NO EVIDENCE OF “GRAY” DUST FROM COMPOSITE QUASAR SPECTRA

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ABSTRACT

Two recent studies based on composite reddened quasar spectra have indicated the presence of “gray” dust in quasar environments. This gray dust has a relatively flat extinction law in the UV, consistent with the theoretical expectation of a lack of small dust grains close to a quasar. In contrast, individual reddened quasars in the Sloan Digital Sky Survey tend to have steep extinction laws in the UV, similar to that in the SMC. We analyze the method used in determining extinction laws from composite quasar spectra in order to resolve this discrepancy. We show that quasars reddened by SMC-type dust that are present in quasar samples have a negative correlation between $E_{B-V}$ and redshift, due to selection effects. The fact that the highest redshift quasars (which contribute to the UV part of a composite spectrum) are less extincted leads to shallower extinction in the UV. We construct a composite quasar spectrum from a simulated sample of quasars reddened by SMC-type dust and show that the extinction curve derived from the composite does not recover the intrinsic extinction law. We conclude there is no evidence of gray dust in quasar environments.

Subject headings: dust, extinction — galaxies: active

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1. INTRODUCTION

Only $<0.01\%$ of matter in galaxies is composed of dust—coagulations of atoms and molecules with sizes ranging from a few angstroms to a few microns (Seaquist et al. 2004). However, the combined effects of extinction, scattering, and thermal emission from dust have a profound impact on our view of the universe. For example, about half of the energy emitted as visible/UV radiation by stars in distant galaxies has been reprocessed by dust into infrared emission.

Understanding the properties of this dust is vital. While dust in our Galaxy and the Magellanic Clouds has been heavily studied (see, e.g., the review by Draine 2003), there has been only limited work in external galaxies, especially at high redshift. Of particular interest is the possibility that “gray” dust is commonplace at high redshifts. Gray dust is characterized by a flat extinction curve in the UV and as such could be hard to identify from rest-frame UV data alone (i.e., observed-frame optical for sources at high redshift). Large surveys underway to measure cosmological parameters from the Hubble diagram of Type Ia supernovae could be seriously affected by the presence of unknown quantities of gray dust at high redshift (Aguirre 1999).

One of the best ways to study dust extinction in distant galaxies is via the effect that dust has on background quasars. Quasars provide a bright UV source that can still be detected at high significance even after significant absorption. However, a caveat is that if the dust extinction occurs close to the active nucleus, then the unusual gas density and radiation field could lead to atypical dust properties.

In the past, radio-loud quasar surveys have proved most fruitful for searching for reddened quasars due to the fact that radio emission is unaffected by dust (Webster et al. 1995; Baker & Hunstead 1995; Gregg et al. 2002; White et al. 2003). However, the vast area and generous color selection criteria employed by the Sloan Digital Sky Survey (SDSS) mean that it has discovered hundreds of reddened quasars (Richards et al. 2003). In an analysis of the continuum shapes of 9566 SDSS quasars, Hopkins et al. (2004) showed that the dust extinction is best fit by dust similar to that in the SMC, i.e., extinction increasing sharply in the UV. This work included 1886 SDSS quasars with Two Micron All Sky Survey matches, which give the longer wavelength baseline necessary to better distinguish between different extinction laws.

In stark contrast to the results from Hopkins et al. (2004), there have been two recent studies that claim that the UV extinction curves in quasars are gray or flatten in the UV (Czerny et al. 2004; Gaskell et al. 2004). Both these works use the ratios of reddened and unreddened composite quasars to derive quasar extinction laws. In this Letter we analyze their methodology to understand the discrepancy between these works and that of Hopkins et al.

2. USING COMPOSITE QUASAR SPECTRA TO DERIVE EXTINCTION LAWS

The existence of large digital quasar surveys has led to the commonplace technique of combining spectra of many quasars into a composite spectrum (Francis et al. 1991; Baker & Hunstead 1995; Zheng et al. 1997; Brotherton et al. 2001; Vanden Berk et al. 2001). These composites improve the signal-to-noise ratio and wavelength baseline and also allow “typical” quasar properties to be determined. However, the range in rest-frame wavelengths as a function of redshift probed by optical spectroscopy means there may be very little overlap between the quasars that formed the rest-frame optical and UV parts of the spectrum. Given that luminosity and redshift are always correlated in flux-limited samples, this means that there is also a luminosity dependence of the composite as a function of wavelength.

