Publ. Astron. Soc. Aust., 1995, **12**, 146–52

Dust Obscuration in the Universe

F. J. Masci and R. L. Webster

School of Physics, University of Melbourne, Parkville, Vic. 3052, Australia
fjm@tauon.ph.unimelb.edu.au, webster@tauon.ph.unimelb.edu.au

Received 1994 October 24, accepted 1994 December 6

Abstract: A substantial population of red quasars has been discovered in a complete sample of flat-spectrum radio sources. Dust is the most likely cause of the reddening in this sample. The location of the dust is poorly known, but may either be in the line-of-sight to the quasar, or in the immediate quasar environment. In this paper we are interested in models where the dust is located in the line of sight to the quasar. We calculate the probability distribution of the optical depth in galactic dust as a function of source redshift, using a range of parameters which might describe real galaxies. We compare these results with those found for our sample of radio quasars. If the dust content is unevolving, then it is not possible to account for all the observed reddening in the quasar sample using these models. Our minimum dust model predicts that 15% of background quasars to $z \sim 5$ will have a line of sight within 5 kpc of a galaxy's centre, and would therefore be reddened out of B-band flux-limited samples.

Keywords: galaxies: quasars: general — ISM: dust: extinction

1. Introduction

As early as 1930, Trumpler showed that optical observations of distant stellar clusters were affected by dust, which he suggested was in a thin absorbing layer in the galactic plane. Similarly, sources at large redshift might be severely affected by dust in intervening galaxies, thus biasing our knowledge of the distant Universe. An historical review of cosmological studies of obscuration by dust is given by Rudnicki (1986).

This paper is motivated by recent observations of a radio-selected sample of quasars (Webster et al. 1995), which is optimal for the study of the effects of dust on high-redshift quasars. A large fraction of the quasars in our sample are red, much redder than is characteristically assumed in searches for quasars. We argue that the reddening is due to dust, although the location of the dust is uncertain. There are two obvious possibilities: either the dust is in the local quasar environment or else it is in the line of sight to the quasar. In this paper, we investigate the effects of an intervening dust component, which is located in galaxies in the line of sight.

The effect of intergalactic dust on observations of objects at cosmological distances has been discussed by Ostriker & Heisler (1984), Heisler & Ostriker (1988), Fall & Pei (1989, 1992) and Wright (1986, 1990). These authors have all shown that the line of sight from a high-redshift quasar has a high probability of intercepting a galaxy disk, particularly if the dusty disk is larger than the optical radius of the galaxy. The principle issue in these calculations is that realistic dust distributions, which are 'soft' around the edges, will cause many quasars to be reddened without actually removing them from a magnitude-limited sample. There has been little evidence for a population of reddened quasars in the past. This has been considered a strong constraint on models that postulate that dust might obscure a large fraction of the high-redshift universe. Our new observations (Webster et al. 1995) remove this constraint, and will provide a distribution of reddening as a function of redshift against which intervening models can be measured.

Ostriker & Heisler (1984) have suggested that intervening dusty galaxies would individually produce enough extinction to remove background quasars from a flux-limited sample. In order to avoid the problem of generating many reddened quasars, Ostriker & Heisler suggest that the dusty regions are hard-edged: either a quasar is reddened out of the sample or it is not reddened at all. They find that existing quasar observations (in optical, X-ray and radio bands) are consistent with significant obscuration setting in by $z \sim 3$. They estimate that more than 80% of bright quasars at this redshift may be obscured by dust in intervening galaxies and hence missing from optical samples.

In their later models, Heisler & Ostriker (1988) adopt one set of parameters for the dust properties of galaxies. These parameters describe galaxies which are much dustier than those observed in the nearby universe (Giovanelli et al. 1994; Byun

1323-3580/95/020146$05.00

1993). We repeat these calculations using more realistic parameters of the dust properties of galaxies. Results of our calculations are then compared to our flux-limited quasar survey, where the 'empty field' sources are good candidates for quasars that are strongly obscured by dust.

Fall & Pei (1989, 1992) have developed an analytical method to compute the obscuration of quasars by dust in damped Ly-α absorption systems. These intervening systems have column densities of neutral hydrogen in excess of $10^{20}\,\mathrm{cm}^{-2}$ and are believed to be associated with galactic disks. Fall & Pei estimate that 10%–70% of bright quasars at $z = 3$ are obscured by dust in damped Ly-α systems and therefore missing from optical samples. They find that the true comoving density of bright quasars can exceed the observed comoving density by factors of up to 4 at $z = 3$, and by more than an order of magnitude at $z = 4$.

