SWIFT/UVOT GRISM MONITORING OF NGC 5548 IN 2013: AN ATTEMPT AT Mg II REVERBERATION MAPPING

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Received 2015 March 6; accepted 2015 July 30; published 2015 September 2

ABSTRACT

Reverberation-mapping-based scaling relations are often used to estimate the masses of black holes from single-epoch spectra of active galactic nuclei (AGNs). While the radius–luminosity relation that is the basis of these scaling relations is determined using reverberation mapping of the Hβ line in nearby AGNs, the scaling relations are often extended to use other broad emission lines, such as Mg ii, in order to get black hole masses at higher redshifts when Hβ is redshifted out of the optical waveband. However, there is no radius–luminosity relation determined directly from Mg ii. Here, we present an attempt to perform reverberation mapping using Mg ii in the well-studied nearby Seyfert 1 NGC 5548. We used Swift to obtain UV grism spectra of NGC 5548 once every two days from 2013 April to September. Concurrent photometric UV monitoring with Swift provides a well determined continuum light curve that shows strong variability. The Mg ii emission line, however, is not strongly correlated with the continuum variability, and there is no significant lag between the two. We discuss these results in the context of using Mg ii scaling relations to estimate high-redshift black hole masses.

Key words: galaxies: active – galaxies: individual (NGC 5548) – galaxies: nuclei – galaxies: Seyfert

1. INTRODUCTION

The masses of supermassive black holes (SMBHs) at the centers of galaxies and their evolution with time is an important part of the picture of galaxy formation and evolution, as strong correlations between galaxy and black hole properties suggest they are closely connected, e.g., through the M–σ and M–L relations (e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Gültekin et al. 2009; Kormendy & Ho 2013). Much effort over the last several decades has gone into determining the masses of SMBHs in nearby galaxies, through methods such as those using stellar (e.g., Gültekin et al. 2014) and gas dynamics (e.g., Walsh et al. 2013), or reverberation mapping (e.g., Peterson et al. 2004; Bentz et al. 2009b). This nearby sample of SMBHs with black hole mass measurements can then form the basis of scaling relations that can be applied to much more distant objects where direct methods are not possible. One of the most powerful of these scaling relations is the radius–luminosity, R–L, relation which relates the size of the broad emission line region (BLR) in an active galactic nucleus (AGN), as measured by reverberation mapping, to the AGN luminosity.

The basic principle behind reverberation mapping is simple. In AGNs, large amounts of photoionized gas moves under the influence of the central SMBH’s gravity, allowing a direct measurement of the velocity dispersion in the BLR. To determine a mass, the radius of the BLR from the SMBH is needed, which can be obtained using the reverberation mapping technique (Blandford & McKee 1982; Peterson 1993, 2014). In this method, the observed time lag, τ, between an emission line light curve (typically Hβ) and the optical continuum light curve is interpreted as the light-travel time from the continuum emitting region close to the SMBH and the BLR further out (where the continuum is reprocessed into line emission). The lag thus gives the emissivity-weighted average radius of the BLR, R = τc. Combining some measure of the width of the emission line used and the radius leads to a mass measurement via the virial theorem. In this way, reverberation mapping has successfully determined the masses of ~60 supermassive BHs in AGNs (e.g., Peterson et al. 2004; Bentz et al. 2009b; Barth et al. 2011, 2015; Pancoast et al. 2014; Bentz & Katz 2015).

Such mass measurements have allowed the determination of the R–L scaling relation (Kaspi et al. 2000; Bentz et al. 2006b, 2009a, 2013), which is based on the time lag (and hence radius) obtained using the Hβ broad emission line. The R–L relation leads to a mass estimate from a single-epoch AGN spectrum, a measurement of the AGN luminosity gives the BLR radius from the R–L relation, and the broad emission line width can be used to determine the line-of-sight velocity dispersion. This therefore allows estimates of black hole masses in large samples of galaxies (e.g., McLure & Jarvis 2002; Vestergaard 2002; Vestergaard & Peterson 2006; Vestergaard & Osmer 2009). The R–L relation has also successfully been used to discover low-mass (MBH < 2 × 10⁶M⊙) AGNs (Greene & Ho 2007; Baldassare et al. 2015).

