

Cosmological Obscuration by Galactic Dust: Effects of Dust Evolution

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ABSTRACT

We explore the effects of dust in cosmologically distributed intervening galaxies on the high redshift universe using a generalised model where dust content evolves with cosmic time. The absorbing galaxies are modelled as exponential disks which form coevally, maintain a constant space density and evolve in dust content at a rate that is uniform throughout. We find that the inclusion of moderate to moderately weak amounts of evolution consistent with other studies can reduce the mean observed B -band optical depth to redshifts $z \gtrsim 1$ by at least 60% relative to non-evolving models. Our predictions imply that intervening galactic dust is unlikely to bias the optical counts of quasars at high redshifts and their evolution in space density derived therefrom.

Key words: dust, extinction — galaxies: ISM — galaxies: evolution — quasars: general

1 INTRODUCTION

The recent discovery of large numbers of quasars at radio and X-ray frequencies with very red optical-to-near-infrared continua suggests that existing optical surveys may be severely incomplete (eg. Webster et al. 1995 and references therein). Webster et al. (1995) and Masci (1997) have argued that the anomalous colours are due to extinction by dust, although the location of the dust remains a highly controversial issue. Intervening dusty galaxies which happen to lie along the line-of-sight of otherwise normal blue quasars are expected to redden the observed optical continuum, or if the optical depth is high enough, to remove quasars from an optical flux-limited sample (eg. Wright 1990). As suggested by existing observational and theoretical studies of cosmic chemical evolution however (Pei & Fall 1995 and references therein), one expects a reduction in the amount of dust to high redshift. Consequently, one then also expects that the probability of a background object being either reddened or obscured to be reduced.

The effects of foreground dust on observations of objects at cosmological distances has been discussed by Ostriker & Heisler (1984); Heisler & Ostriker (1988); Fall & Pei (1989, 1993); Wright (1986, 1990) and Masci & Webster (1995). Using models of dusty galactic disks, these studies show that

the line-of-sight to a high redshift quasar has a high probability of being intercepted by a galactic disk, particularly if the dust distribution is larger than the optical radius of the galaxy. Based on the dust properties of local galaxies, it is estimated that up to 80% of bright quasars to $z \sim 3$ may be obscured by dusty intervening systems. The principle issue in these calculations was that realistic dust distributions in galaxies which are ‘soft’ around the edges, will cause many quasars to appear reddened without removing them from a flux-limited sample.

None of the above studies however considered the effects of evolution in dust content. Cosmic evolution in dust is indirectly suggested by numerous claims of reduced chemical enrichment at $z \gtrsim 2$. Evidence is provided by observations of trace metals and their relative abundances in QSO absorption-line systems to $z \sim 3$ (Meyer & Roth 1990; Savaglio, D’Odorico & Möller 1994; Pettini et al. 1994; Wolfe et al. 1994; Pettini et al. 1997; Songaila 1997), which are thought to arise from intervening clouds or the haloes and disks of galaxies. These studies indicate mean metallicities $\simeq 10\%$ and $\lesssim 1\%$ solar at $z \sim 2$ and $z \sim 3$ respectively, and dust-to-gas ratios $\lesssim 8\%$ of the galactic value at $z \sim 2$. These estimates are consistent with simple global evolution models of star formation and gas consumption rates in the universe (Pei & Fall 1995). If the observed metallicities in QSO absorption systems are common, then their interpretation as galactic disks implies that substantial evolution has taken place since $z \sim 3$. If the quantity of dust on cosmic

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scales also follows such a trend, then one may expect the effects of obscuration to high redshift to be reduced relative to non-evolving predictions.

In this paper, we continue to model the effects of intervening galactic dust on the background universe at optical wavelengths using a more generalised model where the dust content evolves. We explore the effects of our predictions on quasar number counts in the optical and their implication for quasar evolution.

This paper is organised as follows: The next section briefly describes the generalised model and assumptions. Section 3 describes the model parameters and their values assumed in our calculations. Model results are presented and analysed in Section 4. Implications on quasar statistics and evolution are discussed in Section 5. Other implications are discussed in Section 6 and all results are summarised in Section 7. Unless otherwise stated, all calculations assume a Friedmann cosmology with $q_0 = 0.5$, and Hubble parameter $h_{50} = 1$ where $H_0 = 50h_{50} \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2 THE EVOLUTIONARY DUST MODEL

We calculate the probability distribution in total dust optical depth from model galaxies along any random line-of-sight as a function of redshift by following the method presented in Masci & Webster (1995). This was based on a method introduced by Wright (1986) which did not include any effects of evolution with redshift. Here we generalise this model by considering the possibility of evolution in the dust properties of galaxies. In the discussion below and unless otherwise indicated by a subscript, we define τ to be the total optical depth encountered by emitted photons and measured in an *observer's B bandpass* (effectively at $\lambda = 4400\text{\AA}$).

We assume the following properties for individual absorbing galaxies. Following previous studies (eg. Wright 1986, Heisler & Ostriker 1988), we model galaxies as randomly tilted exponential disks, where the optical depth through a face-on disk decreases exponentially with distance r from the center:

$$\tau(r, z) = \tau_0(z) e^{-r/r_0}. \quad (1)$$

r_0 is a characteristic radius and $\tau_0(z)$, the value of τ through the center of the galaxy ($r = 0$). The redshift dependence of τ_0 is due to the increase in absorber rest frame frequency with redshift.

Since we wish to model the observed *B*-band optical depth to $z \lesssim 6$, we require an extinction law $\xi(\lambda) \equiv \tau_\lambda/\tau_B$ that extends to wavelengths of $\sim 630\text{\AA}$. We use the analytical fit for $\xi(\lambda)$ as derived by Pei (1992) for diffuse galactic dust in the range $500\text{\AA} \lesssim \lambda \lesssim 25\mu\text{m}$. The optical depth in an observer's frame through an absorber at redshift z ($\tau_0(z)$ in equation 1) can be written:

$$\tau_0(z) = \tau_B \xi\left(\frac{\lambda_B}{1+z}\right), \quad (2)$$

where τ_B is the *rest frame B-band* optical depth through the center of an individual galactic absorber.

2.1 Evolution

Equation (2) must be modified if the dust content in each galaxy is assumed to evolve with cosmic time. The optical depth seen through the center of a single absorber at some redshift, $\tau_0(z)$, will depend on the quantity of dust formed from past stellar processes. For simplicity, we assume all galaxies form simultaneously, maintain a constant space density, and increase in dust content at a rate that is uniform throughout. We also assume no evolution in the dust law $\xi(\lambda)$ with redshift. Even though a lower mean metallicity at high redshift may suggest a different wavelength dependence for the dust law, there is no evidence from local observations of the diffuse ISM to support this view (eg. Whittet 1992).

