Understanding Supermassive Black Holes Using the Dark Energy Survey and OzDES

DISSERTATION

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By

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Abstract

I present the initial results of characterizing moderate redshift ($z \leq 2$) quasars in the Dark Energy Survey (DES) by their variability. As the scales associated with supermassive black holes (SMBHs) are too small to be resolved directly, alternative methods are necessary to learn about their structure, how they grow, and how they impact their environments. One such method is through variability. Quasars are naturally variable objects, and by measuring the time delay to different emitting regions as they respond to changes in the extreme ionizing UV photons produced at the inner edge of the disk, we can estimate normally inaccessible size scales associated with SMBHs. This technique is known as reverberation mapping.

I first apply this technique to probe accretion disk sizes. Only a handful of such measurements exist in the literature, sampled through reverberation mapping or gravitational microlensing. I measure time delays between the DES photometric bands to place constraints on accretion disk sizes, and then present a software extension to the JAVELIN code that provides a Bayesian framework for fitting a thin accretion disk model directly to the data rather than the individual lags themselves. This is tested on fake data as well as the highest quality dataset available for a local active galaxy, NGC 5548, before being applied to a sample of DES quasars. This
new framework, under our thin disk assumption, gives competitive accretion disk sizes for quasars with our survey quality data alone, and adds over a dozen objects to the relatively small number of quasars with measured disk properties.

Next, I present the serendipitous discovery of a $z=0.65$ low-ionization broad absorption line (LoBAL) quasar in a post-starburst galaxy in the DES data, spectroscopically confirmed with the Australian Dark Energy Survey (OzDES) project. LoBAL quasars are a minority of all BALs, and rarer still is that this object also exhibits broad FeII (an FeLoBAL) and Balmer absorption. This is the first BAL quasar that has signatures of recently truncated star formation, which we estimate ended about 40 Myr ago. The characteristic signatures of an FeLoBAL require high column densities, which could be explained by the emergence of a young quasar from an early, dust-enshrouded phase, or by clouds compressed by a blastwave. The age of the starburst component is comparable to estimates of the lifetime of quasars, so if we assume the quasar activity is related to the truncation of the star formation, this object is better explained by the blast wave scenario.

Finally, I conclude with describing our efforts for the spectroscopic reverberation mapping campaign with DES and OzDES. As with the accretion disks, the goal is to measure a time delay, this time between the quasar continuum emission and the response of the broad emission lines from the broad line region. Coupled with the gas velocity dispersion from the spectra, this enables us to estimate the mass of the
SMBHs, on which we will calibrate relationships to make future mass measurements far less resource intensive.
Dedication

Dedicated to my mom for encouraging me to get where I am today, and to Christine and Fuzzbutt for keeping me sane while writing this.
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Chapter 1: Introduction

1.1. Introduction to Active Galactic Nuclei (AGNs) and Reverberation Mapping

The current paradigm on galaxy formation and structure posits that most, if not all, galaxies host a central supermassive black hole (SMBH). As such, learning how these black holes form, grow, and affect the development of their host galaxies is crucial for understanding the universe as observed today. When and how they form is still subject to much debate, but many empirical relationships have been uncovered that show a link between the black hole’s properties and those of their host galaxies as a whole (e.g., Ferrarese & Merritt 2000; Kaspi et al. 2005; Bentz et al. 2009). For these and numerous other reasons, being able to reliably and accurately measure SMBH masses is a key aim of extragalactic astronomy.

These SMBHs gain mass through accretion of matter and through mergers with other SMBHs. During these growth phases, they have a hot accretion disk that provides a large continuum luminosity via viscous heating of material dissipating through the disk as well as reprocessing of incident radiation on the disk. This continuum is observed in the spectra of these active galactic nuclei (AGNs), but the spectra also show several other distinctive features. One is the presence of emission lines from excited and ionized gas that arise from two separate regions around the AGN. The narrow emission lines originate in a more extended region much farther from the central engine itself, up to around a kiloparsec away (although by variability arguments it is suggested it may be much smaller than this, at least in some cases; Peterson et al. 2013). The broad emission lines instead come from a much more compact region closer to the SMBH, on the scale of light-days to light-weeks. Based on the inferred temperature and density of the gas in this broad line region (BLR),
the width of these lines comes from orbital motion of the gas rather than any sort of pressure or Doppler broadening from its temperature. In some AGN, these broad lines are not observed, which may result from a dust torus around the AGN that is thicker than the BLR and obscures lines of sight to the BLR depending on the orientation towards the observer.

These broad emission lines change in response to any changes in the ionizing flux provided by the accretion disk. By tracking the reverberation of the BLR gas to variations in the ionizing radiation from the disk, one can infer the spatial extent of the BLR gas (e.g., Blandford & McKee 1982; Peterson et al. 2004; Peterson 2010). This technique is known as reverberation mapping. Assuming that (a) the BLR is larger than the source of the continuum emission, (b) the recombination time for the BLR gas is small, and (c) the BLR is generally optically thin to its own emission, one can derive the orbit of the gas from observing the change in its emission line profile over time. Since light travel time is finite, an observer would see the BLR gas directly along the line of sight to the continuum source respond immediately to any such ionizing flux change. There is a lag in the response of the BLR gas on the opposite side of the continuum source, however, due to the path length difference of the emission line photons from the BLR gas. As the recombination timescale is short compared to the light travel time, these delays correspond to light travel distances to BLR clouds.

By measuring the time spacing between a continuum flux feature, a proxy for the ionizing radiation that affects the BLR clouds, and the same feature in the AGN’s broad emission lines, one obtains the average distance out to the BLR. More generally, however, one can relate the line luminosity to the continuum luminosity via a transfer function as outlined by Blandford & McKee (1982). The various moments of the transfer function encode properties of the structure of BLR gas orbits. The average BLR distance is especially useful. Coupled with some measure of the gas’ velocity, ΔV, typically inferred from the FWHM or line dispersion of the emission line profiles, this radius R can be used to estimate a “virial mass” of the SMBH, given by

\[ M_{BH} = f \frac{\Delta V^2 R}{G}, \]  

(1.1)
where the $f$ factor encodes the geometry of the BLR cloud orbits and is of order unity.

1.2. Reverberation Mapping in Practice

Measuring BLR delays for AGN began in the mid 1980s. Early works were undertaken with both ground-based observatories looking at hydrogen transitions (e.g., Wanders et al. 1993) and higher ionization carbon and magnesium lines from space missions (Ulrich et al. 1991 and references therein). Over the decades, the database of systems with BLR and mass measurements has increased and now includes roughly 60 galaxies spanning over two orders of magnitude in mass and luminosity, many of which have been revisited multiple times to update and verify their lags (see Bentz & Katz 2015). In particular, NGC 5548 has been observed off and on for 25 years, providing the most-continuous baseline for observing long-term trends in nearby AGN.

A primary reason that so many of these systems have been involved in multiple campaigns to detect lags is that both observation strategies and analysis techniques undergone significant changes since the 1980s. Although Blandford & McKee (1982) lay out the basics of reverberation mapping details while focusing on the transfer function, it is difficult to characterize the transfer function from even the most robust data. As such, most work prior to the last few years focused on the average lag rather than recovering the full BLR orbits. There was still the question, however, of how to treat the irregular time series sampling of AGN light curves.

Initially, there were two main techniques for surmounting this problem of correlating the slightly sporadic continuum and emission line light curve measurements. The first was the cross-correlation function (CCF), which linearly interpolates in the data between the gaps in real measurements to provide a method of directly comparing the two light curves (e.g., Gaskell & Sparke 1986; Gaskell & Peterson 1987). The second was the discrete correlation function (DCF) which, instead of interpolating gaps in data, opts to bin the two light curves in time such that each bin is well-sampled and then calculates the lag between the binned continuum and emission line light curves (Edelson & Krolik 1988).
Recently, it has been found that changes in quasar luminosity can be well-characterized by a damped random walk (DRW) model dictated by two parameters—the variability amplitude and the damping timescale on which the quasar returns to its average flux state (Kelly et al. 2009; MacLeod et al. 2010). Zu et al. (2011) use this information in the development of SPEAR, Stochastic Process Estimation for AGN Reverberations. By fitting light curves for the two parameters above, SPEAR (and later its successor, JAVELIN) interpolates in missing data points while simultaneously providing (statistical) error bars on its output values. When providing multiple light curves, by assuming that all the data are simply shifted and smoothed variations of the "driving" light curve, it also uses the data from the non-driving data to fill in gaps in the data. The authors test this on over 100 AGN light curves found in the literature to recompute their lags using a top-hat transfer function, which are generally in agreement with their previous values, and has been used in numerous studies since its creation (e.g., Grier et al. 2013b).

In terms of observational strategy, adopting a proper cadence has become vital for determining lags. Blandford & McKee (1982) originally proposed monitoring of bright AGN on a biweekly basis, but it has become clear that many of these objects have H$\beta$ lags that are closer to a few days rather than a few weeks (e.g., Peterson et al. 2004; Bentz & Katz 2015) and thus require more dedicated observations. To highlight one system in particular, Markarian 6 has been involved in multiple campaigns for determining its lag. In a campaign with a long baseline but low sampling rate, the lag was calculated at $\tau = 21.1$ days (Doroshenko et al. 2012), whereas in a shorter campaign with closer to daily cadence it was found to be $\tau = 9.2$ days (Grier et al. 2012). The latter work runs the former’s light curves through the same analysis they do for their own light curves and recover the longer lag, but when restricting to the highest time sampling portion of the light curve, they recover a lag for the Doroshenko et al. (2012) data similar to their own. As such, Grier et al. (2012) posit that the more infrequent sampling (median of >10 days) of the previous campaign caused it to be insensitive to recovering the true lag, which serves as a cautionary tale for future monitoring expeditions.
After the lag/radius, the remaining information required to get the SMBH mass is (a) the velocity of the BLR gas and (b) the geometric $f$ factor from Equation 1.1. Traditionally, the velocity has been measured from the full-width half-maximum (FWHM) of the broad emission lines. Another choice is the line dispersion $\sigma$, the square root of the second moment of the line profile. The FWHM is useful in that it is much easier to measure than the line dispersion, but the masses have been calibrated using $\sigma$, and for objects with multiple reverberation mapping measurements, $\sigma$ gives a more consistent mass than FWHM (Collin et al. 2006). It has also been seen that the ratio of FWHM/$\sigma$ changes as a function of FWHM (Peterson et al. 2004), which produces a bias at fixed luminosity that tends to overestimate the highest mass SMBHs and underestimate the lowest mass ones. Measuring the line dispersion or FWHM from the root-mean spectrum (RMS) rather than the average spectrum over the campaign is also suggested as the RMS spectrum has the advantage of identifying only the variable portion of the emission line, which minimizes contribution from any component of the emission arising from the narrow line region (or any other location) rather than the BLR.

