

SPACE TELESCOPE AND OPTICAL REVERBERATION MAPPING PROJECT.  
III. OPTICAL CONTINUUM EMISSION AND BROAD-BAND TIME DELAYS IN NGC 5548

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ABSTRACT

We present ground-based optical photometric monitoring data for NGC 5548, part of an extended multi-wavelength reverberation mapping campaign. The light curves have nearly daily cadence from 2014 January to July in nine filters (*BVRI* and *ugriz*). Combined with UV data from the *Hubble Space Telescope* and *Swift*, we confirm significant time delays between the continuum bands as a function of wavelength, extending the wavelength coverage from 1158 Å to the *z*-band ( $\sim 9160$  Å). We find that the lags at wavelengths longer than the *V* band are equal to or greater than the lags of high ionization-state emission lines (such as He II  $\lambda 1640$  and  $\lambda 4686$ ), suggesting that the continuum emitting source is of a physical size comparable to the inner broad line region. The trend of lag with wavelength is broadly consistent with the prediction for continuum reprocessing by an accretion disk with  $\tau \propto \lambda^{4/3}$ . However, the lags also imply a disk radius that is 3 times larger than the prediction from standard thin-disk theory, assuming that the bolometric luminosity is 10% of the Eddington luminosity ( $L = 0.1L_{\text{Edd}}$ ). Using optical spectra from the Large Binocular Telescope, we estimate the bias of the inter-band continuum lags due to broad line region emission observed in the filters. We find that the bias for filters with high levels of BLR contamination ( $\sim 20\%$ ) can be important for the shortest continuum lags, and likely has a significant impact on the *u* and *U* bands due to Balmer continuum emission.

**Keywords:** galaxies: active — galaxies: individual (NGC 5548) — galaxies: nuclei — galaxies: Seyfert

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## 1. INTRODUCTION

The continuum emission of radio-quiet active galactic nuclei (AGN) is believed to originate in an accretion disk around a super-massive black hole (SMBH). At accretion rates and masses appropriate for SMBHs, geometrically thin, optically thick accretion disks have maximum temperatures between  $\sim 10^5$ – $10^6$  K, which naturally accounts for the characteristic peak of AGN spectral energy distributions (SEDs) in the far ultraviolet (UV, Burbidge 1967; Shakura & Sunyaev 1973; Shields 1978). However, a large variety of competing models of the accretion flow exist, for example, thick disk ge-

ometries at extremely super- or sub-Eddington accretion rates (Abramowicz et al. 1988; Narayan & Yi 1995). In addition, AGN exhibit non-thermal X-ray emission, which requires a hot plasma component or “corona” (e.g., Haardt & Maraschi 1991; Chakrabarti & Titarchuk 1995). The potential configurations and complex interplay between the hot corona and accretion disk admit a wide range of models with many free parameters, and searching for the unique observational signatures of a given disk model is very challenging (Sun & Malkan 1989; Laor et al. 1997; Koratkar & Blaes 1999; Vestergaard & Wilkes 2001; Telfer et al. 2002; Kishimoto et al. 2004, and references therein).

Reverberation mapping (RM, Blandford & McKee 1982; Peterson 1993) can provide insight into the structure of the accretion disk, and has become a standard tool for AGN astrophysics over the last 25 years (Clavel et al. 1991; Peterson et al. 1991; Horne et al. 1991; Kaspi et al. 2000; Peterson et al. 2004; Bentz et al. 2009; Denney et al. 2010; Grier et al. 2013b; Pancoast et al. 2014; Pei et al. 2014; Barth et al. 2015, and references therein). The basic principle of RM is that emission at two different wavelengths is causally connected, so that the time delay (or lag) between two light curves represents the light-crossing time within the system, and thereby provides a straightforward measurement of the system’s physical size. For example, because the AGN continuum powers the prominent emission lines observed in Seyfert galaxy/quasar spectra, the time delays between continuum and broad line light curves are commonly used to determine the physical extent of the line-emitting gas (the so-called broad line region, BLR).

In a similar way, RM techniques can be used to constrain the physical processes governing AGN continuum emission. X-ray emission from the corona may irradiate and heat the accretion disk. If the corona is relatively compact and centrally located, the UV and optical emission would be expected to respond to the incident X-ray flux, “echoing” the X-ray light curve after a time delay corresponding to the light travel-time across the disk (Krolik et al. 1991). On the other hand, X-ray light curves would be expected to lag behind UV and optical light curves if the X-rays are produced by Comptonization of thermal UV/optical disk photons (Haardt & Maraschi 1991). Observational investigations of the relation between X-ray and UV/optical emission have produced ambiguous results. X-rays have been found to lead the optical emission by one to several days in some objects (e.g., Arévalo et al. 2009; Breedt et al. 2010; Shappee et al. 2014; Troyer et al. 2015), but the X-ray variability on long ( $> 1$  year) time scales cannot always account for the optical variations (Uttley et al. 2003; Breedt et al. 2009). In addition, other studies find no long-term X-ray/optical correlations (Maoz et al. 2002), or find optical variations that lead the X-rays on shorter time scales ( $\sim 15$  days, Marshall et al. 2008).

RM can also reveal information about the size and structure of the continuum emitting source. Emission from different portions of the disk peaks at different wavelengths depending on the local disk temperature. By translating the wavelength of the continuum emission into a characteristic temperature, time delays between continuum light curves can be used to map the temperature profile of the disk. The first statistically significant inter-band time delays were found in NGC 7469 by Wanders et al. (1997) and Collier et al. (1998). Sergeev et al. (2005) carried out intensive optical monitoring of 14 AGN, and found evidence that longer wavelengths lag shorter wavelength emission. More recent continuum RM campaigns have used the *Swift* observatory (Gehrels et al. 2004) to obtain unprecedentedly well-sampled light curves across X-ray, near UV, and optical wavelengths: Shappee et al. (2014) observed NGC 2617

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with *Swift* on a nearly daily basis for several months in 2014, while McHardy et al. (2014) monitored NGC 5548 with  $\sim 2$  day cadence for approximately 2 years (excepting seasonal gaps). These studies found trends of lag with wavelength that are well fit by the expectation for X-ray/far-UV reprocessing.

The present study is the third in a series describing the results of the AGN Space Telescope and Optical Reverberation Mapping (STORM) project, an intensive, multi-wavelength monitoring campaign of NGC 5548. The AGN STORM campaign is anchored by daily far UV observations using the Cosmic Origins Spectrograph (COS, Green et al. 2012) on the *Hubble Space Telescope* (*HST*). De Rosa et al. (2015, hereinafter Paper I) give a complete introduction to the project and an analysis of the *HST* data. The COS program was complemented by a four-month broad-band photometric monitoring campaign using *Swift*, the first results of which are presented by Edelson et al. (2015, hereinafter Paper II). The *Swift* campaign achieved  $\sim 0.5$  day cadence and detected significant lags between the UV and optical continua, which follow the expected lag-wavelength relation of a thin accretion disk ( $\tau \propto \lambda^{4/3}$ ).

Supplementing these space-based observations are ground-based optical monitoring programs. The present study details the optical broad-band photometric monitoring component, which extends the analysis in Paper II using data in nine optical filters with  $\lesssim 1$  day cadence for seven months. The similarly intensive ground-based spectroscopic monitoring will be presented by Pei et al. (in prep, hereinafter Paper IV). In terms of cadence, temporal baseline, and wavelength coverage, the combination of UV and optical observations of the AGN STORM project represents the most complete RM experiment ever conducted.

The present work has three primary goals. The first is to directly compare the far UV and optical light curves of NGC 5548 over a concurrent monitoring period. The far UV light curve ( $\sim 1350 \text{ \AA}$ ) is expected to closely trace the true ionizing continuum ( $\leq 912 \text{ \AA}$ ), while the optical continuum ( $\sim 5100 \text{ \AA}$ ) appears to be delayed and somewhat smoothed compared to the UV emission. Since ground-based RM campaigns use the optical continuum as a proxy for the driving continuum light curve, understanding how the continuum emission changes as a function of wavelength is important for understanding any systematic effects in optical RM experiments. The second goal is to search for time delays between the UV and optical data, in an attempt to probe the structure of the continuum emitting region. However, because broad-band filters pick up spectral features that arise in the BLR (e.g., strong emission lines), and these features have large lags relative to the underlying continuum (several days for a Seyfert galaxy such as NGC 5548), inter-band lags estimated from broad-band photometry may be biased indicators of the accretion disk size. Therefore, our final goal is to estimate the impact of BLR emission on the observed inter-band time delays.

In §2, we describe the observations, data reduction, flux calibration, and general properties of the ground-based photometric light curves. In §3, we describe our time series analysis, measuring the lag as a function of wavelength of the broad-band filters. We then explore the impact of BLR emission on the observed inter-band lags in §4. Finally, in §5, we discuss our results, and we summarize our conclusions in §6. Where relevant, we assume a standard cosmological model with  $\Omega_M = 0.28$ ,  $\Omega_\Lambda = 0.72$ , and  $H_0 = 70 \text{ km s}^{-1}$  (Komatsu et al. 2011).

## 2. OBSERVATIONS AND DATA REDUCTION

In conjunction with the *HST COS* UV RM campaign described in Paper I, NGC 5548 was observed between 2013 De-

cember and 2014 August by 16 ground-based observatories in optical broad-band filters (Johnson/Cousins *BVRI* and SDSS *ugriz*). A short description of each telescope, the relevant imager, and the number of contributed epochs is given in Table 1. All observatories followed a common reduction protocol: images were first overscan-corrected, bias-subtracted, and flat-fielded following standard procedures. The reduced data, as well as nightly calibration frames, raw images, and observing logs, were then uploaded to a central repository, and the image quality was assessed by eye. Images taken in reasonable atmospheric conditions and free of obvious reduction errors were analyzed as described below.

### 2.1. Differential Photometry

The analysis is based on the *ISIS* image subtraction software package (Alard & Lupton 1998). Images are first registered to a common coordinate system, and the images with the lowest backgrounds and best seeing are combined into a high signal-to-noise “reference” image. The other images are then rescaled to match the effective exposure time of the reference image. Next, the reference image is convolved with a spatially variable kernel to match the PSF of each individual epoch, and then subtracted to leave the variable flux in each pixel. We use *ISIS*’s built in photometry package to extract light curves from the subtracted images at the position of the AGN in NGC 5548, in units of differential counts relative to the reference image. Because each telescope/filter/detector combination has slightly different properties (pixel scales, fields of view, gains, etc.), we built reference frames and subtracted images for each unique data set. This procedure corrects for variable seeing conditions and removes non-variable sources such as host galaxy starlight, allowing a clean measurement of the variable AGN flux.

### 2.2. Measurement Uncertainties

The formal errors found by *ISIS* sometimes underestimate the full uncertainties because they only account for local Poisson error contributions. In order to estimate more reliable measurement uncertainties, we examined the residual fluxes of stars in the subtracted images, and rescaled the formal *ISIS* errors to be consistent with the observed scatter. Our method is similar to that of Hartman et al. (2004, §4.1).

We first used *ISIS* to extract differential light curves at the positions of each unsaturated star in the reference images. For stars with constant flux in time, the distribution of residual fluxes at each epoch serves as an estimate of the uncertainty in the subtraction. Since we are only concerned with the magnitude of the residuals, we first take their absolute value. We then divide these values by their formal *ISIS* uncertainties, so that the resulting ratios indicate the factor by which the true uncertainties are underestimated. We set a minimum value of 1.0 for this ratio, since the uncertainty cannot be smaller than the local photon noise. Finally, we multiply the formal uncertainty for the AGN at the matching epoch by the median of the rescaling factors from all stars. The procedure ensures that the measurement uncertainty in a given image is consistent with the observed scatter of the subtracted stars. The median rescaling factor for all images was 2.9, while 75% of the rescaling factors are less than 6.6 and 98% are less than 25.0. The remaining 2% have rescaling factors between 30 and 87. The poorest subtractions result when *ISIS* cannot accurately construct the image PSF, usually because the image has too few stars.

To assess the effectiveness of this method, we adjusted the stars’ uncertainties by the derived rescaling factor for each image, and then checked the goodness-of-fit for a constant flux

**Table 1**  
Contributing Observatories

Observatory Name	Obs ID	Aperture	Detector	Pixel Scale	Field of View	Observing Period	Filters	Epochs
Bohyunsan Optical Astronomy Observatory	BOAO	1.8m	e2v CCD231-84	0''21	15' × 15'	March-April	V	5
Crimean Astrophysical Observatory	CrAO	0.7m	AP7p CCD	1''76	15' × 15'	Dec-June	BVRI	76
Fountainwood Observatory	FWO	0.4m	SBIG 8300M	0''35	19' × 15'	Jan-August	V	60
Hard Labor Creek Observatory	HLCO	0.5m	Apogee USB/Net	0''75	25' × 25'	April-June	V	27
La Silla Observatory	GROND	2.2m	Gamma-ray Burst Optical/ Near-IR Detector	0''33	5' × 5'	Feb-July	griz	6
Las Cumbres Observatory Global Telescope Network	LCOGT	1.0m	SBIGSTX-16803/ Sinistro CCD-486BI	0''23 0''39	16' × 16' 27' × 27'	Jan-August	BVugriz	263
Lick Observatory Katzman Automatic Imaging Telescope	KAIT	0.8m	AP7 CCD	0''80	7' × 7'	Jan-July	V	80
Liverpool Telescope	LT	2.0m	e2v CCD 231	0''15	10' × 10'	Feb-August	ugriz	120
Maidanak Observatory	MO15	1.5m	SNUCAM	0''27	18' × 18'	April-August	BVR	45
Mt Laguna Observatory	MLO	1.0m	CCD2005	0''41	14' × 14'	June-August	V	10
Mt. Lemmon Optical Astronomy Observatory	LOAO	1.0m	KAF-4301E	0''68	22' × 22'	Feb-July	V	26
Nordic Optical Telescope	NOT	2.5m	e2V CCD42-40	0''19	6' × 6'	April	V	3
Robotically Controlled Telescope	RCT	1.3m	SITe CCD	0''30	10' × 10'	Dec-May	BV	55
Svetloe Observatory	SvO	0.4m	ST-7XME CCD	2''00	12' × 8'	Jan-May	BVRI	49
West Mountain Observatory	WMO	0.9m	Finger Lakes PL-3041-UV	0''61	21' × 21'	Jan-July	BVR	44
Wise Observatory	WC18	0.5m	STL-6303E CCD	1''47	75' × 50'	Dec-July	BVRI	126

model of each star. The goodness-of-fit is calculated by

$$\chi^2/\text{dof} = \frac{1}{N-1} \sum_i^N \left( \frac{c_i - \bar{c}}{\sigma_i} \right)^2 \quad (1)$$

where  $\text{dof} = N - 1$  is the number of degrees of freedom of the fit,  $c_i$  is the counts in the light curve at epoch  $i$ ,  $\sigma_i$  is the rescaled uncertainty, and  $\bar{c}$  is the mean counts of the light curve. 90% of the rescaled values of  $\chi^2/\text{dof}$  are between 0.32 and 2.09, and the distribution peaks at 0.81, somewhat lower than would be expected for purely Gaussian statistics. This may indicate that our rescaling method is slightly overestimating the measurement uncertainties. However, given our large data set, we can afford to be conservative in this regard.

Data from the KAIT telescope and the  $u$  band Liverpool Telescope (LT, Steele et al. 2004) required a different treatment since these images have 10 stars or fewer, which are not enough to provide robust estimates of the error-rescaling factors. We instead calculated global rescaling factors from all available epochs, rather than individual corrections from single images. Using Equation 1, we calculate  $\chi^2/\text{dof}$  for all available stars, using the unscaled ISIS uncertainties for  $\sigma_i$ . We then multiplied the uncertainties of the AGN light curve by the average value of  $(\chi^2/\text{dof})^{1/2}$ . We found that the mean rescaling factor was 8.99 for the KAIT data and 2.23 for the  $u$  band LT data. Although this method does not account for epochs with high-quality subtractions, we find the cautious approach preferable to underestimating the uncertainties.