Wright (1986) has described a numerical method to compute the total optical depth due to intervening dusty galaxies. In a later paper, Wright (1990) examines the relationship between the reddening observed in the colours of background quasars with their extinction in the blue passband due to intervening galaxies. He finds that models in which individual galaxies have 'soft' edges and greater central optical depths [than those assumed in the Heisler & Ostriker (1988) model] can significantly reduce the numbers of quasars in flux-limited samples, while still agreeing with their observed optical colours.

We modify a statistical method introduced by Wright (1986) to calculate the net optical depth in dust along a random line of sight to a source at redshift z. This method is described in Section 2. Section 3 gives the galaxy parameters for four different models and the results of the calculations. Finally, Section 4 investigates constraints on quasar number counts. Throughout this paper, all calculations use a Friedmann cosmology with $q_0 = \frac{1}{2}$ ($\Omega = 1$) and a Hubble constant of $H_0 = 100\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$.

2. Optical Depth Distribution

In order to describe the effect of dust in intervening galaxies on quasar observations, the probability distribution of optical depth τ as a function of redshift z along any random line of sight is calculated. The optical depth for photons emitted at a redshift z is the sum of the optical depths due to galaxies at redshifts $< z$. We define τ to be the total optical depth that is encountered by the emitted photons which are observed at $z = 0$ in the B waveband

The method used is based on Wright (1986). We initially follow Wright by modelling the universe as a series of concentric thin shells. The observed extinction τ between redshifts 0 and z can be represented as a sum of extinctions over intermediate redshifts,

$$\tau(0,z) = \tau(0,z_1) + \tau(z_1,z_2) + \cdots + \tau(z_n,z). \quad (1)$$

For a uniform dust distribution, the τ in each redshift bin are all definite numbers, but if the absorption is due to dusty galaxies then each τ is treated as an independent random variable. The probability density function $p(\tau\,|\,0,z)$ for optical depth τ over some redshift range 0–z can thus be written as a repeated convolution of probabilities $p(\tau\,|\,z_i,z_{i+1})$ over the intermediate redshift bins:

$$p(\tau\,|\,0,z) = p(\tau\,|\,0,z_1) \otimes \cdots \otimes p(\tau\,|\,z_n,z), \quad (2)$$

where $\otimes$ represents convolution. A versatile Fourier transform method described by Wright (1986), with a few modifications, is then used to calculate $p(\tau\,|\,0,z)$ in terms of model-dependent galaxy parameters to be discussed later. We wish to obtain an explicit expression for $p(\tau\,|\,0,z)$ that may be computed for any set of values of the galaxy parameters.

If we denote $p_i(\tau) \equiv p(\tau\,|\,z_i,z_{i+1})$ as the probability density that a photon passing through the ith shell encounters an optical depth τ, then the Fourier transform, $\tilde{p}_i(s)$, of $p_i(\tau)$ is defined by

$$\tilde{p}_i(s) = \int e^{2i\pi s\tau}\, p_i(\tau)\, \mathrm{d}\tau. \quad (3)$$

By convolving the n thin shells as in equation (2) and taking the Fourier transform of this convolution, we have the following

$$\tilde{p}(s\,|\,0,z) = \tilde{p}(s\,|\,0,z_1) \otimes \cdots \otimes \tilde{p}(s\,|\,z_n,z)\,, \quad (4)$$

$$\Rightarrow\ \tilde{p}(s\,|\,0,z) = \int e^{2i\pi s\tau}\, p(\tau\,|\,0,z)\, \mathrm{d}\tau\,. \quad (5)$$

