EVIDENCE THAT MOST TYPE-1 AGNs ARE REDDENED BY DUST IN THE HOST ISM

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ABSTRACT

The typical optical–UV continuum slopes observed in many type-1 active galactic nuclei (AGNs) are redder than expected from thin accretion disk (AD) models. A possible resolution to this conundrum is that many AGNs are reddened by dust along the line of sight. To explore this possibility, we stack 5000 SDSS AGNs with luminosity $L \approx 10^{45}$ erg s$^{-1}$ and redshift $z \sim 0.4$ in bins of optical continuum slope $\alpha_{\text{opt}}$ and width of the broad H$\beta$ emission line. We measure the equivalent width (EW) of the NaI/D absorption feature in each stacked spectrum. We find a linear relation between $\alpha_{\text{opt}}$ and EW(NaI), such that EW(NaI) increases as $\alpha_{\text{opt}}$ becomes redder. In the bin with the smallest H$\beta$ width, objects with the bluest slopes, which are similar to AD predictions, are found to have EW(NaI) = 0, supporting the line of sight dust hypothesis. This conclusion is also supported by the dependence of the H$\alpha$/H$\beta$ line ratio on $\alpha_{\text{opt}}$. The implied relationship between continuum slope and dust reddening is given by $E_{\text{B−V}} \approx 0.2 \cdot (-0.1 - \alpha_{\text{opt}})$, and the implied reddening of a typical type-1 AGN with $\alpha_{\text{opt}} = -0.5$ is $E_{\text{B−V}} \approx 0.08$ mag. Photoionization calculations show that the line of sight dusty gas responsible for reddening is too ionized to produce the observed sodium features. Therefore, we argue that the sodium absorption arises in regions of the host ISM that are shielded from the AGN radiation along lines of sight to the stars, and the correlation with $\alpha_{\text{opt}}$ arises since ISM columns along shielded and non-shielded sightlines are correlated. This scenario is supported by the similarity of the relation between $E_{\text{B−V}}$ and the NaI column implied by our results with the relation in the Milky Way found by previous studies.

Key words: dust, extinction – galaxies: active – quasars: absorption lines – quasars: general

1. INTRODUCTION

The unified model of active galactic nuclei (AGN) consists of a central engine, believed to be an accretion disk (AD), around a black hole (BH) with mass $M_{\text{BH}} = 10^6$–$10^{10} M_\odot$, and dust and gas that surround it (Antonucci 1993; Urry & Padovani 1995). While many details have been added over the years (for a recent review, see Netzer 2015), this picture still gives an adequate description of the central part of galaxies containing active BHs and the geometry in their centers. According to this picture, the observed spectrum of an AGN depends on the viewing angle relative to the distribution of the dusty nuclear gas. Broadly speaking, AGNs are classified into type-1 (unobscured) and type-2 (obscured) AGNs. In type-1 AGNs, the line of sight provides a direct view of the dust-free gas close to the center that contains the central disk and fast-moving high-density clouds, while for type-2 AGNs the emission from the AD and inner gas clouds is completely obscured by dust.

Richards et al. (2003) showed that the majority of UV-selected type-1 AGNs at redshift $0.3 < z < 2.2$ exhibit an optical–UV continuum, which at wavelengths $\sim 1500$–$4000$ Å is consistent with a single power law. The optical–UV spectral slopes have a Gaussian distribution with $\alpha_{\text{opt}} \sim -0.5 \pm 0.25$, where $\alpha_{\text{opt}}$ is defined such that $L_\nu \propto \nu^{\alpha_{\text{opt}}}$. However, the distribution of slopes also has a “red-tail” that includes AGNs with redder continua than the general population, which also exhibit the characteristic continuum curvature expected from extinction by intervening dust. This sub-class, which includes $\sim 10\%$ of UV-selected AGNs, is known as dust-reddened, or simply “reddened” QSOs.

What is the value of $\alpha_{\text{opt}}$ expected from models of geometrically thin, optically thick ADs? Such models are based on the general model presented in Lynden-Bell (1969) and Shakura & Sunyaev (1973) with various improvements like general relativistic corrections and radiative transfer in the disk atmosphere (e.g., Hubeny et al. 2000; Davis & Laor 2011; Slone & Netzer 2012; Capellupo et al. 2015, 2016). Standard thin AD models are characterized by a slope of $\alpha_{\text{opt}} \sim 1/3$ at long wavelengths. At intermediate frequencies where value depends on BH mass, BH spin, and accretion rate, the slope becomes very flat with $\alpha_{\text{opt}} \sim 0$, while at the highest frequencies close to the peak temperature of the disk the slope becomes “red” with $\alpha_{\text{opt}} < 0$ (Pringle & Rees 1972). For the typical mass and accretion rate of the sources considered in the present work ($L/L_{\text{Edd}} \sim 0.1$, $M_{\text{BH}} \sim 10^8 M_\odot$, see below), the 3000–5100 Å slope predicted by the AD model is in the range $-0.1$ to $+0.2$, with some dependence on $M_{\text{BH}}$ and little dependence on BH spin. This predicted slope is considerably bluer (“harder”) than the typical observed slope of $\alpha_{\text{opt}} \sim -0.5$ noted above. This discrepancy between the predicted and observed slopes has been pointed out by several studies that compared AD models with observed AGN spectra (Koratkar & Blaes 1999; Davis et al. 2007; Jin et al. 2012; Shankar et al. 2016). More detailed work on a small sample (17 objects; see Shang et al. 2005) and a comprehensive work on a medium-sized sample (39 objects; see Capellupo et al. 2015, 2016) show better agreement with thin AD spectra, especially when intrinsic reddening and the host contribution (at longer wavelength) are taken into account.

In this work we explore the possibility that the discrepancy between predicted and observed slopes is due to extinction of the AD emission by dust along the line of sight (e.g., de Zotti & Gaskell 1985; Netzer 1985; Ward et al. 1987; Netzer

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et al. 1995; Bechtold et al. 1997; Gaskell et al. 2004; Richards et al. 2006; Davis et al. 2007; Dong et al. 2008; Stern & Laor 2012; Dunn et al. 2015). That is, many AGNs could also be extincted by dust, though by a smaller amount than the “red-tail” AGNs mentioned above. Demonstrating that the majority of type-1 AGNs are indeed mildly reddened would provide valuable observational support for the standard AD models.

Stern & Laor (2012, hereafter SL12) provided evidence, based on a large number of Sloan Digital Sky Survey (SDSS) type-1 AGNs, that supports the ubiquitous reddening scenario. They showed that the ratio of ultraviolet (UV) to broad H$\alpha$ emission correlates with $\alpha_{\text{opt}}$ in luminous type-1 AGNs, even when excluding the “red-tail” population. The slope of this correlation is consistent with the slope expected if the AD and broad-line region (BLR) of typical type-1 AGNs are extincted by dust. Also, the bluest $\alpha_{\text{opt}}$ in the SL12 sample is consistent with AD predictions. These findings followed earlier studies based on smaller samples, which showed that the continuum slope is correlated with certain line ratios such as $L_\alpha/H\beta$ (e.g., Netzer & Davidson 1979; Puetter et al. 1981; Soifer et al. 1981; Allen et al. 1982; Netzer et al. 1995; Bechtold et al. 1997; Baskin & Laor 2005, where Baskin & Laor 2005 also suggest that the dust has a planar distribution). The implied reddening of a typical quasar with $\alpha_{\text{opt}} \sim -0.5$ is $E_{B-V} \approx 0.07$ mag (SL12), compared to significantly lower reddening values implied by assuming that the typical quasar is not reddened (Richards et al. 2003; Hopkins et al. 2004; Lusso et al. 2013; Krawczyk et al. 2015).