### 2.3. Intercalibration of Light Curves

In order to combine differential light curves in the same filter but from different telescopes, it is necessary to intercalibrate the light curves to a common flux scale. This accounts for the different mean flux levels and ADU definitions between the reference images, as well as small differences in filter transmission functions, detector efficiencies, etc. of the many telescopes. We model the difference of any two light curves by a multiplicative rescaling factor  $a$  and an additive shift  $b$ . While it is trivial to solve for these parameters by matching epochs where the fluxes are known to be equal, no two observations

occur at precisely the same time and it is therefore necessary to interpolate the light curves. Furthermore, this method can only treat two light curves at a time, and therefore loses information by ignoring the global probability of the ensemble calibration parameters for all telescopes. In order to address both these problems, we built a full statistical model of the intercalibrated light curve using the software package JAVELIN, following the SPEAR formalism of Zu et al. (2011).

JAVELIN models the light curves as a damped random walk (DRW). Although recent studies using *Kepler* light curves have shown that the DRW over-predicts the amplitude of AGN continuum variability on short timescales (Edelson et al. 2014; Kasliwal et al. 2015), the DRW provides an adequate description of the observed light curves for the noise properties and cadence/timescales of this study (which are similar to those of Kelly et al. 2009; MacLeod et al. 2010; Zu et al. 2013). In brief, points sampled from a DRW have an exponential covariance matrix, which is described by an amplitude  $\sigma_{\text{DRW}}$  that characterizes the strength of short-term variations, and a damping time-scale  $\tau_{\text{DRW}}$  over which the light curve becomes decoherent. Using a Markov Chain Monte Carlo (MCMC) calculation, we simultaneously fit for the shifts and rescaling factors of all light curves in a single filter. We also fit for  $\sigma_{\text{DRW}}$ , but our lightcurves do not have a long enough temporal baseline to meaningfully constrain  $\tau_{\text{DRW}}$ . We therefore fixed  $\tau_{\text{DRW}} = 164$  days, so as to match the value determined from multi-year historical lightcurves of NGC 5548 (Zu et al. 2011). The model provides a well-defined and self-consistent means of interpolating all the light curves simultaneously (see Zu et al. 2011; Li et al. 2013 for further details).

Our fitting procedure requires one light curve to be chosen to define the flux scale and mean flux level of the resulting intercalibration, so that this reference light curve is assigned a shift of 0 and a rescaling factor of 1. In the Johnson *BVRI* bands, we use the Wise C18 (WC18, Brosch et al. 2008) data as the calibration light curve, owing to its dense time sampling, long baseline, and large number of comparison stars (>400). For the SDSS *ugriz* bands, we use the LT light curves, since they have the longest baseline and most complete time sampling.

Uncertainty in the intercalibration parameters for a given telescope contributes to the final measurement uncertainty. For

a flux measurement  $f(t_i)$  at epoch  $t_i$ , the calibrated measurement is  $f_c(t_i) = af(t_i) + b$ , and standard error propagation shows that the uncertainty introduced per point is  $\sigma_{f_c}^2 = \sigma_a^2 f(t_i)^2 + \sigma_b^2 + 2f(t_i)\text{cov}(a, b)$ . Since  $a$  and  $b$  are usually anti-correlated,  $\sigma_{f_c}$  is often small compared to the uncertainties from image subtraction. However, this is not always the case for telescopes with very small numbers of observations, so we calculated  $\sigma_a$ ,  $\sigma_b$ , and  $\text{cov}(a, b)$  from the posterior distributions of these parameters for each telescope, and added  $\sigma_{f_c}$  in quadrature to the rescaled ISIS uncertainties for each epoch. This treatment is very conservative, since the intercalibration uncertainty is strongly correlated between points from a single telescope. A summary of the mean intercalibration uncertainties is given in Table 2.

The choice of reference light curves defines the physical flux level of the AGN from the corresponding ISIS reference image (WC18 and LT). We convert the intercalibrated differential light curves to physical flux units by performing aperture photometry on these reference images. For the AGN and all unsaturated stars in the field, we measured the flux enclosed in a  $5.''0$  radius circular aperture, and converted the summed fluxes to instrumental magnitudes. This means that the host galaxy light within the aperture is included in the measurement of the AGN flux, and this issue is discussed in §2.4. The background sky level was estimated from an annulus with inner/outer radius of  $14.''0/29.''0$  for the stars, and  $118.''0/132.''0$  for the AGN (so as to avoid light from the host galaxy).

We then matched all stars to the SDSS data release 7 catalog (Abazajian et al. 2009), and computed the offset between instrumental magnitudes and the SDSS AB magnitudes. We did not find any significant color terms in the flux calibration from the comparison stars, although the spectral slope of the AGN would be a poor match to such color terms regardless of their small values. For the Johnson/Cousins *BVRI* bands, we determined the comparison star magnitudes using the filter-system transforms given by Fukugita et al. (1996), and converted these to AB magnitudes using Fukugita et al. (1996) Table 8. The filter transforms have an uncertainty of  $\sim 0.03$  mag, which we adopt as a floor for the *BVRI* flux calibration uncertainty. The final flux-calibrated light curves are shown in Figure 1 and given in Table 3.

#### 2.4. Light Curve Properties

Table 4 gives a summary of the sampling properties of the AGN STORM continuum light curves, and shows that the light curves have approximately daily cadence over the entire campaign. Paper I and Paper II only presented the *HST* 1367 Å continuum light curve—here, we include three additional UV continuum light curves measured from the *HST* COS spectra, extracted from 5–6 Å windows centered at 1158 Å, 1479 Å, and 1746 Å. These continuum windows were chosen to be as uncontaminated as possible by absorption lines and broad emission-line wings. We also drop the *Swift* *V* band light curve from this analysis, because its mean fractional uncertainty is much larger than that of the ground-based Johnson *V* band light curve (3.2% compared to 0.8%). The reported wavelengths of the optical light curves are pivot wavelengths calculated from the filter response curves of the optical bands, and they are independent of the source spectrum (atmospheric cut-offs at 3000 Å and 1 μm were imposed for these calculations). Figure 2 shows a comparison of all the continuum lightcurves used in this study.

Table 4 also gives the variability properties of the light curves. Column 8 gives the mean flux and rms scatter of the light curves, corrected for Galactic extinction assuming a Cardelli, Clayton, & Mathis (1989) extinction law with  $R_V =$

**Table 2**  
Mean Intercalibration Uncertainty

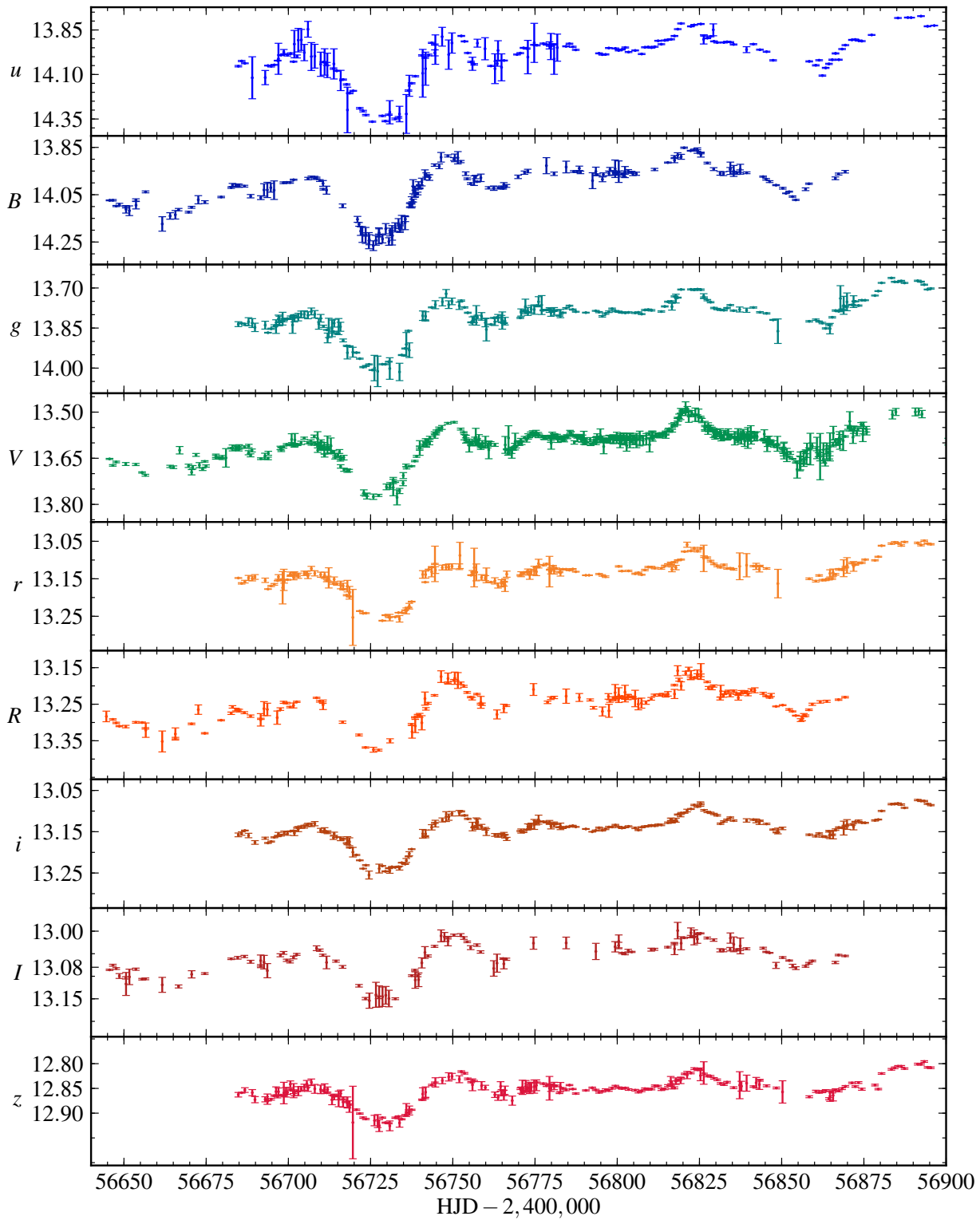
Telescope (Matches Table 1)	<i>B</i> (%)	<i>V</i> (%)	<i>R</i> (%)	<i>I</i> (%)	<i>u</i> (%)	<i>g</i> (%)	<i>r</i> (%)	<i>i</i> (%)	<i>z</i> (%)
WC18	ref	ref	ref	ref	...	...	...	...	...
LT	...	...	...	...	ref	ref	ref	ref	ref
LCOGT1	0.9	0.2	...	...	1.1	1.2	0.5	0.1	0.3
LCOGT2	2.3	0.4	...	...	1.8	0.5	1.9	0.4	1.9
LCOGT3	1.5	0.6	...	...	...	...	...	...	...
LCOGT4	2.7	...	...	...	...	...	0.3	0.1	0.2
LCOGT5	...	0.6	...	...	...	1.3	...	...	0.7
LCOGT6	...	0.5	...	...	...	1.6	1.4	0.4	...
LCOGT7	...	1.9	...	...	...	...	...	...	...
LCOGT8	...	1.3	...	...	...	...	...	...	...
WMO	0.9	0.6	0.3	...	...	...	...	...	...
CrAO	0.2	...	0.3	0.3	...	...	...	...	...
RCT	0.2	0.1	...	...	...	...	...	...	...
MO15	...	0.4	0.7	...	...	...	...	...	...
FWO	...	0.3	...	...	...	...	...	...	...
HLCO	...	0.4	...	...	...	...	...	...	...
KAIT	...	0.1	...	...	...	...	...	...	...
MLO	...	0.7	...	...	...	...	...	...	...
LOAO	...	0.4	...	...	...	...	...	...	...

**Note.** — Percentages are averaged for all epochs of the given telescope, measured relative to the flux at that epoch—see §2.3 for the definition of the intercalibration uncertainty. ‘ref’ is the reference telescope to which the others are aligned.

**Table 3**  
Optical Continuum Light Curves

Filter	HJD (−2400000)	$F_\lambda$ ( $10^{-15}$ erg cm $^{-2}$ s $^{-1}$ Å $^{-1}$ )	Telescope ID (as in Table 1)
<i>u</i>	56684.78	$21.61 \pm 0.08$	LT
	56685.79	$22.19 \pm 0.07$	LT
	56686.77	$21.93 \pm 0.04$	LT
...	...	...	
<i>B</i>	56645.64	$13.39 \pm 0.02$	WC18
	56646.65	$13.40 \pm 0.04$	WC18
	56647.65	$13.10 \pm 0.03$	WC18
...	...	...	
<i>g</i>	56684.78	$13.96 \pm 0.12$	LT
	56685.79	$14.00 \pm 0.02$	LT
	56686.77	$13.95 \pm 0.05$	LT
...	...	...	
<i>V</i>	56645.62	$12.91 \pm 0.02$	WC18
	56646.61	$12.66 \pm 0.03$	WC18
	56647.63	$12.79 \pm 0.03$	WC18
...	...	...	
<i>r</i>	56684.78	$15.73 \pm 0.01$	LT
	56685.79	$15.52 \pm 0.03$	LT
	56686.77	$15.59 \pm 0.05$	LT
...	...	...	
<i>R</i>	56644.64	$12.76 \pm 0.17$	CrAO
	56646.63	$12.67 \pm 0.02$	WC18
	56647.64	$12.56 \pm 0.02$	WC18
...	...	...	
<i>i</i>	56684.78	$10.16 \pm 0.04$	LT
	56685.78	$10.19 \pm 0.04$	LT
	56686.77	$10.26 \pm 0.01$	LT
...	...	...	
<i>I</i>	56645.63	$8.67 \pm 0.01$	WC18
	56646.63	$8.75 \pm 0.02$	WC18
	56647.64	$8.69 \pm 0.02$	WC18
...	...	...	
<i>z</i>	56684.78	$9.30 \pm 0.04$	LT
	56685.78	$9.34 \pm 0.01$	LT
	56686.77	$9.38 \pm 0.04$	LT
...	...	...	

**Note.** — This table is also available in machine-readable format in the online version of this article.



**Figure 1.** *BVRI* and *ugriz* ground-based light curves from the full monitoring campaign in AB magnitudes. Only the measurement uncertainties in the differential fluxes are shown. These uncertainties include those due to intercalibration, summarized in Table 2. Systematic uncertainties for the absolute flux calibration are given in Table 4.

3.1 and  $E(B-V) = 0.0171$  mag (Schlegel et al. 1998; Schlafly & Finkbeiner 2011, Paper I). Columns 10, 11, and 12 give different estimates of their fractional variability. The fractional variability  $F_{\text{var}}$  of a light curve is defined by

$$F_{\text{var}} = \frac{1}{\langle f(t) \rangle} \sqrt{\frac{1}{N} \sum_i^N \left\{ [f(t_i) - \langle f(t) \rangle]^2 - \sigma_i^2 \right\}} \quad (2)$$

and the uncertainty on  $F_{\text{var}}$  is

$$\sigma_{F_{\text{var}}}^2 = \frac{1}{N-1} \sum_i^N \left\{ \frac{[f(t_i) - \langle f(t) \rangle]^2 - \sigma_i^2}{\langle f(t) \rangle^2} - F_{\text{var}}^2 \right\} \quad (3)$$

where  $f(t_i)$  is the value of the lightcurve at epoch  $i$ ,  $\sigma_i$  is the associated uncertainty, and  $\langle f(t) \rangle$  is the (unweighted) mean value of the light curve (Rodríguez-Pascual et al. 1997; Turner et al. 1999). We also estimated the fractional variability using the JAVELIN amplitudes,  $\sigma_{\text{DRW}}/\langle f \rangle$ , since this is an equivalent measure of  $F_{\text{var}}$  under the DRW model. The values of  $\sigma_{\text{DRW}}/\langle f \rangle$  and  $F_{\text{var}}$  are often in good agreement, but with notable exceptions, as given in Table 4.