The R–L relationship is well-established for Hβ, which is easily observed with ground-based observations in the case of local AGNs. However, as z increases, Hβ is shifted to IR wavelengths that become less accessible. At higher redshifts, it is thus desirable to use instead strong rest-frame UV lines, such as C IV λ1549 and Mg ii λ2798. Unfortunately, the R–L relationship is poorly established for C IV and is heavily dependent on one provisional measurement of a high-luminosity quasar (Kaspi et al. 2007). However, gravitational microlensing has allowed measurements of the size of the high-ionization BLR in gravitationally lensed systems, and these data support an R–L relationship that is parallel to that of Hβ.
(Guerras et al. 2013). The situation is even worse for Mg II as there are only two reliable Mg II lags that have been measured, NGC 3783 (Reichert et al. 1994) and NGC 4151, for which there are two independent measurements (Metzroth et al. 2006). Thus far, the best that can be done in the absence of suitable C IV and Mg II reverberation measurements is to assume these lines have R–L relationships that are parallel to that for Hβ and assume that all lines yield the same black hole mass, so that the quantity VP = RΔV2/G, where ΔV is the line width, is constant (McGill et al. 2008; Onken & Kollmeier 2008; Rafiee & Hall 2011; Shen & Liu 2012; Park et al. 2013).

Note that in all cases where it has been testable, VP is found to be consistent between different emission lines (Peterson & Wandel 1999, 2000; Kollatschny 2003; Peterson et al. 2004; Bentz et al. 2010).

Calibration of the black hole mass scale requires another step, usually written as \( M_{\text{BH}} = f \times \text{VP} \), where \( f \) is a dimensionless factor of order unity that depends on the BLR orientation and other generally poorly known parameters. The factor \( f \) is thus expected to vary from system to system, but the consistency of the virial product for multiple lines in a given system suggests that \( f \) is also approximately constant for a given system. With the most recent direct modeling of high-quality reverberation data, it is possible to uniquely model \( f \) for a given system (Brewer et al. 2011; Pancoast et al. 2014), but at this time only a few such measurements have been made. What is usually done instead is to compute an ensemble average value for \( f \) by using another estimate of the black hole mass, in practice from the \( M–\sigma \) relationship. Two recent estimates from this method give \( f = 4.31 \pm 1.05 \) (Grier et al. 2013) and \( f = 4.47 \pm 1.24 \) (Woo et al. 2015). Interestingly, these are consistent with the average of the 5 individual \( f \) values determined from direct modeling by Pancoast et al. (2014; see that paper for a detailed discussion comparing \( f \) values from the two independent and separate approaches).

There has been debate about the reliability of using C IV and Mg II for black hole mass estimates. For instance, Mg II is systematically narrower than Hβ (Wang et al. 2009; Marziani et al. 2013), but may be more reliable than C IV (Trakhtenbrot & Netzer 2012). However, other studies have shown no net bias in using these rest-frame UV lines (Greene et al. 2010; Rafiee & Hall 2011), and good agreement with Hβ-based masses (Assef et al. 2011). Furthermore, the discrepancies and scatter in the relations can be a result of the non-variable component of line profile (Denney 2012) and low signal-to-noise ratio spectra that do not allow for an accurate characterization of the line profile (Denney et al. 2013). Even so, measuring the reverberation of Mg II remains an important goal in order to further validate these scaling routines. Thus far, there has only been one Mg II mass determined (NGC 4151, Metzroth et al. 2006) using archival IUE data, which gives a value consistent with the Hβ mass (Bentz et al. 2006a).