Finding the $f$ factor is more complicated, as an anchor for the true mass must be known. It has been predicted (Silk & Rees 1998; Fabian 1999) and shown empirically (e.g., Ferrarese & Merritt 2000; Ferrarese et al. 2001; Tremaine et al. 2002) that the central SMBH’s mass correlates with the stellar velocity dispersion in both active and quiescent galaxies. One way of calibrating $f$ is to assume that reverberation masses should also lie along this same $M - \sigma_{\text{star}}$ relationship for inactive galaxies, and find what average multiplicative factor shifts the AGN onto it. This is done in several works (e.g., Onken et al. 2004; Park et al. 2012) and found to be roughly 5. In an analysis re-deriving the masses for all the reverberation mapping objects, Grier et al. (2013a) find an average $f$ factor of 4.3, though this is consistent within errors of previous larger values. It should be noted immediately, however, that this is simply an average geometric factor calculated statistically from the reverberation mapping sample, and that any specific object may have a very different “true” $f$. Judging by the scatter after applying these geometric corrections, it is clear that these masses can still be off from their actual values by a factor of a few ($\sim$3).
Reverberation mapping can thus be used to determine the masses of SMBHs that are too distant to measure through other means such as resolved orbits of stars within their spheres of influence. However, it is quite a resource intensive process for even a single object. Ideally, there would be a way to get a comparable mass estimate from only a single or few epochs of data rather than solely from extended campaigns. With still a few more assumptions, one can use the ionization parameter,

\[ U = \frac{L_{\text{ion}}}{4\pi r^2 n_e c}, \]

(1.2)

where \( L_{\text{ion}} \) is the luminosity of ionizing photons, \( r^2 \) is the distance to the gas being ionized, \( c \) is the speed of light, and \( n_e \) is the electron density, to get at the radius without multiple observations. On the grounds of (most) AGN spectra looking similar to one another in their emission line flux ratios, if one assumes that the ionization parameter and particle densities are roughly comparable for all AGN, from the above equation one finds the BLR radius to change with luminosity of the central source as \( r \propto L^{1/2} \). With a single spectrum, one can then measure the luminosity of some continuum region of the spectrum, derive a BLR radius after scaling from a known system, measure the velocity of a broad emission line such as H\( \beta \), and then have the mass from a single epoch of data. This is known as the radius-luminosity (R-L) relationship for AGN and quasars.

Kaspi et al. (2000), with a sample of 17 reverberation mapped quasars, found the slope to be \( 0.7 \pm 0.3 \) for the radius-luminosity relationship, steeper but consistent with the naive theory prediction. A similar analysis using more objects and a wider range of emission lines found slopes for the optical and X-ray continuum to be \( \sim 0.7 \), but somewhat lower at 0.56 for the UV continuum (Kaspi et al. 2005). In both of these instances, they take their statistically significant offset from 0.5 to mean that one or more of the assumptions in generating it are violated. This could imply that either the ionization parameter or density vary from AGN to AGN and/or that these quantities are luminosity-dependent. Other works (Bentz et al. 2013; Bentz et al. 2006) have demonstrated that these slopes result from host galaxy contamination, and that fitting and subtracting off this component brings it down to 0.52 and well consistent with the 0.5 prediction.
As mentioned before, both the FWHM and line dispersion are viable measures of bulk motions within the BLR, each with their own benefits and drawbacks. It has been shown (e.g., Peterson et al. 2004; Denney et al. 2009; Park et al. 2013) that use of $\sigma$ over FWHM, when possible, lowers the scatter in mass estimates. Understanding and reducing this scatter is key for producing relatively accurate single-epoch black hole mass measurements on an industrial scale, aiding in both our knowledge of its evolution with host galaxy properties and evolution over time. As such, it is now generally preferred to use $\sigma$ for velocity measurements rather than FWHM when possible.

With the influx of higher quality data from more dedicated monitoring campaigns, studies are now starting to return to the original goal of the technique, mapping out the orbits of the BLR gas. High quality velocity delay maps (e.g., Bentz et al. 2010; Grier et al. 2013b) of the H$\beta$ and HeII lines, while somewhat ambiguous, prefer inflow and/or inclined disk orbits. In addition to these studies, work has also been done on modeling the BLR orbits from reverberation mapping data (Pancoast et al. 2011, 2012, 2013), from which one can then calculate an independent SMBH mass. This provides the appropriate $f$ value to apply to the system after-the-fact without the need to scale to the $M_{BH} - \sigma$ relationship. While not perfect, the orbital constraints from these dynamical models also tend to advocate for inflow or elliptical orbits in a thick disk and, interestingly, suggest that the H$\beta$ emission comes from the far side of the BLR moreso than the near side (from the observer’s perspective). This could mean that the BLR is at least somewhat self-shielding, preferentially re-radiating towards the continuum source rather than deeper into the clouds (Pancoast et al. 2012, 2013).

1.3. Higher Ionization Lines

Most of the studies discussed thus far have focused on the H$\beta$ emission line, and for good reason. It is a strong broad line that is easily observable from the ground for nearby AGN. There is some blending with unresolved FeII lines that is of concern, but it is at an appropriate wavelength that one can get both the HeII broad line as well as the [OIII] narrow line doublet in the same observation with most
spectrograph configurations. The former is good as a secondary line to detect a lag from, while the latter doublet is often useful for flux calibration, as the narrow line region is sufficiently far away from the central engine that one can assume that these lines should be non-variable over a shorter campaign. They are shown to change over much longer baselines, however, as in NGC 5548 (Peterson et al. 2013). The Hβ line is only observable in nearby galaxies in the optical, however, moving into the NIR at a redshift of \( \sim 0.6 \). This means Hβ must either be chased into the infrared (e.g., Netzer et al. 2007) or shorter wavelength broad lines that redshift into the optical regime as Hβ leaves it must be used instead.

One such candidate line observable from the ground is MgII, which is available roughly in the redshift range \( 0.5 < z < 2 \). McLure & Jarvis (2002) used archival International Ultraviolet Explorer (IUE) data to measure the FWHM of this line for over 20 quasars that have BLR radii and mass estimates available from Hβ. Since the continuum range used for Hβ is typically not available in the spectral coverage when centering on MgII at 2798Å, they opt to use the region around 3000Å as their estimate for their continuum estimation. Since they do not measure MgII lags, they assume that the orbital radius for the MgII gas is the same as that for Hβ on the grounds that both are low-ionization lines and have similar FWHM values. Since their FWHM values for MgII are consistent with Hβ, and they fit the MgII data with its corresponding continuum for a new R-L relationship, which they find to be in accordance with the predicted slope of 1/2. This line recovers, from their single-epoch measurements, the Hβ masses well. Together, this all implies that MgII is a suitable emission line for ground-based reverberation mapping of higher redshift sources, albeit requiring the assumption that the MgII gas is at the same radius as the Hβ gas.

Another candidate line is CIV at 1549Å (e.g., Vestergaard 2002). This wavelength is ideal for probing much higher redshifts than MgII, but it has been faced with greater skepticism as well. Baskin & Laor (2005) claim that CIV is a poor tracer of the BLR for numerous reasons arguing that it can show a blueshift with respect to the systematic velocity in addition to a blueward asymmetry in the line profile, indicative of outflows and hence non-virial motion, a key assumption of
reverberation mapping. These authors find CIV is significantly less accurate and biased when deriving masses compared to those from the Hβ line. Metzroth et al. (2006) investigate the use of several ultraviolet lines from two separate UV campaigns with the IUE on NGC 4151 for measuring reverberation lags. They find that both HeII and CIV suffer from blending while MgII and CIV have self absorption, making the true emission line profile difficult to determine. CIII], meanwhile, is not strong enough to measure reliably. For their best mass measurement, they omit the CIV data as problematic.

Investigating a sample of nearly 500 quasars at z > 1.4 being used for the Sloan reverberation mapping project, Denney et al. (2016b) and Denney et al. (2016a) show that a ubiquitous blueshift in the CIV line is not observed. These authors find that the range of blueshifts for CIV are larger than previously estimated, but that the strength of the blueshifts compared to systemic range from zero to several thousands of kilometers per second. They also note a bias in the automated redshift pipeline as it uses spectral templates that have merged together objects with varying amounts of CIV offsets. Objects with strong, narrow HeII emission are consistent with zero offset for CIV, but those in which the narrow lines are weak compared to the broad HeII emission or undetected do show offsets, which they claim is due to quasar diversity effects. By using those objects which have no systematic blueshift for CIV, then, one can make secure samples for which this line can be used to measure virial velocities without needing to worry about an outflowing component to the gas.

1.4. Accretion Disk Reverberation Mapping

The canonical quasar accretion disk model is the optically thick, geometrically thin disk. For such a Shakura-Sunyaev thin disk (Shakura & Sunyaev 1973), the emission is a combination of the local thermal emission of the viscously dissipated energy and reprocessing of emission from the inner regions. Thin disks are stable at low to moderate accretion rates compared to Eddington

\[ L_{Edd} = \frac{4\pi GMm_p c}{\sigma_T}, \]  

(1.3)
the theoretical maximum luminosity for spherical accretion before the radiation pressure outward becomes stronger than the gravitational force pulling the matter inward. There are also stable slim accretion disks (Abramowicz et al. 1988; Narayan & Yi 1995), where the disks are optically thin, there is no requirement for a small vertical scale height, and accretion rates are near Eddington or somewhat super-Eddington. Hall et al. (2017) propose an extension to the thin disk model for the accretion where the emission is modified by a low density disk atmosphere to be non-thermal, making disks appear to be larger than would be inferred from a black body.