Since the shells are considered to be thin ($\tau \sim 0$), the probability that the optical depth τ within any one shell is nonzero is small. Hence for the ith shell we have

$$p_i(\tau) \approx 1 \quad \text{for } \tau \sim 0$$

$$\Rightarrow \tilde{p}_i(s) \sim \int e^{2i\pi s\tau}\, \mathrm{d}\tau = 1\,, \quad (6)$$

from equation (3). Thus we may write using equation (4),

$$\begin{aligned}\ln \tilde{p}(s\,|\,0,z) &= \sum_{i=1}^{n} \ln \tilde{p}_i(s) \approx \sum_{i=1}^{n} [\tilde{p}_i(s) - 1] \\ &= \sum_{i=1}^{n} \left[\int e^{2i\pi s\tau}\, p_i(\tau)\, \mathrm{d}\tau - \int p_i(\tau)\, \mathrm{d}\tau\right] \\ &= \sum_{i=1}^{n} \int (e^{2i\pi s\tau} - 1)\, p_i(\tau)\, \mathrm{d}\tau\,. \quad (7)\end{aligned}$$

Taking the limit where the shell size reduces to zero ($\Delta z \to 0$ and hence $n \to \infty$) we have, from equation (7),

$$\ln \tilde{p}(s\,|\,0,z) = \int_0^z \mathrm{d}z' \int (e^{2i\pi s\tau} - 1)\, p(\tau, z')\, \mathrm{d}\tau\,. \tag{8}$$

The function $p(\tau, z')$ in the integrand of equation (8) gives the probability density distribution for τ for some interval $z' \to z' + \mathrm{d}z'$. Thus, the quantity $p(\tau, z')\,\mathrm{d}\tau\,\mathrm{d}z'$ gives the probability that the optical depth τ lies within the range $\tau, \tau + \mathrm{d}\tau$ for the interval $\mathrm{d}z'$.

Our method for calculating final result $p(\tau\,|\,0,z)$ now differs from Wright (1986). We wish to express $p(\tau, z')$ in equation (8) in terms of observables, such as the mean numbers and optical depths of individual galaxies within any interval Δz. We can do this by noting that the mean optical depth for the interval $\mathrm{d}z$ in which τ lies within $(\tau, \tau + \mathrm{d}\tau)$ can be defined by

$$\bar{\tau}_{\mathrm{d}z} = \tau\, p(\tau, z)\, \mathrm{d}\tau\, \mathrm{d}z\,. \tag{9}$$

We can also write this mean optical depth in terms of the mean galaxy numbers, $\mathrm{d}\bar{n}$, within $\mathrm{d}z$ and their individual optical depths. Assuming that each galaxy within $\mathrm{d}z$ has a uniform dust distribution with optical depth τ_0, so that $p_{\mathrm{gal}}(\tau) = \delta(\tau - \tau_0)$, we have

$$\bar{\tau}_{\mathrm{d}z} = \mathrm{d}\bar{n}\, \tau_0\, \delta(\tau - \tau_0)\, \mathrm{d}\tau\,. \tag{10}$$

The mean number of galaxies, $\mathrm{d}\bar{n}$, along a line of sight within some redshift range $z \to z + \mathrm{d}z$ is defined as (Weinberg 1972)

$$\mathrm{d}\bar{n} = \sigma\, n_0\, \frac{c}{H_0}(1+z)(1+2q_0 z)^{-1/2}\mathrm{d}z\,, \tag{11}$$

where σ is the cross-sectional area of a typical face-on galaxy, and n_0 is the local comoving galaxy number density, which is assumed to be constant. In other words, we will assume a non-evolving galaxy distribution. Combining equations (9), (10) and (11) we have, for any interval $\mathrm{d}z$,

$$p(\tau, z)\, \mathrm{d}\tau\, \mathrm{d}z \approx \sigma\, n_0\, \frac{c}{H_0}(1+z)(1+2q_0 z)^{-\frac{1}{2}} \times \tau_0\, \delta(\tau - \tau_0)\, \frac{\mathrm{d}\tau}{\tau}\mathrm{d}z\,. \tag{12}$$

Substituting equation (12) into equation (8) and evaluating the integral with respect to τ, we arrive at

$$\ln \tilde{p}(s\,|\,0,z) = \sigma\, n_0\, \frac{c}{H_0} \int_0^z \mathrm{d}z'\, (1+z')(1+2q_0 z')^{-\frac{1}{2}} \times (e^{2i\pi s \tau_0(z')} - 1)\,. \tag{13}$$

Equation (13) holds for the case of uniform galactic disks where the optical depth of an individual galaxy, τ_0, is constant throughout the disk. Note that τ_0 in equation (13) is a function of redshift z. This arises from the fact that the frequency of light emitted at a redshift z, ν_e, decreases steadily as it travels toward the observer to a final observed frequency ν_0, by a factor $1 + z$. Therefore, the optical depth through a galaxy encountered along the path will depend upon the redshift of the absorber. In other words, the optical depth τ_0 has a redshift dependence that exactly corresponds to its frequency dependence and hence the extinction properties of dust in a particular galaxy.