As discussed above, there have only been two objects where a Mg II lag has been successfully recovered (Reichert et al. 1994; Metzroth et al. 2006). It is useful to discuss other cases where reverberation of Mg II has been looked for, and where the variability of Mg II has been studied. One of the more intense monitoring campaigns that looked for Mg II variability was the 1989 IUE campaign of NGC 5548 (Clavel et al. 1991). While there was significant variability in the continuum (ratio of maximum to minimum flux \( \sim 4.5 \)) and high-ionization lines, Mg II was the least variable with a maximum to minimum flux ratio of \( \sim 1.3 \). Clavel et al. (1991) attempted to measure a lag but found it was not well constrained, with \( \tau = 34–72 \) days. During the monitoring campaign of NGC 3783, even though Reichert et al. (1994) were successfully able to measure a lag, Mg II is again the least variable emission line, and the authors worry about whether variable Fe II contributes to the Mg II variability. No other studies have had the intense monitoring required to attempt Mg II reverberation, however, there are a number of studies looking at Mg II variability from fewer observations. Five Hubble Space Telescope (HST) observations of NGC 3516 also showed significant lack of variability in Mg II, with the variability constrained to be less than 7% even though the UV continuum varied by a factor of 5 (Goad et al. 1999a, 1999b). More recent observations of Mg II variability in higher luminosity quasars have found mixed results. For instance, Woo (2008) found significant variability (8%–17% rms) in 4 of the 5 quasars studied over 1–1.5 year rest-frame timescales, and Hryniewicz et al. (2014) find a 25% change in Mg II flux in the quasar LBQS 211–4538 from observations 6 months apart. On the other hand, little or no Mg II variability is seen in studies of two other quasars (Trevese et al. 2007; Modzelewska et al. 2014). Finally, a study of spectral variability of quasars in the SDSS Stripe 82 region found Mg II variability to be weak, and less variable compared to Balmer emission lines (Kokubo et al. 2014). Thus, there are a number of examples of low variability in Mg II, with only a few exceptions, and very few attempts at Mg II reverberation mapping.

The Swift/UVOT allows a route to doing UV reverberation mapping using the U grism on board. Swift’s observing schedule is flexible, allowing for short (1 or 2 ks) daily monitoring of AGNs. The effective area of the U grism peaks at around the wavelength of Mg II, and thus can, in principle, be used to perform direct Mg II reverberation mapping. In order to expand the number of AGNs with Mg II reverberation mapping, and as a first step toward an ultimate goal of determining a Mg II R–L relation, we undertook a long-term (\( \sim 6 \) month) monitoring campaign of NGC 5548 in 2013. NGC 5548 (an SO/a Seyfert galaxy at \( z = 0.01718 \)) was chosen since it is the best-studied reverberation-mapped AGN to date, with many years of monitoring (see, e.g., Peterson et al. 2002; Bentz et al. 2007, 2010; De Rosa et al. 2015; Edelson et al. 2015, and references therein), and also had previous IUE data (Clavel et al. 1991) to allow for a feasibility study.

Our Swift/UVOT U grism monitoring campaign of NGC 5548 took place from 2013 April 1 to September 12 (PI: Cackett). We have also supplemented the UV continuum light curve with concurrent Swift photometric monitoring that took place immediately before and during our grism campaign. An analysis of the UV photometric light curves during this period has already been presented by both Kaastra et al. (2014) and McHardy et al. (2014). Furthermore, the broadband spectral energy distribution of NGC 5548 during this period (including Swift U grism spectra) has been examined by Mehdipour et al. (2015).

The data reduction is described in Section 2, and our time series analysis is given in Section 3. We discuss our results and their implications in Section 4.
2. DATA REDUCTION

2.1. UV Grism Data

Grism observations were taken from 2013 April 1 to 2013 September 12 approximately once every two days (on average). Each observation typically consists of a total of 2 ksec exposure time on the source. However, this is usually performed as two separate \( \sim 1 \) ksec exposures, taken within a couple of hours of each other. The \textit{Swift} target IDs of the grism observations are 91711, 91737 and 91739. Of the total 82 grism observations, 7 (all target ID 91737) were taken at a roll angle where a nearby star was dispersed adjacent to the dispersed NGC 5548 spectrum. It was not possible to cleanly extract a spectrum from these observations that did not contain continuum emission from the star. Excluding those 7 observations, we are left with a total of 75 grism observations of NGC 5548. Of the remaining 75 observations, 7 exposures (target ID 91739) had a roll angle that put a zeroth-order image of a star at approximately 2000 Å in the dispersed first order spectrum of NGC 5548. These observations could not be used for the mean and rms spectrum, but we were still able to calculate line fluxes because the first order spectrum around the Mg II line is not contaminated.

