multiple bands ($g, r, i, z$). In order to account for optical continuum variability of typically smaller amplitudes and longer timescales, the ground-based monitoring began before and ended after the UV observations. By extending the ground-based monitoring beyond the UV monitoring, we enable detecting lags shorter or longer than SS73 prediction.

3 Data Reduction

3.1 HST Cycle 25 DASH UV Reductions

The DASH observing complicates extracting photometry from the images since the targets move around and may be smeared. Standard reduction methods don’t work, since they’re designed to reject things that appear at a fixed location in only one sub exposure, like cosmic rays (high-energy particles that frequently impact the detector). Even worse, the magnitude of the drift was considerably larger than expected in $\gtrsim 90\%$ of visits. Therefore, we performed custom data reductions to account for this unique observing mode.

We used the calibrated, flat-fielded individual exposures (“FLT” files) to visually locate our quasar targets, identifying similar objects appearing close to each other in successive subexposure images. We then measured the point-spread function (PSF) through SAOImageDS9. Our quasar targets are less point-like and fainter than the cosmic rays, resulting in a broader PSF with a lower maximum, as shown in Figure 4. This difference also translates to a visual distinction between cosmic rays and quasar targets in the images.

We were only able to locate the faintest of our quasar targets (RM634) in five orbits, and therefore, we discontinued the analysis of this object. The remaining four quasars were identified in at least one subexposure image in 82% of the visits.

We used the Astropy photutils (Bradley et al., 2017) software package to extract fluxes from aperture photometry. Identifying the optimal aperture for the flux extraction was complicated by the DASH observing method since the targets blurred into different shapes in each subexposure dither pointing. To account for this, we performed aperture photometry with circular apertures of increasing radii, $r_{\text{aperture}}$. Testing radii on a range of $0 < r_{\text{aperture}} < 10$ pixels was sufficient for most targets but this was adjusted for more smeared targets to a range of $0 < r_{\text{aperture}} < 20$ pixels. We estimated the local background within a circular annulus of $r_{\text{inner}}$ equal to the maximum of the range for $r_{\text{aperture}}$ and $r_{\text{outer}} = r_{\text{inner}} + 2$ pixels. This results in an aperture mask for each subexposure. We use the sigma clipped median estimator to obtain the local
Figure 4 Comparison between the point spread functions (PSFs) for a cosmic ray and quasar target: RM622 (left) and RM824 (right). Cosmic rays typically appear with sharp edges on the image and thus have a narrower full-width at half-maximum (FWHM) compared to a point source quasar. We used this additional identification method during the visual inspection to distinguish our quasar targets from cosmic rays. The average FWHM for RM551 and RM622 is about 2.5 pixels compared to the average cosmic ray FWHM of 1.3 pixels.

background. Using a median avoids outliers caused by the presence of high-flux cosmic rays in the annulus. The total background within each aperture is the local background times the circular aperture area.

We measured the target flux as 90% of the maximum, illustrated in Figure 5. Photometry failed for targets that overlapped with cosmic rays and/or were too smeared. Overall we were able to obtain good photometric measurements from 70% of the subexposure images for the four observed targets (RM622, RM551, RM824, and RM399).

We compute UV flux uncertainties assuming a Poisson error distribution. We use the error array of the flat-fielded final pipeline outputs and compute the total flux uncertainty in each subexposure, $\sigma_{\text{tot}}$, as the sum of measurement uncertainties inside each aperture, such that $\sigma_{\text{tot}}^2 = \sum_{\text{aperture}} \sigma_{\text{error}}^2$. We improved the final light curve quality by rejecting outlying flux measurements that were offset by more than three times the normalized median absolute deviation (NMAD).

3.2 HST Cycle 26 UV Reductions

The Cycle 26 observations were performed with a standard approach rather than the DASH method and are therefore much easier to reduce. We used the same approach as the previous Cycle 25 observations for consistency. We again use the flat-fielded subexposures and perform aperture photometry using the Astropy photutils (Bradley et al., 2017) software package. We test a sequence of 50 circular apertures in the range $1 < r_{\text{aperture}} < 15$ pixels while estimating the local background from the sigma clipped median estimator. We obtain the optimal aperture by computing the local maxima in the sum of flux over each $r_{\text{aperture}}$ and...
Figure 5  **Right:** An example of the four subexposure images for one of the quasars (RM622) observed with the DASH method. The target smearing varies in shape and direction, resulting in maximal smearing in the fourth image in this example. **Left:** Curves of growth for the flux as a function of aperture radius. We performed aperture photometry on a sequence of increasing circular radii ranging from 0 to 12 pixels. The chosen aperture size corresponds to 90% of the target’s flux saturation point (blue horizontal dashed line). The red vertical dotted line illustrates the final radius in pixels.

compute the final target flux as 90% of the maximum flux. We again estimate the flux uncertainties using the root of the sum of the squared uncertainties by placing the optimal aperture over the flat-fielded direct error outputs.