Another prediction of the reddening scenario is that absorption features from gas associated with the dust should become stronger with decreasing $\alpha_{\text{opt}}$. Testing this prediction is the main goal of the current paper. While the relation between absorption features and spectral slope has been addressed by numerous papers (Sprayberry & Foltz 1992; Yamamoto & Vansevičius 1999; Hall et al. 2002; Reichard et al. 2003; Richards et al. 2003; Baskin & Laor 2005; Shen & Ménard 2012; Baskin et al. 2013; Dunn et al. 2015), these studies focused on absorption-selected samples. Since broad and narrow absorption lines are detected in only $\sim$10% and $\sim$2% of UV-selected AGNs, respectively (Richards et al. 2003; Shen & Ménard 2012), absorption-selected AGNs are not necessarily representative of the general AGN population, which is the focus of the present work.

In this paper we wish to check whether the strength of absorption features correlates with spectral slope in the general AGN population, by comparing the spectral slope with the strength of the NaID absorption doublet (\$\lambda\lambda5896, 5890\$) in stacked SDSS spectra. Such a relation between NaID absorption and dust reddening in stacked spectra has been found in the Milky Way (MW) and other galaxies. Poznanski et al. (2012) used all the extragalactic objects from the SDSS to study the mean properties of the NaID absorption doublet in the MW and showed that there is a simple relation between the equivalent width (EW) of the doublet and dust reddening (see also Munari & Zwitter 1997; Shih & Rupke 2010). There is also an ongoing effort to map the strength of the doublet in neighbouring galaxies, such as the Small and Large Magellanic Clouds (SMC, LMC), which present radiation fields and gas-to-dust ratios that are different from those of the MW (see, for example, Cox et al. 2006; Welty et al. 2006; van Loon et al. 2013, D. Welty et al. 2016, in preparation). The present paper extends this effort to AGN hosts.

Our paper is organized as follows. In Section 2 we present the AGN sample and measure the strength of the NaID absorption feature in stacked spectra as a function of continuum slope. We demonstrate that NaID absorption increases with decreasing continuum slope. In Section 3 we provide additional evidence for the connection between continuum slope and dust reddening suggested by the observed EW(NaID) versus continuum slope relation. We discuss our results in Section 4, and conclude in Section 5.

2. DATA AND METHODS

2.1. AGN Sample

The seventh data release (DR7) of the SDSS contains about a million extragalactic spectra covering the wavelength range of 3800–9200 Å with 2.5 Å resolution. This includes the spectra of 105,783 AGNs brighter than $M_i = -22.0$ mag (Schneider et al. 2010), which have an average signal-to-noise ratio (S/N) of 10 pixel$^{-1}$. Shen et al. (2011) present a compilation of the properties for these AGNs, including continuum and emission line measurements around the H$\alpha$, H$\beta$, and Mg$\text{II}$ wavelength regions which we use in this paper. The SDSS pipeline measures redshift, $z$, using the broad emission lines in AGNs with errors of $\Delta z = 0.002$ (Hewett & Wild 2010) compared to the host galaxy. We choose to use the redshifts measured by Hewett & Wild (2010) based on the narrow emission lines, which are likely more accurate. We limit our sample to AGNs with $0.35 < z < 0.5$ in order to include the NaID absorption doublet (5889.95 Å, 5895.92 Å) and the 3000 Å continuum in our wavelength window. The spectra are corrected for MW foreground dust, using the maps of Schlegel et al. (1998) and the extinction law derived by Cardelli et al. (1989).

Our final sample consists of 4946 QSOs. We present in Figure 1 their distribution in $z$, FWHM of the broad H$\beta$ line, and bolometric luminosity $L_{\text{bol}}$. The value of $L_{\text{bol}}$ is derived
from the $L_{3000}$ measurements of Shen et al. (2011) using the bolometric correction factor of Richards et al. (2006). Figure 1 also shows the distribution of the optical continuum slope $\alpha_{\text{opt}}$, which is calculated as follows:

$$\alpha_{\text{opt}} = \frac{\log[L_\lambda(3000\text{ Å})/L_\lambda(5100\text{ Å})]}{\log(5100/3000)} - 0.25$$

(1)

where $L_\lambda$ is the monochromatic luminosity at rest frame wavelength $\lambda$ measured by Shen et al. (2011). The offset of $-0.25$ is introduced since on average 13% of the emission at 3000 Å is due to line and bound-free emission (Trakhtenbrot & Netzer 2012).

The relation between $\alpha_{\text{opt}}$ and the intrinsic AD slope depends on both the amount of extinction along the line of sight and the host contribution to the continuum emission $f_{\text{host}}(\lambda)$. We note that since we use a relatively small baseline to measure the slope ($\log(5100/3000) = 0.23$), the relation between intrinsic emission and $\alpha_{\text{opt}}$ is quite sensitive to $f_{\text{host}}$ at 5100 Å and 3000 Å, e.g., a value of $f_{\text{host}} = 0.1$ at either wavelength will change the implied intrinsic slope by $\pm 0.2$. We discuss the effect of $f_{\text{host}}$ further below.

We interpolate each spectrum to an identical grid of 0.5 Å in rest frame wavelength, in the range 5700–6100 Å, which contains the NaID absorption doublet. We use the Savitzky–Golay (SG) smoothing algorithm (Savitzky & Golay 1964) with a third order polynomial fit and a moving window size of 35 Å to fit and divide out the continuum, thus obtaining normalized fluxes. We exclude from the fitting range the wavelengths 5875–5920 Å, in order to avoid the He I emission line (5875.6 Å) and NaID absorption lines (5889.95 Å, 5895.92 Å). The NaID absorption line is not detected in almost all individual spectra due to the limited S/N of the SDSS spectra.

### 2.2. Stacked Spectra

We divide the spectra into two-dimensional bins based on their optical slope and the FWHM of their broad H/β line. The latter binning is done since the NaID absorption doublet lies on the red wing of the broad He I feature, which has a width that correlates tightly with the broad H/β width. Therefore, stacking in bins of FWHM avoids spurious features that are created when stacking objects with very different FWHMs. We find that in order to reach a sufficient S/N to measure the depth of the NaID line, we must stack at least 200 spectra. In order to have a similar number of spectra in every bin, we choose the following FWHM bins: 1000–3000, 3000–4000, 4000–6000, and 6000–10,000 km s$^{-1}$. Each of the FWHM bins contains roughly 1200 spectra, and we divide them into six $\alpha_{\text{opt}}$ bins, which we stack using the median at each wavelength. Our final sample contains 24 stacked spectra with S/N in the range 27–39.

Figure 2 shows the six stacked spectra with different optical slopes for each FWHM bin. These are the independent spectra with which we perform the fitting throughout the paper. One can see that the NaID absorption profile lies on the red wing of the He I emission line at 5876 Å. Although there is some variation in the He I profile between different $\alpha_{\text{opt}}$ bins, the EW of the NaID absorption grows markedly as $\alpha_{\text{opt}}$ decreases.

One can see additional absorption features in the stacked spectra. The absorption line at 5780 Å shows little change as a function of the optical slope and its EW is approximately 2 Å throughout the different bins. We speculate that this line is due to Fe I absorption (5780 Å). However, a certain identification requires a detailed comparison with the strengths of other known Fe absorption lines (in the 4000–5600 Å wavelength range) and is beyond the scope of our paper. Figure 2 shows an additional absorption feature at 5855 Å on the blue side of the He I emission line, which we call the blue absorption feature (BAF). The origin of the BAF is likely not NaID, since it is usually a resolved trough and is offset from the rest wavelength of NaID by about 1800 km s$^{-1}$. The BAF strength is not correlated with the strength of other photospheric features’ strength (such as Fe I 5780 Å). However, we account for this absorption when modelling the He I and NaID lines.

In most bins the NaID doublet appears as a single blended profile, suggesting the width of the individual lines are typically larger than their wavelength separation of 6 Å (300 km s$^{-1}$). Only in the reddest spectra of the FWHM $= 2200$ km s$^{-1}$ bin is the doublet clearly resolved. The combined profile of the NaID doublet has an FWHM in the range 7–9 Å (350–450 km s$^{-1}$).