To perform the \textit{Swift}/UVOT grism data analysis, we use Paul Kuin’s UVOTpy software version 2.0.3 (Kuin 2014), which is designed specifically for analysis of \textit{Swift}/UVOT grism data. Details of the calibration of the \textit{Swift}/UVOT grism and of the software are given in Kuin et al. (2015).

We extract the grism spectrum using the uvotgetspec tool, and default parameters for the width of the extraction regions for the source and background. For the vast majority of observations, a short UVW2 image is taken during the same pointing. Since with grism spectroscopy the wavelength scale depends on the location of the zeroth-order image, the software uses the UVW2 image in order to anchor the wavelength scale. In a small number of pointings, no photometric image was taken, leading to a more poorly defined anchor position.

The 1σ wavelength accuracy of the UV grism in clocked mode is 9 Å (Kuin et al. 2015), thus, we use the Mg II line itself in order to provide a better wavelength determination. For each spectrum we find the centroid of the Mg II using the wavelength range where the flux of the line is \( >70\% \) of the peak value. We find a mean absolute wavelength shift of 9 Å when a photometric image has been taken (consistent with the \textit{Swift} calibration: Kuin et al. 2015), and 39 Å when no photometric image exists.

Once the wavelength shifts have been applied, we calculate the mean and rms spectra, shown in Figure 1. All flux densities are given in the emitted frame, and are corrected for Galactic reddening assuming \( E(B-V) = 0.0199 \) (Schlegel et al. 1998) and the dust reddening law of Seaton (1979). We use Seaton (1979) for easy comparison with previous work on NGC 5548 which also use this reddening law, though the choice does not make any difference in determining lags. The effective area of the UV grism drops off rapidly at about 1800 Å. Furthermore, at wavelengths longer than about 3000 Å, the second-order spectrum can overlap and contaminate the first-order spectrum. We therefore concentrate on the spectrum between 1800–3400 Å. The Mg II line at a rest wavelength of 2798 Å can clearly be seen. Other features in the spectrum include the C III] λ1909 semi-forbidden emission line, and the Fe II emission line complex (most prominent in the region 2200–2800 Å, see e.g., Baldwin et al. 2004). Mehdipour et al. (2015) present a fit to the broadband spectral energy distribution of NGC 5548, which includes the mean UV grism spectrum, and the reader is referred to that paper for more details on individual components. In the rms spectrum, the Mg II can be identified, but it is not a strong feature, already indicating that it is not highly variable during our monitoring of NGC 5548. The mean continuum flux at 2670 Å is approximately the same as during the 1989 IUE observations presented by Clavel et al. (1991).

The Mg II line is well modeled by a single Gaussian. Both a direct measurement and the best-fitting Gaussian give a FWHM = 68 Å. However, this does not take into account the significant instrumental broadening. Unfortunately, the line spread function is not accurately known at all wavelengths (N. P. M. Kuin 2015, private communication). The resolving power is given as \( R = 75 \) at 2600 Å (Kuin et al. 2015), which for the observed wavelength of Mg II corresponds to \( \Delta \lambda = 38 \) Å. Correcting for this broadening (assuming a Gaussian with FWHM = 38 Å) gives an intrinsic FWHM = 56.5 Å, or \( \Delta \nu = 5960 \) km s\(^{-1}\). For comparison, the FWHM of \( H\beta \) in NGC 5548 has been seen to range from 3078 km s\(^{-1}\) (Peterson et al. 2002) to 11177 km s\(^{-1}\) (Bentz et al. 2010), with line width anti-correlated with AGN luminosity.