Figure 3 shows the mean flux and variability properties of these light curves. The top panel shows the mean SED (corrected for Galactic extinction). The vertical error bars show the minimum and maximum states of the AGN, which occur at  $\text{HJD} - 240000 = 56723.1$  and  $56818.9$ , respectively. These dates are based on the *HST* 1367 Å light curve, and the other bands are adjusted for inter-band time delays that are measured in §3. The middle panel shows the logarithm of the difference in flux between the minimum and maximum states of the AGN, which cleanly isolates the variable component of the spectrum and better traces the shape of the accretion disk SED. For comparison, a standard thin accretion disk SED with  $\lambda F_{\lambda} \propto \lambda^{-4/3}$  is shown, arbitrarily normalized to match the Johnson *V* band differential flux. Although the data are in excellent agreement with the prediction at longer wavelengths, the UV data lie significantly below the model SED. This discrepancy may be due to extinction internal to the AGN, or the inner edge of the disk, which will display an exponential Wien cut-off rather than  $\lambda F_{\lambda} \propto \lambda^{-4/3}$ . A more complete discussion and modeling of the variable spectrum will be presented by Starkey et al. (in prep). Finally, the bottom panel shows  $F_{\text{var}}$  as a function of wavelength. The far UV light curves have values of  $F_{\text{var}} \geq 0.20$ , which sharply decrease with wavelength to about 0.06 in the *V* band. At longer wavelengths, the trend flattens, reaching 0.02 in the *z* band.

At least part of this effect is due to the constant flux contributed by the host galaxy, which becomes increasingly important at longer wavelengths. Based on spectral decomposition models and synthetic photometry (described in §4.1 and §4.2), the host galaxy contributes about 20% of the observed flux in the *B* band, and about 54% in the *I* and *z* bands. We corrected  $\langle f(t) \rangle$  for this constant component, and Figure 3 and Table 4 also show the host galaxy flux and revised values of  $F_{\text{var}}$ . The effect on the trend in Figure 3 is fairly subtle, and does not change the flattening at optical wavelengths.

The larger variability amplitudes at short wavelength suggest that the SED of NGC 5548 becomes bluer in higher flux states. The same effect was seen by Cackett et al. (2015) in NGC 5548 with near UV grism monitoring data from *Swift*. However, the trend is driven by the light curves at wavelengths  $< 5000$  Å, and is most significant at wavelengths  $\lesssim 3500$  Å, which may be why optical studies of AGN variability do not always find any “bluer when brighter” trend (e.g., Sakata et al. 2010).

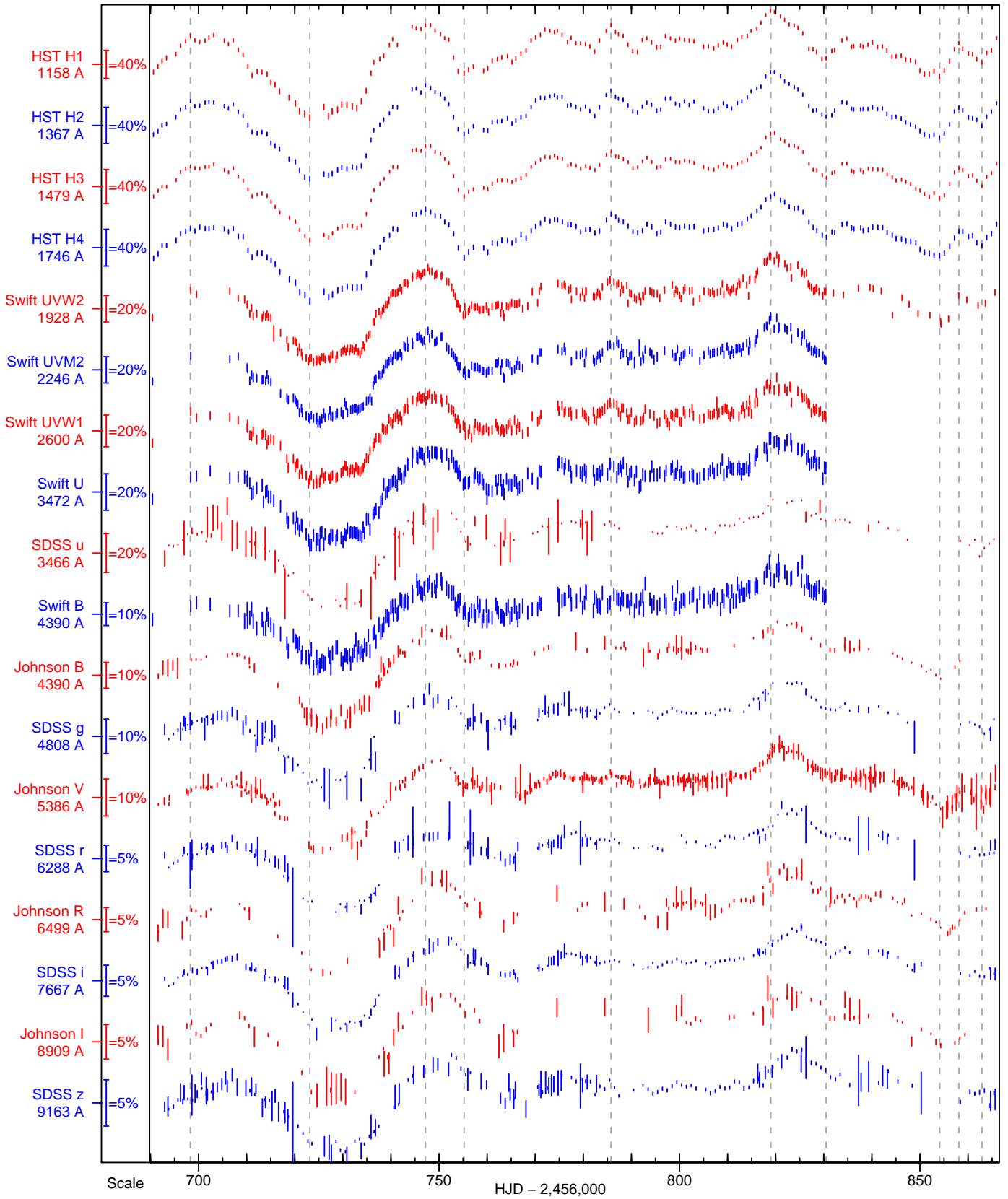
### 3. TIME SERIES ANALYSIS

We measure the lags between light curves using two methods. First, we use the interpolated cross-correlation function (ICCF), as employed by Peterson et al. (2004), and estimate the uncertainty of the lag using a Monte Carlo method. Second, we use JAVELIN, which measures lags by modeling reverberating light curves as shifted, scaled, and smoothed versions of the driving light curve.

In the first method, the ICCF is calculated by shifting one light curve on a grid of lags  $\tau$  spaced by 0.1 days, and calculating the correlation coefficient  $r_{cc}(\tau)$  by linearly interpolating the second light curve. The lags are estimated from the centroid of the ICCF, defined as the mean ICCF-weighted lag for which  $r_{cc}(\tau) > 0.8r_{\text{max}}$ . Uncertainties are estimated using the flux randomization/random subset selection (FR/RSS) method, wherein a distribution of ICCF centroids is built from cross correlating  $10^3$  realizations of both light curves. Each realization consists of randomly selected epochs (chosen with replacement), and the corresponding flux measurements are adjusted by random Gaussian deviates scaled to the measurement uncertainties. The lags reported here correspond to the medians of the ICCF centroid distributions, while the lower and upper uncertainties define their central 68% confidence intervals.

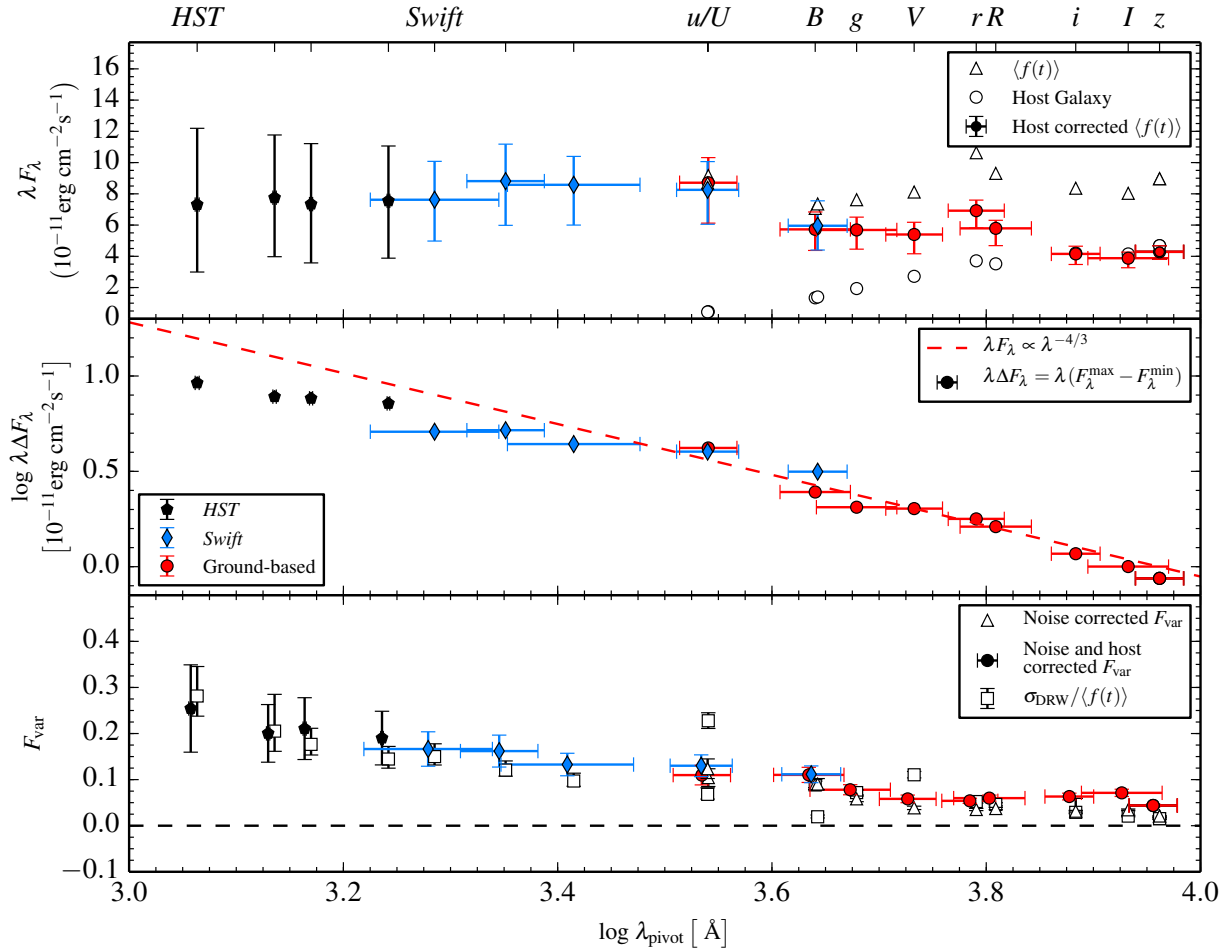
We detrended the light curves, as is common practice in RM studies (Peterson et al. 2004, Paper II), in order to remove long-term secular trends that are poorly sampled in the frequency domain and may bias the observed lag (Welsh 1999). The detrending procedure consists of subtracting a second-order polynomial linear-least squares fit (with equal weight given to all data points) from the observed light curves. Following Paper I and Paper II, we restricted the analysis to the time period coincident with the *HST* campaign, and measured the time delays relative to the *HST* 1367 Å light curve. When calculating the ICCF, we only interpolate the 1367 Å light curve. Table 5 summarizes the resulting mean lags, corrected for cosmological time dilation (the redshift of NGC 5548 is  $z = 0.017175$ , Paper I). Lags for the hard and soft X-ray bands of the *Swift* XRT are also included, as determined in Paper II. The ICCF for all bands is shown in Figure 4 by the solid black lines, while the centroid distributions are shown by the gray histograms. We found that the *HST* 1158 Å and 1479 Å lags were only slightly larger than the spacing of our interpolation grid (0.1 days), so we repeated the procedure on these lightcurves using a grid of 0.01 days. This did not have a noticeable effect on the ICCF centroids, but did change the ICCF peaks by  $\sim 0.05$  days. The lags reported in Table 5 make use of the finer grid for these light curves.

Our treatment of the *Swift* light curves (*UVW2*, *UVM2*, *UVW1*, *U*, and *B*) results in lags systematically larger than those found in Paper II, although the tension is only moderate (typically  $\lesssim 1.5\sigma$ ). These differences are primarily due to the different detrending procedures of the two studies. Paper II detrended the *Swift* light curves using a 30-day running mean, while we use a low-order polynomial. A running mean corresponds to a lower-pass filter than a polynomial trend, so this detrending procedure removes more low-frequency power from the light curve, and is therefore expected to result in smaller lags. However, several of our light curves have very irregular sampling, which makes the calculation of the running mean poorly defined, so we instead use the low-order polynomial. The ground-based SDSS *u* and *Swift* *U* lags and the Johnson *B* and *Swift* *B* lags are consistent at the  $\sim 0.6\sigma$  level using the polynomial detrending, so it is likely that the detrending procedure accounts for most of the difference between the near UV lags. Two other smaller effects may be important for



**Figure 2.** AGN STORM UV and optical continuum lightcurves used in this analysis, restricted to the observing window of the *HST* campaign. Lightcurves have been converted to AB magnitudes, but are rescaled and shifted for clarity—the scales along the vertical axis show the fractional variations. The vertical dashed lines mark local extrema in the *HST* 1158 Å lightcurve.





**Figure 3. Top Panel:** Mean SED of NGC 5548 from far UV to optical wavelengths, corrected for Galactic extinction. The vertical error bars represent the AGN in the maximum and minimum states of the campaign. The horizontal error bars represent the rms width of the filter transmission curves. See §4 for a discussion of the host galaxy estimate. **Middle Panel:** Variable SED component, calculated from the difference in flux between the minimum and maximum states, which more cleanly identifies the accretion disk spectrum. The dashed red line is the predicted spectrum for a standard thin disk—discrepancies at short wavelengths may be due to extinction internal to the AGN or the inner-edge of the disk. **Bottom Panel:** Fractional variability  $F_{\text{var}}$  as a function of wavelength.  $\sigma_{\text{DRW}}$  is the DRW amplitude from the JAVELIN fits. For clarity, a small shift in wavelength to the  $F_{\text{var}}$  points has been applied.