In Figure 3, we compare the velocity profile of the stacked NaID absorption feature with the velocity distribution of narrow Mg II absorbers found by Shen & Ménard (2012, hereafter SM12). SM12 found that 2% of SDSS AGNs at $0.4 < z < 2$ exhibit a narrow Mg II absorption feature in single spectra. The top-left panel in Figure 3 shows the velocity distribution of the SM12 absorbers. As in this study, the systemic velocity of the host in the Mg II-absorber sample is derived from the velocity of the narrow emission lines. SM12 argue that Mg II absorbers with velocities $v < -1500$ km s$^{-1}$ are consistent with cosmologically intervening absorbers along the line of sight toward the AGN (see also Wild et al. 2008) since the velocity distribution profile flattens out at $v < -1500$ km s$^{-1}$. Therefore, to assess the velocity distribution of the associated (non-intervening) absorbers, we fit the positive velocity part of the distribution with a Gaussian. In the bottom-left panel we compare this Mg II velocity distribution with the NaID absorption profile of the $\alpha_{\text{opt}} = -0.74$, FWHM = 3400 km s$^{-1}$ bin. This bin is chosen since it shows strong NaID absorption which facilitates the comparison. The black line is the stacked AGN spectrum after subtracting out the He I line, where we use the H/β profile as a template for He I. The profiles of He I and H/β are compared in the right panel. The red dashed line in the bottom-left panel is the expected profile for a NaID doublet convolved with the Gaussian shown in the top-left panel. Figure 3 shows that the velocity profile of the stacked NaID absorption feature is consistent with the velocity distribution of associated Mg II absorbers found by SM12.

### 2.3. EW Measurements

In order to measure the EW of the NaID line in the stacked spectra, we perform a joined fit. The He I line is modeled with the H/β profile of the same stacked spectrum. The NaID doublet profile is modeled as a single unresolved line with the width suggested by the Mg II absorption distribution shown in Figure 3. The BAF strength correlates with $\alpha_{\text{opt}}$, and therefore changes from one stacked spectrum to the next. We fit a Gaussian function to account for it. To solve for the various
parameters of interest, we minimize the $\chi^2$ of the following function:

$$f(\lambda) = a_H \cdot H\beta(\lambda) + b + a_N \cdot N(\lambda) + G(a_G, \sigma, \lambda_0, \lambda)$$

(2)

where $H\beta(\lambda)$ is the shifted and rescaled $H\beta$ profile (with a fixed width), $N$ is the NaID profile, and $G$ is the Gaussian function that accounts for the BAF. We allow the continuum parameter, $b$; the scaling parameters $a_H$, $a_N$, and $a_G$; and the width of the BAF, $\sigma$, to change from one stacked spectrum to the next. The central wavelengths for all the features are fixed. The NaID EW is then extracted from the best fit. Different fitting procedures, e.g., using a Voigt profile for the BAF and Gaussians for the NaID doublet, give essentially the same EWs.

Figure 2. Stacked AGN spectra at wavelengths near the NaID absorption features, in bins of FWHM (H$\beta$) and continuum slope. The spectra are normalized by the continuum level using a Savitzky–Golay smoothing algorithm. The insets zoom in on the NaID doublet. Note how EW (NaID) grows with decreasing $\alpha_{opt}$. 

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Figure 3. (Top-left) The velocity distribution of associated Mg II absorbers from SM12 (blue bars). The dashed line marks a Gaussian fit to the red wing of the distribution. (Right) A comparison of the He I and H\beta profiles in the stacked spectrum of AGNs with $\alpha_{\text{opt}} = -0.74$ and FWHM = 3400 km s$^{-1}$. We use the rescaled H$\beta$ as a template for He I. (Bottom-left) A comparison of the stacked spectrum of AGNs with $\alpha_{\text{opt}} = -0.74$ and FWHM = 3400 km s$^{-1}$, after subtracting out the He I feature (black solid line), with the profile of a NaID doublet convolved with the Gaussian velocity distribution of the Mg II absorbers (red dashed line). The velocity distribution of the Mg II absorbers is consistent with the profile of the stacked NaID absorption feature.

2.4. EW Versus $\alpha_{\text{opt}}$

For a given FWHM bin, in addition to dividing the spectra into six bins of different $\alpha_{\text{opt}}$, we sort the spectra in $\alpha_{\text{opt}}$ and use a running median filter with a precision of 0.01 in $\alpha_{\text{opt}}$. Using the running median, we essentially incorporate the information of every low S/N spectrum into many high S/N spectra. The stacked spectra of the running median are therefore not statistically independent. We measure the EW of these spectra and present them as small crosses (with no uncertainties) in Figure 5. This is done in order to trace the behavior qualitatively and examine the scatter around each of the 24 independent stacked spectra.

Additionally, we measure the EW of NaID and the median $\alpha_{\text{opt}}$ for 24 independent spectra. The uncertainties in $\alpha_{\text{opt}}$ are dominated by the uncertainty of 0.08 in the correction for emission lines discussed in Section 2.1. The uncertainties in EW(NaID) are calculated during the line fitting.

Figure 5 shows the EW(NaID) versus $\alpha_{\text{opt}}$ relation for the four FWHM bins. The measured EW(NaID) is linearly proportional to $\alpha_{\text{opt}}$, with similar slopes in the different FWHM bins. We fit a linear function of the form

$$\text{EW(NaID)} = a(\alpha - \alpha_0) + b$$  \hspace{1cm} (3)

to the six independent measurements of EW versus $\alpha_{\text{opt}}$ in each FWHM bin, where $\alpha_0$ is the bluest $\alpha_{\text{opt}}$ at each FWHM. We use an orthogonal least square minimization, which takes into account the uncertainties in both variables. The best linear fits are shown in Figure 5 and listed in Table 1.

3. ADDITIONAL EVIDENCE FOR THE CONNECTION BETWEEN $\alpha_{\text{opt}}$ AND $E_{B-V}$

What is the underlying physical explanation of the EW(NaID) versus $\alpha_{\text{opt}}$ relations seen in Figure 5 and listed in Table 1? In observed AGN spectra, $\alpha_{\text{opt}}$ is expected to depend on three components: the slope of the disk SED, the slope of the stellar SED, and the reddening of both. The NaID absorption feature can originate from gas along the line of sight to the AGNs or to the stars, but also from absorption in the photospheres of the stars.

Figure 5 shows that in the lowest-FWHM bin, EW(NaID) goes to zero at $\alpha_{\text{opt}} = -0.1$. As explained in Section 1, and discussed some more in Section 4.2 below, this value of $\alpha_{\text{opt}}$ is similar to the intrinsic spectral slope expected in ADs around BHs in the mass and accretion rate range considered hereafter allowing for host galaxy contribution. Hence, objects that show no NaID absorption also exhibit the continuum slope expected from AD models. This correspondence is consistent with a scenario where the observed distribution in $\alpha_{\text{opt}}$ is driven by the distribution of column of dusty gas along the line of sight, as previously suggested by Ward et al. (1987), Gaskell et al. (2004), and SL12. The blue intrinsic AGN SED is seen only in the few objects with $\alpha_{\text{opt}} = -0.1$ and EW(NaID) ~ 0, while most objects show a redder $\alpha_{\text{opt}} \approx -0.5$ and EW(NaID) \approx 0.8 Å due to extinction by dust and absorption by gas associated with the dust. In the three large FWHM bins,
the slopes of the EW versus $\alpha_{\text{opt}}$ relations are similar to the slope in the FWHM = 2200 km s$^{-1}$ bin. This similarity suggests that the EW versus $\alpha_{\text{opt}}$ relations in all FWHM bins could be driven by the distribution of dusty gas columns along the line of sight. In this section we provide additional observational evidence supporting this conjecture, and in the next section...
Fit parameters for the linear relations between EW and FWHM bins. In the FWHM and listed in Table 1. The slopes of the relations are similar in the different FWHM bins. In the FWHM = 2200 km s⁻¹ bin, we find EW(NaID) = 0 at \( \alpha_{\text{opt}} = -0.1 \). This \( \alpha_{\text{opt}} \) is similar to the intrinsic continuum slope expected from an accretion disk with a BH mass and an accretion rate similar to the ones in our sample. We therefore suggest that most type-1 AGN are reddened by dusty gas along the line of sight where the dust redens the observed slopes to \( \alpha_{\text{opt}} < -0.1 \). The intrinsic accretion disk spectrum is not extincted only in the few AGNs with \( \alpha_{\text{opt}} \approx -0.1 \). The implied \( E_{B-V} \) for each \( \alpha_{\text{opt}} \) (Equation (9)) are noted on top.