We parameterise evolution in dust content by following simulations of the formation of heavy metals in the cold dark matter scenario of galaxy formation by Blain & Longair (1993a, 1993b). These authors assume that galaxies form by the coalescence of gaseous protoclusters through hierarchical clustering as prescribed by Press & Schechter (1974). A fixed fraction of the mass involved in each merger event is converted into stars, leading to the formation of heavy metals and dust. It was assumed that the energy liberated through stellar radiation was absorbed by dust and re-radiated into the far-infrared. They found that such radiation can contribute substantially to the far-infrared background intensity from which they use to constrain a model for the formation of heavy metals as a function of cosmic time. Their models show that the comoving density of heavy metals created by some redshift z , given that star formation commenced at some epoch z_{SF} follows the form

$$\Omega_m(z) \propto \ln\left(\frac{1+z_{SF}}{1+z}\right), \quad \text{where } z < z_{SF}. \quad (3)$$

We assume that a fixed fraction of heavy metals condense into dust grains so that the comoving density in dust, $\Omega_d(z)$, follows a similar dependence as equation (3). The density in dust relative to the present closure density in n_0 exponential disks per unit comoving volume is given by

$$\Omega_d = \frac{n_0 M_d}{\rho_c}, \quad (4)$$

where $\rho_c = 3H_0^2/8\pi G$ and M_d is the dust mass in a single exponential disk. This mass can be estimated using Eq.7-24 from Spitzer (1978) where the total density in dust, ρ_d , is related to the extinction A_V along a path length L in kpc by

$$\langle \rho_d \rangle = 1.3 \times 10^{-27} \rho_g \left(\frac{\epsilon_o + 2}{\epsilon_o - 1}\right) (A_V/L). \quad (5)$$

ρ_g and ϵ_o are the density and dielectric constant of a typical dust grain respectively and the numerical factor has dimensions of gm cm^{-2} - see Spitzer (1978). Using the exponential profile (equation 1) where $\tau(r) \propto A_V(r)$ and integrating along cylinders, the dust mass in a single exponential disk can be found in terms of the model parameters τ_B and r_0 . We find that the comoving density in dust at some redshift scales as

$$\Omega_d(z) \propto \tau_B(z) n_0 r_0^2, \quad (6)$$

where $\tau_B(z)$ is the central *B-band* optical depth and r_0 the dust scale radius of each disk. Thus, the central opti-

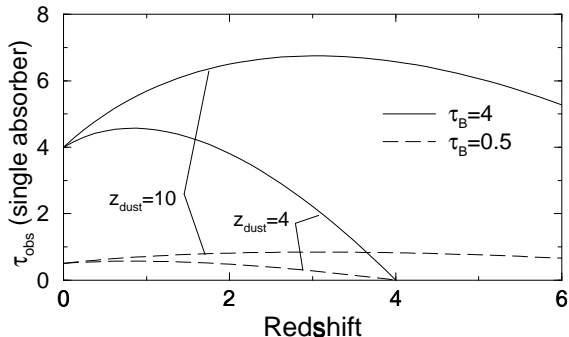


Figure 1. Optical depth in an observer’s B -bandpass as a function of redshift through a single model absorber defined by equation (8). τ_B is the rest frame central B -band optical depth and z_{dust} the dust formation epoch.

cal depth, $\tau_B(z)$, in any model absorber at some redshift is directly proportional to the mass density in dust or heavy metals as specified by equation (3):

$$\tau_B(z) \propto \ln \left(\frac{1+z_{SF}}{1+z} \right). \quad (7)$$

The redshift dependence of optical depth observed in the fixed B -bandpass due to a *single* absorber now involves two factors: first, the extinction properties of the dust as defined by equation (2) and second, its evolution specified by equation (7). The star formation epoch z_{SF} can also be interpreted as the redshift at which dust forms. From here on, we therefore refer to this parameter as z_{dust} - a hypothesised “dust formation epoch”. By convolving equations (2) and (7), and requiring that locally: $\tau_0(z=0) = \tau_B$, the *observed* optical depth through a *single* absorber at some redshift $z < z_{\text{dust}}$ now takes the form:

$$\tau_0(z) = \tau_B \xi \left(\frac{\lambda_B}{1+z} \right) \left[1 - \frac{\ln(1+z)}{\ln(1+z_{\text{dust}})} \right]. \quad (8)$$

Figure 1 illustrates the combined effects of evolution and increase in observed frame B -band extinction with redshift defined by equation (8). The extinction initially increases with z due to a decrease in corresponding rest frame wavelength. Depending on the value for z_{dust} , it then decreases due to evolution in dust content. This latter effect dominates towards z_{dust} .

The characteristic galactic dust radius r_0 defined in equation (1) is also given a redshift dependence in the sense that galaxies had smaller dust-haloes at earlier epochs. The following evolutionary form is adopted:

$$r_0(z) = r_0 (1+z)^\delta, \quad \delta < 0, \quad (9)$$

where δ gives the rate of evolution and r_0 is now a ‘local’ scale radius. Evolution in radial dust extent is suggested by dynamical models of star formation in an initially formed protogalaxy (Edmunds 1990 and references therein). These studies show that the star formation rate and hence metallicity in disk galaxies has a radial dependence that decreases outwards at all times. It is thus quite plausible that galaxies

have an evolving effective ‘dust radius’ which follows chemical enrichment from stellar processes.

Our parameterisation for evolution in galactic dust (equations 7 and 9) is qualitatively similar to the ‘accretion models’ for chemical evolution of Wang (1991), where the effects of grain destruction by supernovae and grain formation in molecular clouds is taken into account. The above model is also consistent with empirical age-metallicity relationships inferred from spectral observations in the Galaxy (Wheeler, Snedin & Truran 1989), and models of chemical evolution on a cosmic scale implied by absorption-line observations of quasars (Lanzetta et al. 1995; Pei & Fall 1995).