2.2. Photometric Data

As described above, NGC 5548 was monitored intensely with \textit{Swift} during 2013. UVW2 was the filter most commonly used throughout the monitoring, thus, we use those data to determine the UV continuum light curve covering the period immediately before and throughout our grism monitoring. In addition to the UVW2 observations associated with our grism observations (117 observations in total), we take advantage of other, shorter, photometric monitoring campaigns of NGC 5548 taking place at the same time: target IDs 91404 (32 observations between 2012 November 17 and 2013 March 29,
The UVW2 observations are often split into two separate pointings. Rather than combine all pointings within a given day together, we analyze them separately in order to get the highest time cadence. The UVW2 photometric light curve (along with other filters) during this period has already been presented by Kaastra et al. (2014), McHardy et al. (2014), Mehdipour et al. (2015) and Edelson et al. (2015). We perform photometry on NGC 5548 using uvotsource with a 5″ circular source extraction region, and a 10″ background region offset from the galaxy. As described by McHardy et al. (2014), Mehdipour et al. (2015) and Edelson et al. (2015) a small number of observations were found to be anomalously low (>15% lower) compared to the surrounding local mean, with the origin thought to be instrumental rather than intrinsic to the source. We manually removed these “drop-outs” from the light curve (see McHardy et al. 2014; Edelson et al. 2015 and Mehdipour et al. 2015 for more detailed discussion). The UVW2 photometric light curve is shown in panel (b) of Figure 2.

2.3. UV Continuum and Mg II Light Curves

We use the individual grism spectra to determine the UV continuum flux and Mg II light curves. For the UV continuum light curve, we calculate the mean flux density from 2950 to 3150 Å. This light curve is also shown in panel (a) of Figure 2. As can be seen, the 2950–3150 Å light curve is strongly correlated with the UVW2 light curve. The UVW2 bandpass peaks at a shorter wavelength at about 2100 Å, and the effective area drops off significantly by 3000 Å. Figure 3 shows the UVW2 count rate versus the 2950–3150 Å continuum flux, demonstrating the strong correlation between the two. The UVW2 is highly variable with a variability amplitude (Vaughan et al. 2003) of $F_{var} = 0.33$.

To determine the Mg II line flux we take two approaches. First we take a simple approach involving defining the continuum in regions either side of the line, as is typically done in AGN reverberation studies, since the goal is to capture the line flux variations in a model-independent fashion, rather than to capture all the line flux. Second, we perform multi-component spectral fitting to try and separate the contribution of the Fe II complex from the Mg II line and continuum.

2.3.1. Mg II Line Flux: Simple Approach

In this first approach, we determine the Mg II integrated line flux by fitting the local continuum either side of the line. We fit a straight line to the continuum including data in the ranges 2560–2695 Å and 2950–3150 Å. We then integrate the line flux above the continuum from 2695–2900 Å. The line light curve from this method is also shown in panel (c) of Figure 2. We find that the uncertainties in line flux estimated directly from the uncertainties in individual flux bins appears to be overestimated, with mean fractional uncertainty in the line flux being 0.134. We verified this overestimate by comparing flux differences between data points on timescales as short as 2 days. Assuming those flux differences are stochastic, and that the fractional error is the same on all points, we get a fractional error of 0.081. This is an upper limit on the flux uncertainties since there may be intrinsic flux variability on two-day timescales. We adopt fractional errors of 0.081 on the Mg II line flux measurements. The light curve only has small amplitude variability, with $F_{var} = 0.074$. By eye, there does not appear to be a correlation between the continuum and Mg II light curves, and this is also clear when looking at UVW2 count rate versus Mg II line flux in Figure 3.

We also explore the continuum light curves at different wavelengths, calculating the mean flux density in the range 2015–2215 Å and also 4430–4625 Å. We compare these light curves in Figure 4. The light curves are clearly correlated, and there is an obvious decrease in variability amplitude with increasing wavelength. This decrease in variability amplitude with wavelength can also be seen in the rms spectrum (Figure 1). The light curves indicate that the spectrum is bluer when brighter.