### Table 1

| FWHM (km s⁻¹) | \( \alpha_{\text{opt}} \) | EW at \( \alpha_{\text{opt}} \) (Å) | EW Versus \( \alpha_{\text{opt}} \) Slope |
|---------------|----------------|---------------------------------|---------------------------------|
| 2200          | -0.11          | 0.05 ± 0.10                     | -1.92 ± 0.09                   |
| 3400          | -0.12          | 0.58 ± 0.14                     | -1.96 ± 0.08                   |
| 4900          | -0.43          | 1.67 ± 0.16                     | -2.10 ± 0.10                   |
| 7300          | -0.33          | 2.08 ± 0.19                     | -2.00 ± 0.11                   |

**Note.** Fit parameters for the linear relations between EW(NaID) and \( \alpha_{\text{opt}} \) shown in Figure 5.

discussion we confront this conjecture with photoionization calculations of gas exposed to AGN radiation.

### 3.1. Contribution from Stellar Photospheres

In Figure 6 we compare the NaID absorption feature with the Mg b absorption complex. Mg b absorption likely originates in stellar photospheres since it requires a significant population of excited ions, while in the ISM most ions are at the ground state. Hence, we can use Mg b to estimate the stellar photosphere contribution to the trends of EW(NaID) versus \( \alpha_{\text{opt}} \) and EW(NaID) versus FWHM seen in Figure 5. The right panels in Figure 6 show the Mg b absorption features in the normalized spectra from Figure 2, where different rows plot different FWHM bins and different colors denote different \( \alpha_{\text{opt}} \) bins. These features can be compared to the NaID features shown in the left panels.

Measuring EW(Mg b) accurately is complicated by the fact that its wavelengths coincide with the wavelengths spanned by the optical BLR Fe II forest. However, it is evident from Figure 6 that in a given FWHM bin, the Mg b feature does not significantly change with \( \alpha_{\text{opt}} \), in contrast to the significant trend apparent in NaID. The lack of trend in Mg b with \( \alpha_{\text{opt}} \) suggests that the trend of NaID with \( \alpha_{\text{opt}} \) is not due to an increasing contribution from stellar photospheres. In contrast, the strength of the Mg b features increases with increasing FWHM. Therefore, it seems plausible that the trend of
EW(NaID) with FWHM is associated with an increasing contribution from stellar photospheres. The trend of EW with FWHM is further addressed in the discussion.

A stellar photosphere origin is also unlikely to explain the largest EW(NaID) = 4.8 Å we observe (Figure 5) since the maximum EW(NaID) seen in the spectrum of individual stars is 5.6 Å (Burstein et al. 1984; Faber et al. 1985). Therefore, in order to explain an EW of 5 Å with stellar photospheres, one has to populate the entire AGN host with stars that have the maximum EW(NaID), and assume the contribution of the AGN continuum at 6000 Å is entirely negligible, which is unlikely.

3.2. $H\alpha/H\beta$ Versus $\alpha_{opt}$

Various studies suggest that the BLR resides within the dust sublimation radius (Netzer & Laor 1993; Kaspi et al. 2000; Suganuma et al. 2006; Bentz et al. 2009; Koshida et al. 2014), and hence any dust surrounding the AGN will reside on larger scales. The BLR is therefore likely to also be extincted by the dust which reddens the AGN continuum. In this section we test this prediction by comparing the observed BLR Balmer ratio $H\alpha/H\beta$ with $\alpha_{opt}$. This is somewhat similar to Dong et al. (2008) where the aim was to find the line ratio in the bluest (largest $\alpha_{opt}$) AGNs. As shown below, our analysis is more general and applied to the entire sample rather than the sub-group with the smallest $H\alpha/H\beta$.

To calculate the expected $H\alpha/H\beta$ as a function of $\alpha_{opt}$ in our scenario, we quantify the dust extinction in magnitude at wavelength $\lambda$ as $R_{EB-V}$, where $E_{B-V}$ is the color excess which is proportional to the dust column, and $R_{a}$ is the assumed extinction law. Since in our suggested picture $\alpha_{opt}$ is determined by the dust column along the line of sight, $\alpha_{opt}$ is related to $E_{B-V}$ via

$$\alpha_{opt} = R_{3000} - R_{5100} - 2.5 \log(5100/3000) \ E_{B-V}.$$  (4)

Assuming the reddening dust completely covers the BLR, then

$$\log \left( \frac{(H\alpha/H\beta)_{int}}{(H\alpha/H\beta)_{obs}} \right) = \frac{R_{4861} - R_{6563}}{2.5} \ E_{B-V},$$  (5)

where $(H\alpha/H\beta)_{int}$ and $(H\alpha/H\beta)_{obs}$ are the intrinsic and observed $H\alpha/H\beta$ ratios, respectively. Combining Equations (4) and (5) we therefore expect

$$\log \left( \frac{(H\alpha/H\beta)_{obs}}{(H\alpha/H\beta)_{int}} \right) = 0.23 (\alpha_{opt} - \alpha_{opt}) \frac{R_{4861} - R_{6563}}{R_{3000} - R_{5100}} \approx 0.1 (\alpha_{opt} - \alpha_{opt}).$$  (6)

The approximation in Equation (6) is based on the Pei (1992) formulation for the MW-, LMC-, and SMC-type extinction curves, in which $0.23(R_{4861} - R_{6563})/(R_{3000} - R_{5100})$ is equal to 0.099, 0.100, and 0.096, respectively. The similarity of these values is the result of the narrow wavelength range considered here. It suggests that the exact nature of the extinction law is a minor source of uncertainty. In low-density gas $(H\alpha/H\beta)_{int}$ is equal to 2.74–2.86, assuming “Case B” recombination (Osterbrock & Ferland 2006). However, in the dense BLR gas ($>10^9$ cm$^{-3}$), the value of $(H\alpha/H\beta)_{int}$ may be different due to line optical depths and collisional effects (Netzer 2013).

To derive the median $(H\alpha/H\beta)_{obs}$ as a function of $\alpha_{opt}$, we use the catalog of Shen et al. (2011) who measured the broad components of the $H\alpha$ and $H\beta$ emission lines. As the $H\alpha$ emission line is observable only for redshifts $z < 0.4$, we use only the 1296 AGN in the redshift range $0.35 < z < 0.4$. We group the AGN into bins with width $\Delta \alpha_{opt} = 0.1$, and plot the median $(H\alpha/H\beta)_{obs}$ in each bin in the left panel of Figure 7. The uncertainty on $\alpha_{opt}$ is calculated in Section 2.4 and the uncertainty of the median $(H\alpha/H\beta)_{obs}$ is the weighted median of the uncertainties in every $\alpha_{opt}$-bin, where the uncertainties in each bin are measured using the line measurement uncertainties given by Shen et al. (2011). We also show the median $(H\alpha/H\beta)_{obs}$ in different FWHM bins, where each $\alpha_{opt}$ bin contains the same number of objects.

The dashed lines in the left panel of Figure 7 are the expected relations between $(H\alpha/H\beta)_{obs}$ and $\alpha_{opt}$ (Equation (6)), for $\alpha_{opt} = -0.1$ and $(H\alpha/H\beta)_{int} = 3.02 \pm 0.21$, close to the value expected from Case B recombination. This best-fit value is consistent with the Balmer ratio of blue AGNs previously measured by Dong et al. (2008). The uncertainty of 0.21 on the mean $H\alpha/H\beta$ ratio is due to the uncertainties of the mean ratios and the best fit.