The size of the standard thin disk (Morgan et al. 2010) is

\[ R_{\lambda_0} = \left[ \frac{45G\lambda_0^4 M_{BH} \dot{M}(3 + \kappa)}{16\pi^6 hc^2} \right]^{1/3} \]

\[ = 9.7 \times 10^{15} \left( \frac{\lambda_0}{\mu m} \right)^{4/3} \left( \frac{M_{BH}}{10^9 M_\odot} \right)^{2/3} \left( \frac{L}{\eta L_{Edd}} \right)^{1/3} \text{ cm} \] (1.4)

where the disk temperature is \( kT = hc/\lambda_0 \), \( M_{BH} \) is the black hole mass, \( \dot{M} \) is the accretion rate onto the black hole, \( \kappa \) is the ratio of local to external radiative heating, and \( \eta \) is the accretion efficiency related to the luminosity by \( L = \eta \dot{M} c^2 \). The disk has a radial temperature profile \( T \propto R^{-1/\beta} \) with \( \beta = 4/3 \) so that \( R_\lambda \propto \lambda^\beta \propto \lambda^{4/3} \). This can be generalized by asserting the disk size is related to wavelength by

\[ R_\lambda = R_{\lambda_0} \left( \frac{\lambda}{\lambda_0} \right)^\beta \] (1.5)

where the standard thin disk has \( R_{\lambda_0} \) as given in Equation 1.5 and \( \beta = 4/3 \).

If the temporal variability of the disk is driven by fluctuations in the irradiated flux from a central source, the so-called "lamppost" model (see Cackett et al. 2007 and references therein), then the time delay for light to reach any radius in the disk implies that there should be delays in the response at different wavelengths. If the size-wavelength relation is given by Equation 1.5, then the observed lag \( \tau \) between wavelengths \( \lambda_0 \) and \( \lambda \) is

\[ \tau = \frac{R_\lambda}{c} \left[ \left( \frac{\lambda}{\lambda_0} \right)^\beta - 1 \right] \] (1.6)
More explicit derivations are given in Morgan et al. (2010) and Fausnaugh et al. (2016).

Until recently, the majority of quasar accretion disk sizes have been measured using gravitational microlensing. In quasar microlensing, the amplitude of the variability encodes the disk size (see, e.g., the review by Wambsganss 2000). At optical wavelengths, disk appear to follow the $M_{2/3}$ scaling expected for thin disks (note a factor of $M_{BH}$ from Equation 1.5 is buried in the $\dot{M}$ parameter via Equation 1.3 from $L_{Edd} = \eta \dot{M} c^2$), but are larger in absolute size than predicted from Equation 1.5 by a factor of 2-3 (Morgan et al. 2010). While it will be feasible to expand these studies to hundreds of lenses in the era of the Large Synoptic Survey Telescope, they will always be a relatively rare subset of quasars.

The reverberation mapping method can also be used to measure the relative time lag between the continuum emission at two wavelengths, which is then a proxy for the difference in the disk radii contributing to the emission (Equation 1.5). Early attempts at disk reverberation mapping include Wanders et al. (1997) and Collier et al. (1998) for NGC 7469 and Peterson et al. (1998) for NGC 4151. More recently, Sergeev et al. (2005) measured (at 2σ) continuum lags or upper limits for approximately a dozen objects. Interpreting the lags as light travel delays across the disk, the lags implied disk sizes growing as $L^{0.4-0.5}$. Shappee et al. (2014) and Fausnaugh et al. (2016) both observed a wide range of wavelengths tracking the broadband variability of NGC 2617 and NGC 5548 (respectively) from the X-rays through the infrared. Both studies found the wavelength dependence to be consistent with the thin-disk prediction of $\beta = 4/3$. Their size estimates were larger than thin disk theory predicts given the black hole mass estimates, in agreement with the microlensing results. In particular, the Space Telescope and Optical Reverberation Mapping (AGN STORM) campaign for NGC 5548 (e.g., De Rosa et al. 2015) is the highest quality variability dataset for a single object, and Edelson et al. (2015) and Fausnaugh et al. (2016) conclude that the accretion disk is roughly three times larger than expected. The Pan-STARRS collaboration performed a similar analysis for $g$, $r$, $i$, and $z$ on a sample of higher luminosity quasars. They restricted their work to two redshift bins that minimized broad emission line contamination to the
optical filters, and consistently find that the accretion disks are larger than expected from thin disk theory (Jiang et al. 2017).

1.5. Broad Absorption Line Quasars and Post-Starburst Galaxies

Correlations of the mass of the central SMBH with host galaxy properties such as stellar velocity dispersion (Gebhardt et al. 2000; Ferrarese & Merritt 2000) suggest that a SMBH’s growth is linked to the evolution of the host galaxy through some feedback process (e.g. Heckman & Best 2014). The most pronounced phase of SMBH growth is the quasar phase, where most of the spectral energy distribution can be explained by a thin accretion disk of material around the SMBH (Shakura & Sunyaev 1973; Koratkar & Blaes 1999), a hot corona, and a broad line region on larger scales (e.g. Peterson 1997). One method of triggering quasar activity is a merger that involves at least one gas-rich galaxy (Sanders et al. 1988; Silk & Rees 1998; Komossa et al. 2003; Di Matteo et al. 2005; Piconcelli et al. 2010). During gas-rich mergers, gas funnels towards the central regions of the galaxies and some fraction accretes onto the central SMBH. This substantial influx of gas and dust may often obscure the early phases of quasar activity.

Gas-rich mergers also produce a large increase in star formation, up to 100-1000 times the galaxy’s quiescent rate. These rates can quickly exhaust the gas supply, and eventually the star formation rate must return to a lower value. It is unclear if this is primarily caused by the expulsion of star-forming gas due to the quasar, feedback from the star formation process, or consumption of the gas by star formation and the SMBH. If the increased star formation rate decreases quickly compared to the total star formation history, the galaxy goes through a post-starburst phase, which is characterized by the strong absorption lines prevalent in A type stars combined with a K type spectrum from an older population (Dressler & Gunn 1983; Zabludoff et al. 1996). The absence of stellar features due to shorter-lived O and B type stars would indicate star formation ceased tens to hundreds of Myr ago. Some post-starburst galaxies also exhibit blueshifted absorption from winds (Tremonti et al. 2007; Coil et al. 2011), and at least some wind-driven outflows from starbursts appear to be
delayed by 10 Myr or more after the star formation burst (Sharp & Bland-Hawthorn 2010; Ho et al. 2016).

A significant fraction of all post-starburst galaxies host quasars (Brotherton et al. 1999, 2002; Cales et al. 2013) or some form of lower luminosity active galactic nuclei (AGN). Goto (2006) found that 0.2% of all galaxies are in a post-starburst state, compared to 4.2% of quasars having these post-starburst features. Quasars hosted by post-starburst galaxies typically had intense star formation that ended $10^{8-9}$ years ago. Cales et al. (2013) found that older post-starburst quasars in elliptical galaxies tend to have signs of a recent merger, which suggests that a major merger event fueled both the previous star formation and current quasar activity. Tremonti et al. (2007) and others argue that the presence of blueshifted absorption of a few hundred to a few thousand km s$^{-1}$ in some post-starburst quasars is evidence that these objects had a large, galaxy-scale wind $\sim 10^8$ years ago, although the energy in these winds may not be enough to have quenched star formation (Coil et al. 2011). Similar winds are seen in ongoing starbursts, but these tend to be a factor of a few weaker than in post-starbursts of comparable luminosity (Tremonti et al. 2007).

When the winds from a quasar are especially prominent, they are classified as broad absorption line (BAL) quasars. BALs are characterized by prominent, blueshifted absorption lines of 2000 km s$^{-1}$ or more (Weymann et al. 1991). BALs are present in 20-40% of all quasars, depending on the selection method (Trump et al. 2006; Dai et al. 2008; Urrutia et al. 2009). The majority of BALs only exhibit absorption in high ionization states, such as CIV, and are referred to as HiBALs. BALs with absorption in lower ionization lines, such as MgII, are referred to as LoBALs. A small subset of LoBALs also have FeII and/or FeIII absorption and are known as FeLoBALs (Hazard et al. 1987). Rarest of all are the handful of objects with absorption in the Balmer lines (Hall 2007; Zhang et al. 2015). Using SDSS data, Trump et al. (2006) find that HiBALs, LoBALs, and FeLoBALs constitute 26%, 1.3%, and 0.3%, respectively, of their sample of over 16,000 quasars. In contrast, Dai et al. (2008) and Urrutia et al. (2009) find BALs are much more common. When selected with both SDSS and 2MASS to alleviate the bias from reddening,
they report 37%, 32%, and 32% of quasars are HiBALs, LoBALs, and FeLoBALs, respectively. This selection method identifies all LoBALs as FeLoBALs.

FeLoBALs are the most heavily reddened BAL subtype, and the iron features necessitate high column densities (e.g. Korista et al. 2008). They can have broad iron emission and absorption from FeIII in addition to FeII, and, in very rare cases, only FeIII (Hall et al. 2002). The absorption troughs are also observed to vary between objects from several distinct, narrow troughs, to blanketing most of the emission from the quasar shortward of the MgII doublet. Both LoBALs and FeLoBALs also tend to be X-ray faint, further implying that there is a large column density that prevents a direct view of the central source (e.g. Mathur et al. 1995; Green et al. 2001).

There remains much debate about the exact nature of FeLoBALs. With their considerable reddening and high inferred column densities, some argue that they are transitional quasars, moving from a dust-enshrouded star formation phase to an unobscured quasar phase (Voit et al. 1993; Egami et al. 1996; Farrah et al. 2007, 2010). The highly absorbed FeLoBALs are also more likely to be radio sources, and may be transition objects between radio loud and radio quiet quasars (Becker et al. 1997). Alternatively, Faucher-Giguère et al. (2012) propose that the absorption is from high density clouds along the line of sight that have been disrupted by a blast wave from the SMBH, rather than a wind pushing out a dusty cocoon. This would create the absorbers in-situ, allowing them to be either close to the central AGN or farther out in the galaxy but along our line of sight. The young, dust-enshrouded scenario is less flexible, as the absorbers should be within the central few parsecs.