3 MODEL PARAMETERS AND ASSUMPTIONS

3.1 Model Parameters

Our model depends on four independent parameters which describe the characteristics and evolutionary properties of intervening galaxies. The parameters defined ‘locally’ are: the comoving number density of galaxies n_0 , the characteristic dust radius r_0 , and dust opacity τ_B at the center of an individual absorber. The evolution in τ_B and r_0 is defined by equations (7) and (9) respectively. Parameters defining their evolution are δ for r_0 , and the ‘dust formation epoch’ z_{dust} for τ_B . Both n_0 and r_0 have been conveniently combined into the parameter τ_g where

$$\tau_g = n_0 \pi r_0^2 \frac{c}{H_0}, \quad (10)$$

with $\frac{c}{H_0}$ being the Hubble length. This parameter is proportional to the number of galaxies and mean optical depth introduced along the line-of-sight (see Section 4). It also represents a ‘local’ covering factor in dusty galactic disks - the fraction of sky at the observer covered in absorbers.

In all calculations, we assume a fixed value for n_0 . From equation (10), any evolution in the comoving number density n_0 is included in the evolution parameter δ for r_0 (equation 9). Thus in general, δ represents an effective evolution parameter for both r_0 and n_0 . Our model is therefore specified by four parameters: τ_g , τ_B , δ and z_{dust} .

3.2 Assumed Parameter Values

Our calculations assume a combination of values for the parameters (τ_g , τ_B) and (δ , z_{dust}) that bracket the range consistent with existing observations. The values (τ_g , τ_B) are chosen from previous studies of dust distributions and extinction in nearby spirals. From the studies of Giovanelli et al. (1994) and Disney & Phillipps (1995) (see also references therein) we assume the range in central optical depths: $0.5 \lesssim \tau_B \lesssim 4$, while dust scale radii of $5 \lesssim (r_0/\text{kpc}) \lesssim 30$ are assumed from Zaritsky (1994) and Peletier et al. (1995). For a nominal comoving galactic density of $n_0 = 0.002 h_{50}^3 \text{Mpc}^{-3}$ (eg. Efstathiou et al. 1988), these scale radii correspond to a range for τ_g (equation 10): $0.01 \lesssim \tau_g \lesssim 0.18$. These ranges are consistent with those assumed in the intervening galaxy obscuration models of Heisler & Ostriker (1988) and Fall & Pei (1993).

The values for (δ , z_{dust}) were chosen to cover a range of evolution strengths for r_0 and τ_B respectively. To cover

a plausible range of dust formation epochs, we consider $6 \leq z_{dust} \leq 20$, consistent with a range of galaxy ‘formation’ epochs predicted by existing theories of structure formation (eg. Peebles 1989). The upper bound $z_{dust} = 20$ corresponds to the star formation epoch considered in the galaxy formation models of Blain & Longair (1993b).

We assume values for δ similar to those implied by observations of the space density of metal absorption systems from QSO spectra as a function of redshift (Sargent, Boksenberg & Steidel 1988; Thomas & Webster 1990). These systems are thought to arise in gas associated with galaxies and their haloes and it is quite plausible that such systems also contain dust. Here we assume a direct proportionality between the amount of dust and heavy metal abundance in these systems.

In general, evolution in the number of metal absorption line systems per unit z , that takes into account effects of cosmological expansion, can be parameterised:

$$\frac{dN}{dz} = \frac{c}{H_0} n_z \pi r_0(z)^2 (1+z)(1+2q_0z)^{-1/2}. \quad (11)$$

Evolution, such as a reduction in absorber numbers with redshift, can be interpreted as either a decrease in the comoving number density n_z , or effective cross-section $\pi r_0(z)^2$. With our assumption of a constant comoving density $n(z) = n_0$, and an evolving dust scale radius r_0 as defined by equation (9), we have $dN/dz \propto (1+z)^\gamma$, where $\gamma = 0.5 + 2\delta$ for $q_0 = 0.5$. Hence for *no evolution*, $\gamma = 0.5$.

Present estimates on the evolution of absorber numbers with redshift are poorly constrained. Thomas & Webster (1990) have combined several datasets increasing absorption redshift ranges to give strong constraints on evolution models. For CIV absorption ($\lambda\lambda 1548, 1551\text{\AA}$), which can be detected to redshifts $z \gtrsim 3$ in high resolution optical spectra, evolution has been confirmed for the highest equivalent width systems with $W_0 \gtrsim 0.6\text{\AA}$. It is more likely that these systems are those associated with dust rather than the lower equivalent width (presumably less chemically enriched) systems with $W_0 \lesssim 0.3\text{\AA}$ which have a trend consistent with no evolution. Their value for the evolution parameter γ , for the highest equivalent width systems is -0.1 ± 0.5 at the 2σ level. Converting this 2σ range to our model parameter δ using the discussion above, we assume the range: $-0.5 < \delta < -0.05$.

3.3 Comparisons with QSO Absorption-Line Studies

We can compare our assumed ranges in evolutionary parameters: $6 \leq z_{dust} \leq 20$ and $-0.5 < \delta < -0.05$ with recent determinations of the heavy element abundance in damped Ly- α absorption systems and the Ly- α forest to $z \sim 3$. The damped Ly- α systems are interpreted as the progenitors of galactic disks (Wolfe et al. 1986), and recent studies by Pettini et al. (1994; 1997) deduce metal abundances and dust-to-gas ratios at $z \sim 1.8 - 2.2$ that are $\sim 10\%$ of the local value. The Lyman forest systems however are more numerous, and usually correspond to gas columns $> 10^7$ times lower than those of damped Ly- α absorbers. High resolution metal-line observations by Songaila (1997) deduce metallicities $\lesssim 1.5\%$ solar at $z \sim 2.5 - 3.8$.

To relate these metallicity estimates to cosmic evolution in dust content as specified by our model, we must first note

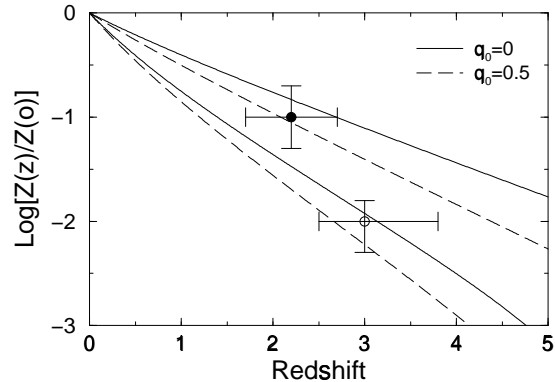


Figure 2. Relative metallicity as a function of redshift. Regions within the solid and dashed curves represent the ranges predicted by our model for $q_0 = 0$ and $q_0 = 0.5$ respectively. The filled and open data points with 1σ error bars are mean observed values from Pettini et al. (1994) and Songaila (1997) respectively.