### 3.3 Ground-based Optical Reductions

Optical monitoring comes from Las Cumbres Observatory and Liverpool Telescope observations that are concurrent with the *HST* UV monitoring. Ground-based observations are affected by local atmospheric conditions and so we use non-varying stars observed alongside the (varying) quasar targets in order to calibrate out the effects of weather. To produce the relative photometric light curves for the ground-based observations, we select five standard stars for each telescope/field/pointing. We perform aperture photometry using the *photutils* (Bradley et al., 2017) software package on the five standard stars of a magnitude similar to that of the quasars and extract the relative flux by calculating the ratio of the quasars’ net integrated counts (see Figure 6).

The aperture photometry is again performed similar to the Cycle 25 UV reductions: computing the flux in the flat-fielded, sky background-subtracted image over 100 circular apertures in the range $1 < r_{\text{aperture}} < 20$. We estimated the local sky background for each target from the $r_{\text{inner}} = r_{\text{aperture}} + 3$ pixels and
Figure 6 Uncalibrated raw quasar light curve (top), standard stars (middle), and the final difference imaging light curve for RM840 (bottom). We use the light curve of the non-varying star to correct for weather variations and arrive at a calibrated quasar light curve that reflects only intrinsic variation.

$router = r_{aperture} + 6$ pixels. We again find the optimal aperture for each standard star/quasar using the local maxima of the flux over the aperture sequence.

4 Time-Series Analysis

4.1 Light Echo Time Lags

We use the time-series analysis method JAVELIN (Zu et al., 2011) to measure the time lags between variability in the UV and echoes of the same variations in the different optical light curves. Rather than using linear interpolation between data points, JAVELIN uses a damped random walk (DRW) model to describe the light curves’ stochastic variability (Kelly et al., 2009; MacLeod et al., 2010, 2012; Kozlowski, 2016). It assumes the reverberating light curve model is a smoothed, scaled, and shifted (i.e. echoed) version of the UV driving light curve. It then simultaneously fits a DRW model that describes the light curve variability and fits a transfer function to maximize the likelihood of the model using a Markov chain Monte Carlo (MCMC) approach (Grier et al., 2017).

To extract the most accurate time lag from the light curves using JAVELIN, we tested multiple combinations of parameters for the fitting. We adopt a lag search range of ±45 days (Cycle 25) and ±60 days (Cycle 26), chosen to be $\sim \times 2/3$ of the $\sim 60$ and $\sim 80$ day monitoring duration. We allow the DRW amplitude to be a free parameter but tested fixing both the DRW damping timescale and the transfer function width in order to find the best DRW model. We fixed the DRW damping timescale to 50, 100, 200 and 300 days and found no significant differences in the measured lags. We also tested a wide range of fixed transfer function widths, including 0.25, 0.5, 0.75, 1, 2, 10 days. The transfer function’s width had no significant effect on the final lags as long as JAVELIN chain converged. The final width we selected was 0.5 days. JAVELIN returns a lag distribution from $62500$ MCMC simulations, which are used to compute JAVELIN lag, $\tau_{jav}$, and we
Table 3. Significant UV/Optical Rest-frame Lag Measurements