1.6. The Dark Energy Survey and OzDES

The research for this dissertation used data from both the Dark Energy Survey (DES) and its spectroscopic counterpart, OzDES. DES is a five-year, five band (grizY) optical photometric survey covering 5000 square degrees of the southern sky carried out on the Blanco 4m telescope in Chile at Cerro Tololo Inter-American Observatory. The primary goal of the survey is to investigate the expansion of the universe by via four probes (Flaugher et al. 2005; Flaugher et al. 2015): weak lensing,
baryon acoustic oscillations, galaxy clusters, and Type Ia supernovae. As part of the supernova search, 30 square degrees of the regular survey footprint are repeatedly observed with approximately weekly cadence in the $g$, $r$, $i$, and $z$ filters for the duration of DES, amounting to 20-30 epochs per filter per year (Kessler et al. 2015). In these fields, we are monitoring a set of quasars as part of the DES reverberation mapping campaign to measure masses for these objects (King et al. 2015). These quasars go as faint as 23.6 magnitude in $g$, and were selected heterogeneously through a number of quasar detection techniques (e.g., Banerji et al. 2015, Tie et al. 2017).

These quasars are spectroscopically confirmed using OzDES (Australian DES; Yuan et al. 2015; Childress 2017) data from the 4m Anglo-Australian Telescope (AAT). This is a complimentary survey to DES designed to get spectra of transients found in the DES supernova fields, as well as get spectra for the reverberation mapping project. OzDES is set up on a gradually increasing time allocation for nights, meaning that as the survey progresses, more nights each year are given for observations. With this sliding scale, the cadence is poorest for the first year, and highest for the final years, with generally monthly cadence overlapping the same observing season as DES. The 2dF multi-object fiber positioner allows for simultaneous spectra of approximately 400 targets across a nearly identical field of view as a DES photometric pointing with the Blanco telescope. Roughly 70 of these are allocated to dedicated quasar monitoring per observation.

1.7. Scope of the Dissertation

The outline of this dissertation is as follows: In Chapter 2, I discuss the serendipitous discovery of the first BAL quasar hosted in a post-starburst galaxy found within our reverberation mapping sample. In Chapter 3, I present accretion disk measurements for a subset of highly variable quasars in the DES supernova fields, along with an extension to the JAVELIN package to aid in future disk lag analyses. In Chapter 4, I outline both the steps that have been taken and future work to be done for measuring quasar masses with reverberation mapping with the OzDES data. Finally,
in Chapter 5, I summarize the results of the dissertation and elaborate briefly on opportunities for future research directions in these areas.
Chapter 2: Serendipitous Post-Starburst BAL Discovery

In this chapter, I describe the discovery of the first known low-ionization broad absorption line quasar with prominent iron absorption (FeLoBAL) features that is hosted in a post-starburst galaxy and discuss the implications of this on the coevolution of galaxies with their central supermassive black holes.

2.1. Observations Overview

We have discovered an FeLoBAL (low-ionization broad absorption line quasar with prominent iron absorption) quasar with Balmer absorption and a post-starburst spectrum that was selected using data obtained by the the Dark Energy Survey (DES; Flaugher 2005; Flaugher et al. 2015) and the OzDES\(^1\) collaboration (Yuan et al. 2015). The quasar was found in one of the 10 “supernova fields” (3 deg\(^2\) each, Kessler et al. 2015) that are monitored to discover Type Ia supernovae. Several of the targets for the DES/OzDES reverberation mapping project are BAL quasars that were selected to monitor their long-term absorption and emission line variability. Upon stacking several spectra, we discovered that one of these objects, DES QSO J033049.33-283249.7 (hereafter DES QSO J0330-28), resides in a post-starburst galaxy. This appears to be the first known BAL quasar in a post-starburst galaxy. We also note that this is a FeLoBAL with Balmer absorption, making it rare even among BALs, and that it was first chosen as a target candidate from a combination of optical (\(g\) and \(i\)) and infrared (\(K\), \(W1\), and \(W2\)) color cuts described by Banerji.

\(^1\)Australian Dark Energy Survey; alternatively, Optical redshifts for DES
et al. (2015) and reproduced below as Equation 2.2:

\[
(g - i)_{AB} < 1.1529 \times (i_{AB} - K_{\text{Vega}}) - 1.401 \\
(W1 - W2) > 0.7 \\
-0.003 < i_{\text{spreadmodel}} < 0.0028 \\
i < 21.5.
\] (2.1)

Here, \(i_{\text{spreadmodel}}\) is a measure of the extent of the object in the \(i\)-band photometry, separating stars and quasars (point sources) from extended local galaxies.

In Section 2.2, we describe the DES and OzDES observations and accumulate other values from the literature on this unique object. In Section 2.3, we characterize both the outflow and model the properties of the host galaxy stellar population using the stacked OzDES spectra. We summarize and present our conclusions in Section 2.4.

### 2.2. PSB Observations

All of the spectra of DES QSO J0330-28 were obtained with the AAT 4m at Siding Spring Observatory as part of the OzDES project. The double beam fiber-fed spectrograph uses the 580V grating and 385R gratings leading to dispersions of 1Å/pixel and 1.6Å/pixel in the blue and red arms, respectively, with the dichroic split at 5700Å. The resolution of the spectrograph is \(R \sim 1400\), and the wavelength range spans 3700-8800Å.

We present the stacked spectrum in Figure 2.1 in both the observed and rest frame. This is a combination of four spectra taken over the course of two years (2013-2015) and the combined exposure time is 160 minutes. We derived the host galaxy redshift of \(z = 0.65\) based on the higher order Balmer lines around rest-wavelength 4000Å. There is also a prominent Balmer break shortward of the absorption. These are the signs of a post-starburst galaxy with recently quenched star formation. At shorter wavelengths, there is a sharp drop in flux at the rest wavelength of the Mg\textsc{II} 2798Å emission line doublet. This corresponds to blueshifted absorption out to 5000 km s\(^{-1}\) from the systemic redshift. Other absorption troughs
in the rest-frame UV correspond to metastable states of FeII, particularly at 2750Å, 2880Å, and 2985Å. There may be MgI 2853Å, but this falls in an FeII absorption trough. The most common FeIII features are blueward of our spectral coverage.

We provide photometry for this object in Table 2.4. This incorporates *grizY* from DES, *JHK* from the VHS survey (McMahon et al. 2013), and *W1, W2, W3, W4* from *WISE* (Wright et al. 2010). The DES and WISE magnitudes are calculated using PSF fits, whereas the VHS data use a 2″ aperture. All magnitudes have been transformed to the AB system. Both the very red colors (e.g. \( r - K = 0.86 \) AB) and spectral shape indicate very substantial reddening, which is quite common with FeLoBALs (Hall et al. 1997, 2002; Dunn et al. 2015). The DES g, r, i and VISTA K images are shown in Figure 2.2. These images show several small objects in the immediate vicinity of the quasar that suggest an interacting or merging system, and three of the objects have photometric redshifts consistent with DES QSO J0330-28. This quasar was also detected as a radio source in the ATLAS survey (Franzen et al. 2015; Mao et al. 2012) at 1.474 GHz. If we extrapolate the ATLAS measurement to 5 GHz with a \( \alpha = 0.7 \), the ratio of rest frame 5 GHz flux density to that at 4400Å is about two. This quasar is consequently radio quiet/intermediate under the definition that a ratio less than one is quiet and greater than ten is radio loud. The result is consistent with the idea that LoBALs may be quasars moving between a radio loud and radio quiet phase and some work suggests that the LoBAL fraction in quasars decreases as a function of radio luminosity (Dai et al. 2012). This object unfortunately has no archival *Chandra* or *XMM-Newton* data, and thus we cannot determine if it is X-ray faint, as has been found for other FeLoBALs (Mathur et al. 1995; Green et al. 2001).

### 2.3. Spectral Analysis

#### 2.3.1. Post-Starburst

We fit the stacked spectrum with STARLIGHT (Cid Fernandes et al. 2004, 2005a,b) over the wavelength span not dominated by the FeLoBAL’s broad absorption and emission lines (see Figure 2.3). This corresponds to approximately 3300-4800Å in the rest frame. We do not fit to longer wavelengths in order to avoid Hβ contamination.
nor shorter wavelengths because of the broad absorption lines of the quasar. To account for the quasar component, we created a quasar template from stacked spectra of 10 quasars from the reverberation mapping sample that are most similar in redshift and luminosity to DES QSO J0330-28. We verify that the template created from the OzDES sample is very similar in continuum slope and emission line strength to the SDSS composite quasar from Vanden Berk et al. (2001) and use it in the rest of the analyses.

We initially ran STARLIGHT over a grid of models supplied by Bruzual & Charlot (2003) that span ages of 1 Myr to 13 Gyr and metallicites from 0.005-2.5\(Z_\odot\). The best fit model has approximately 45% of the light from two young stellar populations of 40 and 55 Myr, 40% from our quasar template, and the remainder from an older population of 6-7 Gyr. The metallicity for the varied components is consistent with sub-solar to solar. This fit has \(\chi^2_{\text{red}} = 0.85\). We also performed fits at single metallicities and found in most instances that between 30-50% of the light is from 40 and 55 Myr populations and 20-50% is from the quasar. These fits had \(\chi^2_{\text{red}}\) ranging from 0.9-1.2 and show the relative insensitivity of the population ages to the metallicity. The strength of the higher order Balmer lines depths do not match perfectly with any age/metallicity combination. This is likely because of the impact of Balmer absorption in the BAL, and perhaps also some mismatch with the quasar template and this quasar.