For galaxies with a non-uniform dust distribution, the optical depth is a function of the impact parameter r, so that $\tau_0(z)$ in equation (13) is replaced by $\tau(r, z)$, where r is the distance from the galaxy's centre. Following Wright (1986), we will model the absorbers as exponential galactic disks, where the optical depth through a face-on disk decreases exponentially with distance r from the centre;

$$\tau(r, z) = \tau_0(z)\, e^{-r/r_0}\,, \tag{14}$$

where r_0 is a characteristic galactic radius and $\tau_0(z)$, now, is the value of τ through the centre of the galaxy ($r = 0$). Thus the cross section σ in equation (13) of an exponential profile, is replaced by an integral over r. Making these replacements, equation (13) becomes

$$\ln \tilde{p}(s\,|\,0,z) = n_0\, \frac{c}{H_0} \int_0^z \mathrm{d}z'\, (1+z')(1+2q_0 z')^{-\frac{1}{2}} \times \int_0^\infty (\exp[2i\pi s \tau_0(z')\, e^{-r/r_0}] - 1)\, 2\pi r \mathrm{d}r \tag{15}$$

Furthermore, we will allow the disks of galaxies to be tilted with respect to the line of sight by some random inclination angle $((\pi/2) - \theta)$ (θ being the angle between the plane of the disk and the plane of the sky). To introduce tilts we will need to consider a random inclination factor μ, where

$$\mu = \cos\theta \qquad (0 \le \mu \le 1)\,. \tag{16}$$

As a consequence, optical depths $\tau(r, z)$ will be increased by this factor and cross-sectional areas, σ, decreased by the same amount. Thus with the substitutions:

$$\tau(r, z) \to \frac{\tau(r, z)}{\mu} = \frac{\tau_0(z)}{\mu}\, e^{-r/r_0}\,, \qquad \sigma \to \mu\, \sigma\,,$$

and averaging over μ, where μ is uniformly distributed between 0 and 1, equation (15) becomes

$$\ln\tilde{p}(s\,|\,0,z) = n_0\,\frac{c}{H_0}\int_0^z dz'\,(1+z')\times(1+2q_0z')^{-\frac{1}{2}} \times\int_0^\infty\int_0^1\left(\exp\left[2\,i\,\pi\,s\,\frac{\tau_0(z')}{\mu}\,e^{-r/r_0}\right] -1\right)\mu\mathrm{d}\mu\,2\pi r\mathrm{d}r\,. \qquad (17)$$

With the change of variables $y = e^{-r/r_0}$ and $t = 1/\mu$ and rearranging terms, we reach the final expression

$$\ln\tilde{p}(s\,|\,0,z) = -2\,\tau_{\rm g}\int_0^z \mathrm{d}z'\,(1+z')(1+2q_0z')^{-\frac{1}{2}} \times\int_0^1 \mathrm{d}y\,\frac{\ln y}{y}[E_3(-2\,i\,\pi\,s\,\tau_0(z')\,y)-\tfrac{1}{2}]\,, \qquad (18)$$

where the constant $\tau_{\rm g}$, defined as

$$\tau_{\rm g} \;=\; n_0\,\pi r_0^2\,\frac{c}{H_0}\,, \qquad (19)$$

is a model-dependent parameter discussed in the next section, and

$$E_3(-2\,i\,\pi\,s\,\tau_0(z')\,y) \equiv \int_1^\infty \frac{e^{(2\,i\,\pi\,s\,\tau_0(z')\,y)\,t}}{t^3}\,\mathrm{d}t \qquad (20)$$

is a standard mathematical function termed the 'exponential integral'.