Czerny et al. (2004) used the five SDSS composites generated by Richards et al. (2003) to determine the quasar extinction law. These composites were generated from quasars separated into five bins based on the relative $g' - i'$ colors (the colors with respect to the median as a function of redshift; see Richards et al. for more details); composites 1 and 2 lie on the blue side of the $g' - i'$ distribution, and 3 and 4 lie on the red side. The quasars for composite 5 (the “reddened composite”)
were defined by a relative $g' - i'$ that was a function of redshift to incorporate the redshift-dependent effect of dust reddening on observed frame colors. Richards et al. considered the asymmetric color distribution and the emission-line properties of composites 1–5 and concluded that the differences between 1–4 were due to a combination of dust reddening and intrinsic spectral slopes, and that the intrinsic differences dominate. Czerny et al., however, assume that the bluest quartile SDSS composite 1 represents an unreddened quasar and composites 3–5 differ from 1 solely due to dust reddening. An extinction curve is generated by dividing composites 3–5 by composite 1 and averaging the result. For this reason alone, we do not expect the Czerny et al. curve to truly represent dust reddening. As we will show, there is a further effect that casts doubt on their results.

Gaskell et al. (2004) used composite quasars from Baker & Hunstead (1995) to determine a quasar extinction law. Baker & Hunstead generated composite quasar spectra for four groups of radio-loud quasars from the Molonglo Quasar Survey (MQS). The groups were defined by the ratio of the radio fluxes of the core and lobe, $(R)$. $(R)$ is an orientation indicator, and Baker & Hunstead found that the composite spectrum of low-$\mathcal{R}$ quasars is redder than the high-$\mathcal{R}$ composite, presumably due to dust reddening by a torus perpendicular to the radio jet axis. Baker & Hunstead also produced a composite compact steep-spectrum quasar, and this also appeared highly reddened, although in this case the explanation is more likely to be an evolutionary effect. Gaskell et al. used a similar method to Czerny et al. and compared the $\mathcal{R} < 0.1$ composite to the $\mathcal{R} \geq 1$ composite and the compact steep-spectrum composite to the $0.1 \leq \mathcal{R} < 1$ composite. The extinction curves from these two pairs agree very well. Gaskell et al. also compared the $\mathcal{R} \geq 1$ composite to the UV-selected composite spectrum of the Large Bright Quasar Survey (LBQS; Francis et al. 1991), which showed a similar extinction curve. However, since the $\mathcal{R} \geq 1$ composite is the least reddened of all the radio-loud composites, it is not clear that differences between this and the LBQS composite can be attributed to reddening rather than intrinsic spectral differences associated with the different selection methods (radio-loud vs. radio-quiet).

Both Czerny et al. and Gaskell et al. found the result that the extinction laws are flatter in the UV than the extinction laws of the SMC, LMC, or Milky Way. Both extinction curves are plotted in Figure 1 along with the curves for the SMC and Milky Way. The curve of Gaskell et al. is flat at all wavelengths below $0.4 \mu m$. The Czerny et al. curve is similar to that of the SMC down to $0.25 \mu m$, and below this it flattens to become much flatter than that of either the SMC or the Milky Way at $<0.13 \mu m$. These flat UV extinction curves are particularly interesting since they agree with theoretical predictions based on the grain size distribution close to an active galactic nucleus (AGN) with the destruction of small grains due to grain growth and sputtering in a high-density, high-radiation environment (e.g., Maiolino et al. 2001a, 2001b).

As discussed above, there are serious concerns about combining quasar spectra that span a wide range of rest-frame wavelengths into a composite. This is especially true when dealing with reddened quasars. Richards et al. (2003) and White et al. (2003) showed that the majority of the quasars with reddening $E_{B-V} \geq 0.2$ in their surveys (which are optical- and optical+radio-selected, respectively) are found at redshifts $z < 1$. Although similarly reddened quasars do exist at higher redshifts, they are less likely to be found in quasar samples with an optical magnitude limit. We outline here several reasons

why, in practice, quasar surveys contain more highly reddened quasars at lower redshifts:

1. At high redshift the selection is based on the rest-frame UV spectrum and $A_{UV} \gg A_g$ for SMC or Milky Way extinction laws. Therefore, the $A_g$ necessary to exclude quasars from samples due to optical magnitude limits is a function of redshift.

2. There is mounting evidence of an increase in the fraction of obscured AGNs at lower luminosities (e.g., Ueda et al. 2003; Simpson 2005). Due to the optical magnitude limit, quasars at lower redshifts are typically less luminous. Therefore, the ratio of the space densities of lightly reddened to unobscured quasars is greater at low redshifts than at high redshifts.

