

Obscuration by Diffuse Cosmic Dust

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Received 1998 May 4, accepted 1998 August 27

Abstract: If the background universe is observed through a significant amount of diffusely distributed foreground dust, then studies at optical wavelengths may be severely biased. Previous studies investigating the effects of foreground dust on background sources assumed dust to be ‘compactly’ distributed, i.e. on scales comparable to the visible extent of normal galaxies. We show, however, that diffuse dust is more effective at obscuring background sources. Galaxy clusters are a likely location for ‘large-scale’ diffusely distributed dust, and its effect on the counts of background sources is explored. We also explore the implications of a hypothesised diffuse intergalactic dust component uniformly distributed to high redshift with comoving mass density equal to that associated with local galaxies. In this case, we predict a deficit in background sources about three times greater than that found in previous studies.

Keywords: dust: extinction — ISM: general — intergalactic medium

1 Introduction

There are a number of studies claiming that dust in foreground galaxies has a substantial effect on the colours and counts of optically-selected quasars (Ostriker & Heisler 1984; Heisler & Ostriker 1988; Fall & Pei 1993; Wright 1990). It is estimated that at least 50% of bright quasars at redshifts $z \gtrsim 3$ may be obscured by foreground galactic dust and hence missing from optical samples. These studies assumed that dust was confined only within the visible extent of normal massive galaxies. However, distant populations such as faint field galaxies and quasars may also be observed through foreground diffuse dust distributions. Such distributions may be associated with galaxy clusters and extended galactic haloes.

A truly diffuse intergalactic dust component is ruled out on the basis of counts of quasars and reddening as a function of redshift (e.g. Rudnicki 1986; Ostriker & Heisler 1984). Such observations indicate that if a significant amount of dust exists, it must be patchy and diffuse, with relatively low optical depth so that quasars will appear reddened without being removed from flux-limited samples.

Galaxy clusters provide a likely location for ‘large-scale’ diffusely distributed dust. Indirect evidence is provided by several studies that report large deficits of distant quasars or clusters of galaxies behind nearby clusters (Boyle, Fong & Shanks 1988; Romani & Maoz 1992 and references therein). These studies proposed that extinction by intracluster dust was the major cause. Additional evidence for diffuse dust distributions is provided by observations of massive local galaxies where, in a few cases, dust haloes

extending to scales $\gtrsim 50$ kpc have been confirmed (Zaritsky 1994; Peletier et al. 1995).

Does uniformly distributed dust really exist in the intergalactic medium (IGM)? Galactic winds associated with prodigious star formation at early epochs may have provided a likely source of metal enrichment and hence dust for the IGM (e.g. Nath & Trentham 1997). Observations of metal lines in Ly- α absorption systems of low column density ($N_{\text{HI}} \lesssim 10^{15} \text{ cm}^{-2}$) indeed suggest that the IGM was enriched to about $Z \sim 0.01Z_{\odot}$ by redshift $z \sim 3$ (Womble, Sargent & Lyons 1996; Songaila & Cowie 1996). A source of diffuse dust may also have been provided by an early generation of pre-galactic stars (i.e. population III stars) associated with the formation of galactic haloes (McDowell 1986). Studies have shown that possible reddening from uniformly distributed IGM dust is limited by observations of radio-selected quasars. Since radio-selected quasars should have no bias against reddening by dust, such a component must be of sufficiently low optical depth to avoid producing a large fraction of ‘reddened’ sources at high redshift (see Webster et al. 1995; Masci 1997).

In this paper, we show that a given quantity of dust has a much greater effect on the background universe when diffusely distributed. We shall investigate the effects of diffuse dust first, from, possible distributions on galaxy cluster scales and second, from a hypothesised uniformly distributed component in the IGM.

This paper is organised as follows. In the next section, we explore the dependence of background source counts observed through a given mass of

dust on its spatial extent. In Section 3, we investigate the spatial distribution of dust optical depth through galaxy clusters, and its effect on the counts and colours of background sources. Section 4 explores the consequences if all dust in the local universe were assumed to be uniformly distributed in the IGM. Further implications are discussed in Section 5, and all results are summarised in Section 6. All calculations use 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 Compact versus Diffuse Dust Distributions

In this section, we explore the dependence of obscuration of background sources on the spatial distribution of a given mass of dust. For simplicity, we assume that the dust is associated with a cylindrical face-on disk with uniform dust mass density. We quantify the amount of obscuration by investigating the number of background sources behind our absorber that are missed from an optical flux-limited sample.