that the metallicity at any redshift $Z(z)$, is generally defined as the mass fraction of heavy metals relative to the total gas mass: $Z(z) = \Omega_m(z)/\Omega_g(z)$. At all redshifts, we assume a constant dust-to-metals ratio, $\Omega_d(z)/\Omega_m(z)$, where a fixed fraction of heavy elements is assumed to be condensed into dust grains. Therefore the metallicity $Z(z)$, relative to the local solar value, Z_\odot , can be written:

$$\frac{Z(z)}{Z_\odot} = \frac{\Omega_d(z) \Omega_g(0)}{\Omega_d(0) \Omega_g(z)}. \quad (12)$$

From the formalism in section 2.1, the mass density in dust relative to the local density, $\Omega_d(z)/\Omega_d(0)$, can be determined and is found to be independent of the galaxy properties r_0 and τ_B , depending only on our evolution parameters, δ and z_{dust} . This is given by

$$\frac{\Omega_d(z)}{\Omega_d(0)} = \left[1 - \frac{\ln(1+z)}{\ln(1+z_{dust})} \right] (1+z)^{2\delta}. \quad (13)$$

The gas ratio, $\Omega_g(0)/\Omega_g(z)$, is adopted from studies of the evolution in gas content of damped Ly- α systems. These systems are believed to account for at least 80% of the gas content in the form of neutral hydrogen at redshifts $z \gtrsim 2$ (Lanzetta et al. 1991). We adopt the empirical fit of Lanzetta et al. (1995), who find that the observed evolution in $\Omega_g(z)$ is well represented by $\Omega_g(z) = \Omega_g(0) \exp(\alpha z)$, where $\alpha = 0.6 \pm 0.15$ and 0.83 ± 0.15 for $q_0 = 0$ and $q_0 = 0.5$ respectively.

Figure 2 shows the range in relative metallicity implied by our evolutionary dust model (equations 12 and 13) as a function of redshift for two values of q_0 . The solid and dashed lines correspond to respectively $q_0 = 0$ and $q_0 = 0.5$ and the regions between these lines correspond to the ranges assumed for our assumed model parameters: $6 \leq z_{dust} \leq 20$ and $-0.5 < \delta < -0.05$. For comparison, the mean metallicities $Z \approx 0.1Z_\odot$ and $Z \approx 0.01Z_\odot$ observed in damped Ly- α systems at $z \approx 2.2$ and the Lyman forest at $z \gtrsim 2.5$ respectively are also shown. These agree well with our model predictions, suggesting that our model assumptions will pro-

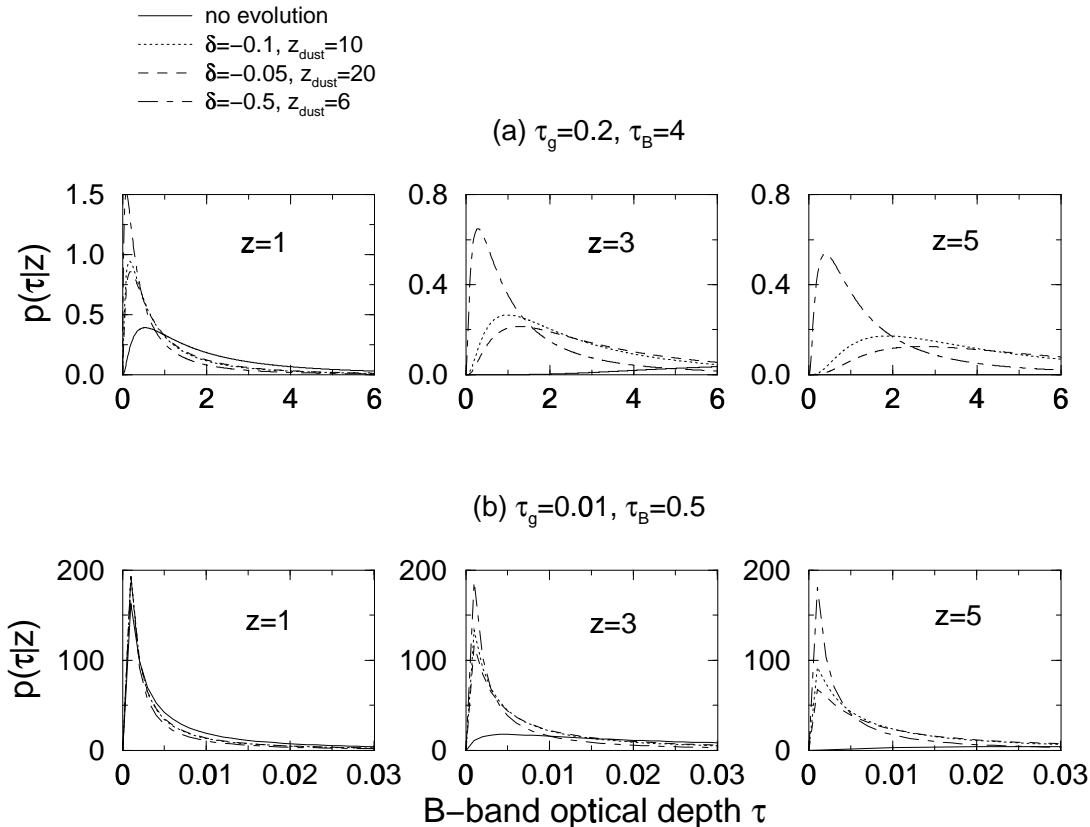


Figure 3. Optical depth probability distribution functions $p(\tau|z)$ to redshifts $z=1, 3$ and 5 , where τ is the total optical depth observed in the B -band. Two different sets of galaxy parameters (τ_g, τ_B) are considered: (a) $(0.2, 4)$ and (b) $(0.01, 0.5)$ (see section 3.1). For each of these, we show four evolutionary models specified by (δ, z_{dust}) . ‘No evolution’ corresponds to $\delta = 0$ and $z_{dust} = \infty$ and the ‘Strongest evolution’ to $\delta = -0.5$ and $z_{dust} = 6$.

vide a reliable measure of dust evolution which are at least compatible with other indirect estimates.

4 RESULTS AND ANALYSIS

Using the formalism of Masci & Webster (1995) and replacing the parameters τ_B and r_0 by their assumed redshift dependence as defined in section 2.1, Fig. 3 shows probability density functions $p(\tau|z)$ for the total optical depth up to redshifts $z=1, 3$ and 5 . Results are shown for two sets of galaxy parameters (τ_g, τ_B) , with four sets of evolutionary parameters (δ, z_{dust}) for each.