Equation (18) can be calculated numerically and the inverse Fourier transform of $\tilde{p}(s\,|\,0,z)$ gives the required probability density distribution function for the optical depth, $p(\tau\,|\,0,z)$, as a function of z, i.e.

$$p(\tau\,|\,0,z) \;=\; \int_{-\infty}^{\infty} e^{-2\,i\,\pi\,s\,\tau}\,\tilde{p}(s\,|\,0,z)\,\mathrm{d}s\,. \qquad (21)$$

We have followed Wright (1986) equations (1)–(7) by dividing the universe into a series of concentric shells, each with a distribution of galaxies. Using a Fourier transform method and convolving the effect due to each shell, we have obtained the probability density function for the total optical depth τ due to intervening galaxies in the range $0 \to z$. Once the probability distribution function $p(\tau\,|\,0,z)$ is calulated from equations (18)–(20) (for some set of galaxy parameters), we can then determine the probability that the total optical depth is some given value τ along any line of sight to a redshift z.

3. Model Parameters and Results

Our model depends on three parameters which describe the characteristics of the intervening galaxies. The parameters n_0 and r_0 are included in $\tau_{\rm g}$ (equation 19), which gives the average number of intersections in a Hubble length of a light ray within r_0 of a galaxy's centre. The third parameter, $\tau_{\rm B}$, is the dust opacity at the centre of an individual absorber. In this work we assume that the optical depth has a simple linear dependence on frequency, thus

$$\tau_0(z) \;=\; \tau_{\rm B}\,(1+z)\,, \qquad (22)$$

where $\tau_{\rm B}$ is the optical depth in the B band at the centre of a local galaxy ($z = 0$) and $\tau_0(\nu_0) \propto \nu_e = \nu_0(1+z)$. More complex models where the extinction curve includes a 2200 Å bump, as in the Milky Way are considered by Heisler and Ostriker (1988). However recent work (Calzetti, Kinney & Storchi-Berg 1994) finds no evidence of such a feature in the extinction curves of nearby galaxies.

Table 1 gives the values of the three parameters for each of four models considered. Model 1 uses the values of Heisler and Ostriker (1988). Their value of $\tau_{\rm g} = 0{\cdot}2$ was chosen to yield a sky-covering fraction of galaxies which is consistent with the percentage of quasars detected with damped Ly-α absorption systems along the line of sight. They find (from equation 19) that $r_0 = 33$ kpc, which is large compared to typical present day spirals ($r_0 \sim$ 4–5 kpc, Freeman 1970). Heisler and Ostriker have set $\tau_{\rm B} = 0{\cdot}5$ from a study of the range of absorption in galaxies by Phillips (1986).

Table 1. Adopted model parameters for calculation of the distribution functions $p(\tau|z)$

Model	n_0 (Mpc^{-3})	r_0 (kpc)	$\tau_{\rm g}$	$\tau_{\rm B}$
1 (Heisler & Ostriker 1988)	0·02	33	0·2	0·5
2 (Wright 1990)	0·005	33	0·05	2
3 Our model	0·02	10	0·0188	2
4 Our model	0·01	5	0·0023	2

Model 2 uses the values of Wright (1990), who studied correlations between reddening and obscuration of background quasars. This model contains the same total amount of dust as Model 1 but the dust is concentrated in a smaller number of more opaque clouds. In other words, by making $\tau_{\rm B}$ larger, one can approach the opaque, hard-edged disk limit.

The values in Models 3 and 4 are those considered in this paper as being more representative of local galaxies. In both of these models $\tau_{\rm B} = 2$, consistent with lower limits in spiral galaxies derived by Disney, Davies & Phillipps (1989), Byun (1993) and Giovanelli et al. (1994). Model 3 has a characteristic radius of $r_0 = 10$ kpc, while Model 4 represents a minimal model with $r_0 = 5$ kpc and $n_0 = 0{\cdot}01\,\mathrm{Mpc}^{-3}$.

For each set of galaxy parameters (n_0, r_0, τ_B), distribution functions $p(\tau\,|\,z)$ for the total optical depth have been calculated from equations (18)–(20) in redshift intervals of 0·5 up to $z = 6$. Figures 1 and 2 show the optical depth probability density distributions at different redshifts for Models 1 and 4 respectively. These represent two extremes of our models. The curves in Figure 1 closely resemble those computed by Heisler and Ostriker (1988) (see their Figure 1), except that the median points differ. This is due to Heisler and Ostriker adopting a different extinction curve for the dust which involves the 2200 Å feature. The probability that the total optical depth in the B band due to light emitted at some redshift z lies within the interval $0 \to \tau_{\rm max}$ is given by the area under the normalised curve,

$$P(0 \leq \tau \leq \tau_{\rm max}\,|\,z) = \int_0^{\tau_{\rm max}} p(\tau\,|\,z)\,{\rm d}\tau\,. \quad (23)$$

For each curve in Figures 1 and 2, a dot is drawn to indicate the median point where the curve integrated over τ equals $\frac{1}{2}$. Physically, this means that for the specific dust model, we should expect that in an optical quasar survey complete up to some redshift $z_{\rm max}$, 50% of sources with redshifts $z \sim z_{\rm max}$ should at most suffer extinctions corresponding to $\tau \geq \tau_{\rm median}$.