It is important to note that the distribution of $H\alpha/H\beta$ ratios for the bluest objects is quite broad ($3.02 \pm 1.19$), and there are many objects with $H\alpha/H\beta$ significantly larger and significantly smaller than 3 with individual uncertainties that clearly distinguish them from the mean. Thus, we see no evidence for a “single-value $H\alpha/H\beta$” which is also supported by Schnorr-Müller et al. (2016), who studied the BLR of nine Seyfert 1 galaxies using up to six broad H$\alpha$ lines in each spectrum. Figure 7 demonstrates that the slope of the relation between $(H\alpha/H\beta)_{obs}$ and $\alpha_{opt}$ is consistent with the expected slope. The best-fit slope of the entire sample is:

$$\log \left( \frac{(H\alpha/H\beta)_{obs}}{3.02} \right) = (0.0950 \pm 0.053)(\alpha_{opt} - \alpha_{opt}),$$  (7)

while the best fit for each of the FWHM 2200, 3400, 4900, and 7300 km s$^{-1}$ bins is

$$\log \left( \frac{(H\alpha/H\beta)_{obs}}{3.01} \right) = (0.103 \pm 0.0091)(\alpha_{opt} - \alpha_{opt})$$

$$\log \left( \frac{(H\alpha/H\beta)_{obs}}{3.36} \right) = (0.064 \pm 0.016)(\alpha_{opt} - \alpha_{opt})$$

$$\log \left( \frac{(H\alpha/H\beta)_{obs}}{3.37} \right) = (0.0876 \pm 0.0094)(\alpha_{opt} - \alpha_{opt})$$

$$\log \left( \frac{(H\alpha/H\beta)_{obs}}{3.50} \right) = (0.0728 \pm 0.0079)(\alpha_{opt} - \alpha_{opt})$$  (8)

respectively. Therefore, the dependence of $(H\alpha/H\beta)_{obs}$ on $\alpha_{opt}$ supports our interpretation that $\alpha_{opt}$ is determined by the dust column along the line of sight, such that $E_{B-V}$ can be derived from $\alpha_{opt}$ via Equation (4).

Given the typical $E_{B-V}$, we can also study the effect of reddening on additional broad lines at shorter wavelengths, in particular the Lo/H$\beta$ ratio. For galactic-type reddening, and $E_{B-V} = 0.08$ mag, we would predict the observed ratio to be 3.8 times smaller than the intrinsic one. This issue has been discussed extensively in numerous papers since the late 1970s (see Netzer & Davidson 1979). Moreover, Netzer et al. (1995) and Bechtold et al. (1997) showed that the Lo/H$\beta$ ratio is strongly correlated with the continuum luminosity ratio.
These studies, and several others that followed, are all based on very small samples and will not be discussed further in this paper.

We also calculate the median \((\text{H}\alpha/\text{H}\beta)_{\text{obs}}\) of the NLR as a function of \(\alpha_{\text{opt}}\), using the narrow components of \(\text{H}\alpha\) and \(\text{H}\beta\) measured by Shen et al. (2011). These NLR measurements might be subjected to significant uncertainties since the NLR is weak compared to the BLR in luminous AGNs and separating the two profile components is challenging and occasionally highly uncertain. The relation between \((\text{H}\alpha/\text{H}\beta)_{\text{obs}}\) in the NLR and \(\alpha_{\text{opt}}\) is shown in the right panel of Figure 7. The value of \((\text{H}\alpha/\text{H}\beta)_{\text{obs}}\) at \(\alpha_{\text{opt}} = \alpha_0\) is 4.07 ± 0.48, larger than the Case B value of 2.74–2.86. This is not unexpected, since the Balmer photons are likely extincted by dust within the NLR clouds, thus increasing \((\text{H}\alpha/\text{H}\beta)_{\text{int}}\) above the Case B value (see Figure 6 in Stern et al. 2014 and also Dopita et al. 2002). The observed slope of the relation between \((\text{H}\alpha/\text{H}\beta)_{\text{obs}}\) and \(\alpha_{\text{opt}}\) in the NLR is shallower than the expected slope derived in Equation (6) and observed in the BLR. The weaker reddening of the NLR may be because the NLR emission line region is extended, and hence only part of the sightlines to the NLR traverse the extincting dust. This is in contrast with the BLR, which is compact and lies behind all the dust.

### 3.3. Comparison with \(N_{\text{NaI}}\) Versus \(E_{B-V}\) in Local Galaxies

In our suggested scenario, \(\alpha_{\text{opt}}\) is related to \(E_{B-V}\) via Equation (4). The coefficient in Equation (4) can be calculated for an assumed extinction law, which gives

\[
E_{B-V,\text{MW}} = 0.188(\alpha_0 - \alpha_{\text{opt}})
\]
\[
E_{B-V,\text{SMC}} = 0.209(\alpha_0 - \alpha_{\text{opt}})
\]
\[
E_{B-V,\text{LMC}} = 0.194(\alpha_0 - \alpha_{\text{opt}})
\]
\[
E_{B-V,\text{GB}} = 0.239(\alpha_0 - \alpha_{\text{opt}})
\]

where we used the prescriptions for the MW, SMC, and LMC extinction laws from Pei (1992), and also the “gray dust” formulation from Gaskell & Benker (2007). For simplicity, we henceforth assume an MW extinction law, though the results remain the same when applying SMC, LMC, or GB extinction laws instead. Equation (9) implies that for \(\alpha_0 = -0.1\), a typical AGN with \(\alpha_{\text{opt}} = -0.5\) has \(E_{B-V} = 0.08\) mag.

Applying Equation (9) to the EW(NaID) versus \(\alpha_{\text{opt}}\) relation found for the FWHM = 2200 km s\(^{-1}\) bin (Table 1) we get

\[
\frac{\text{EW(NaID)_{QSO}}}{\text{Å}} = (10.08 \pm 0.55)E_{B-V}
\]

This relation is seen in Figure 5 (black dashed line).

In the left panel of Figure 8, we compare Equation (10) to the EW(NaID) versus \(E_{B-V}\) relations observed in the ISM of local galaxies. We show the measurements of Poznanski et al. (2012, hereafter P12), who used over a million extragalactic SDSS spectra stacked in the observer frame to study the mean relation between sodium absorption and dust extinction in the MW. Figure 8 shows that in the MW, EW(NaID) saturates after reaching EW \(\sim 1\) Å, while in the AGN studied here a linear dependence between EW(NaID) and \(E_{B-V}\) persists to higher values of EW(NaID). The difference in the EW where the absorption feature saturates may be due to the difference...
between the integrated velocity fields along stacked MW sightlines, compared to the integrated velocity fields along stacked sightlines to the centers of AGN hosts.

In order to compare the P12 relation to the relation found here, we fit a linear relation to the measurements of P12 in the optically thin regime (blue line), which is:

$$\frac{\text{EW}(\text{NaID})_{\text{MW}}}{\text{Å}} = (12.54 \pm 0.35) E_{B-V}.$$  

One can see that this relation is close to that we find for AGNs in Equation (10).

Additional NaID measurements for the MW and Magellanic Clouds (SMC, LMC) have been compiled by Welty et al. (2012, hereafter W12)\(^5\) and contain measurements by Welty et al. (2006) and Cox et al. (2006). Since the W12 measurements are given toward individual lines of sight rather than in stacked spectra, the relation exhibits a large scatter. This scatter implies an uncertainty in the $E_{B-V}$ limit in which the optically thin regime ends. We therefore can obtain only lower and upper limits on the linear relation of EW(NaID) and $E_{B-V}$:

$$\frac{\text{EW}(\text{NaID})_{\text{SMC}}}{\text{Å}}_{\text{min}} = (9.92 \pm 0.72) E_{B-V}$$

$$\frac{\text{EW}(\text{NaID})_{\text{SMC}}}{\text{Å}}_{\text{max}} = (15.05 \pm 0.61) E_{B-V}.$$  

The upper and lower limit for the SMC measurements is also shown in Figure 8. This relation is consistent with the AGN relation.