**Table 4**  
Light Curves Properties

Source	Filter	$\lambda_{\text{pivot}}$ (Å)	Flux Calibration Uncertainty (mag)	$N_{\text{obs}}$	$\Delta t_{\text{ave}}$ (days)	$\Delta t_{\text{med}}$ (days)	$\langle f(t) \rangle^a$	Host <sup>a</sup>	$F_{\text{var}}$	$F_{\text{var}2}^b$	$\sigma_{\text{DRW}}/\langle f(t) \rangle$
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)
<i>HST</i>	$\lambda 1158$	1158	0.050	171	1.03	1.00	52.41 ± 13.38	...	0.254 ± 0.095	0.254 ± 0.095	0.281 ± 0.054
<i>HST</i>	$\lambda 1367$	1367	0.050	171	1.03	1.00	49.17 ± 9.89	...	0.200 ± 0.063	0.200 ± 0.063	0.205 ± 0.062
<i>HST</i>	$\lambda 1479$	1479	0.050	171	1.03	1.00	43.54 ± 9.20	...	0.211 ± 0.067	0.211 ± 0.067	0.176 ± 0.029
<i>HST</i>	$\lambda 1746$	1746	0.050	171	1.03	1.00	38.26 ± 7.32	...	0.190 ± 0.058	0.190 ± 0.058	0.145 ± 0.024
<i>Swift</i>	<i>UVW2</i>	1928	0.030	284	0.62	0.39	34.71 ± 5.83	...	0.166 ± 0.037	0.166 ± 0.037	0.150 ± 0.023
<i>Swift</i>	<i>UVM2</i>	2246	0.030	256	0.55	0.35	33.83 ± 5.55	...	0.162 ± 0.035	0.162 ± 0.035	0.121 ± 0.017
<i>Swift</i>	<i>UVW1</i>	2600	0.030	270	0.52	0.38	29.70 ± 4.01	...	0.133 ± 0.024	0.133 ± 0.024	0.097 ± 0.014
<i>Swift</i>	<i>U</i>	3472	0.020	145	1.20	0.99	24.43 ± 2.59	1.22 ± 0.02	0.104 ± 0.019	0.110 ± 0.021	0.228 ± 0.017
Ground	<i>u</i>	3467	0.035	270	0.52	0.38	23.18 ± 2.94	1.16 ± 0.02	0.124 ± 0.021	0.130 ± 0.024	0.068 ± 0.012
Ground	<i>B</i>	4369	0.030	151	1.11	0.98	15.15 ± 1.36	2.88 ± 0.05	0.089 ± 0.011	0.110 ± 0.016	0.089 ± 0.007
<i>Swift</i>	<i>B</i>	4392	0.016	271	0.52	0.37	15.69 ± 1.48	2.98 ± 0.05	0.090 ± 0.012	0.112 ± 0.018	0.019 ± 0.003
Ground	<i>g</i>	4776	0.034	172	1.01	0.97	15.06 ± 0.89	3.83 ± 0.08	0.058 ± 0.006	0.078 ± 0.011	0.072 ± 0.005
Ground	<i>V</i>	5404	0.030	429	0.41	0.31	14.29 ± 0.56	4.79 ± 0.10	0.039 ± 0.004	0.058 ± 0.008	0.111 ± 0.007
Ground	<i>r</i>	6176	0.032	172	1.01	0.93	16.49 ± 0.59	5.76 ± 0.12	0.035 ± 0.002	0.054 ± 0.006	0.052 ± 0.004
Ground	<i>R</i>	6440	0.030	136	1.28	0.96	13.88 ± 0.52	5.25 ± 0.10	0.037 ± 0.003	0.060 ± 0.007	0.046 ± 0.003
Ground	<i>i</i>	7648	0.021	178	0.98	0.96	10.59 ± 0.33	5.33 ± 0.10	0.031 ± 0.002	0.063 ± 0.007	0.029 ± 0.017
Ground	<i>I</i>	8561	0.030	98	1.73	1.02	9.15 ± 0.32	4.73 ± 0.08	0.034 ± 0.002	0.071 ± 0.008	0.021 ± 0.002
Ground	<i>z</i>	9157	0.011	186	0.93	0.91	9.57 ± 0.21	5.00 ± 0.08	0.021 ± 0.001	0.044 ± 0.004	0.015 ± 0.002

**Note.** —  $N_{\text{obs}}$  gives the number of epochs in the lightcurve,  $\Delta t_{\text{ave}}$  gives the average cadence,  $\Delta t_{\text{med}}$  gives the median cadence,  $\langle f(t) \rangle$  gives the mean flux (the uncertainty gives the rms scatter of the lightcurve), “Host” gives the host-galaxy flux,  $F_{\text{var}}$  is defined in §2.4, and  $\sigma_{\text{DRW}}$  is the DRW amplitude. The flux calibration uncertainty is the systematic uncertainty for conversion to physical units (i.e., zeropoint errors). For *HST*, these values are taken from Paper I, while for *Swift* the values are from Table 6 of Poole et al. (2008). The uncertainties for the ground-based lightcurves represent our calibration to the SDSS AB mag photometric system. A correction for Galactic extinction has been applied to these data (see §2.4 for details).

<sup>a</sup>  $10^{-15} \text{erg cm}^{-2} \text{s}^{-1} \text{\AA}^{-1}$

<sup>b</sup> Corrected for host-galaxy flux

the lag determinations. First, the *Swift* UVOT optical filters are much narrower than the standard Bessell filters used for the ground-based light curves, so the observed variations are not perfectly identical (the *Swift* lightcurves also have slightly shorter baselines). Second, the *Swift* optical light curves have much larger fractional uncertainties, which may shift the ICCF centroid distribution of the otherwise similar lightcurves.

We also estimate the lags using JAVELIN, which calculates a maximum likelihood lag, scale factor, and kernel width (assuming a top-hat transfer function) from the DRW covariance matrices. JAVELIN internally employs a linear detrending procedure, so we do not apply the second-order detrending as for the ICCF analysis. We found that the JAVELIN fits for the ground-based light curves often failed to converge to a realistic solution of model parameters, but that these results were driven by several observations with very small uncertainties. We identified points that likely have underestimated uncertainties by employing a modified  $\sigma$ -clipping routine—points greater than  $5\sigma$  away from the interpolation described in §2.3 had their uncertainties rescaled to be consistent with the interpolated model at  $1\sigma$ . The light curves required between 4 and 20 epochs to be rescaled, which represent between 2% and 13% of the epochs in the corresponding filters.

The resulting model solutions are much more stable than the solutions without  $\sigma$ -clipping, and the posterior distribution of these lags are shown by the red histograms in Figure 4. The median lags are always consistent with the ICCF analysis, although the posterior distributions are extremely narrow. This is because the small uncertainties of our data impose a very restricted range of parameters on the simple model employed by JAVELIN. This restricted range may indicate that there is significantly more information in RM data sets than can be captured with standard cross-correlation methods. Paper I found a similar result, where the shape of the line light curves was not always a good match to the observed continuum light curve. Smoothing the continuum light curve by a simple transfer function cannot therefore always reproduce the line

light curve, suggesting that other processes are important for the observed line emission (perhaps, for example, anisotropic emission/reprocessing). A more detailed investigation of this result will be pursued in Paper IV through the analysis of optical emission lines.

Several of the distributions are multimodal, which either represents multiple lag signals or aliasing. Multiple lag signals may be produced by BLR emission contaminating the broad-band filter lightcurves, (for example, Lira et al. 2015 found that JAVELIN was able to pick out both the accretion disk and dusty torus variability in near infra-red filters for MCG-6-30-15). However, many peaks are spaced by  $\sim 1$  day, which is the cadence of the driving  $1367 \text{\AA}$  *HST* light curve, so aliasing is probably an important effect. For now, we simply select the peak in the posterior distribution nearest the ICCF lag, and Table 5 gives the medians of these peaks and their central 68% confidence intervals.

Using either lag estimation technique, we find that longer wavelength continuum variations follow those at shorter wavelengths. Figure 5 shows the lags as a function of the pivot wavelength of each filter. While the far and near UV light curves have time delays  $\tau < 1$  days, the *V* band lags the  $1367 \text{\AA}$  continuum by  $2.04 \pm 0.21$  days, and the *z* band lags it by  $3.93 \pm 0.42$  days. For comparison, the He II UV and optical lines ( $1640 \text{\AA}$  and  $4686 \text{\AA}$ ) have a mean lag of  $\sim 2.5$  days relative to the  $1367 \text{\AA}$  light curve (Paper I, Paper IV). The optical light curves have a time delay comparable to, and frequently larger than, that of high ionization-state lines in the BLR.

The trend of larger lags at longer wavelengths is nearly monotonic. The most notable exceptions are 1) in the longest wavelength filters, where the trend appears to level out near the *i* band, and 2) in the *u* and *U* bands. The *u* and *U* bands have mean lags of  $2.03 \pm 0.41$  days and  $1.80 \pm 0.24$  days, respectively, comparable to or larger than the lags of the *g* and *V* band light curves. This may be due to emission originating in the BLR picked up in the *u* and *U* band filters, which would contaminate measurements of the AGN continuum emission

and artificially increase the observed lag. A similar explanation may exist for the down turn at the  $I$  and  $z$  bands, since Paschen continuum emission from the BLR begins at 8204 Å (see Korista & Goad 2001). Depending on the fine structure of the light curves, BLR contamination may also result in the bimodal lag distributions for several bands found from the JAVELIN analysis. We return to the question of BLR contamination in §4.

In order to quantify the trend of lag with wavelength, we fit a model to the data presented in Figure 5, using the functional form

$$\tau = \alpha \left[ \left( \frac{\lambda}{\lambda_0} \right)^\beta - 1 \right] \quad (4)$$

where  $\tau$  is the observed lag,  $\lambda_0$  is a reference wavelength, and  $\alpha$  and  $\beta$  are free parameters. As in Paper II, we set  $\lambda_0 = 1367$  Å, and report all covariances between parameters. The results of the fits are summarized in Table 6. We find that  $\alpha = 0.97 \pm 0.24$  days and  $\beta = 0.90 \pm 0.12$ . The parameters are strongly correlated, with a normalized correlation coefficient  $\rho(\alpha, \beta) = -0.99$ , and  $\chi^2 = 25.94$ , which approaches a low probability for 18 degrees of freedom ( $\chi^2/\text{dof} = 1.44$  and  $P(\chi^2|\text{dof}) = 0.05$  for a one-tailed  $\chi^2$  test). Since there is good reason to suspect that the  $u$  and  $U$  bands are affected by BLR emission (see §4), we also fit the data excluding these lags. With these bands excluded, we find  $\alpha = 0.79 \pm 0.22$  days and  $\beta = 0.99 \pm 0.14$ . The normalized correlation coefficient does not change, but the goodness-of-fit is now  $\chi^2 = 16.85$  with  $\text{dof} = 16$ , and  $\chi^2/\text{dof} = 1.05$  (and  $P(\chi^2|\text{dof}) = 0.60$  for the same one-tailed test). The interpretation of Equation 4 is discussed in §5.3.

#### 4. CONTAMINATION BY BROAD LINE REGION EMISSION

As noted above, the  $u$  and  $U$  lags are outliers from the trend in Figure 5. A major component of the flux observed in these filters is the “small blue bump,” caused by bound-bound and bound-free hydrogen emission (the so-called Balmer continuum), as well as blended Fe II lines that originate in the BLR. This BLR emission may cause the  $u$  and  $U$  band lags to be biased estimators of the light-crossing time within the continuum source. In fact, several filters pick up other spectral features that originate in the BLR. The strongest is the prominent H $\alpha$  line in the  $r$  and  $R$  bands, although additional emission lines and a diffuse continuum consisting of bound-free, free-free, electron scattering, and reflection is expected to be present at all wavelengths (Korista & Goad 2001). Understanding the impact of BLR emission on the observed lags is therefore important for interpreting the inter-band time delays.

In this section, we assess the effect of BLR emission on the inter-band continuum lags. First, we decompose spectra of NGC 5548 into models of each emission component. We then estimate the fractional contribution from BLR emission in each filter using synthetic photometry. Finally, we simulate broad-band filter observations by combining mock continuum and BLR light curves, and search for biases in the lags by cross-correlating each emission component with the 1367 Å light curve.

##### 4.1. Spectral Decomposition

We begin by decomposing spectra of NGC 5548 into models of each emission component. We obtained moderate resolution ( $R \sim 2000$ ) optical spectra of NGC 5548 using the Multi-Object Double Spectrographs (MODS, Pogge et al. 2010) on the Large Binocular Telescope (LBT, Hill et al. 2010). These observations are from 2014 June 08 and 2014 June 25 (HJD

=2,456,817 and 2,456,834, respectively). The spectra were reduced and flux-calibrated using the `modsIDL` Spectral Reduction Pipeline.<sup>67</sup> The spectra cover the wavelength range from 3000 Å to 1  $\mu\text{m}$ . Wavelength solutions were derived from comparison lamp calibrations for each observing run. Relative flux calibration was performed using 3 standard stars observed on the same nights as NGC 5548; however, the observations were taken in poor atmospheric conditions, making their absolute flux calibration unreliable. We therefore rescaled the spectra so that the integrated [O III]  $\lambda 5007$  fluxes match the value measured for the photometric nights of the optical spectral RM campaign,  $(5.01 \pm 0.11) \times 10^{-13} \text{ erg s}^{-1} \text{ cm}^2$  (Paper IV). The slit width and extraction window of the MODS spectra were 5'' and 15'', respectively, chosen to match those of the optical monitoring spectra. This ensures that the relative contribution of host galaxy light, narrow-line emission, and BLR emission are the same in both data sets. We corrected for Galactic extinction following the prescription described in §2.4. We did not make any correction for telluric absorption because broad-band filters suffer from the same effect.

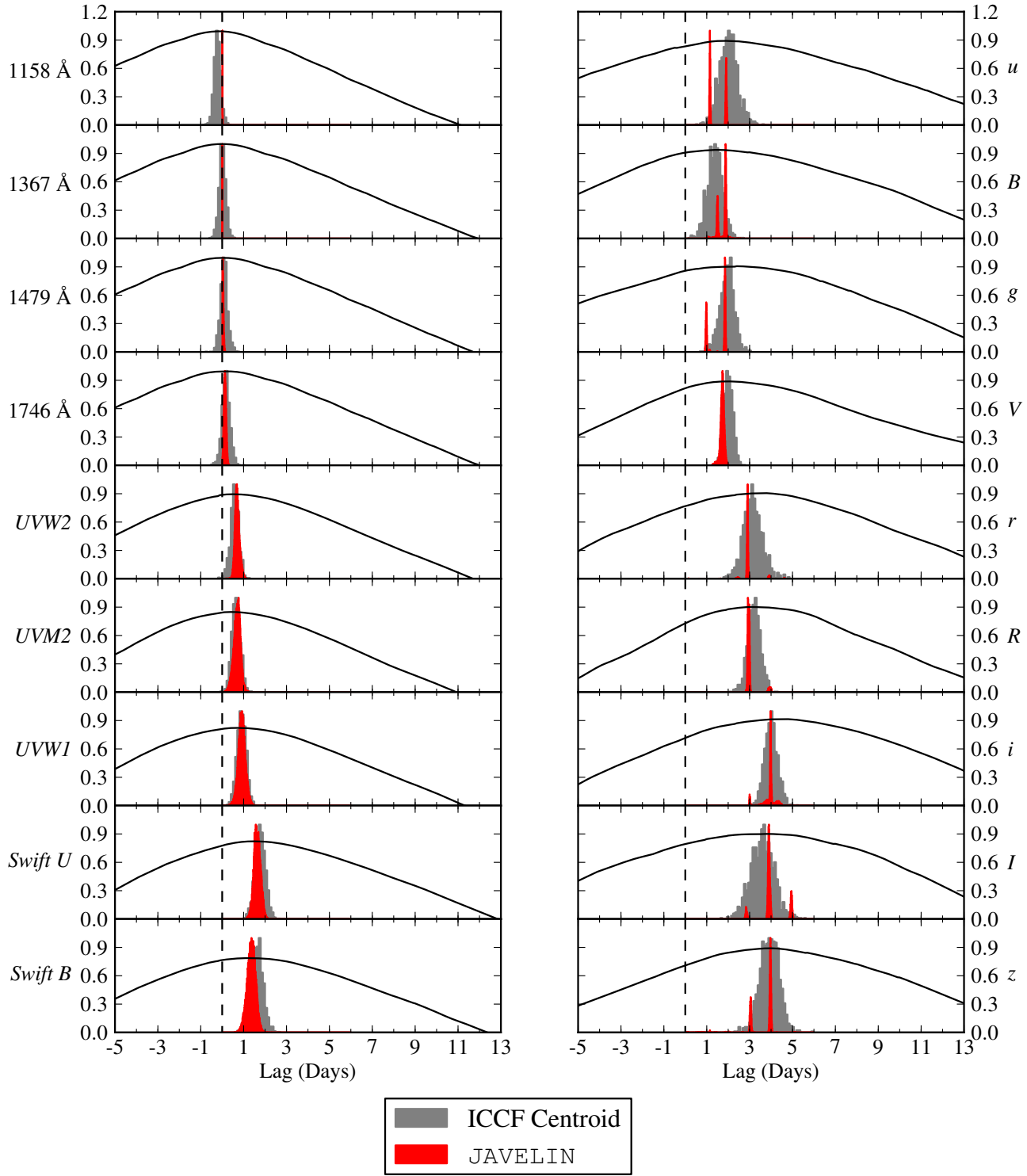
Since we are only concerned with the relative magnitude of various emission components to the broad-band filter fluxes, we employed a minimal spectral decomposition, which is relatively coarse compared to state-of-the-art spectral modeling. Accordingly, we do not interpret any of our model parameters as indicative of physical conditions within the AGN, and instead focus on finding a model that provides a good fit of the data (based on minimizing  $\chi^2$ ). Our decomposition has three components—host galaxy starlight, the underlying AGN continuum, and the Balmer continuum shortwards of  $\sim 3648$  Å (rest frame). We ignore the diffuse continuum at other wavelengths, since it is poorly constrained, while the Balmer continuum can be determined from the shape and amplitude of the small blue bump. Emission line fluxes are then estimated by subtracting the summed model components from the observed spectrum.

We simultaneously fit each component with an MCMC calculation, masking AGN emission lines and telluric absorption. We also masked the long and short edges of the spectra, because the MODS flux calibration is unreliable at  $\lambda < 3200$  Å and  $\lambda > 9100$  Å (rest frame). At these wavelengths, we set the observed flux equal to the summed model, which implicitly sets the emission line flux to zero. This has a small effect on the estimated BLR contamination in the  $u$ ,  $U$ ,  $I$ , and  $z$  bands, but is more robust than using the unreliable flux calibration.