2.3.2. Fe Template Fitting

Strong Fe II emission is visible in the spectrum, and thus to determine more robustly the Mg II line flux we perform multi-component spectral fitting in order to decompose the Fe II, Mg II and continuum components. A similar Fe template fitting approach has been used by Barth et al. (2013) to successfully recover optical Fe II lags in two AGNs.

For the Fe II line complex we use the template model of Vestergaard & Wilkes (2001). In addition to the Fe template, we also include a power-law continuum and a Gaussian to model the Mg II line. The model is then convolved with a Gaussian with FWHM = 38 Å to match the instrument resolution and fitted to the individual spectra in the 2000–3000 Å region.

When fitting this model, we consistently found reduced-$\chi^2$ values significantly less than 1.0, once again indicating that the uncertainties in the flux from uvotsource appear to be overestimated. We therefore scale the uncertainties by $\sqrt{\chi^2 / \nu}$, the mean scale factor is 0.5.

Figure 5 shows a spectral fit, using the first Swift observation in 2013 April (obsID: 00091711002) as an example. The example demonstrates how the Fe II emission overlaps with the Mg II line.

There is good agreement between the line flux determined by the simple approach and the Fe template fitting method. We show the Mg II light curve from this method in panel (d) of Figure 2, and a comparison of the line fluxes from both methods in Figure 6. The Mg II flux is slightly lower when determined from the Fe template fitting method, because a small amount of Fe contributes to the total flux within the wavelength limits of the Mg II emission line. The mean fractional uncertainty in the Mg II line flux is 0.073 from this method, very similar to what we estimated for the simple method based on variability between adjacent data points.

The integrated flux from the Fe II line complex over the 2000–3000 Å region is shown in panel (e) of Figure 2. However, the Fe II flux is poorly constrained from the spectral fitting, with a mean fractional uncertainty of 0.29. The resulting light curve is noisy with no clear variability pattern. Since the individual spectra are reasonably noisy, and the response of Fe II is expected to be longer than that of Hβ (Vestergaard &
Peterson 2005), we also tried binning the spectra in time, by up to 5 epochs, to improve the light curve. While this reduces scatter in the light curve, it does not show any clear correlated variability with the continuum light curve.

3. CROSS CORRELATION ANALYSIS

We use the standard cross correlation analysis techniques to determine if there is a time lag between the UV continuum and the Mg II line. Since the UVW2 light curve is significantly longer than the 2950–3150 Å light curve, we use the UVW2 light curve to search for a lag. We calculate the cross correlation function (CCF) between the Mg II and UVW2 light curves, using the linear interpolation method as described by White & Peterson (1994). The CCFs are shown in Figure 7 when using the Mg II light curves determined both from the simple and Fe template fitting methods. Regardless of the Mg II light curve used there are two peaks in the CCF with one at approximately 20 days and the other at approximately 70 days. However, the CCF does not peak at a high value (the peak is <0.5 for both Mg II light curves), indicating that the UVW2 and Mg II light curves are not strongly correlated.

We use the standard Monte Carlo flux randomization/random subset sampling method as implemented by Peterson et al. (2004) in order to generate 10,000 pairs of light curves, and we determine the peak and centroid value of the CCF for each pair. We use the mean value of the distribution of centroid values as our best value for the lag centroid, \( \tau_{\text{cent}} \), though we note that the centroid distribution is also double peaked, like the CCF. We find \( \tau_{\text{cent}} = 34^{+24}_{-24} \) days when using the Mg II light curve from the simple method and \( \tau_{\text{cent}} = 13^{+14}_{-12} \) days when using the Fe template method light curve, again indicating there is no significant non-zero lag. Note that the CCFs from both methods peak at around 20 days, and the difference in centroid lags comes from the stronger secondary peak at 70 days in the CCF from the simple method. We also note that the peak in the CCF that can be seen at around 70 days in Figure 7 is narrower than the auto-correlation function (ACF) of the UVW2 light curve, and thus likely not real. If the line light curve is formed in response to changes in the continuum light curve then the