The area under any normalised curve in Fig. 3 gives the fraction of lines-of-sight to that redshift which have optical depths within some interval $0 \rightarrow \tau_{max}$. Towards high redshifts, we find that obscuration depends most sensitively on the parameter τ_g , in other words, on the covering factor of absorbers (equation 10). Figure 3 shows that as the amount of dust at high redshift decreases, i.e., as δ and z_{dust} decrease, the curves show little horizontal shift towards larger optical depths from $z=1$ to $z=5$. A significant shift becomes noticeable however for the weaker evolution cases,

and is largest for ‘no evolution’ (solid lines). This behaviour is further investigated below.

In order to give a clearer comparison between the amount of obscuration and strength of evolution implied by our model parameters $(\tau_g, \tau_B, \delta, z_{dust})$, we have calculated the mean and variance in total optical depth as a function of redshift. Formal derivations of these quantities are given in the appendix. Here we briefly discuss their general dependence on the model parameters.

A quantity first worth considering is the number of galaxies intercepted along the line-of-sight. In a $q_0 = 0.5$ ($\Lambda = 0$) universe, the average number of intersections within a scale length r_0 of a galaxy’s center by a light ray to some redshift is given by

$$\bar{N}(z) = \left(\frac{2}{3 + 4\delta} \right) \tau_g [(1+z)^{1.5+2\delta} - 1]. \quad (14)$$

Where δ and τ_g are defined in equations (9) and (10) respectively.

In the case where we have *no-evolution*, i.e. where $\delta = 0$ and $z_{max} = \infty$, and for a dust law that scales inversely with wavelength (i.e. $\xi_\lambda \propto 1/\lambda$ which is a good approximation at $\lambda \gtrsim 2500\text{\AA}$), exact expressions follow for the mean and vari-

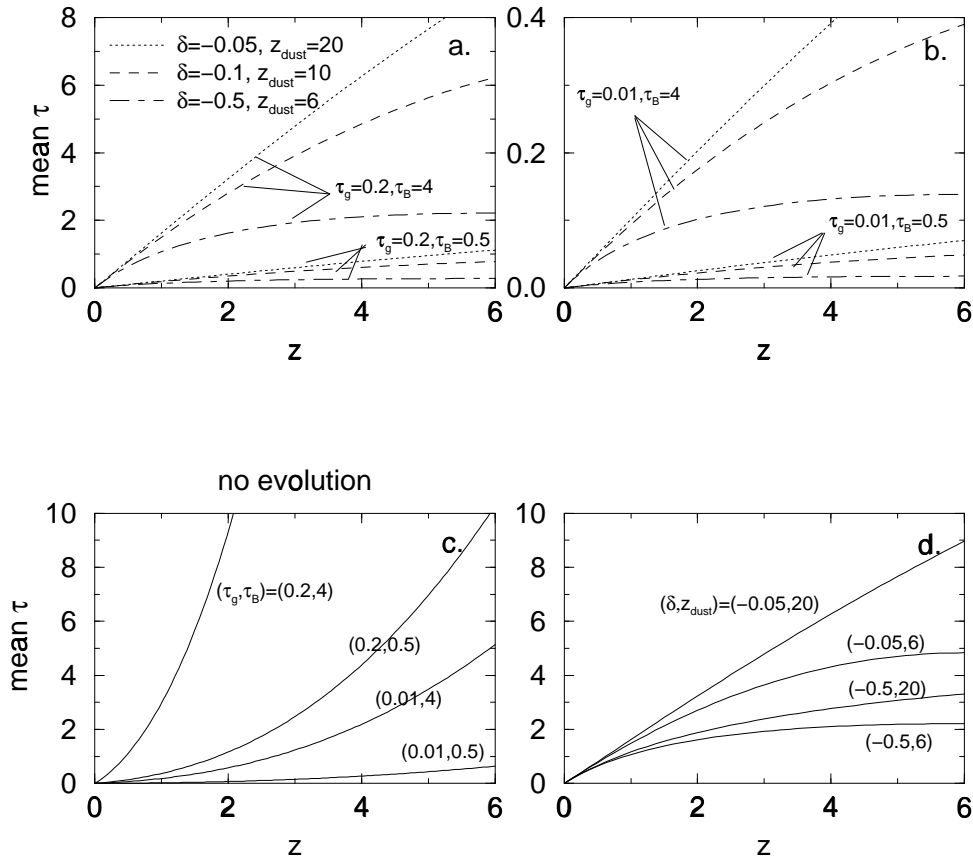


Figure 4. Behaviour in mean reddening, $\langle \tau \rangle$, as a function of redshift for a range of model parameters (τ_g, τ_B) and (δ, z_{dust}) . (a) For $(\tau_g, \tau_B) = (0.2, 4)$ and $(0.2, 0.5)$, (b) Same as (a) but for $\tau_g = 0.01$, (c) Redshift dependence of mean reddening in *no-evolution* model for a range of parameters (τ_g, τ_B) . (d) Scaling of the mean reddening with respect to the evolutionary parameters (δ, z_{dust}) with (τ_g, τ_B) fixed at $(0.2, 4)$.

ance in total optical depth along the line-of-sight. The mean optical depth can be written:

$$\bar{\tau}(z) = 0.8 \tau_g \tau_B [(1+z)^{2.5} - 1], \quad (15)$$

and the variance:

$$\sigma_\tau^2(z) = 0.57 \tau_g \tau_B^2 [(1+z)^{3.5} - 1]. \quad (16)$$

The variance (equation 16) or ‘scatter’ about the mean to some redshift provides a more convenient measure of reddening. The mean optical depth has a simple linear dependence on the parameters τ_g and τ_B and thus gives no indication of the degree to which each of these parameters contributes to the scatter. As seen from the probability distributions in Fig. 3, there is a relatively large scatter about the mean optical depth to any redshift. From equation (16), it is seen that the strongest dependence of the variance is on the central absorber optical depth τ_B . Thus, larger values of τ_B (which imply ‘harder-edged’ disks), are expected to introduce considerable scatter amongst random individual lines of sight, even to relatively low redshift.

In Fig. 4, we show how the mean optical depth varies as a function of redshift for a range of evolutionary parameters. ‘Strong evolution’ is characterised by $\delta = -0.5$,

$z_{dust} = 6$ (dot-dashed curves), as compared to the ‘no’, ‘weak’ and ‘moderate’ evolution cases indicated. The mean optical depth flattens out considerably towards high redshift in the strong evolution case, and gradually steepens as δ and z_{dust} are increased. Note that no such flattening is expected in mean reddening for the no evolution case (Fig. 4c). The mean optical depth to redshifts $z \gtrsim 1$ in evolution models can be reduced by factors of at least three, even for low to moderately low evolution strengths.