For each grid of models, we also fit for the best global extinction and best extinction for each component. The best fits are for \(A_V = 0 - 0.04\) mag for nearly all model combinations for both the quasar and post-starburst components. The youngest, single-metallicity solutions are approximately solar, have ages of about 5 Myr, and higher extinction \((A_V = 0.37)\), although these fits are somewhat worse, including to the stellar absorption features. No model is able to reproduce both the spectral shape at 3300-4800\(\AA\) and remain below the flux of the absorption troughs. More extinction of both the quasar and post-starburst components would be necessary to not overpredict the flux in the MgII absorption troughs, but we find no solution that added sufficient reddening to the post-starburst spectrum that did not overpredict the flux redward of 4000\(\AA\). The solution could be underestimated.
uncertainties in the wavelength-dependent flux calibration of the AAOmega spectra (discussed by Hopkins et al. 2013) and/or that a simple screen is a poor approximation to the dust distribution in the host galaxy. We addressed the first of these two possibilities with additional analyses of spectra obtained at different epochs, which had different and better calibration (Childress 2017, in preparation), but this calibration did not resolve the issues with the fit at short wavelengths.

The mass of the host galaxy from the STARLIGHT fit is $2 \times 10^{11} M_\odot$. Cid Fernandes et al. (2015) found that STARLIGHT stellar mass estimates agree with spectral synthesis estimates to better than 0.4 dex. The uncertainty is likely larger than typical for this QSO, due to the relatively small contribution from the old stellar population, and uncertainties in the extinction.

2.3.2. BAL QSO

There are a number of absorption troughs present at shorter wavelengths than the stellar absorption features in addition to broad absorption associated with some of the Balmer lines. BAL features are typically described by their balnicity index. This metric originated by Weymann et al. (1991) for HiBALs and the CIV line. By their definition, a quasar was considered a BAL if it had a balnicity index $BI > 0$. Later, Hall et al. (2002) proposed the intrinsic absorption index (AI) as an alternative identifier, which is more sensitive to troughs at lower velocities and likewise identifies BALs with $AI > 0$. Both BI and AI are integrals over velocity on the blue side of an emission line. The BI requires the trough to extend at least 3000 km s$^{-1}$ and drop by at least 10% of the normalized continuum flux. The AI, however, begins the integral at 0 km s$^{-1}$ and is more sensitive to lower velocity and weaker troughs.

We perform a similar analysis to Hall (2007) for our H$\beta$ absorption to determine a lower limit column density $N_{H\beta} = 5.2 \times 10^{14} \text{ cm}^{-2}$. This value is about a factor of 100 smaller than the column density measurement for the Hall (2007) FeLoBAL, but likely underestimated for DES QSO J0330-28 due to the host galaxy emission at these wavelengths. The H$\beta$ and MgII absorption also prohibits a measurement of a black hole mass estimate.
It is difficult to measure these values in FeLoBALs like DES QSO J0330-28 because these objects have such heavy reddening and the widespread iron absorption/emission makes the continuum poorly defined. The STARLIGHT fit, partially because it could only fit a narrow wavelength range due to the BAL features, has a best fit $A_V = 0.04$ mag. However, DES QSO J0330-28 is clearly highly reddened at shorter wavelengths (see Figure 2.1). To correct for this, we applied various values of $A_V$ to our quasar template for an SMC extinction curve (Gordon et al. 2003) until we found the best fit to the red half of the MgII emission line at 2798Å. While no single value gives a satisfactory fit to either the extinction or the continuum, the spectral slope on the blue end is broadly consistent with $A_V = 1.5$ mag. This is small given how X-ray faint (Green et al. 2001) and red many LoBALs are, but is also poorly constrained by the available data. A likely cause for the difficulty is that there may be partial obscuration; that is, varying amounts of extinction to different regions of the galaxy and quasar emission region. Without a good continuum fit, we cannot reliably measure AI or BI for this object. Nevertheless, the velocity spread of the absorption troughs is reasonably clear. Figure 2.4 shows that the MgII absorption spans approximately 5000 km s$^{-1}$ before a small rise that is likely due to FeII emission at 2750Å, which then has its own blueshifted absorption. The depth and width of the trough means that this object would likely meet the conditions for both AI and BI $> 0$ for MgII.

We next compare the velocity extent of the MgII component to other absorption troughs, namely FeII at 2750Å, 2880Å, and 2985Å, and H$\beta$. Figure 2.4 shows in both cases the data are consistent with a similar range of blueshifted absorption, and this suggests a common origin.

BALs have a broad diversity of spectral morphologies, and DES QSO J0330-28 is most similar to SDSS J112526.13+002901.3 (Hall et al. 2002) with regard to the approximate shape and strength of the emission and absorption features. That SDSS quasar has zero balnicity index, but an intrinsic absorption index of almost 500 km s$^{-1}$. While we cannot cleanly measure the continuum of DES QSO J0330-28, it should also have a nonzero intrinsic absorption index. Hall et al. (2002) also classified SDSS J112526.13+002901.3 as a many narrow troughs FeLoBAL with HeI
absorption. We do not see evidence for either of these characteristics in DES QSO J0330-28. SDSS J112526.13+002901.3 also does not have the same post-starburst features that make DES QSO J0330-28 unique.

2.4. Post-starburst BAL Discussion and Conclusion

The current picture for quasar evolution in the merger scenario begins with the collision of a dust- and gas-rich galaxy with another system. Dynamical processes drive material towards the galaxies’ centers and fuels star formation and accretion onto the SMBH. The quasar is initially obscured by the dust, but eventually the material disperses and the quasar becomes easily visible. FeLoBALs have attracted particular interest because the very high column density absorption is indicative of a substantial outflow, perhaps associated with this transition from obscured to unobscured. A second scenario proposed by Faucher-Giguère et al. (2012) is that a blast wave is launched from the quasar that impacts a high density cloud along the line of sight. This would also create the observed column densities, reddening, and absorption troughs seen in FeLoBALs. One distinction between these scenarios is in where the absorbing material lies. For the transition objects, the absorbing material would be around the quasar and in the process of being blown away, whereas for the blast wave model it is possible to impact a cloud on much larger scales than the central few parsecs.

Variability is one way to test the location of the absorbers. The constraints from several variable FeLoBALs (e.g., Hall et al. 2011; McGraw et al. 2015; Vivek et al. 2012) place the absorbing material on the order of a few to tens of parsecs from the central source. This assumes a cloud-crossing model where the changes arise from an absorber moving across the line of sight. In contrast, other studies suggest the absorption is on kpc scales (Moe et al. 2009; Bautista et al. 2010; Dunn et al. 2010). Moe et al. (2009) derived a distance to one outflow of ~3 kpc and, for an assumed covering fraction of 0.2, find that the energy in the BAL outflow is comparable to 1% of the total luminosity of the quasar.

We find that the obscuration of DES QSO J0330-28 cannot be fit by a single-screen model. It is clear that the quasar light is highly reddened at the
shortest wavelengths, which implies substantial extinction of the AGN accretion disk despite the small $A_V$ of the best fit. We see little to no extinction of the host galaxy in the region over which we fit the models, but extrapolating the stellar population to rest frame 2800Å and shorter overpredicts the flux in the absorption lines. This implies there is dust in the outer regions of the galaxy as well, though it is not necessarily the same absorption level as the quasar emission, and the discrepancy between the model stellar flux and the absorption trough is greater than for the quasar component. The “transition object” scenario has this geometry as the young quasar begins to clear out the dust immediately surrounding it to become optically visible. However, such extinction could also arise from a Faucher-Giguère et al. (2012) blast wave colliding with a dense cloud along our line of sight, either close to the AGN or much farther out in the galaxy. For the latter case, the quasar can be highly absorbed and the stellar component less so if there is a low covering fraction of the galaxy-wide absorbers, or both can be reddened if there is a high covering fraction.

If we assume the quasar and starburst triggered simultaneously, we can use the starburst age to evaluate which model FeLoBAL scenario is more probable. Star formation was truncated or quenched in DES QSO J0330-28 around 50 Myr ago in most of our models. This time is comparable to estimates for quasar lifetimes of around $10^{7-8}$ years (e.g., Yu & Tremaine 2002; Martini 2004) and implies that this FeLoBAL did not turn on recently, which is in conflict with the young quasar scenario. The FeLoBAL features cannot be due to the same feedback processes that abruptly ended the star formation ~50 Myr ago, as they would have dispersed due to Kelvin-Helmholtz or Rayleigh-Taylor instabilities. These features are consistent with the Faucher-Giguère et al. (2012) model in which the absorption is produced by clouds of material that have been compressed by a radiative blast wave. The key aspect of the blast wave model for DES QSO J0330-28 is that the blast wave is not tied to a particular evolutionary phase of the quasar.