The fraction of sources missing to some luminosity L relative to the case where there is no dust extinction is simply $1 - N_{obs}(> L) / N_{true}(> L)$, where $N_{obs}(> L)$ represents the observed number of sources in the presence of dust. For a uniform dust optical depth τ , $N_{obs}(> L) \equiv N_{true}(> e^\tau L)$. For simplicity, we assume that background sources are described by a cumulative luminosity function that follows a power law: $\Phi \propto L^{-\beta}$, where β is the slope. This form for the luminosity function is often observed for ‘luminous’ ($L > L_*$) galaxies and quasars, which dominate high-redshift ($z \gtrsim 0.5$) populations in flux-limited samples. With this assumption, the fraction of background sources missing over a given area when viewed through our dusty absorber with uniform optical depth τ is given by

$$f_{miss}(\tau) = 1 - e^{-\beta\tau}. \quad (1)$$

If the ‘true’ number of background sources per unit solid angle is n_{true} , then the total number of background sources lost from a flux-limited sample within the projected radius R of our absorber can be written as

$$N_{lost}(\tau) = n_{true} \frac{\pi R^2}{D^2} (1 - e^{-\beta\tau}), \quad (2)$$

where D is the distance of the absorber from us.

To investigate the dependence of background source counts on the spatial dust distribution, we need first to determine the dependence of τ in equation (2) on the spatial extent R for a *fixed* mass of dust M_d . This can be determined from the individual properties of grains as follows. The extinction optical depth at a wavelength λ through

a slab of dust composed of grains with uniform radius a is defined as

$$\tau_\lambda = Q_{ext}(\lambda, a) \pi a^2 n_d l_d, \quad (3)$$

where Q_{ext} is the extinction efficiency, which depends on the grain size and dielectric properties, n_d is the number density of grains, and l_d is the length of the dust column along the line of sight. Assuming that our cylindrical absorber (whose axis lies along the line of sight) has a uniform dust mass density $\rho_{dust} = M_d / \pi R^2 l_d$, where R is its cross-sectional radius, we can write $n_d = \rho_{dust} / \frac{4}{3} \pi a^3 \rho_d$, where ρ_d is the mass density of an individual grain. We use the extinction efficiency Q_{ext} in the V -band as parametrised by Goudfrooij et al. (1994) for a graphite and silicate mixture (of equal abundances) with mean grain size $a \sim 0.1 \mu\text{m}$, characteristic of the galactic ISM. The value used is $Q_{ext}(V, 0.1 \mu\text{m}) = 1.4$. We use a galactic extinction curve to convert to a B -band extinction measure, where typically $\tau_B \sim 1.3\tau_V$ (e.g. Pei 1992). Combining these quantities, we find that the B -band optical depth, τ_B , through our model absorber can be written in terms of its dust mass and cross-sectional radius as

$$\tau_B \simeq 1 \left(\frac{M_d}{10^8 M_\odot} \right) \left(\frac{R}{20 \text{ kpc}} \right)^{-2} \left(\frac{a}{0.1 \mu\text{m}} \right)^{-1} \times \left(\frac{\rho_d}{2 \text{ g cm}^{-3}} \right)^{-1}, \quad (4)$$

where we have scaled to a dust mass and radius typical of local massive spirals and ellipticals (e.g. Zaritsky 1994). This measure is consistent with mean optical depths derived by other means (e.g. Giovanelli et al. 1994 and references therein).

From equation (4), we see that the dust optical depth through our model absorber for a *fixed* dust mass varies in terms of its cross-sectional radius R as $\tau \propto 1/R^2$. For the nominal dust parameters in equation (4), the number of sources missed behind our model absorber (equation 2) can be written as

$$N_{lost}(< R) = N_{true}(< 20 \text{ kpc}) R_{20}^2 (1 - e^{-\beta R_{20}^{-2}}), \quad (5)$$

where $R_{20} = R/20 \text{ kpc}$ and

$$N_{true}(< 20 \text{ kpc}) \equiv n_{true} \frac{\pi (20 \text{ kpc})^2}{D^2} \quad (6)$$

is the ‘true’ number of background sources falling within the projected scale radius $R = 20 \text{ kpc}$.

From the functional forms of equations (2) and (5), there are two limiting cases:

1. For optical depths $\tau \gg 1/\beta$, the factor $1 - e^{-\beta\tau}$ in equation (2) is of order unity. This corresponds to values of R such that $0 < R_{20} \ll \beta^{\frac{1}{2}}$ for the

nominal parameters in equation (4). For values of R in this range, we have $N_{lost} \propto R^2$ and the obscuration of background sources will depend most strongly on R .