3. Low-redshift, low-luminosity quasars can have significant contamination of the red end of their spectra by light from the host galaxy. If this is not identified as host galaxy contamination, it could lead to the quasar being classified as reddened. At high redshift and luminosities there is little contamination by the hosts. For example, the SDSS composite quasar of Vander Berk et al. (2001) shows a spectral steepening longward of $0.5 \mu m$ due to host galaxy contamination in low-redshift quasars.

4. Red quasar selection is sometimes based on the observed frame color or spectral index. For an extinction law that induces spectral curvature (such as the SMC), the relationship between observed color or spectral index and $E_{B-V}$ is also a function of redshift, such that high-redshift quasars have an $E_{B-V}$ lower than that of low-redshift quasars with the same color. Richards et al. (2003) attempted to take account of this bias in their composite 5 spectrum; however, they did not for composites 3 and 4, which Czerny et al. also used to represent reddened quasars.

The consequence of all these points is that the quasars going
into a composite spectrum will have a negative correlation between \( E_{B-V} \) and redshift.

To illustrate the significance of these effects in the light of the current discussion, in Figure 2 we plot optical spectral index, \( \alpha_{\text{opt}} \), against redshift for the MQS sample of Baker et al. (1999), which was used to generate the composites in Baker & Hunstead (1995). It can be seen that in this sample, most of the reddest quasars (\( \alpha_{\text{opt}} > 1.5 \)) are at lower redshifts. This is a consequence of points 1–3 outlined above. However, there is not a significant correlation between redshift and \( \alpha_{\text{opt}} \) in the full sample because the bluest quasars are also predominantly at low redshift.

The fact that there is no strong positive or negative correlation of \( \alpha_{\text{opt}} \) with redshift does not mean, however, that there will be no bias when making a composite from these quasars, because of point 4. In Figure 2 we also plot curves showing how the observed spectral index changes with reddening as a function of redshift. For simplicity we represent a quasar by a single power law with \( \alpha_{\text{opt}} = 0.4 \) and determine the observed \( \alpha_{\text{opt}} \) by the ratio of fluxes in observed-frame wavelength bins 0.8–0.85 \( \mu \text{m} \) and 0.35–0.4 \( \mu \text{m} \) (roughly corresponding to the extreme useful range of optical spectroscopy). The power law is reddened by \( A_{\text{V}} = 0.5, 1, \) and 1.5 adopting the SMC and Milky Way (excluding the 0.22 \( \mu \text{m} \) feature not usually seen in quasars) extinction laws (Pei 1992) and \( A_{\text{V}} = 2, 4, \) and 6 adopting the law of Gaskell et al. (2004). For the SMC and Milky Way laws there is a strong correlation of \( A_{\text{V}} \) with redshift in this sample. For the SMC dust, almost all the quasars with \( A_{\text{V}} > 0.5 \) are at \( z < 1 \). Even for the Milky Way law, which does not induce such strong curvature, a correlation is seen at \( z > 2 \).

This plot also illustrates a fundamental problem with the extinction law of Gaskell et al. (2004). The extreme flatness in the UV means that a huge \( A_{\text{V}} \) is necessary to get any reddening at all of the UV continuum. Many surveys, including the MQS and the SDSS, contain reddened quasars at \( z > 2 \) where only the UV is visible in optical spectroscopy. According to the extinction law of Gaskell et al., the quasars with \( \alpha_{\text{opt}} \approx 1.5 \) in the MQS must be reddened by \( A_{\text{V}} \sim 20 \) and therefore have intrinsic absolute magnitudes of \( M_{\text{B}} \sim -45 \) ! What is actually found for high-redshift quasars in the SDSS that have rest-frame optical data available is that the reddening in the optical is much lower than in the UV, similar to SMC dust (Hopkins et al. 2004).

3. SIMULATING THE BIASES OF COMPOSITE REDDENED QUASARS

It is clear that combining the quasars in Figure 2 into composites could lead to serious problems for deriving a dust extinction law. In particular, there is an inconsistency in the extinction law of Gaskell et al. (derived from the MQS) and the existence of red high-redshift quasars in the MQS. To understand this quantitatively we now consider what would happen if one were to generate a composite from a quasar sample selected on the basis of their red observed optical colors (or equivalently, steep \( \alpha_{\text{opt}} \)). This analysis only includes the bias due to point 4 in § 2.

We consider a hypothetical sample of 211 quasars distributed smoothly over the redshift range \( 0.4 \leq z \leq 2.5 \). This redshift range is typical of quasar samples such as the MQS and the SDSS study of Richards et al. (2003). It is also the redshift range where the observed-frame wavelengths of optical spectroscopy (assumed 0.38–0.92 \( \mu \text{m} \)) in the SDSS are covered by our composite spectrum (0.1–0.8 \( \mu \text{m} \)). We assume that the intrinsic spectrum of each quasar is represented by a composite spectrum specifically constructed from the SDSS to represent a typical unreddened quasar (C. J. Willott et al. 2005, in preparation).