We plan to obtain future, higher signal-to-noise ratio spectra over a broader wavelength range to derive better stellar population and reddening parameters. We will also obtain new spectral epochs as the OzDES program progresses, and we will...
use these data to search for BAL variability to attempt to measure the distance of the absorber from the central source.
Fig. 2.1.— Stacked spectrum of DES QSO J0330-28 at $z = 0.65$. The LoBAL features are prominent at wavelengths shorter than the MgII line at rest-frame 2798Å. The absorption features around rest-frame 3900Å are from host galaxy stars.
Fig. 2.2.— DES images of DES QSO J0330-28 in $g$ (top left), $r$ (top right), $i$ (bottom left), and $K$ (bottom right). Each box is 30′′ on a side centered on the quasar. The $g$, $r$, and $i$ images are from DES, and the $K$ band image is from the VISTA VIDEO (Jarvis et al. 2013) survey. The three crosses in the $r$ image correspond to three sources that have photometric redshifts consistent with DES QSO J0330-28, which suggests a merger.
Fig. 2.3.— The best fit single metallicity model with $Z = 0.02Z_\odot$. The data (thick solid) are fit by a model (lighter, dot-dashed) that combines a quasar template (dark, dashed) and three major stellar components: 44% of the light comes from a younger, recently quenched population with an age of 40 Myr (lighter, dashed), and 24% comes from older populations of 10 and 13 Gyr (dark dashed and dotted, respectively). The remainder of the light comes from the quasar. The masked regions are left out of the fit due to possible broad quasar emission from H$\beta$ and broad absorption in the wings of higher order Balmer lines from the quasar. Note that while this low metallicity value is the best fit that we find, this value is not well constrained, as most single-metallicity models find roughly similar light fractions and ages for the young stellar component at a modest increase in $\chi^2_{\text{red}}$. At shorter wavelengths, both the post-starburst and quasar components separately overpredict the flux at the base of the broad absorption lines. However, no combination of templates and extinction is able to reproduce the flux limits in the absorption lines as well as the normalization of the red half of the spectrum.
Fig. 2.4.— Highlight of the BAL troughs. In each inset, the arrows correspond to the systemic redshift and the horizontal bars correspond to a blueshift velocity of 5000 km s$^{-1}$. This fits well for MgII and FeII, and there is also Balmer absorption that is consistent with this outflow velocity. The dotted line is the best fit model for the quasar and stellar components. The model fits well around the Balmer lines, but vastly overestimates the flux at shorter wavelengths.
<table>
<thead>
<tr>
<th>Band Name</th>
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<th>Magnitude (Error)</th>
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<tr>
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<td>20.11 (0.02)</td>
</tr>
<tr>
<td>r</td>
<td>6590Å</td>
<td>19.31 (0.02)</td>
</tr>
<tr>
<td>i</td>
<td>7890Å</td>
<td>19.02 (0.02)</td>
</tr>
<tr>
<td>z</td>
<td>9760Å</td>
<td>18.94 (0.02)</td>
</tr>
<tr>
<td>Y</td>
<td>1µm</td>
<td>19.00 (0.02)</td>
</tr>
<tr>
<td>J</td>
<td>1.25µm</td>
<td>18.89 (0.04)</td>
</tr>
<tr>
<td>H</td>
<td>1.65µm</td>
<td>18.77 (0.05)</td>
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</tr>
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<td>4.6µm</td>
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</tr>
<tr>
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<td>12µm</td>
<td>15.92 (0.06)</td>
</tr>
<tr>
<td>W4</td>
<td>22µm</td>
<td>15.01 (0.22)</td>
</tr>
<tr>
<td>ATLAS</td>
<td>1.474 GHz</td>
<td>256^a(20)</td>
</tr>
</tbody>
</table>

Photometry for DES QSO J0330-28 taken from DES for *grizY*, VHS for *JHK* (McMahon et al. 2013), and WISE for W1-W4 (Wright et al. 2010). The DES data are PSF magnitudes obtained from the coadd of the first year of observations. All magnitudes are given in the AB system aside from the radio data from ATLAS (Franzen et al. 2015; Mao et al. 2012).

^aThis is in µjanksy rather than magnitudes.

Table 2.1. DES QSO J0330-28 Photometry
Chapter 3: Continuum Reverberation Mapping

In this chapter, I discuss using DES photometry to constrain quasar accretion disk sizes, of which only a handful exist in the literature to date.

3.1. Analysis

We used the image subtraction pipeline developed for the analysis of supernova light curves \cite{Kessler15, Goldstein15} to create our quasar light curves. We visually inspected each of the approximately 800 reverberation mapping quasar light curves in the DES SN fields to look for good continuum candidates. We constructed our initial list of candidates from the subset of all quasars that had a substantial flux variation ($\geq 5$ times the photometric errors) on a timescale of weeks in both the $g$ and $z$ bands, excluding the first or last few data points of each observing season. These bands provide the longest wavelength baseline as well as maximum ($g$) and minimum ($z$) level of expected variability, and thus give the best indication of whether we will recover a time delay.

Table 3.2 summarizes the general properties of the quasars in our final sample of 15 quasars that were classified as our best photometric lag candidates based on the strongest observed short-timescale variability described above. We derive lag results from the observations in the season in which the high amplitude variability is observed. Five quasars in the sample did exhibit strong variability in more than one season (and in all three seasons for two of them), which we analyze independently. The light curves have, on average, 30 epochs per season per band, with an average cadence of 6-8 nights between observations. All four bands are typically observed on the same night.
3.1.1. Lag Measurements

We use two separate analysis techniques to measure the time delays between the continuum bands. The first is the interpolated cross correlation function (ICCF) method (Peterson et al. 2004), where two light curves are shifted along a grid of time lags and the cross correlation coefficient $r$ is calculated at each spacing. The lag distribution is given by the mean of the lags for which $r > 0.8 r_{\text{max}}$. This method linearly interpolates between epochs to fill in missing data. A series of 1,000 Monte Carlo runs re-sampling (with replacement) the light curves provide the error on the lag detection using the flux randomization/random subset replacement method. This approach will tend to overestimate the uncertainty.

For the second method, we used JAVELIN\textsuperscript{1}, which models quasar variability as a damped random walk (DRW, Zu et al. 2013). The DRW models quasar light curve behavior quite well on long time scales of months to years (MacLeod et al. 2010; Zu et al. 2013), although there may be extra variability power on the much shorter timescales (tens of minutes compared to days) sampled by the Kepler data (Edelson et al. 2014; Kasliwal et al. 2015). JAVELIN has been used in previous emission line (e.g., Zu et al. 2013; Grier et al. 2012a,b; Pei et al. 2017) and continuum (Shappee et al. 2014; Fausnaugh et al. 2016) reverberation mapping campaigns.

JAVELIN assumes that all light curves are shifted, scaled, and smoothed versions of a driving light curve. It uses the DRW model to carry out the interpolation between epochs. For this purpose it is not essential that the DRW model exactly describe the true variability of the quasar - it need only be a reasonable approximation. The model has five parameters if fitting two light curves: the DRW amplitude and timescale, the relative flux scale factor, the top hat smoothing time scale, and the time lag. For relatively short, sparsely-sampled light curves, it is not possible, either statistically or physically, to determine all of these parameters. Therefore we restrict the damping timescale to 100-300 days, as has been found for a larger sample of quasars from the Sloan Digital Sky Survey (SDSS; MacLeod et al. 2010).

\textsuperscript{1}Available at https://bitbucket.org/nye17/javelin.
We also fixed the top hat width at one day, and find that this choice does not significantly alter the lag distributions from fits with the top hat as a free parameter.

JAVELIN also assumes that the measurement errors are well-characterized and Gaussian, which can lead to underestimation of the uncertainties if either of these assumptions is incorrect. This has been noted in other studies (e.g., Fausnaugh et al. 2016), and we compare our lag distributions from JAVELIN to those obtained through the ICCF in Figure 3.3. The general trend is that the two methods are consistent with one another, with the cross-correlation centroid distributions somewhat broader in most cases.

We provide a summary of our lag posterior distributions in Table 3.2. It is clear that some of these lags are consistent with no time delay in the continuum emission at the 1-3σ level, but the wavelength-dependent offsets in many cases strongly suggest an upper limit on the lag has been observed.

### 3.1.2. JAVELIN Disk Models

We created an extension to JAVELIN for constraining the $R_{\lambda_0}$ and $\beta$ disk parameters by fitting all the continuum light curves simultaneously. The benefit of this approach is that it reduces the number of parameters and uses all the photometric data to essentially produce a better sampled light curve. The $R_{\lambda_0}$ parameter from Equation 1.5 sets the absolute size of the disk and depends on the quasar properties (mass, mass accretion rate, radiative efficiency, etc.) while $\beta$ corresponds to the temperature profile of the disk as a function of radius.

We tested these modifications to JAVELIN in two ways. First, the JAVELIN website provides a simulated 5 year quasar light curve, with 8 day cadence and 180 day seasonal gaps to account for realistic seasonable inaccessibility. We used a grid of $R_{\lambda_0}$ and $\beta$ values to generate new light curves based on these data with known shifts. We then analyzed these simulated light curves to determine how well these values were recovered in several regimes. Most critically, we were interested in the performance when the light curve sampling rate was greater than, comparable to, and less than the shifts we applied using our thin disk parameters. Recovery of the
input $R_{\lambda_0}$ and $\beta$ works well in many cases, although it has some trouble recovering the model parameters in the instances with steep $\beta$ ($>3$) or small $R_{\lambda_0}$ compared to the sampling timescale ($<1/10$th of the cadence). Figure 3.5 shows the results of one of these tests.

We also reanalyzed the data from Fausnaugh et al. (2016) on NGC 5548. Fausnaugh et al. (2016) performed pairwise lag analyses on sets of Hubble Space Telescope (HST), Swift, and ground-based light curves to detect lags with respect to 1367 Å. From these pairwise lags, the authors fit for the $R_{\lambda_0}$ ($\alpha$ in that paper) and $\beta$ parameters implied by various subsets of their data, particularly subsets that excluded bands that may be contaminated by emission from other physical processes (e.g., broad emission lines or the Balmer continuum). We reanalyzed their data with our modified code and fit a total of 17 light curves simultaneously excluding the $U$ and $u$ bands due to Balmer continuum contamination and fixing the damping timescale at 164 days. The $u$- and $U$-band exclusion was adopted by Fausnaugh et al. (2016) and the damping timescale based on previous, longer time baseline studies of NGC 5548 by Zu et al. (2011). Our result is consistent with the Fausnaugh et al. (2016) values with tighter constraints on $R_{\lambda_0}$ and $\beta$, albeit now with a double solution, shown in Figures 3.4 and 3.6.

We then used this algorithm for the DES quasars that had yielded tentative $r$, $i$, and/or $z$ lag measurements relative to $g$ band. We still restrict the DRW damping time scale to fall between 100-300 days for this analysis. We also fixed $\beta = 4/3$, as we found we were unable to provide good constraints on both $R_{\lambda_0}$ and $\beta$ simultaneously for any object. Figure 3.7 shows an example posterior distribution for $R_{\lambda_0}$ for a quasar whose full posterior distributions for all model parameters is in Figure 3.8. Five objects in our current quasar sample have large amplitude variability in more than one DES observing season, and we compare their disk sizes with this method to check its performance. Two of these objects have disk sizes from three DES seasons. Figure 3.9 illustrates the $R_{\lambda_0}$ values for each of these objects, and we see that they are all consistent, albeit with large $2\sigma$ errors.