2. For $\tau \ll 1/\beta$ or equivalently $R_{20} \gg \beta^{1/2}$, N_{lost} will approach a constant limiting value, independent of the dust extent R . From equation (5), this limiting value can be shown to be $N_{lost}(<R) = N_{true}(<20 \text{ kpc})\beta$.

As a simple illustration, we show in Figure 1 the dependence of the number of background sources missing behind our model dust absorber on R , for a fixed dust mass of $10^8 M_\odot$ as defined by equation (5). We have assumed a cumulative luminosity function slope of $\beta = 2.5$, a typical value for luminous galaxies and quasars. From the above discussion, we see that when $R_{20} \gtrsim \beta^{1/2}$, i.e. $R \gtrsim 30 \text{ kpc}$ (or when $\tau \lesssim 1/\beta = 0.4$), the obscuration will start to approach its maximum value and remain approximately constant as $R \rightarrow \infty$.

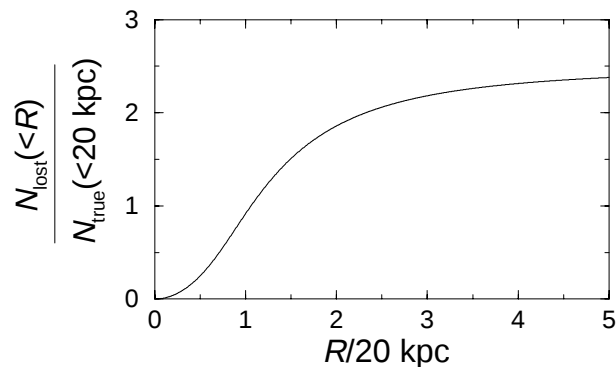


Figure 1—The number of sources missing from an optical flux-limited sample behind a face-on dusty disk with fixed mass $M_{dust} = 10^8 M_\odot$, as a function of its radial extent R . This number is normalised against the ‘true’ number of background sources (in the absence of the absorber) that fall within the solid angle $\pi(20 \text{ kpc})^2/D^2$ subtended by our nominal radius of 20 kpc at distance D —see equation (5).

We conclude that when dust becomes diffuse and extended on a scale such that the mean optical depth τ through the distribution satisfies $\tau < 1/\beta$, where β is the cumulative luminosity function slope of background sources, obscuration starts to be important and is maximised for $\tau \ll 1/\beta$. The characteristic spatial scale at which this occurs will depend on the dust mass through equation (4). For the typical grain values in equation (4), this characteristic radius is given by

$$R \simeq 31 \left(\frac{\beta}{2.5} \right)^{1/2} \left(\frac{M_d}{10^8 M_\odot} \right)^{1/2} \text{ kpc}. \quad (7)$$

The simple model in Figure 1 shows that the obscuration of background sources due to a normal foreground galaxy will be most effective if dust is distributed over a region whose radius is a few times

the optical radius of the galaxy. This prediction may be difficult to confirm observationally due to possible contamination from light in the galactic absorber. In the following sections, we explore two examples of possible ‘large-scale’ diffuse dust distributions that can be explored observationally.

3 Diffuse Dust in Galaxy Clusters

A number of studies have attributed the existence of large deficits of background sources behind nearby galaxy clusters to extinction by dust. Bogart & Wagoner (1973) found that distant rich Abell clusters were anticorrelated on the sky with nearby ones. They argued for a mean extinction of $A_V \approx 0.4$ mag extending to ~ 2.5 times the optical radii of the nearby clusters. Boyle, Fong & Shanks (1988), however, claimed a $\sim 30\%$ deficit of background quasars within $4'$ of clusters consisting of tens of galaxies. These authors attributed this to an extinction $A_V \approx 0.15$ mag, and deduced a dust mass of $\sim 10^{10} M_\odot$ within 0.5 Mpc of the clusters. Romani & Maoz (1992) found that optically selected quasars from the Véron-Cetty & Véron (1989) catalogue avoid rich foreground Abell clusters. They also found deficits of $\sim 30\%$ out to radii $\sim 5'$ from the clusters, and postulated a mean extinction of $A_V \approx 0.4$ mag.

The number of background sources behind clusters is also expected to be modified by gravitational lensing (GL) by the cluster potential. Depending on the intrinsic luminosity function of the background population, and the limiting magnitude to which the sources are detected, GL can cause either an enhancement or a deficit in the number of background sources. The GL effect has been used to explain various reports of overdensities of both optically and radio-selected quasars behind foreground clusters (Bartelmann & Schneider 1993; Bartelmann, Schneider & Hasinger 1994; Rodrigues-Williams & Hogan 1994; Seitz & Schneider 1995). The reported overdensities for *optically selected* QSOs are contrary to the studies above where anticorrelations with foreground clusters are found. These overdensities, however, are claimed to occur on angular scales $\sim 10' - 30'$ from the cluster centres, considerably larger than the scales on which most of the underdensities have been claimed, which are of order a few arcminutes. One interpretation is that dust obscuration bias may be greater towards cluster centres due to the presence of greater quantities of dust. On the other hand, the reported anticorrelations on small angular scales can perhaps be explained by the optically crowded fields, where QSO identification may be difficult. At present, the effects of clusters on background source counts still remains controversial.