Figure 4d shows the scaling of mean optical depth with respect to the evolutionary parameters. It is seen that reddening depends most sensitively on the parameter δ , which controls the rate of evolution in galactic dust scale radius r_0 . A similar trend is followed in Fig. 5, which shows the dependence of variance in optical depth on evolution as a function of redshift, for fixed (τ_g, τ_B) . Considerable scatter is expected if the dust radius of a typical galaxy evolves slowly with cosmic time as shown for the ‘weakest’ evolution case $\delta = -0.05$ in Fig. 5.

Our main conclusion is that the inclusion of evolution in dust content, by amounts consistent with other indirect studies can dramatically reduce the redshift dependence of

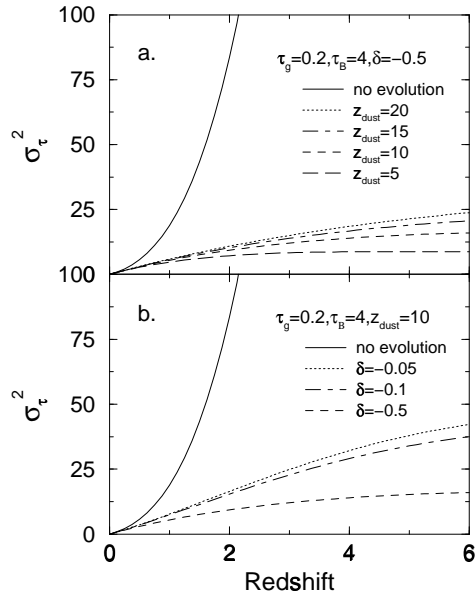


Figure 5. Variance (σ_τ^2) in optical depth as a function of redshift showing scaling with respect to the evolution parameters (δ , z_{dust}). (τ_g, τ_B) are fixed at (0.2, 4). (a) δ fixed at -0.05 and z_{dust} is varied. (b) z_{dust} fixed at 10 and δ is varied.

total reddening along the line-of-sight to $z \gtrsim 1$, contrary to non-evolving models.

5 IMPLICATIONS ON QSO NUMBER COUNTS

There are numerous observations suggesting that the space density of bright quasars declines beyond $z \approx 3$ (Sandage 1972; Schmidt, Schneider & Gunn 1988). This has been strongly confirmed from various luminosity function (LF) estimates to $z \sim 4.5$ (Hartwick & Schade 1990; Pei 1995 and references therein), where the space density is seen to decline by at least an order of magnitude from $z = 3$ to $z = 4$. Heisler & Ostriker (1988) speculate that the decline may be due to obscuration by intervening dust, which reduces the number of quasars observed by ever-increasing amounts towards high z . The results of Fall & Pei (1993) however show that the observed turnover at $z \sim 2.5$ and decline thereafter may still exist once the effects of intervening dust (mainly associated with damped Ly α systems) are corrected for. Since no evolution in dust content was assumed in either of these studies, we shall further explore the effects of intervening dust on inferred quasar evolution using our evolutionary galactic dust model.

Since we are mainly interested in “bright” quasars ($M_B \lesssim -26$) at high redshifts, a single power-law for the observed LF should suffice:

$$\phi_o(L, z) = \phi_{*o}(z)L^{-\beta-1}, \quad (17)$$

where $\beta \simeq 2.5$. This power law model immensely simplifies the relation between observed and “true” LFs (corrected for obscuration by dust). In the presence of dust obscuration,

inferred luminosities will be decreased by a factor of $e^{-\tau}$. Since there is a probability $p(\tau | z)$ of encountering an optical depth τ as specified by our model (see Fig. 3), the observed LF can be written in terms of the true LF, ϕ_t as follows:

$$\phi_o(L, z) = \int_0^\infty d\tau \phi_t(e^\tau L, z) e^\tau p(\tau | z) \quad (18)$$

The extra factor of e^τ in equation (18) accounts for a decrease in luminosity interval dL in the presence of dust. Equations (17) and (18) imply that the true LF can be written

$$\phi_t(L, z) = \phi_{*t}(z)L^{-\beta-1}, \quad (19)$$

and the ratio of observed to true LF normalisation as

$$\frac{\phi_{*o}(z)}{\phi_{*t}(z)} = \int_0^\infty d\tau e^{-\beta\tau} p(\tau | z). \quad (20)$$

The observed comoving density of quasars brighter than some absolute magnitude limit M_{lim} as a function of redshift is computed by integrating the LF:

$$N_o(z | M_B < M_{lim}) = \int_{L_{lim=L(M_{lim})}}^\infty dL \phi_o(L, z). \quad (21)$$

Thus, the true comoving number density N_t , can be easily calculated by replacing ϕ_o in equation (21) by $\phi_t \equiv (\phi_{*t}/\phi_{*o})\phi_o$ leading to the simple result:

$$N_t(z | M_B < M_{lim}) \simeq \left(\frac{\phi_{*o}(z)}{\phi_{*t}(z)} \right) N_o(z | M_B < M_{lim}), \quad (22)$$

where the normalisation ratio is defined by equation (20).

Figure 6 shows both the observed and true comoving density of bright quasars (with $M_B < -26$) as a function of redshift. The observed trends are empirical fits deduced by Pei (1995). The true comoving density in all cases was determined by assuming relatively ‘weak’ evolution in the dust properties of intervening galaxies. Two sets of galactic dust parameters for each q_0 defined by $(\tau_B, r_0) = (1, 10\text{kpc})$ (Figs a and c) and $(\tau_B, r_0) = (3, 30\text{kpc})$ (Figs b and d) are assumed. We shall refer to these as our “minimal” and “maximal” dust model respectively which bracket the range of parameters observed for local galaxies.

Comparing the ‘true’ QSO redshift distribution with that observed, two features are apparent. First, the true number density vs. z relation has qualitatively the same behaviour as that observed. No flattening or increase in true quasar numbers with z is apparent. Second, there appears to be a shift in the redshift, z_{peak} , where the quasar density peaks. This shift is greatest for our maximal dust model where z_{peak} is increased by a factor of almost 1.5 relative to that observed. This implies that the bulk of quasars may have formed at earlier epochs than previously inferred from direct observation.