<table>
<thead>
<tr>
<th>ID</th>
<th>$\tau_{UV-g}$</th>
<th>$\tau_{UV-r}$</th>
<th>$\tau_{UV-i}$</th>
<th>$\tau_{UV-z}$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>days</td>
<td>days</td>
<td>days</td>
<td>days</td>
</tr>
<tr>
<td>267</td>
<td>-</td>
<td>2.31$^{+1.92}_{-1.17}$</td>
<td>-2.02$^{+4.3}_{-3.29}$</td>
<td>3.67$^{+2.47}_{-1.84}$</td>
</tr>
<tr>
<td>300</td>
<td>2.55$^{+4.09}_{-3.35}$</td>
<td>4.89$^{+2.36}_{-2.11}$</td>
<td>-</td>
<td>2.41$^{+2.99}_{-2.36}$</td>
</tr>
<tr>
<td>399</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>551</td>
<td>-</td>
<td>3.45$^{+3.71}_{-3.56}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>622</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>824</td>
<td>-</td>
<td>2.32$^{+4.28}_{-4.21}$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>840</td>
<td>-</td>
<td>3.05$^{+3.38}_{-3.38}$</td>
<td>-</td>
<td>5.14$^{+3.94}_{-3.78}$</td>
</tr>
</tbody>
</table>

Compute the lag uncertainty from the 16th and 84th percentile of the distribution.

For each target, we measure the inter-band lags between the UV-band and optical $g, r, i, z$ bands. Figure 7 illustrates target RM840’s light curves in all bands along with the JAVELIN lag distributions. Among the targets in our sample, JAVELIN was unable to obtain a continuum model for RM551, but successfully produced the DRW light curves after the error bars were rescaled by 80%.

4.2 Accretion Disk Fits

One of our main goals is to use the UV/optical time-delays to study accretion disk structure as a function of $M_{BH}$ and accretion rate by fitting a parameterized model to the measured lags. Therefore, once the time lag per filter associated with each quasar has been determined, we extract other quasar characteristics through comparison with the SS73 disk model (Equation 1). For simplicity, we refer to each of the measured UV/optical lag and model-predicted SS73 as a “disk size.” More precisely, these quantities are the relative distances corresponding to the differences between the characteristic light travel time lags from each waveband.

We combine the significant lag measurements for our targets (see Table 3) and use a Bayesian approach to fit the disk size normalization ($\tau_0$), black hole mass ($M_{BH}$) and luminosity ($\lambda L_{3000}$) (as a proxy for accretion rate) using Equation 2, which is similar to Equation 1 except that it is normalized to be specific to the time delay difference of the UV/optical lags.

$$
\tau_{opt} - \tau_{UV} = \tau_0 \left( \frac{\lambda_{opt}}{2700\text{Å}} \right)^{\beta} - \left( \frac{\lambda_{UV}}{2700\text{Å}} \right)^{\beta} \frac{M_{BH}}{\langle M_{BH} \rangle} \frac{\lambda L_{3000}}{\langle \lambda L_{3000} \rangle}^{\delta}
$$

We adopt a Markov chain Monte Carlo approach to fit the accretion disk using three steps: a single parameter fit for disk size normalization, a double-parameter fit involving disk size normalization and $M_{BH}$ and a three-parameter fit that includes disk size normalization, $M_{BH}$, and luminosity. Table 4 provides a brief summary of these different fitting strategies using the JAVELIN lags along with their uncertainties ($\sigma$).

Our disk sizes are larger than the SS73 model predictions, however, this is likely due to our sample bias. “Industrial scale” monitoring projects, including our SDSS-RM parent sample, tend to report average disk sizes consistent with model predicted disk size but with significant scatter around the mean. Our quasars were likely preferentially drawn from the larger-lag portion of this wide range of disk size around the mean, resulting in our larger disk size normalization measurements.

In general, there are multiple possible underlying causes for quasars having larger disk sizes. One possibility is that diffuse nebular emission, diffuse Balmer continuum and iron emission from the BLR is increasing time lags (Chelouche, 2013) and making the continuum longer than from disk reverberation alone. Cackett...
Figure 7 The right panels show an example of the UV and optical $g, r, i, z$ light curves, from top to bottom, for target RM840. The best-fit light curve models from JAVELIN are shown as the colored lines. The right panels are the probability distribution functions for the best-fit lag between the UV and each of the optical bands.