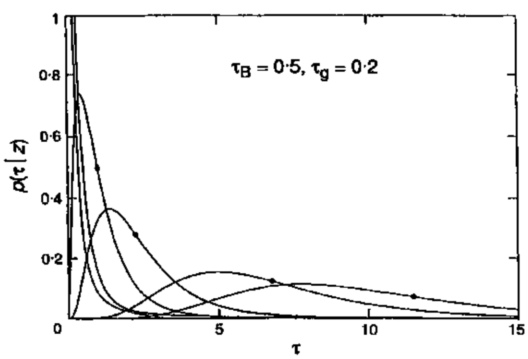

Figure 1—Optical depth probability distribution functions $p(\tau\,|\,z)$ for Model 1 (see Table 1) and redshifts $z =$ 0·5, 1, 2, 3, 5, and 6. The horizontal axis is the total optical depth τ observed in the B band. The median point for each curve (for $z \geq 2$) is indicated by a dot.

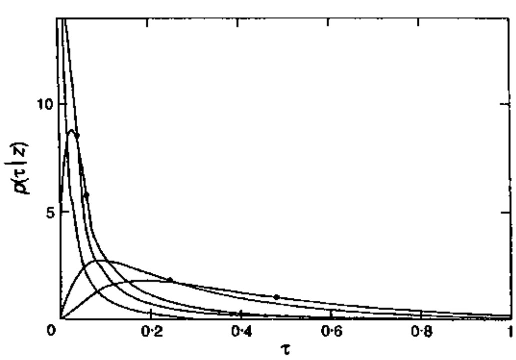

Figure 2—Optical depth probability distribution functions for Model 4 (see Table 1) and redshifts $z = 0{\cdot}5$, 2, 3, 5 and 6. Median points are indicated by dots.

Figure 3 shows the probability that the total optical depth towards some redshift z is greater than 1, computed from the distribution functions for Models 1, 2, 3 and 4 in Table 1. The probability $P(\tau > 1)$ up to a redshift z is the fraction of the sky to that redshift which has at least $\tau = 1$. Model 1 predicts that all sources with $z > 4$ should have at least $\tau = 1$, whereas the percentage drops to 80% and 50% for Models 2 and 3 respectively. Model 4 predicts that more than 30% of sources with redshifts $z > 6$ are likely to encounter an optical depth of at least $\tau = 1$.

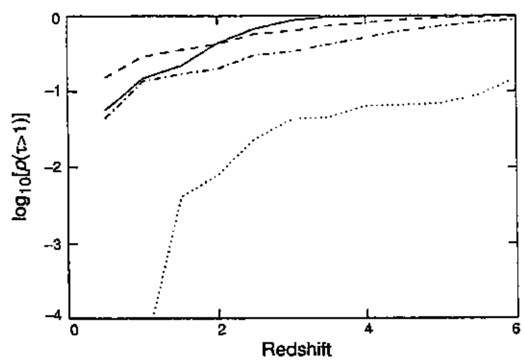

Figure 3—Probability that the total optical depth τ is greater than 1, as a function of z. The vertical axis represents $\log_{10} p(\tau > 1)$. Model 1 (solid curve), Model 2 (short-dashed), Model 3 (dot-dashed) and Model 4 (long-dashed) (see Table 1).

Model 1, corresponding to 'soft'-edged galactic disks, predicts that obscuration should be less severe by as much as a factor of 2 at redshifts $z < 2$ than that of the harder-edged disk Model 2. For redshifts $z > 2$, the situation reverses: optical depths predicted by Model 1 dominate over those predicted by Model 2. This can be explained by use of the parameters defining these models in Table 1. The harder-edged galaxies with higher central optical depths of Model 2 are more effective in causing significant obscuration at lower redshifts ($z < 2$). Light emitted from a source is more likely to suffer reddening once it encounters a harder-edged disk than for a softer-edged disk (Model 1), even though Model 1 contains a greater number of galaxies per unit redshift interval. At redshifts $z > 2$, obscuration becomes more dependent on the number of galaxies intercepting a light ray (the parameter $\tau_{\rm g}$ in Table 1). Model 1, with four times as many galaxies along the line of sight, dominates reddening at high redshifts.