Details of the model components are as follows:

1. **Host Galaxy:** We determined the host galaxy spectrum using the `STARLIGHT` spectral synthesis code (Cid Fernandes et al. 2004). `STARLIGHT` fits the observed spectrum with a linear combination of a large library of synthetic stellar populations that span a wide range of ages and metallicities (150 templates from Bruzual & Charlot 2003). The best-fitting models consist of several very old (usually  $> 10^{10}$  year) stellar populations at a range of metallicities ( $0.4\text{--}2.5 Z_\odot$ ), and provide a reasonable match to the galaxy templates used by Denney et al. (2010) and Mehdipour et al. (2015). The resulting host templates have one parameter, the flux normalization. We also impose a tight prior on the flux at 5100 Å (rest frame), chosen to match the value measured by Bentz et al. (2013) adjusted to the MODS slit width and extraction window,  $(4.52 \pm 0.45) \times 10^{-15} \text{ erg s}^{-1} \text{ cm}^2 \text{ \AA}^{-1}$ .

<sup>67</sup> A full description can be found at <http://www.astronomy.ohio-state.edu/MODS/Manuals/modsIDL.pdf>



**Figure 4.** ICCF for all light curves, with the y-axis showing the correlation coefficient  $r_{cc}$ . Lags for data from Paper I and Paper II (following our reanalysis) are shown in the left column, ground-based optical lags are presented in the right column. The grey histograms are the ICCF centroid distributions from the FR/RSS method, the red histograms are from JAVELIN. Both histograms are in units of relative probability.

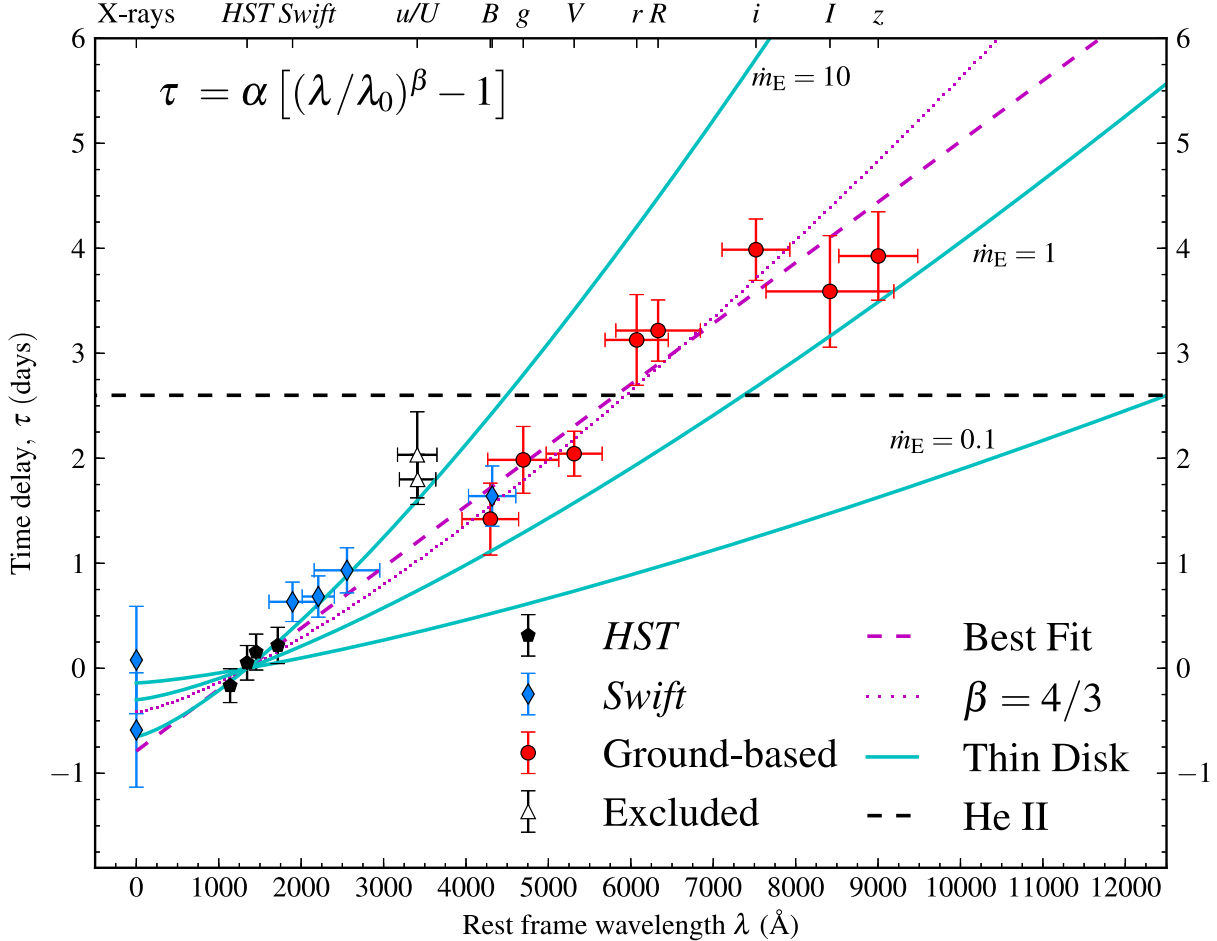
**Table 5**  
Time Delays

Source	Filter	$\lambda_{\text{pivot}}$ (Å)	ICCF $\tau_{\text{cent}}$ (days)	$\tau_{\text{peak}}$ (days)	$r_{\text{max}}$	JAVELIN $\tau_{\text{JAV}}$ (days)
<i>Swift</i>	HX	4.4	$-0.65^{+0.45}_{-0.45}$	$-0.46^{+0.49}_{-0.39}$	$0.35 \pm 0.20$	...
<i>Swift</i>	SX	25.3	$0.08^{+0.51}_{-0.51}$	$0.23^{+0.29}_{-0.39}$	$0.44 \pm 0.07$	...
<i>HST</i>	$\lambda 1158$	1158	$-0.17^{+0.16}_{-0.16}$	$-0.21^{+0.08}_{-0.10}$	$1.07 \pm 2.53$	$-0.12^{+0.04}_{-0.04}$
<i>HST</i>	$\lambda 1479$	1478	$0.15^{+0.18}_{-0.16}$	$0.14^{+0.23}_{-0.06}$	$1.03 \pm 1.08$	$0.03^{+0.03}_{-0.03}$
<i>HST</i>	$\lambda 1746$	1746	$0.22^{+0.16}_{-0.19}$	$0.21^{+0.10}_{-0.10}$	$0.98 \pm 0.01$	$0.13^{+0.06}_{-0.05}$
<i>Swift</i>	<i>UVW2</i>	1928	$0.63^{+0.19}_{-0.18}$	$0.59^{+0.20}_{-0.10}$	$0.92 \pm 0.16$	$0.68^{+0.11}_{-0.09}$
<i>Swift</i>	<i>UVM2</i>	2246	$0.68^{+0.19}_{-0.20}$	$0.59^{+0.20}_{-0.10}$	$0.90 \pm 0.27$	$0.69^{+0.14}_{-0.17}$
<i>Swift</i>	<i>UVW1</i>	2600	$0.93^{+0.20}_{-0.23}$	$0.88^{+0.29}_{-0.20}$	$0.89 \pm 0.01$	$0.90^{+0.16}_{-0.16}$
<i>Swift</i>	<i>U</i>	3467	$1.80^{+0.24}_{-0.24}$	$1.47^{+0.20}_{-0.29}$	$0.88 \pm 0.35$	$1.60^{+0.16}_{-0.15}$
Ground	<i>u</i>	3472	$2.03^{+0.43}_{-0.39}$	$2.04^{+0.29}_{-0.39}$	$0.83 \pm 0.04$	$1.87^{+0.05}_{-0.02}$
Ground	<i>B</i>	4369	$1.42^{+0.36}_{-0.33}$	$1.22^{+0.20}_{-0.29}$	$0.91 \pm 0.02$	$1.48^{+0.05}_{-0.03}$
<i>Swift</i>	<i>B</i>	4392	$1.64^{+0.31}_{-0.27}$	$1.28^{+0.29}_{-0.39}$	$0.82 \pm 0.02$	$1.34^{+0.19}_{-0.21}$
Ground	<i>g</i>	4776	$1.98^{+0.34}_{-0.29}$	$1.64^{+0.29}_{-0.39}$	$0.89 \pm 0.02$	$1.82^{+0.02}_{-0.02}$
Ground	<i>V</i>	5404	$2.04^{+0.22}_{-0.20}$	$1.87^{+0.29}_{-0.10}$	$0.84 \pm 0.02$	$1.70^{+0.08}_{-0.08}$
Ground	<i>r</i>	6176	$3.13^{+0.41}_{-0.46}$	$3.12^{+0.29}_{-0.59}$	$0.85 \pm 0.04$	$2.85^{+0.02}_{-0.03}$
Ground	<i>R</i>	6440	$3.22^{+0.30}_{-0.29}$	$2.88^{+0.39}_{-0.20}$	$0.87 \pm 0.11$	$2.90^{+0.04}_{-0.04}$
Ground	<i>i</i>	7648	$3.99^{+0.29}_{-0.29}$	$3.90^{+0.20}_{-0.29}$	$0.90 \pm 0.02$	$3.91^{+0.06}_{-0.08}$
Ground	<i>I</i>	8561	$3.59^{+0.53}_{-0.54}$	$2.88^{+0.59}_{-0.88}$	$0.86 \pm 0.06$	$3.84^{+0.05}_{-0.04}$
Ground	<i>z</i>	9157	$3.93^{+0.44}_{-0.40}$	$3.71^{+0.88}_{-0.20}$	$0.84 \pm 0.04$	$3.90^{+0.04}_{-0.03}$

**Note.** — Measured relative to the *HST* 1367 Å light curve and corrected to the rest frame. The *Swift* lags are recalculated from Paper II using a second-order polynomial detrending routine, as described in §3.

**Table 6**  
Parameters for lag–wavelength fits

Model	$\alpha$ (days)	$\beta$	$\rho(\alpha, \beta)$	$\chi^2$	$\chi^2/dof$
All	$0.97 \pm 0.24$	$0.90 \pm 0.12$	-0.99	25.94	1.44
	$0.43 \pm 0.02$	4/3		38.66	2.03
No <i>Uu</i>	$0.79 \pm 0.22$	$0.99 \pm 0.14$	-0.99	16.85	1.05
	$0.42 \pm 0.02$	4/3		22.64	1.33
No <i>UuIR</i>	$0.58 \pm 0.20$	$1.18 \pm 0.19$	-0.99	12.4	0.89
	$0.45 \pm 0.02$	4/3		13.0	0.87



**Figure 5.** Time delay (ICCF centroid) as a function of pivot wavelength of the filters. The horizontal error bars represent the rms width of the filters. The best fit model is shown by the dashed magenta line, while the fit fixing  $\beta = 4/3$  is shown by the dotted magenta line. Predictions for a thin-disk model with  $\dot{m}_E = L/L_{\text{Edd}}$  are shown by the solid cyan lines, although the assumptions of the model are unlikely to hold at large  $\dot{m}_E$  (see §5.3). The mean lag of the He II  $\lambda 1640$  and  $\lambda 4686$  lines is shown by the horizontal dashed black line (Paper I, Paper IV).

2. **Power Law:** A broken power-law is used to model the AGN continuum emission. This component has four free parameters—a flux normalization factor, two spectral indices, and the location of the transition between indices. A loose prior (a Gaussian distribution with mean  $5700 \text{ \AA}$  and width  $700 \text{ \AA}$ ) is imposed on the transition wavelength, to prevent it from moving to the edges of the spectra.
3. **Balmer continuum:** The Balmer continuum component is estimated from a grid of models calculated by Dietrich et al. (2002), evaluated at varying temperatures, electron densities, and optical depths. Again, we simply choose the template that produces the overall minimum value of  $\chi^2$ . The templates have a single parameter, a flux rescaling factor.

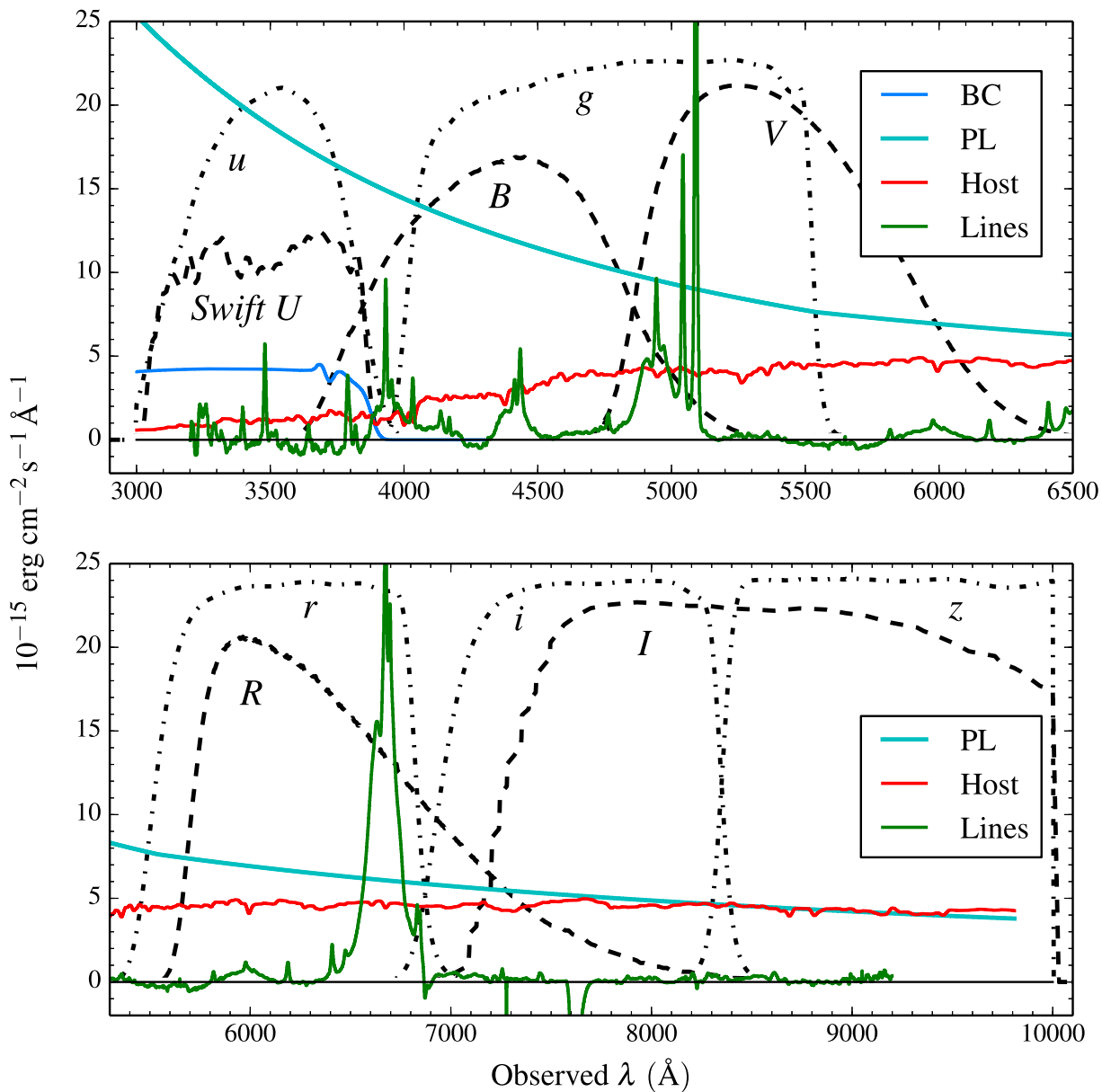
We ignored blended Fe II emission, because Fe emission is relatively weak in NGC 5548 (Denney et al. 2009; Mehdipour et al. 2015) and varies with an amplitude  $<50\text{--}75\%$  that of  $H\beta$  (Vestergaard & Peterson 2005). This component is therefore expected to contribute very little flux to the broad-band photometric measurements and have a negligible impact on the observed lag. In order to assess the effect of this omission, we also fit the spectra with the small blue bump template of Mehdipour et al. (2015), which includes blended Fe II emis-

sion lines. We found that these templates produce a poorer fit than the Dietrich et al. (2002) templates at the blue end of the spectrum, which may be a result of the limited wavelength coverage of our MODS spectra in the near-UV.