One possible concern is the contamination of the quasars’ broad emission lines in the photometric bandpasses affecting the lag signal. If the broad emission
lines contribute a significant fraction of the flux, then it is likely that any lag detection will be tracing at best a combination of the accretion disk and broad line region, and at worst almost entirely the broad line region. For the redshift range considered in our subsample of lag detections from DES (0.7 < z < 1.6), the MgII emission line is present in the g, r, or i band, along with surrounding blends of Fe emission. Fausnaugh et al. (2016) find that the Balmer continuum has a significant contribution to their u and U band data for NGC 5548, and the Hα line gives a comparable 20% contamination in the r and R bands. The emission line equivalent widths in luminous quasars are lower than for less luminous Seyferts like NGC 5548 (the well-known Baldwin Effect; Baldwin 1977). We therefore expect that broad emission lines will have a smaller effect on our sample. For the sample of Pan-STARRS quasars, also a higher luminosity sample, Jiang et al. (2017) find that the emission line contamination to continuum flux for their highest confidence subsample is less than 6% and thus a negligible contribution to the lag signals. What matters for lag measurements for the accretion disk is that the strength of any line variability in the bandpass is much smaller than that of the continuum. The line to continuum flux ratio is a reasonable proxy for this effect, although the line variability is often larger than the continuum variability.

3.1.3. Correlation with Black Hole Masses

To more directly compare our disk sizes with previous studies, we require an estimate of the black hole mass. A reverberation mapping campaign is currently underway for these sources (see King et al. 2015 for simulation results on the survey) which will provide the most accurate masses. For now, we use single epoch mass estimates using the MgII broad emission line, which is in the right wavelength range to be present in the spectra for all quasars in this sample, and the calibration from McLure & Jarvis (2002). The OzDES spectra were calibrated using the DES photometry, and the emission line full-width half-maxima (FWHM) were measured using the IRAF splot package. The resulting masses span more than an order of magnitude, bridging the masses of the more local AGN whose accretion disk sizes have been measured with photometric reverberation and the distant lensed quasars.
We compare our results to other studies in Figure 3.10. To meaningfully compare all objects at the same rest wavelength of 2500Å, we use the results of our JAVELIN thin-disk fit. Despite presenting these individual lags results as upper limits, they are fairly similar to measurements by other studies. We then compared these $R_{\lambda_0}$ constraints from our JAVELIN model to those derived from fitting the lags alone. Figure 3.11 shows these new size measurements compared to both literature values and those shown in Figure 3.10. The measurements are generally consistent with the upper limits we placed by fitting the lags independent of the thin disk model, and we provide a summary of these disk sizes in Table 3.2.

From Equation 1.5, we expect that the disk size should scale as $R_{\lambda_0} \propto M_{BH}^{2/3}$ (note a factor of $M_{BH}$ from Equation 1.5 is buried in the $\dot{M}$ parameter via Equation 1.3 from $L_{Edd} = \eta \dot{M} c^2$) in traditional thin disk theory. There appears to be a weak trend with mass in Figure 3.11, albeit with large scatter in accretion disk size and significant uncertainties in black hole mass. Prior accretion disk measurements have found that disks are larger than expected from thin disk theory by a factor of a few (Poindexter et al. 2008; Mosquera et al. 2013) and our work supports this conclusion. One explanation for larger disks is higher accretion rates for the black holes closer to the Eddington limit (Fausnaugh et al. 2016), but at these rates the disks would no longer remain thin.

3.1.4. Stacking Analysis

After analyzing the individual lag distributions, we investigated whether a stronger signal could be found by combining the posterior distributions for quasars of similar properties. In the standard thin disk model, the absolute size of the disk depends on the quasar properties. Thus, we expect that quasars with similar properties should have similar accretion disk sizes, and by combining their size distributions we may amplify the total signal. We divided our sample into two bins split at a mass of $6 \times 10^8 M_\odot$. This value gives approximately equal numbers of objects in each bin (7 and 8), albeit with different dynamic ranges of masses. The small mass bin covers an order of magnitude in mass, while the larger bin only a factor of two. Given the large systematic uncertainties in the single epoch mass measurements, several of the
objects could move between the bins with their mass errors, which could bias the stacked distributions. We rerun our JAVELIN thin disk object again on each quasar individually without any priors on the parameters and then sum the accretion disk size likelihoods for all the quasars in the same bin after putting them in the rest frame and scaling them to the same reference wavelength (2500Å) assuming \(\beta = \frac{4}{3}\). Figure 3.12 shows the final distributions for our mass bins, which are consistent with one another.

### 3.2. Conclusion

We report quasar accretion disk size measurements using time delays between the DES photometric bandpasses as a proxy for disk distances. We present a new JAVELIN tool that fits a thin disk model directly rather than individual lags, which we test on both NGC 5548 and our DES quasars. Our results are:

1. Even with the long cadence of the DES supernova pointings (~1 week) compared to the few light-day expected size of the accretion disk, we are able to place meaningful upper limits on lags between continuum bands using JAVELIN on many of our objects. These limits are comparable to the sizes found for accretion disks through the gravitational lensing technique as well as other objects that have disk sizes derived from other photometric reverberation mapping studies.

2. Our new extension of JAVELIN, a thin disk model, is able to reproduce the AGN STORM result for NGC 5548 (Fausnaugh et al. 2016) by fitting for the thin disk parameters directly rather than each lag individually. We describe further tests and provide this to the astronomical community as a tool for future accretion disk time series analysis.

3. When we fix the \(\beta\) parameter at \(\frac{4}{3}\), we measure sizes for 14 DES quasars with this thin disk model. The quasar sample spans almost two orders of magnitude in mass, and several of our measurements are of comparable precision to the disk lensing sizes. We find similar disk sizes for our quasar masses to previous results (Morgan et al. 2010; Jiang et al. 2017).
4. We have five quasars with variability in multiple DES observing seasons, and analyze each season of data independently with our thin disk model extension to JAVELIN. In two of these quasars, we have variability in all three seasons. The accretion disk sizes are consistent with each other in all of these cases.
Fig. 3.1.— DES light curves for the quasars in our sample. All of these objects show strong variability in at least one observing season. The DES Y1, Y2, and Y3 data are in the left, middle, and right columns, respectively. The photometry uses the same image subtraction pipeline as used in the supernova fields for the transient search (Kessler et al. 2015).
Fig. 3.2.— (Continued) DES quasar light curves.
Fig. 3.3.— Comparison of the JAVELIN and ICCF cross-correlation centroid distributions for lags in DES J024918.24-001730.98 relative to the $g$-band light curve. The two distributions are consistent with one another, although JAVELIN is much more centrally peaked than the ICCF in the $z$-band distribution. The lag distributions are given in the rest frame of the quasar.
Fig. 3.4.— Comparison of the accretion disk size at 1367 Å for NGC 5548 using our new JAVELIN Thin Disk object (colored points) versus the results reported in (Fausnaugh et al. 2016; black contours). The black contours correspond to their 1, 2, and 3σ constraints on these accretion disk parameters based on the lag profile of UV to optical photometry, whereas the colored points represent probability densities based on chain frequency for these same parameters assuming the light curves are well-described by a Shakura & Sunyaev (1973) thin disk model. We find two families of solutions of approximately equal likelihood, one of which is within the 1σ contours of the previous NGC 5548 analysis.
Fig. 3.5.— Example test on the JAVELIN thin disk model using simulated light curves, highlighting the chain steps for the \( R_\lambda \) and \( \beta \) parameters. The dashed lines correspond to the input values used to created the lagged light curves. The cadence for these data is roughly 8 days, similar to the cadence we have with DES. The input parameters were not recovered for small \( R_\lambda \) compared to the cadence or large \( \beta \) values (> 3), but the figure above shows a successful fit for recovering a disk size of the driving light curve at less than half the observing cadence. Black, dark gray, and light gray correspond to values that fall within the 1, 2, and 3\( \sigma \) likelihood distributions.
Fig. 3.6.— Corner plot for the $R_{\lambda_0}$ and $\beta$ parameters for NGC 5548 using our JAVELIN Thin Disk object. These histograms show clearly the double-valued nature of the fits presented in Figure 3.4. The top and right panels show histograms for $R_{\lambda_0}$ and $\beta$ individually, and the lower left panel illustrates the covariance between the two. Black, dark gray, and light gray correspond to the 1, 2, and 3$\sigma$ likelihood distributions and dashed lines give the best fit values found in Fausnaugh et al. (2016).
Fig. 3.7.— Example $R_{\lambda_0}$ posterior distribution after fitting with our new JAVELIN Thin Disk object and fixing $\beta = 4/3$. The x-axis is the quasar accretion disk size (in light-days) at the wavelength corresponding to the emitting region of the observed DES $g$ band, which runs from approximately 2000-3000Å rest-frame for our sample given its redshift distribution.
Fig. 3.8.— Corner plot for the full parameters for the quasar presented in Figure 3.3, DES J024918.24-001730.98, in the JAVELIN Thin Disk analysis. As mentioned in the text, strong priors were placed on both the damping timescale $\tau_{D_{RW}}$ and wavelength dependence $\beta$. The contours progress from 1-3$\sigma$ as they transition from black to lighter gray. The $R_{\lambda_0}$ parameter is in units of light-days, whereas $\tau$ and all of the widths are in days.
Fig. 3.9.— Comparison of the JAVELIN disk model results for objects that have detections in multiple years. The black circles are measurements for those quasars that have strong enough variability in all three seasons to get three separate $R_{\lambda_0}$ measurements, while the blue squares only have two seasons of large amplitude variability from which disk sizes are fit. The diagonal dashed line is a 1:1 relation. The error bars represent the $1\sigma$ limits on the parameter distributions, and show that the multiple years are all consistent with one another.
Fig. 3.10.— Accretion disk size distribution at 2500 Å as a function of black hole mass. The two slanted lines are the innermost stable circular orbit for a Schwarzchild and Kerr black hole. The DES sample is shown as upper limits based on the 95th percentile of the JAVELIN lag distributions as a conservative estimate given that several of our $g$-$r$ and $g$-$i$ lags were $2\sigma$ consistent with no lag. The black points are taken from lensing measurements (Mosquera et al. 2013). The green points are from photometric reverberation mapping of NGC 5548 (Edelson et al. 2015; Fausnaugh et al. 2016) and NGC 2617 (Shappee et al. 2014), and the magenta for Pan-STARRS (Jiang et al. 2017). The horizontal line corresponds to 1 light day.
Fig. 3.11.— Same as Figure 3.10, but now with our disk sizes obtained from our new Thin Disk JAVELIN extension as cyan squares.
Fig. 3.12.— Stacked distribution of disk sizes at rest frame 2500Å assuming that \( \beta = 4/3 \). The two mass bins are divided at \( 6 \times 10^7 M_\odot \) to give roughly equal numbers in each bin, although the dynamic range of the higher mass bin is smaller than the overall mass scaling uncertainties. We expect a bigger disk for higher mass black holes, but the two distributions are roughly the same.
<table>
<thead>
<tr>
<th>Quasar Name</th>
<th>RA</th>
<th>Dec</th>
<th>z</th>
<th>SN Field</th>
<th>g</th>
<th>BH Mass $10^9 M_\odot$</th>
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<td>J025318.76+000414.20</td>
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<td>20.01</td>
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<td>J024753.20-002137.69</td>
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<td>J021500.22-043007.49</td>
<td>33.75092</td>
<td>-4.50208</td>
<td>1.01</td>
<td>X1</td>
<td>19.62</td>
<td>0.38</td>
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<tr>
<td>J022440.70-043657.60</td>
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<td>-4.61600</td>
<td>0.91</td>
<td>X3</td>
<td>19.87</td>
<td>0.20</td>
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<tr>
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<td>34.96725</td>
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<td>0.66</td>
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Note. — All masses have an uncertainty of 0.4 dex, calculated using the McLure & Jarvis (2002) relationship for MgII.