The mean optical depth to a given z provides a means of making the comparison between the dust contents specified by the sets of model parameters

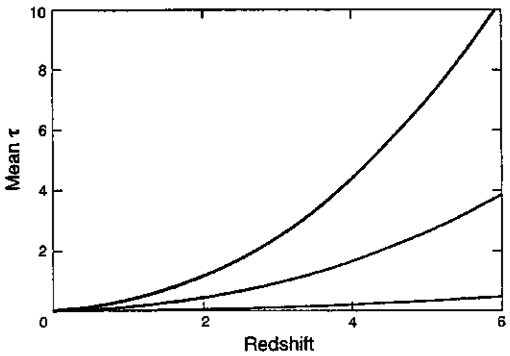

Figure 4—Mean optical depth as a function of redshift along any random line of sight for Models 1 and 2 (top curve; these models contain the same amount of dust), Model 3 (middle curve) and Model 4 (bottom curve).

in Table 1. Heisler and Ostriker (1988) have shown that the mean optical depth to a redshift z scales as the following product:

$$\bar{\tau}(z) = 0{\cdot}8\,\tau_{\rm g}\,\tau_{\rm B}\left[(1+z)^{\frac{5}{2}} - 1\right]. \qquad (24)$$

Equation (24) is plotted in Figure 4 for the models considered in Table 1.

4. Effect on Quasar Number Counts

We will give a simple illustration of the effects of dust in intervening galaxies on quasar counts. Assume that the number counts of quasars at a given redshift follows a power law:

$$N(>L) = N(>L_{\rm l})\left(\frac{L_{\rm l}}{L}\right)^{\beta}, \qquad (25)$$

where $N(>L_{\rm l})$ is the total number of QSOs observed at fixed z with fluxes greater than the limiting flux $L_{\rm l}$, and β is the slope of the quasar luminosity function.

In a dusty Universe, quasars observed through an extinction τ have their true fluxes reduced by a factor $e^{-\tau}$. At a fixed τ, there is a probability $p(\tau\,|\,z)$ that a source with $L < L_{\rm l}e^{\tau}$ will be reddened below the flux limit $L_{\rm l}$. Sources brighter than $L_{\rm l}e^{\tau}$ will be reddened, but remain in the sample. The total number of sources removed from a sample ($N_{\rm dust}(<L_{\rm l})$) relative to numbers observed in a dust free Universe ($N_{\rm true}(>L_{\rm l})$) is then $N_{\rm true}(>L_{\rm l})[1-e^{-\beta\tau}]$. Thus the total fraction of sources lost from the sample is

$$f_z = \frac{N_{\rm dust}(<L_{\rm l})}{N_{\rm true}(>L_{\rm l})} = 1 - \int_0^{\infty} p(\tau\,|\,z)e^{-\beta\tau}{\rm d}\tau. \qquad (26)$$

This fraction will increase with increasing β; in other words, if the luminosity function is steep, then a greater fraction of sources will be reddened below the limiting magnitude of the sample.

From surveys of quasars selected in the B band, the slope β at the bright end of the luminosity function is in the range 2·5–3·0 (Boyle et al. 1990). We have chosen the lower bound of $\beta = 2{\cdot}5$. Figure 5 plots f_z, which, with $\beta = 2{\cdot}5$, is a lower limit on the fraction of quasars that are obscured in a dusty Universe. These sources will then be detectable as 'empty fields' (EFs) in flux-limited radio surveys. Each of our four models is plotted. Model 1 predicts that there should be no quasars at $z > 4$ with optical counterparts within the survey limit $L_{\rm l}$, while from Model 4 we expect at least 15% of quasars at redshifts $z > 6$ to be reddened below the survey limit.