Each quasar is reddened by some amount of SMC-type dust until its observed \( g' - i' \) color equals 0.7. We also repeated the analysis using relative \( g' - i' \) colors equal to 0.5. Note that the use of relative colors takes out the effect of emission lines and is a closer approximation to selecting quasars with a constant \( \alpha_{\text{opt}} \). As we will show, there is little difference in the results when using \( g' - i' \) or relative \( g' - i' \). To get an idea of the amounts of reddening required to produce these colors as a function of redshift, \( A_{\text{V}} = 0.8 \) at \( z = 0.4 \) and \( A_{\text{V}} = 0.19 \) at \( z = 2.5 \) for relative \( g' - i' = 0.5 \). For reference to the MQS data in Figure 2, this corresponds to observed \( \alpha_{\text{opt}} \approx 1.5 \). We repeated our analysis with different values for the colors and found only minor differences in the results.

The individual reddened quasars are then combined using the same procedure as in Vanden Berk et al. (2001). Because we use the geometric mean composite spectrum, the spectral shape, extinction law, and mean extinction should all be preserved in the absence of any biases (Reichard et al. 2003). Therefore, we now divide the composite reddened quasar spectrum by the intrinsic quasar spectrum to determine the extinction curve in the same manner as Czerny et al. and Gaskell et al.

The results are shown in Figure 1, where we plot the curves generated from our two composites (using constant \( g' - i' \) and constant relative \( g' - i' \) reddening). The first thing to notice is that our derived composite extinction curves are nothing like the original SMC curve that was used to redden the individual quasars. The typically lower reddening in the high-redshift quaa-
sars that dominates the UV part of the spectrum leads to a much flatter extinction curve than the SMC. In particular, at $\lambda^{-1} > 6 \mu m^{-1}$, the curves are much flatter than either the SMC or the Milky Way, which is a characteristic of extinction curves generated from composite quasars.

Our simulated extinction curves are even flatter than that of Czerny et al., but have a shape remarkably similar to theirs. The fact that one of three reddened composites used by Czerny et al. was selected taking account of this redshift-dependent bias may account for the fact that their curve is somewhat closer to the SMC curve than our derived curves. Therefore, we find that the difference between the extinction laws of Czerny et al. and the SMC can be fully accounted for by this bias.

The Gaskell et al. law is extremely flat in the UV, so if their curve really does come from quasars extincted with SMC-type dust, then a stronger bias than represented by an approximately inverse square law must exist. We can only speculate on exactly why this is without full rest-frame UV and optical spectroscopy of the MQS quasars that went into the composites. We note that Baker & Hunstead (1995) scaled their quasar spectra before combining to a common flux density at 0.3 $\mu m$. If we repeat our analysis using this scaling, rather than the method of ordering each quasar by its redshift and scaling to the common wavelength region of the previous mean (Vanden Berk et al. 2001), then we find somewhat flatter curves in the UV than shown in Figure 1. Also, we note that the number of quasars in each MQS composite was small (in the range 13–18), and at the extreme wavelength ranges of the composites even fewer quasars were contributing. Therefore, object-to-object differences could have had a large impact. Gaskell et al. claimed that the fact that the broad emission lines revealed the same extinction curve as the continuum was independent evidence of the flat extinction curve. The broad emission lines are subject to exactly the same bias as the continuum, so it is not in fact independent.

4. DISCUSSION

Our analysis shows that the gray UV extinction laws derived using composite quasars are an erroneous artifact of the technique. This is due to the fact that the quasars contributing to the composite in the UV have typically lower reddening than those that contribute in the optical.

There have been other studies that have claimed that gray dust may be present in AGN environments. Maiolino et al. (2001a, 2001b) presented a number of arguments for a different grain size distribution, devoid of small grains. However, their arguments are based largely on mid-infrared extinction (which is dominated by very large grains) and the different observed gas-to-dust absorption ratios in Seyfert nuclei. However, Willott et al. (2004) showed that this difference in gas-to-dust absorption ratios is also present in X-ray–selected quasars whose rest-frame UV and optical reddening can be fit with SMC or Milky Way extinction laws, not gray dust.

We argue that evidence based on rest-frame UV and optical spectral energy distributions for individual reddened quasars (as in Hopkins et al. 2004) is much more reliable than extinction laws based on composite spectra. We conclude that the SMC curve remains a useful description of the reddening in quasar environments and that there is little evidence supporting extinction curves that flatten in the UV.

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