Our predictions for QSO evolution, corrected for obscuration by ‘evolving’ intervening dust differs enormously from that predicted by Heisler & Ostriker (1988). The major difference is that these authors neglected evolution in dust content with z . As shown in Fig. 4, non-evolving models lead to a rapid increase in dust optical depth with z and hence this will explain their claim of a continuous increase in the true QSO space density at $z > 3$. As shown in Fig. 6, the inclusion of even a low-to-moderately low amount of evolution in dust content dramatically reduces the excess number

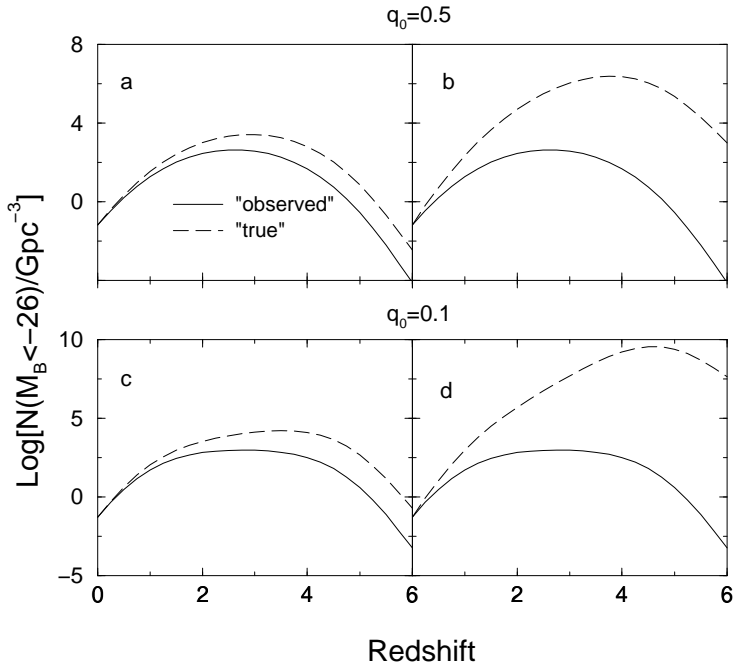


Figure 6. Comoving number density of quasars with $M_B < -26$ as a function of redshift. Observed trends (solid curves) are taken from the empirical fits of Pei (1995) while dashed curves corrects these trends for obscuration by dust. These are predicted assuming our evolving intervening galactic dust model with $\tau_B = 1$ and $r_0 = 10 \text{ kpc}$ (Figs a and c) and $\tau_B = 3$ and $r_0 = 30 \text{ kpc}$ (Figs b and d). In all cases, we have assumed relatively “weak” evolution in dust content with z , defined by the parameters: $z_{dust} = 20$ and $\delta = -0.05$.

of quasars at $z > 3$ than predicted by Heisler & Ostriker (1988).

We find that there is no significant difference in the characteristic timescale, t_{QSO} for QSO formation at $z > z_{peak}$, where

$$t_{QSO} \simeq \left(\frac{N}{\dot{N}} \right)_{z > z_{peak}} \sim 1.5 \text{ Gyr}, \quad (23)$$

is found for both the observed and dust corrected results in Fig. 6. We conclude that the decline in space density of bright QSOs at redshifts $z > 3.5$ is most likely to be real and an artifact of an intrinsic rapid turn-on of the QSO population with time. This is consistent with estimates of evolution inferred from radio-quasar surveys where no bias from dust obscuration is expected (eg. Dunlop & Peacock 1990).

An increased space density of quasars at redshifts $z > 3$ predicted by correcting for dust obscuration has implications for theories of structure formation in the Universe. Our minimal dust model (Figs. 6a and c) predicts that the true space density can be greater by almost two orders of magnitude than that observed, while our maximal dust model (Figs. 6b and d) predicts this factor to be greater than 5

orders of magnitude. These predictions can be reconciled with the quasar number densities predicted from hierarchical galaxy formation simulations involving cold-dark matter (eg. Katz et al. 1994). It is found that there are $> 10^3$ times potential quasar sites at $z > 4$ (associated with high density peaks) than required from current observations. Such numbers can be easily accommodated by our predictions if a significant quantity of line-of-sight dust is present.

To summarise, we have shown that with the inclusion of even weak to moderately weak amounts of evolution in dust content with z , the bias due to dust obscuration will not be enough to flatten the true redshift distribution of bright quasars beyond $z = 3$. A significant excess however (over that observed) in quasar numbers is still predicted.

6 DISCUSSION

Our model predictions may critically depend on the dust properties of individual galaxies and their assumed evolution. For instance, is it reasonable to give galaxies an exponential dust distribution? Such a distribution is expected to give a dust covering factor to some redshift considerably larger than if a clumpy distribution were assumed (Wright, 1986). A clumpy dust distribution (for spirals in particular) is expected, as dust is known to primarily form in dense, molecular star-forming clouds (Wang 1991 and references therein).

As noted by Wright (1986), “cloudy disks” with dust in optically-thick clumps can reduce the effective cross-section for dust absorption by at least a factor of five and hence, are less efficient at both obscuring and reddening background sources at high redshift. A dependence of the degree of dust ‘clumpiness’ on redshift, such as dust which is more diffuse at early epochs and becomes more clumpy with cosmic time is unlikely to affect the results of this paper. This will only reduce the effective cross-section for absorption to low redshifts, leaving the effects to high redshift essentially unchanged. The numbers of reddened and/or obscured sources at high redshift relative to those expected in non-evolving dust models however will always be reduced, regardless of the dependence of absorption cross-section on redshift.

Observations of the optical reddening distribution of quasars as a function of redshift may be used to test our predictions. Large and complete radio-selected samples with a high identification rate extending to high redshifts however are required. The reason for this is that first, radio wavelengths are guaranteed to have no bias against obscuration by dust, and second, the statistics at high redshift need to be reasonably high in order to provide sufficient sampling of an unbiased number of random sight-lines.

The sample of Drinkwater et al. (1997) contains the highest quasar fraction ($\gtrsim 70\%$) than any existing radio sample with a redshift distribution extending to $z \sim 4$. A large fraction of sources appear very red in $B - K$ colour compared to quasars selected by optical means. The dependence of $B - K$ colour on redshift is relatively flat which may at first appear consistent with the predictions of figure 4, although the fraction of sources identified with $z \gtrsim 2$ is only $\sim 5\%$. Also, this sample is known to contain large numbers of sources which are reddened by mechanisms other than dust in the line-of-sight (eg. Serjent & Rawlings 1996). The

role of dust, reddening the optical-to-near-IR continua of radio-selected quasars, and whether it is extrinsic or not still remains a controversial issue. One needs to isolate the intrinsic source properties before attributing any excess reddening to line-of-sight dust. Optical follow-up of sensitive radio surveys that detect large numbers of high redshift sources with known intrinsic spectral properties will be necessary to reliably constrain the rate of evolution in cosmic dust.