Table 3.1. Sample Description
<table>
<thead>
<tr>
<th>Object Name</th>
<th>$\tau_r$</th>
<th>$\tau_i$</th>
<th>$\tau_z$</th>
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<th>$R_{2500\AA}^2$</th>
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<tr>
<td>(Season)</td>
<td>Days</td>
<td>Days</td>
<td>Days</td>
<td>Lt-Days</td>
<td>Lt-Days</td>
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<td>DES J0249-0017 (Y1)</td>
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<td>1.9</td>
<td>1.9$^{+3.5}_{-1.6}$</td>
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<tr>
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<td>1.6$^{+1.9}_{-1.4}$</td>
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<td>3.9</td>
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<tr>
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<td>2.3$^{+1.6}_{-1.5}$</td>
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<td>2.0$^{+2.3}_{-1.7}$</td>
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<td>0.7$^{+0.5}_{-0.5}$</td>
<td>0.7$^{+0.6}_{-0.6}$</td>
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<td>DES J0224-0659 (Y1)</td>
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<td>1.5$^{+2.7}_{-1.5}$</td>
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<td>0.6$^{+1.1}_{-1.1}$</td>
<td>2.1$^{+2.5}_{-1.5}$</td>
<td>2.1</td>
<td>4.8$^{+3.8}_{-3.3}$</td>
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<tr>
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<td>1.5$^{+1.1}_{-0.8}$</td>
<td>2.2$^{+1.4}_{-1.1}$</td>
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<td>10.8$^{+7.0}_{-7.1}$</td>
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<tr>
<td>DES J0221-0617 (Y1)</td>
<td>1.6$^{+2.7}_{-3.2}$</td>
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<td>3.4$^{+2.1}_{-4.5}$</td>
<td>2.3$^{+2.9}_{-2.0}$</td>
<td>5.2</td>
<td>6.4$^{+18.9}_{-6.1}$</td>
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<td>1.5</td>
<td>2.2$^{+3.8}_{-2.0}$</td>
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<td>1.4$^{+2.9}_{-2.2}$</td>
<td>1.7</td>
<td>2.0$^{+17.6}_{-1.8}$</td>
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<td>1.3$^{+1.0}_{-1.0}$</td>
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<td>2.4$^{+3.3}_{-1.9}$</td>
<td>3.1</td>
<td>7.1$^{+3.7}_{-3.7}$</td>
</tr>
</tbody>
</table>

Note. — JAVELIN time lags and disk sizes ($\beta=4/3$) in the quasar rest frame, blank data are for fits that did not converge. $^1$Disk size $2\sigma$ upper limits from riz lags. $^2$Disk sizes from the new thin disk model.

Table 3.2. $R_{2500\AA}$ and Lags
### Table 3.3. DES Quasar Light Curves

<table>
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<th>Quasar</th>
<th>MJD</th>
<th>Mag</th>
<th>MagErr</th>
<th>Band</th>
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<td>20.89</td>
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<td>56579.139</td>
<td>21.06</td>
<td>0.04</td>
<td>g</td>
</tr>
</tbody>
</table>

Note. — Photometry for the DES quasars on which we perform our analyses. Note that all magnitudes are in the AB System.
Chapter 4: Looking Forward

4.1. More on OzDES Reverberation Mapping

While work still needs to be done on the analysis pipeline before the initial measurements will be available, the next immediate goal for the reverberation mapping project is to get black hole mass measurements from both the MgII and CIV emission lines for those objects possible from our total sample of over 700 quasars. From simulations (King et al. 2015), we expect a recovery rate of approximately 30%, which would more than double the size of the current reverberation mapping sample. While this number is optimistic, a recovery fraction of 10% would still be comparable to the total number of currently reverberation-mapped quasars. The DES and OzDES sample is immediately interesting as these direct SMBH masses will span a larger redshift range than previous work. From H\(\beta\) measurements in more local systems, there is a strong correlation between the AGN continuum luminosity near H\(\beta\) and the average radius from which the H\(\beta\) line is emitting in the broad line region (the measured lag for the H\(\beta\) line to respond to changes in the continuum emission, a proxy for the ionizing flux; Peterson 1993; Kaspi et al. 2000; Bentz et al. 2006). This relationship is cleanly predicted by assuming the emitting radius should grow proportionally to the square root of the ionizing radiation due to the geometric dilution of incident flux. The observationally intensive aspect of reverberation mapping is to obtain many spectra to detect the time delay in order to determine the radius of the BLR. This correlation means that with only a single spectrum that measures the luminosity and orbital motion of the gas, a black hole mass estimate can be made by mapping the luminosity directly onto a broad line region radius (Laor 1998). This single-epoch black hole mass estimation technique has been heavily used for SMBHs, and often extrapolated to systems that have properties quite different from the black holes it has been calibrated for.
A principle goal of the OzDES project is to create a reverberation mapping sample of quasars across a wide range of luminosity, redshift, and mass. The current reverberation mapping database (Bentz & Katz 2015) has on the order of 50 objects with secure mass measurements, almost all done with the H$\beta$ emission line. We seek to extend this to the MgII and CIV lines, which due to their rest wavelengths require either monitoring with space-based telescopes for local objects or long time baseline monitoring from the ground of high redshift objects. This ambitious goal is also being attempted with the time domain component of the Sloan Digital Sky Survey (SDSS; Shen et al. 2016), which combined with OzDES will provide the first samples of multiple MgII and CIV lags.

The DES and OzDES target sample was selected to have a high density of quasars in the redshift ranges where the AAOmega spectrograph can capture multiple broad emission lines at once. This subset will allow for us to measure lags in two-to-three emission lines in the same object, enabling cross-calibration of the radius-luminosity relationships of the different lines. Single epoch SMBH mass estimates will thus be more secure, no longer requiring extrapolation over all of quasar parameter space. Along with the more direct OzDES masses, these calibrations will be used to measure the SMBH mass function and its evolution out to a redshift of $z \sim 4$. This is of particular note because it encapsulates the epoch of peak quasar activity at around $z \sim 2$, allowing us to determine what fraction of their total mass occurs during active phases of growth compared to quiescent ones.

We now have enough spectral epochs with OzDES to start measuring lags in quasars that have had substantial flux variations and lags well-matched to our fall within our observing seasons. The next step is to work on proper calibration and fully understanding the uncertainties on these spectra. Securely reducing the errors on our line flux measurements is the best way in which to improve the total number of lags from our sample, as well as their quality, as shown by King et al. (2015). The plan is to use the spectral shape information from F-stars that are routinely observed in each OzDES pointing as well as the DES colors of the quasars to correct the shape of the raw spectra and then calibrate them to the nearest DES photometric epochs.
Once this is done, we will measure lags initially for Mg\textsc{ii} and C\textsc{iv} as our baseline increases, and calibrate the corresponding R-L relationships against one another.

In Chapter 3, I presented disk sizes for roughly a dozen new objects with a technique that has only recently proven fruitful for local AGN, substantially increasing the number of black hole disks with constrained disk sizes. As DES continues through the end of the survey, the amount of quasar photometry for the supernova fields will almost double. Combined with the new JAVELIN extension for fitting thin disk models directly, this will provide a large dataset to which we can get constraints on the accretion disk sizes, and possibly temperature profiles as well. In addition to these objects, recently spectra have been taken to confirm a sample of quasars in DES calibration fields, which go much fainter than normal pointings but have much higher cadence, and provide a wealth of new potential targets with better sampled light curves for photometric reverberation mapping. Though the number of individual quasars that have variability amplitudes capable of meaningful constraints on their own may be low, performing stacking analyses similar to those presented in Section 3.1.4 for quasars of similar luminosities will provide insights on the average properties of accretion disks for these objects. Local AGN have hinted that the temperature profile is flatter than the prediction $\beta = 4/3$, and with a larger sample provided by DES we can see if this is characteristic of quasars as a class, if the thin disk prediction holds true generally, and how the disk properties change as a function of mass, luminosity, or accretion rate.

Lastly, the discovery of the first BAL quasar hosted in a post-starburst galaxy in the OzDES data, discussed in Chapter 2 can bring new insights on quasar and host-galaxy evolution. While only a single object, it provides a unique opportunity to age date the quasar under the assumption that it turned on roughly around when the star formation ended. This is not a strange assertion given the general phenomenological hierarchical growth model of galaxy growth where merging, gas-rich galaxies fuel dust-enshrouded star formation that ends due to a combination of quasar and supernova feedback. With continued OzDES monitoring, there is a chance to observe changes in the absorption lines over time, which would help inform models of absorber properties. Additionally, high resolution imaging would be able
to confirm the distorted morphology suggested by the extended source in the DES photometry. Deeper spectra over a longer wavelength baseline would also allow for better modeling of the post-starburst population.
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