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**Figure 2.** (a) Average flux density between 2950 and 3150 Å in units of \( 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1} \). (b) Swift/UVW2 count rate in counts per second. (c) Integrated Mg II line flux in units of \( 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \) from the simple approach to determining the Mg II line flux. (d) Integrated Mg II line flux in units of \( 10^{-13} \text{ erg s}^{-1} \text{ cm}^{-2} \) from the Fe template fitting approach to determining the Mg II line flux. (e) Fe II flux integrated over the 2000–3000 Å region in units of \( 10^{-12} \text{ erg s}^{-1} \text{ cm}^{-2} \) determined from Fe template fitting.
CCF will be the ACF convolved with the transfer function, and so should be broader (not narrower) than the ACF. Furthermore, the ACF of the Mg II light curve is very narrow, with a secondary peak at 50 days. As noted when discussing the Fe II light curve, we also tried binning up the spectra in time by up to 5 epochs, however, this also led to no lag detection in Mg II.

We also determine whether there is any significant lag between the UVW2 and grism continuum light curves. Since the grism light curves are close to monotonic, we take out the long term trends in the light curves by fitting a low-order polynomial, and subtracting it from the data. Such detrending is shown to improve lag measurements (Welsh 1999), and since we expect the interband lags to be short removing the long-term trends reduces aliasing effects. The lags measured relative
to the UVW2 are \(\tau_{\text{cent}} = -0.9^{+0.8}_{-0.9}\) days, \(\tau_{\text{cent}} = 1.1^{+0.7}_{-0.5}\) days and \(\tau_{\text{cent}} = 0.3^{+0.9}_{-1.9}\) days, for the 2015–2215 Å, 2950–3150 Å, and 4430–4625 Å light curves, respectively.

Wavelength-dependent continuum lags are expected from disk reverberation (thermal reprocessing), where the inner, hotter accretion disk responds to variations in the irradiating flux before the outer, cooler disk (see Cackett et al. 2007, for a detailed description). McHardy et al. (2014) use the photometric light curves during the 2013 campaign to provide a measure of these wavelength-dependent lags, and the even higher cadence Swift monitoring in 2014 have provided an extremely good measure of these (Edelson et al. 2015). While none of our interband lags are significantly non-zero, they are consistent with those expected based on Edelson et al. (2015).

4. DISCUSSION

We monitored NGC 5548 for approximately 170 days with the U grism on board Swift during 2013, obtaining low-resolution UV spectra approximately every other day during the monitoring campaign. By combining these spectra with photometric monitoring before and during our grism campaign, we attempted to compare the variability of the continuum and Mg II emission line. The UV continuum showed significant variability over the campaign, though the flux changes were almost a monotonic increase over the period of grism monitoring. The Mg II emission line, however, was not significantly variable, and hence there is no plausible lag between the continuum and emission line, preventing a reverberation mapping mass estimate from the Mg II line alone.

Even though not significant, it is interesting to note that the peak in the CCF between the UV continuum and Mg II line at approximately 70 days is consistent with the largest peak in the equivalent CCF for Mg II from the IUE monitoring campaign of 1989 (Clavel et al. 1991), though that peak is also of low significance, and quite probably a result of aliasing. An important consideration is whether the lack of response to continuum variability is due to an intrinsic property of the line, the location of the Mg II line emitting region, or whether the near monotonie increase in continuum flux over the grism monitoring period prevented a clear lag measurement. Mg II is a low excitation line, thus is emitted from a region further away from the central AGN than other BLR lines such as H α or C IV. This location further from the AGN could be why we do not see a clear response to continuum variability. If the inner part of the BLR blocks a clean view of the central engine, the Mg II emitting region may see only scattered continuum emission. Certainly there is significant absorbing and obscuring material in the inner region of NGC 5548 as evidenced by the large number of absorption lines seen during both 2013 and 2014 HST observations of NGC 5548 (Kaasra et al. 2014; De Rosa et al. 2015). How absorption affects the Mg II line which is actually a resonant doublet, and how changes in the absorption affect the line variability are not clear since the grism data are not high enough resolution to detect any narrow absorption lines. Such issues are known to cause problems in accurately determining the line profile (Denney et al. 2013). On the other hand, the fact that the continuum light curve during the grism observations shows a near-monotonie increase with no strong peaks or troughs, means that it would be hard to see a clear response from the line. The photometric monitoring that took place immediately before our grism observations began does show several strong variable features, however the lag would have to be almost 100 days to see the two clear peaks in that light curve.