Table 4. Fits to $M_{BH}$ and $\lambda L_{3000}$

<table>
<thead>
<tr>
<th>Free Parameters</th>
<th>$\tau_0$</th>
<th>$\beta$</th>
<th>$\gamma$</th>
<th>$\delta$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\tau_0$</td>
<td>$2.46^{+0.87}_{-0.86}$</td>
<td>fixed(4/3)</td>
<td>fixed(1/3)</td>
<td>fixed(1/3)</td>
<td>-</td>
</tr>
<tr>
<td>$\tau_0, \beta$</td>
<td>$2.0^{+1.9}_{-1.3}$</td>
<td>$1.36^{+0.99}_{-0.64}$</td>
<td>fixed(1/3)</td>
<td>fixed(1/3)</td>
<td>-</td>
</tr>
<tr>
<td>$\tau_0, \beta, \gamma$</td>
<td>$1.7^{+1.93}_{-1.19}$</td>
<td>$1.25^{+1.12}_{-0.77}$</td>
<td>$0.28^{+0.85}_{-0.76}$</td>
<td>fixed (1/3)</td>
<td>$0.94^{+1.1}_{-0.67}$</td>
</tr>
<tr>
<td>$\tau_0, \beta, \delta$</td>
<td>$1.79^{+1.94}_{-1.21}$</td>
<td>$1.06^{+1.01}_{-0.64}$</td>
<td>fixed (1/3)</td>
<td>$0.33^{+1.02}_{-0.48}$</td>
<td>$0.98^{+1.14}_{-0.69}$</td>
</tr>
<tr>
<td>$\tau_0, \gamma, \delta$</td>
<td>$1.32^{+1.95}_{-0.99}$</td>
<td>fixed(4/3)</td>
<td>$0.32^{+1.53}_{-0.99}$</td>
<td>$0.63^{+1.57}_{-0.83}$</td>
<td>$1.05^{+1.19}_{-0.74}$</td>
</tr>
</tbody>
</table>
et al. (2018) reports evidence for diffuse nebular BLR contamination in specific filters and Chelouche & Zucker (2013); Chelouche (2013) found this to be widespread. We compute the fractional BLR contamination for prominent BLR emission lines relevant to each filter including: Lyαλ1215, Hαλ6563, Hβλ4861, HeIIλ1667, MgIIλ2800, CIVλ1549, and CIII[4]λ1909. The fractional BLR contamination is given by the ratio of the emission-line equivalent width (EW_{line}) to the overlapping filter width and multiplying by the RMS variability of the emission line and nearby continuum (EW_{ratio}).

In studying NGC7496, Korista & Goad (2001, 2019) noted a significant effect on lags from the Balmer continuum. This was supported by Cackett et al. (2018) who further reports that the effect is particularly strong around the Balmer transition at 3646 Å. Two main contributions to the diffuse Balmer continuum are from free-bound transitions (recombination) which affect wavelengths bluer than the Balmer edge and high-order bound-bound transitions which affect wavelengths redder than the Balmer edge. This could explain our long UV-g and UV-i lags that overlap with 3646 Å. We reject lags > 10 days that overlap with rest-frame λ3500 - 3900 Å.

Additionally, there are multiple weak emission lines from 344000 FeII in the BLR that form a continuum at wavelengths from UV to infrared (Vestergaard & Wilkes, 2001; Bruhweiler & Verner, 2008) which varies slowly and introduces uncertainty in the true continuum variability (Kuehn et al., 2008). We reject the following outlier measurements that overlap with the FeII complex at λ4434 - 4684 Å (Boroson & Green, 1992) or λ5100 - 5477 Å (Vanden Berk et al., 2001) and have rest-frame lags >10: τ_{uv−i}(RM300) = 14.2^{+3.9}_{−4.7}, τ_{uv−r}(RM399) = 15.9^{+4.7}_{−4.4}, τ_{uv−z}(RM551) = −16.3^{+4.4}_{−4.9}, and τ_{uv−g}(RM840) = 25.7^{+4.6}_{−3.9}.

Another possibility for larger disk sizes is that there is a different reprocessing geometry. If the ionizing corona has a size that is comparable to the accretion disk the light travel time will be significantly increased and the measured lag will be larger (Kammoun et al., 2021). One model for disk reverberation includes a significant effect from magnetic coupling between the X-ray corona and accretion disk (Sun et al., 2020) which predicts that lower luminosity AGNs typically have larger lags (Li et al. 2021, submitted). Our sample generally represents the lower luminosity range of the broader sample of SDSS-RM quasars.