Each epoch was fit independently, and the resulting component parameters are in reasonable agreement, after allowing for the intrinsic variability of the power-law and Balmer continuum. The flux rescaling factors of the power-law and galaxy templates are degenerate, so the prior imposed on the host galaxy flux at  $5100 \text{ \AA}$  (rest frame) does the most to constrain these parameters. Figure 6 shows an example of the decomposition, using the spectrum from 2014 June 08, overlaid with the filter transmission curves.

#### 4.2. Synthetic Photometry

Next, we estimate the contribution of each model component to the observed flux in each broad-band filter. We first reapply Galactic reddening to the model components, since differential extinction may affect the integrated flux across broad-band filters. We then calculate the observed flux using the `synphot` IRAF task and filter transmission curves for the calibration telescopes (WC18 *BVRI* filters and LT *ugriz* filters), truncated at  $3000 \text{ \AA}$  and  $1 \mu\text{m}$  to represent the atmospheric transmission cut-off. Uncertainties on the broad band fluxes of individual components were estimated by resampling the posterior dis-



**Figure 6.** Decompositions of the MODS spectra from 2014 June 08, showing the contribution of the model components to different filters. “BC” is the Balmer continuum, “PL” is the power law, “Host” is the host galaxy component, and “Lines” are the AGN emission lines. The emission lines are estimated by subtracting the total model from the observed spectrum. Johnson/Cousin optical filter transmission curves (and *Swift U*) are shown by the dashed black lines, SDSS filters are shown by the dot-dashed lines. The *Swift U* and *u* bands are truncated at 3000 Å and the *I* and *z* bands are truncated at 1  $\mu\text{m}$ , in order to represent the atmospheric transmission cut-off.

tributions of the model component parameters and rerunning *synphot*  $10^3$  times.

Table 7 shows the results of our synthetic photometry. The “Total” column was calculated from the original spectrum, and the fractional contributions of individual components are reported relative to this value. The uncertainties represent the central 68% confidence interval of the resampled synthetic photometry distributions. The uncertainties are generally less than 1% because of the tight prior on the 5100 Å host galaxy flux, which forces the galaxy template to be nearly constant and limits the variation of the other model components.

We do not consider effects of changing detector sensitivity

with wavelength, since quantum efficiency curves for different instruments are usually much more variable than their filter transmission curves. Quantum efficiency will have the largest impact on the *I* and *z* filters, limiting the response of these filters at wavelength shorter than the cut-off imposed at 1  $\mu\text{m}$ . We investigated this effect by truncating the filter response at 9000 Å and repeating the experiment (essentially simulating a very steep quantum efficiency curve). We found that the final fractional contributions of the host/power law components in these bands changes by 1% or less, and is therefore of minimal importance for our conclusions.

We find that the power-law is the dominant component from

the  $u$  band through the  $V$  band ( $> 50\%$  of the flux), although the host galaxy makes considerable contributions even in the  $B$  band ( $\sim 20\%$ ). At longer wavelengths, the power-law component and host galaxy contribute roughly equal amounts of flux, except for the  $r$  and  $R$  bands, which include a substantial contribution from the  $H\alpha$  line: 20% in the  $r$  band and 15% in the  $R$  band. Line emission in all other filters is  $\leq 10\%$ . Balmer continuum emission accounts for about 19% of the flux in the  $u$  and  $U$  filters. The Mehdipour et al. (2015) blended Fe templates contribute  $< 1\%$  of the observed flux in the  $g$ ,  $V$ , and  $r$  bands, confirming that Fe emission is a negligible component of the broad-band fluxes of this object.

#### 4.3. Impact on Time Delays

The final step is to estimate the impact of BLR emission on the recovered inter-band time delays. First, we simulate light curves for the AGN continuum, Balmer continuum, and BLR emission models. We then sum the component light curves to reproduce light curves as would be observed in a given filter, and calculate the lag between the composite light curve and the  $HST$  1367 Å continuum light curve.

The observed light curve is a superposition of the continuum emission and BLR emission,

$$X_{\text{obs}}(t) = c(t) + l(t) \quad (5)$$

where  $X_{\text{obs}}$  is the observed light curve in filter  $X$ ,  $c(t)$  is the continuum light curve in that filter, and  $l(t)$  is the line light curve, assumed to originate in the BLR. We use the term “line light curve” to refer to any emission produced in the BLR, including the Balmer continuum.

To simulate  $c(t)$ , we calculated the lag  $\tau_{\text{cont}}$  implied by the best-fit parameters in Figure 5 ( $\alpha = 0.79 \pm 0.22$  and  $\beta = 0.99 \pm 0.14$  in Equation 4) at the pivot wavelength of the filter, and shifted the JAVELIN DRW model of the  $HST$  1367 Å light curve by this amount. This method assumes that the  $HST$  1367 Å light curve drives  $c(t)$  through instantaneous reprocessing after some light-travel time delay, as would be expected for X-ray reprocessing in the accretion disk.<sup>68</sup>

In RM, the line emission is assumed to be powered by ionizing continuum emission, so that

$$l(t) = \int \Psi(\tau) C(t - \tau) d\tau \quad (6)$$

where  $C(t)$  is the driving continuum light curve, and  $\Psi(\tau)$  is the transfer function. For simplicity, we assume  $C(t)$  equal to the JAVELIN model of the  $HST$  1367 Å light curve and a top-hat transfer function

$$\Psi(\tau) = \frac{1}{w} \text{ for } (\bar{\tau} - w/2) < \tau < (\bar{\tau} + w/2), \quad (7)$$

where  $\bar{\tau}$  is the mean line lag and  $w$  is the width of the smoothing kernel. The choice of a top-hat function is for mathematical convenience, and does not reflect any particular geometry, although it is widely consistent with a range of BLR configurations (for example, a spherical shell or the gross properties of an inclined disk/annulus, Peterson 2001). We varied  $\bar{\tau}$  and  $w$  by octaves, with  $\bar{\tau} = 2, 4, 8,$  and  $16$  days, and  $w = 0, 2, 4, 8,$  and  $16$  days. These values were chosen to sample the parameter space near the mean  $H\beta$  lag during the monitoring

<sup>68</sup> Reprocessed emission is also expected to be somewhat smoothed in time compared to the driving light curve. We therefore also considered versions of  $c(t)$  which are both smoothed and shifted by convolving the JAVELIN 1367 Å model with a top-hat function of amplitude  $1/(2\tau_{\text{cont}})$  for  $0 < \tau < 2\tau_{\text{cont}}$ . We found that this smoothing made very little difference on the results, and so we only discuss the results for the shifted versions of  $c(t)$  here.

campaign ( $8.57 \pm 0.67$  days, Paper IV). To a low approximation, the Balmer continuum and  $H\alpha$  lag would be expected to lie near this value. Finally, we enforced causality by setting  $\Psi(\tau) = 0$  for  $\tau < 0$ .

We simulate light curves for the  $u$ ,  $U$ ,  $r$ , and  $R$  bands, in order to investigate the impact of Balmer continuum and  $H\alpha$  emission on the recovered lags. After generating the grid of shifted and smoothed line light curves, we renormalized each so as to reproduce the level of BLR contamination inferred from the spectral decomposition (Table 7). We then adjusted the fractional variability amplitude  $F_{\text{var}}$  (defined in §2.4) of both the continuum and line light curves to match their observed values. For the continuum light curves,  $F_{\text{var,cont}}$  is estimated directly from the observed broad-band light curves (Table 4, Column 9). For the line light curve, we set  $F_{\text{var,line}} = 4.6\%$ , derived from the observed  $H\beta$  light curve (Paper IV). We also experimented with changing the fractional variability amplitude of the line light curve to  $F_{\text{var,line}} = 0.012, 0.023, 0.092, 0.184$ . Examples of two composite light curves and their model components,  $c(t)$  and  $l(t)$ , are shown in Figure 7.

After constructing  $c(t)$  and  $l(t)$  for each model, we calculated the lags of these light curves relative to  $C(t)$  using the ICCF method described in section §3. In all cases, we recovered the input values of  $\bar{\tau}$  and  $\tau_{\text{cont}}$  to within the time resolution of the model light curves (0.12 days). We then calculated the ICCF for the composite light curve  $c(t) + l(t)$ , and found that the recovered lags are most sensitive to the choice of  $F_{\text{var,line}}$  and  $\bar{\tau}$ , but are virtually independent of  $w$ . The resulting mean lags are shown in Figure 8 as a function of input  $\bar{\tau}$  for the three values of  $F_{\text{var,line}}$  near that of  $H\beta$  (larger or smaller values of  $F_{\text{var,line}}$  do not plausibly reproduce the observed lags, and are omitted for clarity). Larger values of these parameters tend to increase the recovered lag, but, at the fiducial values of  $H\beta$  the change is 0.6–1.2 days (blue point in Figure 8 with  $\bar{\tau} = 8$ ).

We also checked for an effect of BLR contamination on the lag uncertainties. For each model, we found that larger values of  $F_{\text{var,line}}$  and  $\bar{\tau}$  tend to increase the width of the ICCF. However, there was no correlation between these parameters and the location or width of the ICCF centroid distribution. This means that the lag uncertainties depend more sensitively on the lightcurve quality rather than any BLR contamination.

For values of  $F_{\text{var,line}}$  that are smaller than  $F_{\text{var,cont}}$  ( $F_{\text{var,line}} \leq 0.023$  in  $r$  and  $R$  and  $\leq 0.092$  in  $u$  and  $U$ ), the input line lag only has a limited effect on the recovered lag, evidenced by the flattening of the trends in Figure 8. This result is in contrast to the simple expectation that the observed lag is the flux-weighted mean lag of the line and continuum light curves, which scales linearly with the line lag. Instead, it appears that the observed lag only follows the line lag if the BLR emission dominates the variability properties of the composite light curve, as seen for the the mock  $r$  and  $R$  bands at large  $F_{\text{var,line}}$ . This indicates that the bias of the continuum lag introduced by BLR emission will usually be limited for broad-band filter lightcurves that are dominated by continuum emission, although the bias may still be important for small continuum lags.

Our simulations with these fiducial  $H\beta$  parameters produce  $u$  and  $U$  band lags in excellent agreement with the observed lags, while the simulated  $r$  and  $R$  band lags overestimate the observed lag by about 1 day. Our current campaign cannot directly address the issue of the unknown values of  $F_{\text{var,line}}$  and  $\bar{\tau}$  for these reverberations. However, it is expected from photoionization modeling that the Balmer continuum has a larger response ( $F_{\text{var,line}}$ ) but shorter lag than  $H\beta$ , while  $H\alpha$  should have a smaller response but longer lag (Korista & Goad 2001, 2004). Based on Figure 8, this would serve to reduce the discrepancy between the recovered and observed lag in the  $r$  and



**Table 7**  
Flux percentage contribution by spectral component.

Filter	Total ( $10^{-11}$ erg cm $^{-2}$ s $^{-1}$ )	PL (%)	BC (%)	Host (%)	Lines (%)
2014 June 08					
<i>U</i>	8.42	76.8 ± 1.5	16.7 ± 0.5	4.9 ± 0.1	2.3 ± 1.6
<i>u</i>	8.43	76.6 ± 1.5	16.7 ± 0.5	4.8 ± 0.1	2.7 ± 1.6
<i>B</i>	7.23	72.6 ± 0.9	1.4 ± 0.0	18.2 ± 0.5	7.6 ± 1.0
<i>g</i>	7.40	65.6 ± 0.6	...	24.3 ± 0.7	10.0 ± 0.8
<i>V</i>	7.39	59.0 ± 0.5	...	32.1 ± 0.9	9.1 ± 1.0
<i>r</i>	8.91	47.1 ± 0.4	...	33.4 ± 0.9	19.6 ± 1.0
<i>R</i>	8.44	48.9 ± 0.5	...	36.4 ± 1.0	14.8 ± 1.1
<i>i</i>	7.45	53.5 ± 0.7	...	48.5 ± 1.3	...
<i>I</i>	5.77	50.9 ± 0.7	...	50.3 ± 1.2	0.0 ± 0.1
<i>z</i>	4.60	49.5 ± 0.6	...	50.7 ± 1.0	0.0 ± 0.6
2014 June 25					
<i>U</i>	8.28	72.3 ± 1.5	21.4 ± 0.5	5.1 ± 0.1	1.0 ± 1.6
<i>u</i>	8.29	72.2 ± 1.5	21.4 ± 0.5	5.1 ± 0.1	0.6 ± 1.4
<i>B</i>	7.02	69.7 ± 1.0	1.8 ± 0.0	19.9 ± 0.2	8.5 ± 0.9
<i>g</i>	7.21	62.9 ± 0.7	...	26.6 ± 0.3	10.3 ± 0.9
<i>V</i>	7.29	55.9 ± 0.6	...	34.9 ± 0.4	9.0 ± 0.8
<i>r</i>	8.93	44.3 ± 0.4	...	35.8 ± 0.4	19.9 ± 0.7
<i>R</i>	8.47	46.0 ± 0.5	...	39.0 ± 0.4	15.0 ± 0.7
<i>i</i>	7.53	50.3 ± 0.6	...	51.9 ± 0.5	...
<i>I</i>	5.91	47.8 ± 0.5	...	53.7 ± 0.6	...
<i>z</i>	4.73	46.4 ± 0.5	...	54.0 ± 0.5	...
2014 June 08 (Blended Fe)					
<i>U</i>	8.49	82.6 ± 0.9	11.2 ± 0.5	5.3 ± 0.1	0.8 ± 1.1
<i>u</i>	8.49	82.4 ± 0.9	11.7 ± 0.5	5.3 ± 0.1	0.9 ± 1.1
<i>B</i>	7.23	73.5 ± 0.8	0.9 ± 0.0	20.0 ± 0.3	5.8 ± 1.0
<i>g</i>	7.40	64.5 ± 0.6	0.4 ± 0.0	26.7 ± 0.3	8.4 ± 0.8
<i>V</i>	7.38	55.9 ± 0.5	0.3 ± 0.0	35.3 ± 0.5	8.5 ± 0.7
<i>r</i>	8.90	44.2 ± 0.6	0.1 ± 0.0	36.6 ± 0.5	19.2 ± 0.6
<i>R</i>	8.43	45.7 ± 0.6	...	40.0 ± 0.5	14.4 ± 0.7
<i>i</i>	7.44	49.3 ± 0.9	...	53.3 ± 0.7	...
<i>I</i>	5.77	46.7 ± 0.9	...	55.0 ± 0.7	...
<i>z</i>	4.59	45.1 ± 0.9	...	55.4 ± 0.7	...
2014 June 25 (Blended Fe)					
<i>U</i>	8.41	82.8 ± 0.7	11.4 ± 0.4	5.8 ± 0.1	...
<i>u</i>	8.39	82.8 ± 0.7	12.0 ± 0.5	5.7 ± 0.1	...
<i>B</i>	7.02	70.7 ± 0.9	0.9 ± 0.0	22.8 ± 0.5	5.7 ± 1.2
<i>g</i>	7.21	60.7 ± 0.8	0.4 ± 0.0	30.5 ± 0.7	8.5 ± 1.3
<i>V</i>	7.27	50.4 ± 0.8	0.3 ± 0.0	40.1 ± 0.9	9.4 ± 1.2
<i>r</i>	8.88	38.4 ± 0.7	0.1 ± 0.0	41.3 ± 0.9	20.4 ± 1.1
<i>R</i>	8.40	39.6 ± 0.8	...	45.2 ± 1.0	15.5 ± 1.2
<i>i</i>	7.46	41.9 ± 0.8	...	60.3 ± 1.3	...
<i>I</i>	5.82	38.9 ± 0.9	...	62.5 ± 1.1	...
<i>z</i>	4.65	37.2 ± 0.9	...	63.2 ± 0.9	0.0 ± 0.1

**Note.** — PL is power law, BC is Balmer continuum, Host is the host galaxy, Lines are AGN emission lines.

*R* bands, while the recovered and observed lag in the *u* and *U* bands would remain in good agreement.