In the right panel of Figure 8 we show the relation between $E_{B-V}$ and $N_{NaI}$. We perform the comparison also in $N_{NaI}$ due to the difference in velocity dispersion between the different environments. Since there is no evidence of saturation in the AGN sample, we use the optically thin limit to calculate $N_{NaI}$ (e.g., Draine 2011):

$$N_{NaI} = 3.4 \cdot 10^{12} \left(\frac{\text{EW}(\text{NaID})}{\text{Å}}\right) \text{cm}^{-2},$$

which together with Equation (10) yields

$$N_{NaI} = (3.4 \pm 0.2) \cdot 10^{13} \frac{E_{B-V}}{\text{mag}} \text{ cm}^{-2}. \quad (14)$$

For the other samples we use the $N_{NaI}$ published in the respective papers. Note that while the QSO and P12 measurements are mean relations, the Welty measurements are individual measurements that give a sense of the scatter around this mean. As implied by the left panel, the relation between $N_{NaI}$, EW(NaID) and $E_{B-V}$ is similar in all environments shown in Figure 8.

4. DISCUSSION

4.1. $N_{NaI}$ and Reddening in AGN Photoionized Gas

Gas associated with dust along the line of sight to the central BH will be photoionized by the AGN radiation. We can therefore compare the observed relation between EW(NaID) and $E_{B-V}$ to the relation expected in gas in photoionization equilibrium in the vicinity of the AGNs.
4.1.1. The Expected EW(NaID)

The ratio of the neutral sodium column \( N_{\text{Na}} \) to \( E_{B-V} \) is

\[
\frac{N_{\text{Na}}}{E_{B-V}} = \frac{f_{\text{Na}1}}{\mu_{\text{Na}}} \cdot \frac{N_{\text{H}}}{{m}_p} \cdot \frac{\Sigma_{\text{d}}}{\Sigma_{\text{d}}} = 1.2 \cdot 10^{16} N_{\text{Na}} \cdot \left( \frac{N_{\text{Na}}}{\mu_{\text{Na}}} \right) \left( \frac{\Sigma_{\text{d}}}{\Sigma_{\text{d}}} \right) \text{ cm}^{-2} \text{mag}^{-1} \quad (15)
\]

where \( f_{\text{Na}1} \) is the fraction of sodium which is neutral, \( N_{\text{Na}} \) is the sodium column, \( N_{\text{Na}}/N_{\text{H}} \) is the sodium abundance relative to hydrogen, \( X \) is the hydrogen mass fraction, \( \Sigma_{\text{d}} = N_{\text{d}}/m_{\text{d}}/X \) [g cm\(^{-2}\)] is the gas surface density, and \( \Sigma_{\text{d}} \) is the dust surface density \( (\Sigma_{\text{d}}/\Sigma_{\text{g}} \) is the dust-to-gas ratio). The numerical values are for Galactic dust, while the sodium abundance is normalized by its solar value.\(^6\) Comparison of Equation (15) with (14) suggests \( f_{\text{Na}1} \approx 0.003 \).

The value of \( f_{\text{Na}1} \) depends mainly on the ionization parameter \( U \):

\[
U \equiv \frac{\int_{0}^{\infty} L_\nu/(h\nu) d\nu}{4\pi r_\odot^2 n_e c}, \quad (16)
\]

where \( \nu_\odot \) is the Lyman-edge frequency, \( r_\odot \) is the distance of the gas from the central radiation source, and \( c \) is the speed of light. The dependence of \( f_{\text{Na}1} \) directly on \( n_e \) or \( r_\odot \) (beyond the dependence on \( U \) ) is weak. To constrain \( U \) based on the observed relation, we run version 13.03 of CLOUDY (Ferland et al. 2013) with a MW grain mixture and the following SED shape. The intrinsic optical–UV slope is assumed to be equal the \( \alpha_{\text{opt}} = -0.1 \) found above, in the range 1100 Å < \( \lambda < 1 \) μm. The X-ray luminosity at 2 keV is set such that the (observed) optical to X-ray ratio is equal to typical values seen in \( L = 10^{45} \) erg s\(^{-1}\) AGNs (Just et al. 2007). For simplicity, we interpolate with a single power law between 1100 Å and 2 keV. At \( \lambda > 1 \) μm, 2 keV < \( h\nu < 100 \) keV, and \( h\nu > 100 \) keV we assume spectral slopes of 2, -1, and -2, respectively. We run models with \( U \) in the range \( 10^{-4} \)–\( 10^{-1} \), corresponding to \( n_e = 10^{10} \)–\( 10^{12} \) (\( r_\odot \)/kpc\(^{-2}\)) cm\(^{-3}\) for a \( L_\text{bol} = 10^{45} \text{erg s}^{-1} \) AGN with the above SED. We include in the calculation the effect of radiation pressure on the dust grains, which is significant at \( U \geq 0.01 \) (Dopita et al. 2002; Groves et al. 2004). We use the depleted ISM abundance set implemented in CLOUDY, except for the sodium abundance which we assume has solar abundance. The total gas column is set to equal \( N_{\text{H}} = 4.4 \times 10^{20} \) cm\(^{-2}\) which reproduces the typical \( E_{B-V} = 0.08 \) mag found above.

Figure 9 shows the EW(NaID) calculated by CLOUDY for different \( U \), compared to the observed EW(NaID) \( \approx 0.8 \) Å. The observed EW(NaID) is reproduced for \( U \approx 10^{-2.5} \). Note that only in low-ionized gas (\( U \lesssim 0.01 \)) is any Na I absorption expected. In gas with a higher ionization level \( f_{\text{Na}1} \) is practically zero. This conclusion is robust to reasonable changes in the assumed SED shape, the assumed gas metallicity, or the exact amount of sodium depletion.

\(^6\) Weingartner & Draine (2001) provide circumstantial evidence that sodium is not strongly depleted in the MW ISM.
of the optically thick dust with the optical–UV luminosity (Maiolino et al. 2007; Treister et al. 2008; Mor & Trakhtenbrot 2011; Mor & Netzer 2012; Lusso et al. 2013; Roseboom et al. 2013; Netzer et al. 2015; Stalevski et al. 2016). Both types of analyses suggest $f_\alpha \sim 0.5$ (see review in Netzer 2015).

Figure 9 plots EW(narrow H\textalpha) calculated in the CLOUDY models described above, which span the range $U = 10^{-4} - 10$. Note that we approximate the distribution of $N_{\text{H}_2}$ along different lines of sight with the $N_{\text{H}_2}$ of the typical AGNs. For comparison, we plot the range of EW(narrow H\textalpha emission) from the dusty gas allowed by observations, which is $<14$ Å. The value of 14 Å is the observed EW of the narrow H\textalpha line in our sample measured by Shen et al. (2011). This estimate is an upper limit on the H\textalpha emission from the line of sight dust, since at least some of the narrow H\textalpha emission is expected to originate from optically thick NLR clouds. Figure 9 shows that only high $U > 0.1$ models are consistent with the upper limit on the H\textalpha line. Therefore, any model that reproduces the strength of the NaID absorption implies a huge H\textalpha emission line which is inconsistent with observations, while models that are consistent with the observed narrow H\textalpha lines are inconsistent with our measured EW(NaI). This conclusion is independent of the exact form of the SED shape or the assumed metallicity, and is corroborated by other strong lines such as [O III] 5007 Å.

### 4.2. Alternative Scenario

In Figure 7, we showed that the dust that reddens the continuum also extends the BLR, which suggests that the dust resides along the line of sight to the central source. However, Figure 9 suggests that gas along these sightlines is highly ionized, and is not expected to create a Na I absorption feature. Why then are $\alpha_{\text{opt}}$ and EW(NaID) correlated?