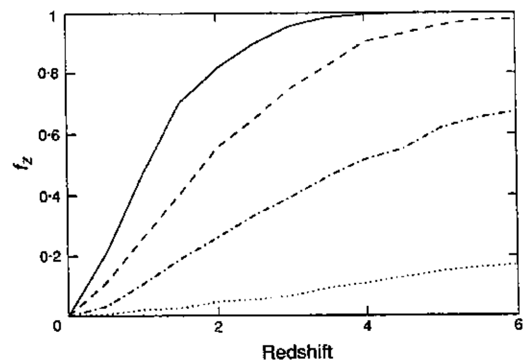

Figure 5—Lower bound on the fraction f_z of QSOs obscured (with fluxes $L < L_{\rm l}$) up to a redshift z due to our intervening dust models (see equation 26). Model 1 (solid curve), Model 2 (short-dashed), Model 3 (dot-dashed), Model 4 (long-dashed).

Let us consider whether the reddening observed in our quasar sample is consistent with all dust being in line of sight galaxies. Two aspects of the observations are relevant (Webster et al. 1995): (i) the heavily reddened quasars are distributed relatively uniformly in redshift, and (ii) overall, more than 50% of the sample is reddened. Model 4 predicts that the number of reddened quasars is small. For example, at $z \lesssim 2$ there is almost no predicted reddening. From our observations, as many as 50% of such quasars show significant reddening. Thus the Model 4 predictions cannot account for all the observed reddening. The most stringent test for Model 1 is at low redshift ($z \lesssim 1$), where less than a magnitude of reddening is predicted for all but a few per cent of quasars. In fact, more than 50% of the quasars in this redshift range are strongly reddened. In this case, though, the predicted number of reddened quasars is closer to the observed value, but the redshift distribution is not as predicted.

5. Conclusions

This paper describes a model that can be used to determine the obscuration due to a distribution of dusty galaxies along the line of sight to some redshift.

We have modelled galaxies as randomly inclined disks with exponential dust profiles. Numbers and dust properties of these galactic disks depend on three parameters, the number density of dusty galaxies, the scale length of the dust distribution, and the central dust opacity. No allowance has been made for possible evolution of the dust properties.

Our main results are:

1. The distribution of reddening in quasars cannot be fully explained by a distribution of dusty line of sight galaxies.
2. Our minimum dust model predicts that flux-limited surveys of optically selected quasars may be at most 90% complete at redshifts $z > 3\cdot5$ and at most 80% complete for $z > 6$. Sources in this latter redshift range may be detectable in the radio. Such a model would not account for all the reddening observed in our sample of radio quasars, but only a fraction of it. This model is almost certainly too conservative.
3. The models depend on a range of parameters which will require detailed fitting of the observations. However, the distribution of reddening as a function of redshift will provide a strong constraint on possible models.

Future work will give a detailed comparison of these models with the full dataset. If the models of dusty line of sight galaxies are correct, then a large fraction of radio-selected quasars at large redshifts are optically faint. If the intervening hypothesis is to be completely ruled out, then current radio surveys will have to identify virtually all empty fields as low-redshift, highly reddened galaxies or quasars that are intrinsically obscured.

Boyle, B. J., Fong, R., Shanks, T., & Peterson, B. A. 1990, MNRAS, 243, 1

Byun, Y. I. 1993, PASP, 105, 993

Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582

Disney, M., Davies, J., & Phillipps, S. 1989, MNRAS, 239, 939

Fall, S. M., & Pei, Y. C. 1989, ApJ, 337, 7

Fall, S. M., & Pei, Y. C. 1992, ApJ, 402, 479

Freeman, K. C., 1970, ApJ, 160, 811

Giovanelli, R., Haynes, M. P., Salzer, J. J., Wegner, G., Da Costa, L. N., & Freudling, W. 1994, AJ, 107, 2036

Heisler, J., & Ostriker, J. P. 1988, ApJ, 332, 543

Ostriker, J. P., & Heisler, J. 1984, ApJ, 278, 1

Phillips, S. 1986, Ap. Lett., 25, 19

Rudnicki, K. 1986, in Proc. Internat. of Physics 'Enrico Fermi', Summer School, 86, 480

Trumpler, R. J. 1930, Lick Obs. Bull., 114, 154

Webster, R. L., Francis, P. J., Peterson, B. A., Drinkwater, M. J., & Masci, F. J. 1995, Nature, submitted

Weinberg, S. 1972, Gravitation and Cosmology: Principles and Applications of the General Theory of Relativity (New York: Wiley)

Wright, E. L. 1986, ApJ, 311, 156

Wright, E. L. 1990, ApJ, 353, 411