Thus, our simulations suggest that contamination by BLR emission can reasonably account for the systematic offset of the measured *u*, *U*, *r*, and *R* lags above the fit in Figure 5. This bias is well resolved in the *u* and *U* bands (the offset from the fit in Figure 5 is  $2.0\sigma$  and  $2.5\sigma$ , respectively), but of small importance in the *r* and *R* bands ( $0.6\sigma$  and  $1.7\sigma$  respectively). This result justifies our exclusion of the *u* and *U* band data in the fit to Equation 4.

## 5. DISCUSSION

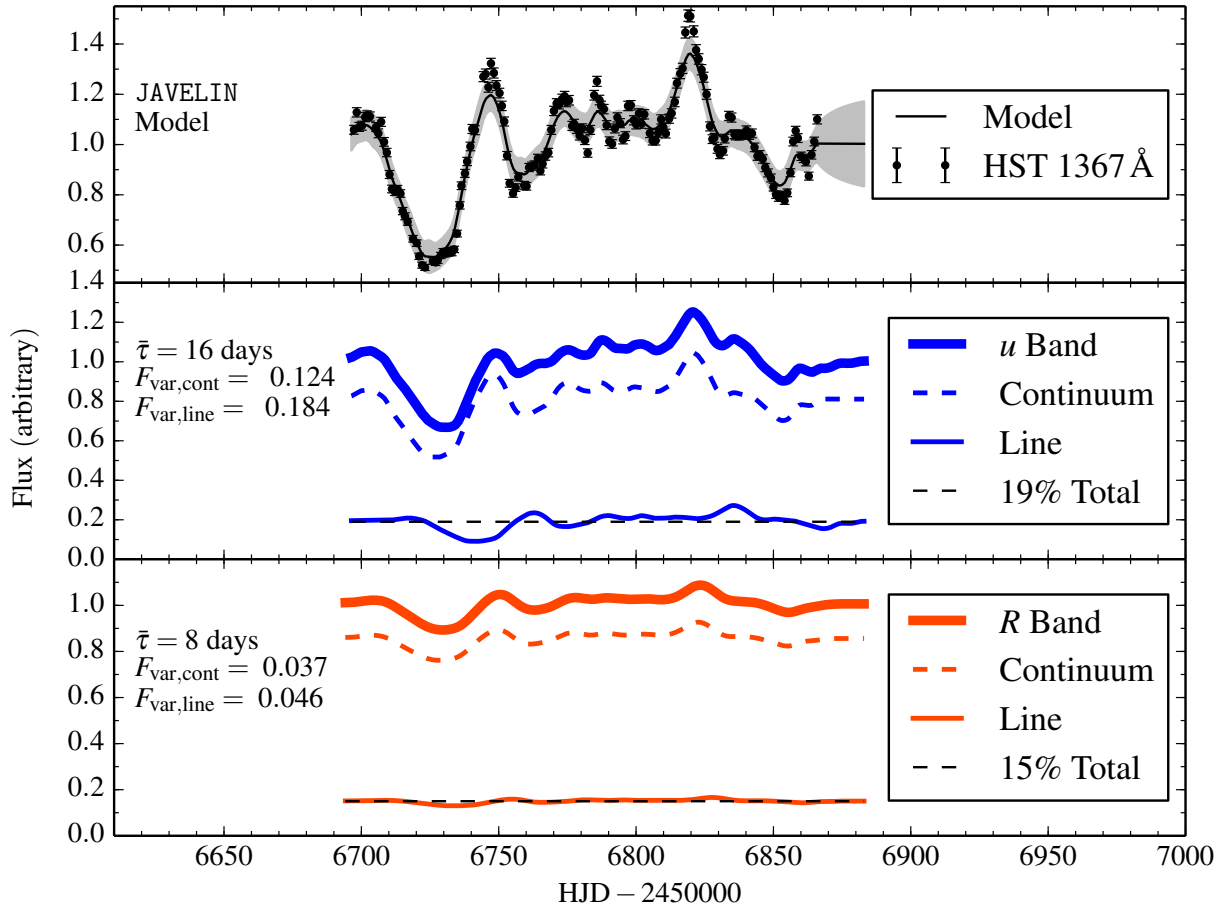
### 5.1. UV/Optical Light Curves and Lags

A primary goal of the AGN STORM project was to investigate how the continuum emission changes as a function of wavelength, and assess any systematic issues introduced by using the optical continuum in place of the far or extreme UV. Figure 2 shows a detailed comparison of the *HST* 1367 Å light curve and all other data used in this study. We draw particular attention to the ground-based *V* band light curve, since this

is the most common choice of ionizing continuum proxy in ground-based RM studies. All of the major events and salient characteristics of the 1367 Å light curve are reproduced in the *V* band. There are, however, several noticeable differences.

#### 5.1.1. UV–Optical lags

The first difference is a time delay between variations in the UV and optical light curves. Emission at 1158 Å, the shortest continuum wavelength available in this study, probably originates from a region of the accretion disk similar to that of the true ionizing continuum at  $\lambda \leq 912$  Å. This is because the lag-wavelength relation must flatten at small wavelengths (due to the inner edge of the disk), but the inner edge already makes an important contribution to emission at  $\sim 1000$  Å (Novikov & Thorne 1973). Extrapolating the fit from Equation 4 to  $\lambda = 912$  Å implies a 0.26 day lag relative to the 1367 Å light curve, which is in reasonable agreement with the 1367 Å–1148 Å lag ( $-0.16 \pm 0.16$  days). We therefore adopt a value of 0.2 days for the lag between the true ionizing continuum and



**Figure 7.** Examples of mock light curves,  $c(t)$ ,  $l(t)$ , and  $X_{obs} = c(t) + l(t)$ , used for the analysis in §4.3. The top panel shows the *HST* 1367 Å light curve and the JAVELIN model used to generate the mock light curves, with the  $1\sigma$  uncertainty shown by the grey band. The middle panel shows an example of a mock *u* band light curve, with a large line lag and high fractional variability, likely to result in the largest change of the observed lag. The bottom panel shows an examples of a mock *R* band light curve, with a more realistic line lag and fractional variability, chosen to be consistent with the  $H\beta$  light curve. See §4.3 for further details.

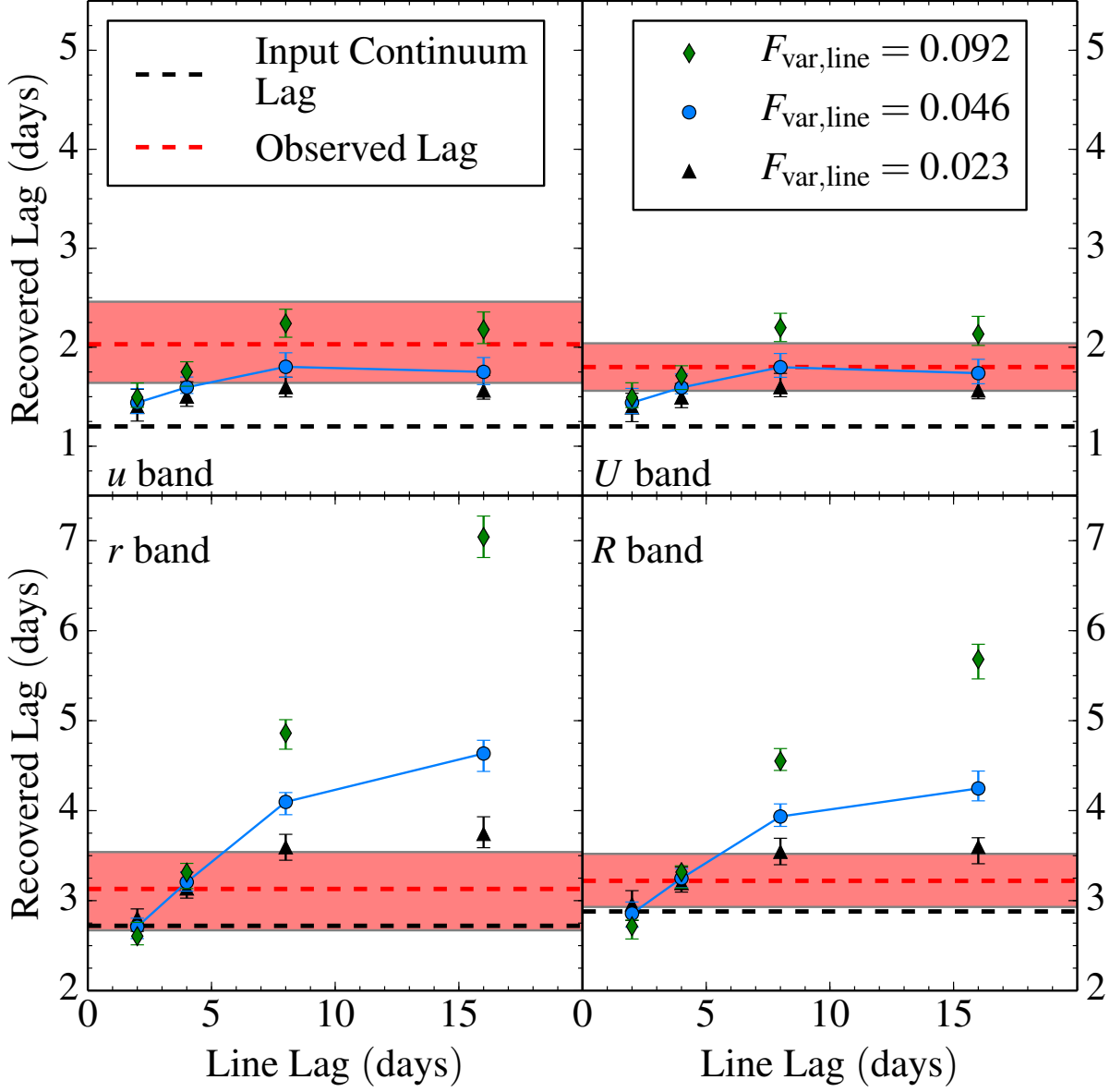
the 1367 Å emission, since the lag for wavelengths  $< 912$  Å are unlikely to be much larger. This translates to a distance between the true ionizing continuum and the optically-emitting portion of the disk of  $\sim 2.2$  light days. A consequence of this UV-optical lag is that the radius of the BLR in NGC 5548 is underestimated when derived from the optical- $H\beta$  lag. The optical- $H\beta$  lag is variable in time, but typically has a value between 6 and 20 days (Peterson et al. 2004; Zu et al. 2011). Thus, if a similar UV-optical lag exists in other AGN, the physical size of the BLR is being systematically underestimated by up to  $\sim 37\%$  (or 11% for a lag of 20 days).

This result does not affect current optical RM SMBH masses, because RM only directly measures the virial product of the BLR,  $c\tau(\Delta V)^2/G$ , where  $\tau$  is the BLR lag and  $\Delta V^2$  is its velocity dispersion (estimated from line profile widths). Since the geometry and dynamics of the BLR are unknown, the virial product must be rescaled by a factor  $f$  in order to produce a SMBH mass. While every AGN has a different value of  $f$ , a statistical average  $\langle f \rangle$  can be calculated by calibrating an ensemble of virial products to some other SMBH mass estimate. Currently, this is done using the  $M - \sigma$  relation of local quiescent galaxies (Onken et al. 2004; Woo et al. 2010, 2013, 2015; Park et al. 2012a,b; Grier et al. 2013a). Thus, any systematic misestimation or bias of the lag (or velocity dispersion) is compensated by the calibration of  $\langle f \rangle$ , while uncertainty of

a single RM SMBH mass is dominated by the statistical uncertainty on  $\langle f \rangle$ , presently about 25–33% (Grier et al. 2013a; Woo et al. 2015). However, any physical interpretation of  $\langle f \rangle$  (for example, a measure of the mean inclination of the BLR, assuming a disk or otherwise flattened geometry) requires a recalibrated value of  $\langle f \rangle$  that takes into account the UV-optical lag.

Single-epoch SMBH mass estimates are also unaffected by this result, since the radius-luminosity (RL) relation is inferred from a sample of RM AGN. While the larger BLR radius measured from the UV data would increase the normalization of the RL relation, a recalibration of  $\langle f \rangle$  exactly cancels this change. The UV-optical lag may introduce a second order effect on single epoch SMBH masses, if it is found that the magnitude of the UV-optical lag correlates with continuum luminosity or SMBH mass. Furthermore, the magnitude of the lag depends on accretion rate (see §5.3), which may also add scatter to existing mass-scaling relations. To investigate these effects, more simultaneous UV and optical RM experiments must be executed, using a sample of AGN with a wide range of luminosities.

Finally, the UV-optical lag has an impact on masses derived from direct dynamical modeling of RM data, since this method interprets the continuum-line lag as a measure of the physical radius of the BLR. To a low approximation, a larger BLR ra-



**Figure 8.** Recovered lags of mock light curves as a function of input line light curve  $l(t)$  lag. The colored points show the results for different variability amplitudes of the line light curve. The solid blue lines indicate the variability amplitude observed in the  $H\beta$  light curve. The black dashed line represents the input lag of the continuum light curve  $c(t)$ , while the red dashed line is the observed lag and the red band is its  $1\sigma$  uncertainty. See §4.3 for further details.

dius implies a proportionally larger SMBH mass. The effect of using UV continuum lightcurves for dynamical modeling studies will be investigated in future papers in this series, but until such modeling is complete, we adopt a RM-based SMBH mass for NGC 5548, since this estimate is less model-dependent. From the  $H\beta$  virial products compiled by Bentz & Katz (2015), and taking  $\langle f \rangle = 4.3 \pm 1.1$  (Grier et al. 2013b), we adopt a mass of  $(5.2 \pm 1.3) \times 10^7 M_{\odot}$  for the SMBH in NGC 5548. We note that this value moves in the correct direction for a larger BLR, but is still consistent within the quoted uncertainties of the dynamically modeled mass in Pancoast et al. (2014).

### 5.1.2. Optical Smoothing

The second difference between the UV and optical continuum light curves is that the  $V$  band light curve appears to be smoother than the  $HST$  light curve. For example, the rapid oscillations in the UV light curve between HJD = 2,456,760 and 2,456,810, also appear in the  $V$  band light curve, but at a much smaller amplitude with gentler inflections. The smoothing becomes increasingly severe at longer wavelengths where the amplitude of short-timescale variations decreases (see §2.4). These effects were also seen in NGC 2617 by Shappee et al. (2014), NGC 6814 by Troyer et al. (2015), and MCG-6-30-15 by Lira et al. (2015). Increased smoothing and decreased amplitudes are expected if shorter-wavelength emission drives the optical continuum, since the size, structure, and inclination of the accretion disk define a “continuum transfer function” that

smooths the reprocessed light curve, while geometric dilution decreases the energy flux incident on large disk radii that contribute most to longer wavelength emission.

In practical terms, the sharpest and strongest features in the  $V$  band AGN STORM light curve are only slightly affected by this smoothing. Since these features provide the most leverage for constraining the CCF (Peterson 1993), we conclude that the smoothing of the optical continuum is not important for ground-based RM studies that aim only to recover a mean emission line lag and a SMBH mass. The smoothing may be more problematic for reconstructing velocity-delay maps, direct dynamical modeling, or regularized linear inversion (Horne et al. 1991, 2004; Bentz et al. 2010b; Grier et al. 2013b; Pancoast et al. 2014; Skielboe et al. 2015). These methods are very sensitive to the fine structure of the driving continuum light curve, and smoothing the light curve will erase information that would otherwise be helpful for reconstruction of the geometry and dynamics of the BLR. Velocity-delay maps, dynamical modeling, and regularized linear inversion for this data set will be presented in upcoming papers in this series.

### 5.1.3. Magnitude of UV-Optical lags

The large lags measured for optical bands, shown in Figure 5, are comparable to, and sometimes larger than, the lags for high ionization state lines such as He II  $\lambda 1640$  and C IV  $\lambda 1549$  (Paper I). If the lags do in fact represent light-travel times across the accretion disk, then the optically-emitting portion of the accretion disk appears to have a similar physical extent as the highly ionized portion of the BLR. This situation implies a close connection between the BLR and continuum emitting source. For example, BLR clouds may be directly above or interior to the portion of the accretion disk emitting in the optical. Another plausible hypothesis is that at least part of the inner, high-ionization BLR emission arises from a wind launched from the surface of the accretion disk (e.g., ?Chiang & Murray 1996; Proga & Kurosawa 2010). Such models are able to reasonably explain many observed features of AGN emission lines, including their profiles, variability, and absorption characteristics (see Proga & Kallman 2004; Eracleous et al. 2009; Denney 2012; Higginbottom et al. 2014, and references therein). Alternatively, the accretion disk may smoothly merge with the BLR somewhere near 2–3 light days (for an analysis of this family of models, see, e.g., Goad et al. 2012). Future papers in this series will attempt to map the geometry and kinematics of the inner BLR using the reverberation signal of high-ionization state lines, which may shed further light on the connection between the accretion disk and BLR.