One possibility is that the dusty gas is the ISM of the host galaxy, as depicted in the schematic cartoon in Figure 10. At host galaxy scales ($\gtrsim$kpc), some of the gas will be ionized by the AGN, but some of the gas will be shielded from the AGN radiation via obscuration on smaller scales (e.g., by the torus). In this picture, dust extinction occurs on all sightlines, both the sightline to the AD and BLR and the sightlines to the stars. Neutral sodium, however, exists only in shielded regions, and hence the Na I absorption feature is imprinted only on the stellar continuum. A correlation between $\alpha_{\text{opt}}$ and EW(NaID) is then expected if ISM columns along shielded and non-shielded sightlines are correlated. Such a correlation seems plausible, for example, if the range of ISM columns is driven by the inclination of our line of sight relative to the host galaxy disk. In this case, both non-shielded and shielded sightlines are expected to have larger columns in edge-on hosts compared with face-on hosts. Another possibility is that the range of ISM columns is driven by the total ISM mass. In this scenario as well, ISM-rich hosts are expected to exhibit larger columns than ISM-poor hosts along all sightlines, which would produce the observed correlation.

Is the relative stellar contribution to the continuum $f_{\text{host}}$ at 6000 Å large enough that the NaID absorption feature is expected to be observable? SL12 found that in low-$z$ SDSS AGNs with $L_{\text{bol}} = 10^{45.2}$ erg s$^{-1}$, which is the mean $L_{\text{bol}}$ of the objects analyzed here (Figure 1), the average host emission through the SDSS 3′′ fiber is half of the AGN continuum emission at 6000 Å, i.e., $f_{\text{host}} (6000 \text{ Å}) = 0.33$ (see their Figure 13). This comparable AGN and host contributions to the continuum is further supported by the median EW(broad H\textalpha) of 300 Å in our sample (measured by Shen et al. 2011 on objects in which H\textalpha is observed), compared to the mean EW(broad H\textalpha) of 570 Å relative to the AGN continuum found by SL12. For comparison, Figure 2 shows that the deepest NaID absorption feature in our stacked spectra is only 10% of the continuum emission. Therefore, it is possible that the NaID absorption feature is imprinted only on the stellar emission.

This suggested scenario naturally explains the similarity of the $N_{\text{Na}_1}$ versus $E_{B-V}$ relation in QSOs and in local galaxies shown in Figure 8 since the conditions in the shielded ISM of AGN hosts are plausibly not very different from those in an inactive galaxy. Also, this large-scale dust scenario is supported by the analysis above of the NLR Balmer ratio (Figure 7) and the analysis of the NLR BPT ratios versus $L_{\text{UV}}/L_{\text{bol}}$ in type-1 AGNs (Stern & Laor 2013), both of which suggest that the scale of the reddening dust is at least as large as the NLR, i.e., on scales much larger than 100 pc for the luminous objects in our sample.

The non-negligible host contribution also suggests the intrinsic AD slope is bluer than the value of $\alpha_{\text{opt}}$ found here. Assuming $f_{\text{host}} (3000 \text{ Å}) = 0.1$ and $f_{\text{host}} (5100 \text{ Å}) = 0.25$, as suggested by Shen et al. (2011) and SL12 for $L_{\text{bol}} = 10^{45.2}$ erg s$^{-1}$ AGN, implies an intrinsic AD slope which is larger by 0.35 than found above, i.e., an intrinsic AGN slope of $\alpha_{\text{opt}} + 0.35 = 0.25$. This value is consistent with the slope of $\sim$0.2 expected for the average $M_{\text{BH}} = 0.7 \cdot 10^6 M_\odot$ and $L/L_{\text{Edd}} = 0.25$ found by Shen et al. (2011) in objects with FWHM = 2000 km s$^{-1}$. We note though that a more careful

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7 We estimate $f_{\text{host}} (3000 \text{ Å})$ by interpolating the values of $f_{\text{host}} (3940 \text{ Å})$ and $f_{\text{host}}$ (NUV) implied by the SL12 calculation. The NUV emission in the SL12 objects corresponds to an average rest frame wavelength of 1900 Å (see Table 2 there).
decomposition between the host continuum, the AGN continuum, and the line emission as a function of FWHM and $\alpha_{\text{opt}}$ is required to derive accurately the true intrinsic AD slope.

4.3. Can the Range in $f_{\text{host}}$ Drive the EW(NaID) Versus $E_{B-V}$ Relation?

In the scenario suggested in the previous section, EW(NaID) is expected to increase with $f_{\text{host}}$. Since host galaxies have redder optical slopes than AGNs, then a large $f_{\text{host}}$ would also imply a relatively red $\alpha_{\text{opt}}$. One may therefore wonder whether the $\alpha_{\text{opt}}$ versus EW(NaID) relation is actually driven by the range in $f_{\text{host}}$ in the sample rather than by the distribution in the dusty gas column as suggested above. We find this possibility unlikely for a few reasons. First, in this varying host contribution scenario one would expect the Mg b feature to become stronger with decreasing $\alpha_{\text{opt}}$. Figure 6 suggests that there might be a weak increase in EW(Mg b) with $\alpha_{\text{opt}}$ in the largest FWHM bins, but this trend is significantly weaker than the trend of EW(NaID) with $\alpha_{\text{opt}}$, and hence the change in the host contribution with $\alpha_{\text{opt}}$ implied by Mg b is insufficient to explain the relation of EW(NaID) with $\alpha_{\text{opt}}$. Second, a change in host contribution fails to explain why the broad Hα/Hβ ratio changes with $\alpha_{\text{opt}}$ (Figure 7). And third, the required change in $f_{\text{host}}$ should be evident as a change in EW(broad Hα) with $\alpha_{\text{opt}}$, in contrast to the reddening scenario where EW(broad Hα) is expected to remain constant. In our sample, objects with $\alpha_{\text{opt}} = -0.4$ have a median EW(broad Hα) = 340 Å which suggests $f_{\text{host}}$ (6560 Å) ≈ 1 − 340/570 = 0.4, while objects with $\alpha_{\text{opt}} = -1.5$ have a median EW(broad Hα) = 270 Å which suggests $f_{\text{host}}$ (6560 Å) ≈ 1 − 270/570 = 0.52. Therefore, $f_{\text{host}}$ likely increases by a mild factor of ~1.3 from objects with $\alpha_{\text{opt}} = -0.4$ to objects with $\alpha_{\text{opt}} = -1.5$. This increase in $f_{\text{host}}$ fails short of the increase in the median EW(NaID) by a factor of 3.6, from 1.1 Å at $\alpha_{\text{opt}} = -0.4$ to 4.0 Å at $\alpha_{\text{opt}} = -1.5$.8 Therefore, the change in $f_{\text{host}}$ implied by the change in EW(broad Hα) is too weak to explain the EW(NaID) versus $\alpha_{\text{opt}}$ relation.

We note that a correlation between $\alpha_{\text{opt}}$ and $f_{\text{host}}$ is also expected if the physical size spanned by the SDSS fiber changes with $\alpha_{\text{opt}}$. However, no such trend exists in our sample. Objects with $\alpha_{\text{opt}} = -2$ have a mean $\varepsilon$ of 0.41, similar to the mean $\varepsilon$ = 0.435 of objects with $\alpha_{\text{opt}} = 0$.

4.4. EW(NaID) and $\alpha_0$ Versus FWHM(H3)

What is the origin of the offset between the EW(NaID) versus $E_{B-V}$ relations in different FWHM bins (Figure 5)? Assuming the BLR is in virial motion, then $M_{\text{BH}} \propto \text{FWHM}^2 R_{\text{BLR}}$, where $R_{\text{BLR}}$ is the size of the BLR. Reverberation mapping studies have shown that $R_{\text{BLR}} \propto L^{0.6-0.1}$ (Kaspi et al. 2005; Bentz et al. 2009). Therefore, in our sample where the dynamical range in L is small (Figure 1), we expect $M_{\text{BH}}$ to increase with FWHM. The different implied $M_{\text{BH}}$ in the different FWHM bins may suggest a different intrinsic AGN SED, which can change $\alpha_0$.

Another possible difference between the different FWHM bins arises from the the well-known relations between $M_{\text{BH}}$ and

8 The values of $\alpha_{\text{opt}} = -0.4$ and $\alpha_{\text{opt}} = -1.5$ are chosen for this test to avoid the difference in FWHM distribution implied by using objects with $\alpha_{\text{opt}} > -0.4$ or $\alpha_{\text{opt}} < -1.5$ (see Figure 5).