It is also important to consider the photoionization properties of Mg II. The observed response of a line to continuum fluctuations will depend both on its local responsivity, that is the marginal response of the line to continuum variations, and geometric dilution, i.e., the blurring of the response due to the distribution of delays set by the geometry of the BLR. Photoionization calculations show the responsivity for Mg II to be low compared to high ionization lines (Goad et al. 1993; O’Brien et al. 1995; Korista & Goad 2000), meaning that the line should not be expected to respond strongly to changes in continuum flux. For instance, Figure 7 of Goad et al. (1993) which shows how the responsivity for Mg II compares to other lines. This can also be seen in Figure 2(b) of Korista & Goad (2000), which shows that the EW of Mg II is generally strongly negatively correlated with the incident ionizing photon flux. This equates to generally small values in the local gas responsivity for Mg II, and also results in large centroids in delay in its 1D transfer function. The latter makes this line’s response also susceptible to geometric dilution. The result is a small response amplitude in Mg II, compared to the other UV emission lines (see also Figure 5(a) of Korista & Goad 2000).

Thus, the lack of variability of Mg II could be due to an intrinsic property of the line, as suggested by Goad et al. (1999a) when discussing the lack of Mg II variability in NGC 3516.

It would be valuable to be able to measure Mg II reverberation mapping masses directly (as we discussed in Section 1). Unfortunately, the lack of significant lag prevents us from doing this. Although a direct reverberation mapping mass was not possible, we can still use the mean spectrum in order to obtain a “single-epoch” Mg II mass estimate to compare with the well-constrained H β mass for NGC 5548. To get a “single-epoch” mass measurement, we combine the line width (\(\sigma = 235 \text{ km s}^{-1}\)) with the mean continuum luminosity at 3000 Å, \(L_\lambda (3000 \text{ Å}) = 5.2 \times 10^{43} \text{ erg s}^{-1}\), and use the relation of McGill et al. (2008) to estimate \(M_{\text{BH}} = 7 \times 10^7 M_\odot\). This is slightly larger than, though still in reasonable agreement with, the \(H_\beta\) reverberation mapping mass for NGC 5548 of \(5.95 \times 10^7 M_\odot\) (assuming an \(f\) factor; Grier et al. 2013), and 3.2 \(\times 10^7 M_\odot\) (from direct modeling; Pancoast et al. 2014).

In summary, we do not detect a significant lag between the Mg II and UV continuum flux in NGC 5548 from a ~6 month monitoring campaign with Swift. However, Swift’s ability to perform long-term monitoring of nearby Seyfert 1s and obtain crude UV spectra could lead to the measurement of a Mg II lag in other bright AGNs if the Mg II line is variable enough.

We thank the Swift team for their hard work and efforts in successfully scheduled this monitoring campaign. Thanks also to Paul Kuin for use of his software and significant help and discussion about Swift/UVOT grism analysis. We thank Mike Goad and Kirk Korista for insightful discussions on the lack of Mg II variability and also thank the referee for suggesting Fe II reverberation mapping for NGC 3516. We thank the NSF through grant AST-1008882 to The Ohio State University. M.C.B. gratefully acknowledges support from the NSF through CAREER grant AST-1253702 to Georgia State University. M.B.P. gratefully acknowledges support from the NSF through grant AST-1008882 to The Ohio State University. M.V. gratefully acknowledges support from the NSF through grant AST-1253702 to Georgia State University.