### 5.2. BLR emission and broad-band filter lags

Based on our spectral decomposition, approximately 19% of the observed emission in the  $u$  and  $U$  bands is due to Balmer continuum emission from the BLR, while 15–20% of  $r$  and  $R$  band emission is due to the prominent  $H\alpha$  line. These ratios may change in time, as shown in Table 7, depending on the luminosity state of the AGN, the difference in phase between the continuum and line light curves, and the light curves’ variability amplitudes. For mean flux levels near the BLR contamination in the  $u$ ,  $U$ ,  $r$ , and  $R$  bands, as well as variability amplitudes and line lags that match the observed  $H\beta$  light curve, our experiments with mock light curves indicate biases in the inter-band continuum lag of  $\sim 0.6$ – $1.2$  days.

These results depend on the assumption that all BLR emission light curves have properties similar to the  $H\beta$  light curve. It is likely that the diffuse continuum actually has a stronger response but smaller lag than  $H\beta$ , while  $H\alpha$  is expected to have a weaker response but larger lag (Korista & Goad 2001, 2004;

Bentz et al. 2010a). Since these parameters have off-setting effects, it is unlikely that the lag biases due to BLR contamination are larger than the fiducial estimates presented here (see Figure 8). Future RM programs can test this result by specifically targeting the diffuse continuum and  $H\alpha$  emission, putting stronger constraints on their variability amplitudes and mean lags.

The systematic tendency for the  $u$ ,  $U$ ,  $r$ , and  $R$  band lags to sit above the fit in Figure 5 can therefore reasonably be explained by BLR contamination. In the case of the  $u$  and  $U$  bands, the offset from the fit to Equation 4 is large compared to the predicted lag (as well as the observational uncertainty), which supports our decision to exclude these data from the final model. On the other hand, the  $r$  and  $R$  band offsets are much smaller, so the BLR bias probably makes little difference for our final model. Extending this reasoning to the  $B$ ,  $g$ , and  $V$  band filters, the BLR contamination is less than 10%, which would result in even smaller biases.

It is therefore unlikely that there are any important biases of the continuum lags in these bands, unless the diffuse continuum component (e.g., free-free emission or the Paschen continuum) makes a substantial contribution. This diffuse continuum component of the spectrum is unconstrained in our spectral decomposition, but provides an intriguing possibility of explaining the down turn of the lag-wavelength relation at the  $I$  and  $z$  bands. The Paschen continuum begins at  $8204 \text{ \AA}$ , between the  $i$  and  $I$  bands, so the true continuum lag-wavelength relation may run through the UV and  $I_z$  band lags, but underneath the lags of the other optical filters. The viability of this explanation requires significant contamination of the optical filters by diffuse BLR emission, which can potentially be estimated through photo-ionization modeling of the *HST* data or additional optical/near IR observations.

### 5.3. Accretion Disk Size

A geometrically thin, optically thick, irradiated accretion disk makes definite predictions about the observed lag-wavelength structure of the AGN. Here, we compare this model to the observed continuum lags, although we do not necessarily interpret the model parameters as indicative of physical conditions within the AGN. Full physical modeling of the AGN STORM data is deferred to future papers in this series (Starkey et al. in prep; Kochanek et al. in prep).

The disk is assumed to have a fixed aspect ratio with scale height much smaller than radius, and is heated internally by viscous dissipation and externally by a UV/X-ray source near the SMBH at a small height  $H$  above the disk. In such a scenario, the temperature profile is

$$T(R) = \left( \frac{3GM\dot{M}}{8\pi\sigma R^3} + \frac{(1-A)L_X H}{4\pi\sigma R^3} \right)^{1/4} \quad (8)$$

where  $M$  is the mass of the central SMBH,  $\dot{M}$  is the mass accretion rate of the disk,  $R$  is the distance away from the black hole and central source of heating radiation,  $L_X$  is the luminosity of the heating radiation, and  $A$  is the albedo of the disk (Cackett et al. 2007). Here, we have ignored the inclination and the inner edge of the disk, as well as any relativistic effects. Inclination and relativity may have a small impact on the temperature profile, but the largest effect is due to the inner edge, which reaches a maximum temperature and probably makes important contributions to emission at wavelengths  $< 2000 \text{ \AA}$  (Novikov & Thorne 1973). This introduces an error when comparing the *HST* lags to this model, although the effect is small relative to the UV–optical lags.

Identifying the temperature with a characteristic emission

wavelength  $T = Xhc/k\lambda$ , where  $X$  is a multiplicative factor of order unity, and the radius with the light-travel time  $R = c\tau$ , we have

$$c\tau = \left(X \frac{k\lambda}{hc}\right)^{4/3} \left(\frac{3GM\dot{M}}{8\pi\sigma} + \frac{(1-A)L_X H}{4\pi\sigma}\right)^{1/3}. \quad (9)$$

The factor  $X$  accounts for systematic issues in the conversion of  $T$  to  $\lambda$  for a given  $R$ , since a range of radii contributes to emission at  $\lambda$ . From the flux-weighted mean radius

$$\langle R \rangle = \frac{\int_{R_0}^{\infty} B(T(R))R^2 dR}{\int_{R_0}^{\infty} B(T(R))R dR} \quad (10)$$

we derive  $X = 2.49$ , where  $R_0$  is the inner edge of the disk,  $B(T(R))$  is the Planck function, and  $T(R)$  is the temperature profile defined in Equation 8.<sup>69</sup>

If we measure  $\tau$  relative to a reference time delay  $\tau_0$  of a light curve with effective wavelength  $\lambda_0$ , then this becomes

$$c(\tau - \tau_0) = \left(X \frac{k\lambda_0}{hc}\right)^{4/3} \left(\frac{3GM\dot{M}}{8\pi\sigma} + \frac{(1-A)L_X H}{4\pi\sigma}\right)^{1/3} \left[\left(\frac{\lambda}{\lambda_0}\right)^{4/3} - 1\right]. \quad (11)$$

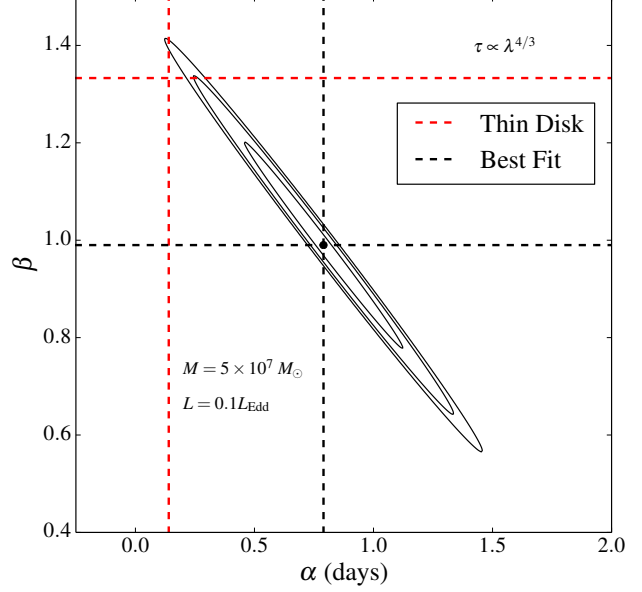
Therefore, the parameter  $\alpha$  in Equation 4 is related to the energy generation rate responsible for heating the disk, while  $\beta$  is predicted to be  $4/3$ . The absolute size of the disk at  $\lambda_0$  can be measured by determining  $\tau_0$ , which is inferred by assuming the corona is located at  $\tau = 0$  and fitting the X-rays lags (in which case  $\tau_0 = \alpha$ ).

We can only estimate  $\dot{M}$  indirectly through an estimate of the bolometric luminosity. We set  $L_{\text{Bol}} = \eta\dot{M}c^2$ , where  $\eta$  is the radiative efficiency for converting rest mass into radiation, and  $L_{\text{Bol}}$  quantifies all emergent radiation from the AGN, including coronal X-rays (in this sense, our model differs from the typical Shakura & Sunyaev 1973 thin-disk model). A convenient parameterization of  $L_{\text{Bol}}$  is the Eddington ratio,  $\dot{m}_E = L_{\text{Bol}}/L_{\text{Edd}}$ . We also simplify Equation 11 by taking  $(1-A)L_X H/R = \kappa GMM/2R$ , where  $\kappa$  is the local ratio of external to internal heating, assumed to be constant with radius.

The equation for  $\alpha$  is then

$$\alpha = \left(X \frac{k\lambda_0}{hc}\right)^{4/3} \left[\left(\frac{GM}{8\pi\sigma}\right) \left(\frac{L_{\text{Edd}}}{\eta c^2}\right) (3+\kappa)\dot{m}_E\right]^{1/3} \quad (12)$$

A common choice for  $\dot{m}_E$  is 0.1, and we further assume that  $\eta = 0.1$  and  $\kappa = 1$  for our fiducial calculations (i.e., the X-rays and viscous heating contribute equal amounts of energy to the disk). For a  $5.2 \times 10^7 M_{\odot}$  SMBH, these assumptions give  $\alpha = 0.14$  days. If we increase the accretion rate by setting  $\dot{m}_E = 1, 10$  then  $\alpha = 0.30, 0.65$  days, respectively. The lag-wavelength relation for these models is shown in Figure 5, and the curves for  $\dot{m}_E = 1-10$  bracket our fit to Equation 4 with  $\alpha = 0.79 \pm 0.22$  days and  $\beta = 0.99 \pm 0.14$ . However, it is important to note that the disk probably does not remain geometrically thin at these high accretion rates, and the assumptions of the model do not hold in this regime (Jiang et al. 2014; Sądowski et al. 2014). Equation 12 is relatively insensitive to the ratio of external to internal heating—even if the X-rays contribute



**Figure 9.** Probability distribution for the parameters  $\alpha$  and  $\beta$  of our best fit model. The contours show the 68, 95, and 99% confidence regions.

a negligible portion of the luminosity ( $\kappa = 0$ ),  $\alpha$  would only change by a factor of  $(3/4)^{1/3}$ .

In Paper II, we found  $\alpha = 0.35 \pm 0.04$  days, somewhat smaller than in this study. The smaller value can be explained by correlations between  $\alpha$  and  $\beta$ , shown in Figure 9. For the final analysis in Paper II,  $\beta$  was fixed to  $4/3$ , and, if we do the same, we find  $\alpha = 0.42 \pm 0.02$  days, in good agreement with Paper II. The fit with fixed  $\beta$  has  $\chi^2/\text{dof} = 1.42$ , making the lower value of  $\beta = 0.99 \pm 0.14$  statistically preferred. However, this result is driven by the flattening of the lags at the reddest wavelengths. If we exclude the  $I$  and  $z$  bands from the fit (as well as  $u$  and  $U$ ), we find  $\beta = 1.18 \pm 0.19$ , and  $\alpha = 0.58 \pm 0.20$  days, with  $\chi^2/\text{dof} = 0.89$ , while fixing  $\beta = 4/3$  gives  $\alpha = 0.45 \pm 0.02$  days and  $\chi^2/\text{dof} = 0.87$ .

We therefore conclude that a reprocessing model can fit the data reasonably well, but requires a much larger disk radius than predicted by standard thin-disk models. Fixing  $\beta = 4/3$  (in order to match the theoretical temperature profile), our best fit value of  $\alpha = 0.42$  days is a factor of 3.0 larger than the standard prediction with  $L/L_{\text{Edd}} = 0.1$ .

A sufficiently high accretion rate can account for this difference by increasing the size of the accretion disk. We note that uncertainties on the SMBH mass do not require  $\dot{m}_E$  to be larger than one, since  $\dot{m}_E \propto \alpha^3/M^2$  (Equation 12), while the SMBH mass may be up to 1.75 times larger at  $3\sigma$  than our adopted value. This would still require  $\dot{m}_E$  to be somewhere between  $\sim 0.1-1$ . On the other hand, a comparison of  $\dot{m}_E$  can be made assuming a thin disk spectrum and using the observed optical luminosity (e.g., Collin et al. 2002; Netzer 2013, Equation 4.53). From our spectral decompositions, we estimate that  $\lambda F_{\lambda} = 4.57 \times 10^{-11}$  erg cm<sup>-2</sup> s<sup>-1</sup> at 5100 Å, which yields  $\dot{m}_E = 0.05$  at a disk inclination of  $\cos i = 0.63$  and radiative efficiency  $\eta = 0.1$ . The accretion rate cannot be much higher (unless the disk is seen very edge-on), so this result implies that a standard thin disk model cannot account for both the observed time delays and the monochromatic luminosity at 5100 Å.

The large disk size found here corroborates the results from

<sup>69</sup> Alternative definitions of  $R$  exist. For example, a weighting function that better characterizes the radius responding to variable irradiation would replace Equation 8 with  $T = T_0(R) + \frac{\partial B(T(R))}{\partial T} \frac{\delta T}{T}$ , and set  $\frac{\delta T}{T}$  equal to a constant fractional temperature variation. This yields  $X = 3.37$ .

Paper II and other recent RM studies (Shappee et al. 2014; McHardy et al. 2014; Lira et al. 2015). The measurements of large disk radii are also in good agreement with the sizes inferred from gravitational microlensing experiments (see Paper II, Figure 6, as well as Poindexter et al. 2008; Morgan et al. 2010; Mosquera et al. 2013). Other sources of tension with the thin-disk/continuum reprocessing model are 1) the weak correlation between the X-ray lightcurves and UV/optical lightcurves (Paper II), and 2) the possible flattening of the lags at the longest wavelengths. The latter phenomenon might contain information about the outer-edge of the disk, or perhaps be explained by contaminating emission from BLR material along the line of sight (Korista & Goad 2001), and/or emission from the inner-edge of the near-side of the obscuring torus (Goad et al. 2012).

## 6. SUMMARY

We have presented results for a ground-based, broad-band photometric monitoring campaign of NGC 5548. Our light curves are of very high quality, achieving cadences of  $\lesssim 1$  day in nine optical bands over an entire observing season. Using full optical-wavelength spectra and synthetic photometry, we estimated the relative contribution of host galaxy starlight, AGN continuum emission, Balmer continuum, and line emission from the BLR to the observed light curves. Our main results are as follows:

- i. Significant time delays are detected between the far UV, near UV, and optical broad-band light curves. The delay between emission at 1367 Å and 2600 Å is less than one day, and the delay between emission at 1367 Å and the *V* band is about 2 days. Such large time delays are comparable to, and sometimes greater than, the lags of the high ionization-state emission lines, suggesting that the continuum emitting source is of a physical size approximately equal to the inner BLR.
- ii. If similar inter-band continuum lags exist in other AGN, it also suggests that the size of the BLR is 11–37% larger than would be inferred from optical data alone. However, there do not appear to be other significant systematic effects associated with the optical light curves, and RM SMBH masses are not affected by this result.
- iii. There is some contamination of the broad-band light curves by BLR emission, with 19% of the *u* and *U* bands attributable to the Balmer continuum, and 15–20% of the *r* and *R* bands attributable to H $\alpha$ . The impact of BLR emission on the observed *u* and *U* band lags is  $\sim 0.6$ –1.2 days, but is probably unimportant in the *r* and *R* bands. This justifies our decision to exclude the *u* and *U* band lags from our final analysis.
- iv. The trend of lag with wavelength is broadly consistent with the prediction for continuum reprocessing by a geometrically thin accretion disk with  $\tau \propto \lambda^{4/3}$ . However, the size of the disk is a factor of 3 larger than the prediction for standard thin-disk theory, assuming that  $L = 0.1L_{\text{Edd}}$ . This result appears to corroborate those from other continuum RM projects and gravitational microlensing studies. Further investigations of the accretion disk structure will benefit from physical modeling of the AGN STORM lightcurves, and several such studies are planned for upcoming papers in this series (Starkey et al., in prep; Kochanek et al., in prep).

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