In terms of the lag dependence on wavelength (i.e., the lags associated with different optical filters g, r, i, z) our significant lags are consistent with the model that τ_{uv−g} < τ_{uv−r} < τ_{uv−i} < τ_{uv−z} (see Figure 8). Furthermore, our fitting resulted in a wavelength scaling parameter $\beta = 1.36^{+0.97}_{−0.64}$ which is consistent with SS73 expectation where $\tau \propto \lambda^{4/3}$. For the lag dependence on black hole mass and luminosity, we find the best-fit values are consistent with theoretical SS73 expectation with $\tau \propto M_{BH}^{1/3}$ and $\tau \propto \lambda^{4/3}_{3000}$. However, there are larger uncertainties when both are simultaneously allowed to be free parameters in the fit.

Overall, we find ten significant UV/optical lags for five of our quasar targets. Using these measured time lags, we fit a parameterized model to the accretion disk. We find that the disk size normalization is larger than predicted by the model, however, this could be accounted for by our sample being biased towards the larger disk size end of the observed scatter about the mean in industrial-size samples. We also observe that our quasar’s temperature profile, i.e. dependence on wavelength, is consistent with the SS73 model. Furthermore, our lag measurements generally agree with previously measured optical/optical lags.

5 Conclusions

Overall, we find ten significant UV/optical lags for five of our quasar targets. Using these measured time lags, we fit a parameterized model to the accretion disk. We find that the disk size normalization is larger than predicted by the model, however, this could be accounted for by our sample being biased towards the larger disk size end of the observed scatter about the mean in industrial-size samples. We also observe that our quasar’s temperature profile, i.e. dependence on wavelength, is consistent with the SS73 model. Furthermore, our lag measurements generally agree with previously measured optical/optical lags.
Figure 8 Rest-frame disk lag versus wavelength for our targets. The colored symbols show the UV-$g$ (green), UV-$r$ (orange), UV-$i$ (red), and UV-$z$ (maroon). The red dashed line displays the SS73 model for the mean $M_{\text{BH}}$ and mean $\dot{M}_{\text{BH}}$ and the shaded region around the red dashed line illustrates the minimum and maximum of the SS73, computed from our sample’s minimum and maximum in $M_{\text{BH}}$ and $\dot{M}_{\text{BH}}$. The shaded grey regions illustrate the Balmer diffuse continuum and the Feii diffuse continuum. Our disk lag measurements show the general expectation of increased disk size as a function of wavelength but also imply disks that are $\sim$4 times larger than the SS73 expectation.

Figure 9 Comparison between our reliable lags in UV/optical and $g-i$ band optical/optical continuum lags, from Homayouni et al. (2019). Each lag is converted to a disk lag of 2700 to 5100 Å (chosen as a representative disk scale that overlaps with both sets of observations). The colored symbols show the UV-$g$ (green), UV-$r$ (orange), UV-$i$ (red), and UV-$z$ (maroon). The dashed one-to-one line is also shown.
6 Future Work

6.1 SDSS-V BHM

In the near future, large time-domain surveys like the SDSS-V Black Hole Mapper (BHM) will significantly increase the number of quasars with multi-band and spectroscopic reverberation mapping. BHM-RM will observe 5 fields of 380 quasars each with 174 epochs of spectra and BHM-AQMES will observe 25,000 quasars with 5-12 spectra over 5 years. With its high cadence and long duration, BHM-RM will permit detailed reverberation mapping and, with its large sample size, BHM-AQMES will enable statistical studies of general variability trends.

6.2 Changing-Look Quasars

Changing-look quasars, the first of which (J015957.64+003310.4) was discovered by LaMassa et al. (2015), are quasars that exhibit the appearance or disappearance of one or more emission lines and switch between being Type 1 and Type 2 (AGN). Type 1 AGN have prominent broad emission lines while Type 2 AGN do not. Previously, the difference between Type 1 and 2 AGN was thought to be due to the individual quasar’s orientation and resulting obscuration of the central engine. However, changing-look quasars challenge this idea (LaMassa et al., 2015).

While variations typically used for reverberation mapping are about 10-20%, changing-look quasars vary by factors of about 10 on the same timescales (Dexter et al., 2019; MacLeod et al., 2016). These transformations have been speculated to be a result of changes in accretion rate of the AGN (Dexter et al., 2019; Runnoe et al., 2016). Whether the accretion disk maintains its structure during these changes remains unclear (MacLeod et al., 2016).

Changing-look quasars provide a unique opportunity to study the relationship between accretion rate and disk structure due to their hyper-variability. Through performing reverberation mapping studies on a sample of changing-look quasars over the course of these Type 1-Type 2 changes we could track the corresponding variability (or non-variability) of the accretion disk structure.
References


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