7 SUMMARY AND CONCLUSIONS

In this paper, we have modelled the optical depth in galactic dust along the line-of-sight as a function of redshift assuming evolution in dust content. Our model depends on four parameters which specify the dust properties of local galaxies and their evolution: the exponential dust scale radius r_0 , central B -band optical depth τ_B , “evolution strength” δ where $r_0(z) = r_0(1+z)^\delta$, and z_{dust} - a hypothesised dust formation epoch. Our evolution model is based on previous studies of the formation of heavy metals in the cold dark matter scenario of galaxy formation.

Our main results are:

1. For evolutionary parameters consistent with existing studies of the evolution of metallicity deduced from QSO absorption-line systems, a significant “flattening” in the mean and variance of observed B -band optical depth to redshifts $z > 1$ is expected. The mean optical depth to $z \gtrsim 1$ is smaller by at least a factor of 3 compared to non-evolving model predictions. Obscuration by dust is not as severe as shown in previous studies if effects of evolution are accounted for.

2. By allowing for even moderately low amounts of evolution, line-of-sight dust is *not* expected to significantly affect existing optical studies of QSO evolution. Correcting for dust obscuration, evolving dust models predict the ‘true’ (intrinsic) space density of bright quasars to decrease beyond $z \sim 2.5$ as observed, contrary to previous non-evolving dust models where a continuous monotonic increase was predicted.

3. For moderate amounts of evolution, our models predict a mean observed B -band optical depth that scales as a function of redshift as $\bar{\tau} \propto (1+z)^{0.1}$. For comparison, evolving models predict a dependence: $\bar{\tau} \propto (1+z)^{2.5}$. We believe future radio surveys of high sensitivity that reveal large numbers of optically reddened sources at high redshift will provide the necessary data to constrain these models.

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APPENDIX A: DERIVATION OF MEAN OPTICAL DEPTH

Here we derive expressions for the mean and variance in total optical depth as a function of redshift in our evolutionary galactic dust model discussed in section 3.2. The galaxies are modelled as exponential dusty disks, randomly inclined to the line-of-sight.

We first derive the average number of galaxies intercepted by a light ray emitted from some redshift z (ie. equation 14). Given a ‘proper’ number density of galaxies at some redshift $n_g(z)$, with each galaxy having an effective cross-sectional area $\mu\sigma$ as viewed by an observer (μ is a random inclination factor, where $\mu = \cos\theta$ and θ is the angle between the sky plane and the plane of a galactic disk), the average number of intersections of a light ray along some path length ds will be given by

$$dN = n_g(z) \mu \sigma ds. \quad (\text{A1})$$

In an expanding universe we have $n_g = n_0(1+z)^3$, where n_0 is a local comoving number density and is assumed to be constant. Units of proper length and redshift are related by

$$\frac{ds}{dz} = \left(\frac{c}{H_0}\right) \frac{1}{(1+z)^2(1+2q_0z)^{1/2}} \quad (\text{A2})$$

(Weinberg 1972). The effective cross-section projected towards an observer for a randomly inclined disk is found by averaging over the random inclination factor μ , where μ is randomly distributed between 0 and 1, and integrating over the exponential profile assumed for each disk with scale radius $r_0(z)$ (see equations 1 and 9). The product $\mu\sigma$ in equation (A1) is thus replaced by

$$\int_0^1 \mu d\mu \int_0^\infty e^{-r/r_0(z)} 2\pi r dr = \pi r_0^2 (1+z)^{2\delta}. \quad (\text{A3})$$

Thus from equation (A1), the average number of intersections to some redshift z is given by

$$\begin{aligned} \bar{N}(z) &= \int_0^z \mu \sigma n_g(z') \left(\frac{ds}{dz'}\right) dz' \\ &= n_0 \pi r_0^2 \left(\frac{c}{H_0}\right) \int_0^z \frac{(1+z')^{1+2\delta}}{(1+2q_0z')^{1/2}} dz'. \end{aligned} \quad (\text{A4})$$

With τ_g defined by $n_0 \pi r_0^2 \left(\frac{c}{H_0}\right)$, this directly leads to equation (14) for $q_0 = 0.5$.

The mean optical depth $\bar{\tau}$ is derived by a similar argument. If $\tau_0(z)$ is the optical depth observed through a face on galaxy at some redshift z (equation 8), then a galactic disk inclined by some factor μ will have its optical depth increased to $\tau_0(z)/\mu$. Multiplying this quantity by equation (A1), the extinction suffered by a light ray along a path length ds is given by

$$d\tau = n_g(z) \sigma \tau_0(z) ds. \quad (\text{A5})$$

Thus the mean optical depth to some redshift z can be calculated from

$$\bar{\tau}(z) = \int_0^z \sigma n_g(z') \tau_0(z') \left(\frac{ds}{dz'}\right) dz'. \quad (\text{A6})$$

Given $n_g(z)$, $\left(\frac{ds}{dz}\right)$ and σ (from the integral over r in equation A3) above, and $\tau_0(z')$ from equation (8), the mean optical

depth follows the general form

$$\begin{aligned} \bar{\tau}(z) &= 2\tau_g \tau_B \int_0^z \frac{(1+z')^{1+2\delta}}{(1+2q_0z')^{1/2}} \xi\left(\frac{\lambda_B}{1+z}\right) \\ &\times \left[1 - \frac{\ln(1+z')}{\ln(1+z_{dust})}\right] dz'. \end{aligned} \quad (\text{A7})$$

Similarly, the variance in the optical depth distribution is defined as follows:

$$\sigma_\tau^2(z) = \langle \tau^2 \rangle - \langle \tau \rangle^2 = \int_0^z \sigma n_g(z') \tau_0^2(z') \left(\frac{ds}{dz'}\right) dz'. \quad (\text{A8})$$

In terms of our model dependent parameters, this becomes

$$\begin{aligned} \sigma_\tau^2(z) &= 2\tau_g \tau_B^2 \int_0^z \frac{(1+z')^{1+2\delta}}{(1+2q_0z')^{1/2}} \xi^2\left(\frac{\lambda_B}{1+z}\right) \\ &\times \left[1 - \frac{\ln(1+z')}{\ln(1+z_{dust})}\right]^2 dz'. \end{aligned} \quad (\text{A9})$$