![Figure 11. Implied $E_{B-V}$ distributions for different FWHM bins (noted in km s$^{-1}$) in the AGN sample. The value of $E_{B-V}$ is derived from $\alpha_{\text{opt}}$ using $E_{B-V} = 0.2 (\alpha_0 - \alpha_{\text{opt}})$ (Equation (9)) and assuming the $\alpha_0$ listed in Table 1. The median $E_{B-V}$ in each panel is marked by a dotted line. The entire sample has a mean $E_{B-V} = 0.11$ mag and a median $E_{B-V} = 0.08$ mag.](image-url)
Figure 11. Alternatively, assuming that $\alpha_0$ at all FWHM bins is equal to the $\alpha_0 = -0.1$ found for FWHM = 2200 km s$^{-1}$ implies a somewhat larger mean $E_{B-V} = 0.13$ mag and median $E_{B-V} = 0.1$ mag. In the extreme case where $\alpha_0$ is equal to the extrapolation of the EW(NaID) versus $\alpha_{opt}$ relation to EW(NaID) = 0 ($\alpha_0 = 0.18, 0.37, 0.71$ for FWHM = 3500, 4900, and 7500 km s$^{-1}$, respectively), the implied mean $E_{B-V}$ is 0.19 mag and the median $E_{B-V}$ is 0.17 mag.

To summarize, at least half of the AGNs in our sample have $E_{B-V} > 0.08$ mag, and at least a quarter have $E_{B-V} > 0.18$ mag. For comparison, Lusso et al. (2013) found that only 24% of type 1s in the XMM-COSMOS survey have $E_{B-V} > 0.1$ mag. Krawczyk et al. (2015) found that 2.5% (13%) of the non-BALs (BALs) in their SDSS-based sample have $E_{B-V} > 0.1$ mag, and 0.1% (1.3%) have $E_{B-V} > 0.2$ mag. Capellupo et al. (2015) found that 70% of their sample have negligible dust columns. The lower dust columns found by previous studies compared to this work (except for Capellupo et al. 2015) are a direct result of their assumption that the typical AGN is not reddened by dust.

Using the cloudy models described above, we obtain the fraction of incident radiation absorbed by the dusty gas for the typical $E_{B-V} = 0.08$ mag AGN ($\alpha_{opt} = -0.5$). We find that given the assumed SED and grain properties, about a third of the incident, radiation, integrated over all wavelengths, is absorbed by the dust along a typical line of sight. This result suggests that the bolometric luminosity $L_{bol}$ of type-1 AGNs, as derived from the optical, are typically underestimated by a factor of $(2/3)^{-1} = 1.5$.

4.6. Expected Far-infrared (FIR) and X-Ray Properties

Given the very high level of ionization of the newly suggested line of sight gas, the corresponding column of dust, and the large covering factor, we need to consider other types of emission and absorption by this component.

The CLOUDY model described above can be used to estimate the fraction of the radiation absorbed by the dusty line of sight component for every value of $E_{B-V}$ and covering factor. As before, we do not consider a component which is less than about 100 pc from the center since our model assumes similar column densities on galactic scales. As already noted, for the typical $E_{B-V} = 0.08$ mag case, approximately a third of the incident radiation is absorbed by the dust. Given the assumed distance, this energy must be re-radiated at FIR energies with peak wavelength that depend on the dust location. For ISM-type densities ($\sim 1$ cm$^{-3}$) and a typical bolometric luminosity of $10^{45}$ erg s$^{-1}$, the required $U$ of $\sim 1$–10 (Figure 9) is achieved at 1–10 kpc. The corresponding dust temperatures, assuming optically thin dust and graybody emission with a spectral emissivity index $\beta = 1.5$–2 is in the range 10–40 K. Given the fraction absorbed and a typical covering factor of $\sim 0.5$, the total luminosity emitted in the FIR is hence of order 0.15 $L_{bol}$. The FIR emission in individual objects may vary significantly around this average value depending on the $E_{B-V}$ distribution along different directions in single sources which could be different than the $E_{B-V}$ distribution seen in a sample. However, the ensemble average FIR emission is very large and such emission cannot escape detection. We note that there are also other claims in the literature for cold dust in AGNs (e.g., Symeonidis et al. 2016), but these results are still open to interpretation.

It is not our intention to investigate the issue of FIR emission by the obscuring dusty gas in this paper. Such a study requires more detailed considerations, comparison with other FIR sources of emission (mostly star formation in the host galaxy), and more. We will return to this topic in a forthcoming publication.

The consideration detailed above, which is summarized in Figure 9, suggests $U \sim 1$–10. Such a large ionization parameter is typical of X-ray gas in AGNs (Netzer 2013) and may have observational consequences that have not been studied so far. For example, if $U \sim 10$ and the UV—X-ray SED is typical of AGNs with $L_{bol} = 10^{45}$ erg s$^{-1}$, elements like O, Ne, Mg, and Si will be very highly ionized. In this case, the strongest X-ray features are absorption and emission lines of O VIII, Ne X, Mg X, etc. Emission line intensities, absorption line EWs, and other properties depend, again, on the gas distribution, velocity field, and level of ionization at different locations. This topic is beyond the scope of the present paper and is differed to our future paper.

5. CONCLUSIONS

We use 4946 $L_{bol} \approx 10^{45}$ erg s$^{-1}$ QSOs at $z \sim 0.4$ from the SDSS and bin them by their optical slope $\alpha_{opt}$ and FWHM of the broad H$\beta$ line. We measure $\alpha_{opt}$ and the EW of the NaID absorption doublet on the stacked spectrum of each bin. Our results can be summarized as follows.

1. For each bin in FWHM, we find a linear relation between $\alpha_{opt}$ and EW(NaID), such that EW(NaID) increases as $\alpha_{opt}$ becomes smaller (redder continuum). The slopes of these relations are similar in all FWHM bins. In the smallest 1000 < FWHM < 3000 km s$^{-1}$ bin we find EW(NaID) = 0 at $\alpha_{opt} = -0.1$. A similar trend is not seen in the Mg$b$ photospheric absorption feature, suggesting that the trend in NaI has an interstellar origin.

2. The blue slope corresponding to EW(NaID) = 0 is similar to that predicted for a thin AD after allowing for the host galaxy contribution. This result is consistent with a scenario where the observed $\alpha_{opt}$ distribution in AGNs is driven by the column of dust along the line of sight, as previously suggested by several studies. The relationship between slope and reddening by dust is given by $E_{B-V} \approx 0.2 \cdot (0.1 - \alpha_{opt})$. The reddening of a typical type-1 AGN with $L_{bol} = 10^{45}$ erg s$^{-1}$ and $\alpha_{opt} = -0.5$ is $E_{B-V} \approx 0.08$ mag, suggesting that AGN bolometric luminosities are typically underestimated by $\approx 40\%$.

3. The ubiquitous reddening dust interpretation is further supported by the observed relation between $\alpha_{opt}$ and the BLR H$\alpha$/H$\beta$ ratio. In unreddened objects the mean line ratio is $H\alpha/H\beta \sim 3$, similar to the result of Dong et al. (2008), though with a broad distribution in the range 1.5–4 which suggests that simple Case B recombination cannot explain the ratio in all sources.

4. Photoionization calculations show that neutral sodium does not exist in appreciable quantities in gas exposed to the AGN radiation. We therefore suggest that the dusty gas is the ISM of the host galaxy, and that the NaID absorption feature arises in regions shielded from the AGN radiation, along the line of sight to the stars. The correlation of $\alpha_{opt}$ with EW(NaID) hence arises from the plausible assumption that the ISM columns along
shielded and non-shielded sightlines are correlated. This suggested scenario is supported by the similarity of the \( E_{\text{B} - \text{V}} \) vs NaI column relation found here and the same relation in the Milky Way found by Poznanski et al. (2012). Therefore, our results suggest that the observed optical–UV continuum slopes of quasars provide a novel constraint on the ISMs of their host galaxies, which could be useful, for example, for studies simulating AGN feedback. Other observational consequences that are not discussed in the present work, are significant FIR emission and X-ray absorption by the new component.

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