More direct evidence for the existence of intra-cluster dust was provided by Hu, Cowie & Wang

(1985) and Hu (1992), who compared the Ly- α flux from emission line systems in ‘cooling flow’ clusters with Balmer line fluxes at optical wavelengths. Extinctions of $A_V \sim 0.2\text{--}1$ mag towards the cluster centres were found, in good agreement with estimates from the quasar deficits above. Intracluster dust has been predicted to give rise to detectable diffuse IR emission (e.g. Dwek, Rephaeli & Mather 1990). The most extensive search was conducted by Wise et al. (1993), who claimed to have detected excess diffuse 60–100 μm emission at the 2σ level from a number of rich Abell clusters. They derived dust temperatures in the range 24–34 K and dust masses $\sim 10^{10} M_\odot$ within radii of ~ 1 Mpc. Recently, Allen (1995) detected strong X-ray absorption and optical reddening in ellipticals situated at the centres of rich cooling-flow clusters, providing strong evidence for dust. These studies indicate that intracluster dust is certainly present, however, the magnitude of its effect in producing background source deficits remains a controversial issue.

In this section, we give some predictions that may be used to further constrain cluster dust properties, or help determine the dominant mechanism (i.e. GL or extinction) by which clusters affect background observations.

3.1 Spatial Distribution of Cluster Dust

X-ray spectral measurements show the presence of hot, metal-enriched gas in rich galaxy clusters with $\sim 0.5\text{--}1$ solar metallicity. This gas is believed to be of both galactic and primordial origin (i.e. pre-existing IGM gas), with the bulk of metals being ejected from cluster galaxies (see Sarazin 1986 for a review). Ejection from galaxies may occur abruptly through collisions between the cluster galaxies, ‘sudden’ ram-pressure ablation, or through continuous ram-pressure stripping by intracluster gas (e.g. Takeda, Nulsen & Fabian 1984). The lack of significant amounts of dust (relative to what should have been produced by stellar evolution) and interstellar gas in cluster ellipticals provides evidence for a mass loss process. On the other hand, in ellipticals that avoid dense cluster environments, significant quantities of neutral hydrogen, molecular gas and dust have been detected (e.g. Lees et al. 1991).

If the dust-to-gas ratio of intracluster gas in rich clusters were similar to that of the Milky Way, then a radial gas column density of typically $\gtrsim 10^{22} \text{ cm}^{-2}$ with metallicity $Z = 0.5Z_\odot$ would produce an extinction of $A_V \gtrsim 4$ mag. This, however, is much greater than the value observed. The likely reason for the deficiency of dust in the intracluster medium is its destruction by thermal sputtering in the hot gas, a process which operates on timescales $t_{\text{sputt}} \lesssim 10^8 n_{-3} a_{0.1} \text{ yr}$, where $n_{-3} = n_H / (10^{-3} \text{ cm}^{-3})$ is the gas density and $a_{0.1} =$

$a / (0.1 \mu\text{m})$ the grain radius (Draine & Salpeter 1979). Dust injection timescales from galaxies are typically of order a Hubble time (e.g. Takeda et al. 1984) and hence grains are effectively destroyed, with only the most recently injected still surviving and possibly providing some measurable extinction.

The spatial distribution in dust mass density remains a major uncertainty. A number of authors have shown that under a steady state of continuous injection from cluster galaxies, destruction by thermal sputtering at a constant rate, and assuming instantaneous mixing with the hot gas, the resulting mass density in dust will be of order

$$\rho_{\text{dust}} \sim 10^{-31} \left(\frac{a}{0.1 \mu\text{m}} \right) \left(\frac{Z_d}{0.01} \right) h_{50} \text{ g cm}^{-3} \quad (8)$$

(e.g. Dwek et al. 1990), where Z_d is the injected dust-to-gas mass ratio, assumed to be equal to the mean value of the galactic ISM, $Z_d \simeq 0.01$ (Pei 1992). According to this simple model, the dust mass density is independent of gas density and position in the cluster. If we relax the assumption of instantaneous mixing of dust with the hot gas, however, so that the spatial distribution of gas is different from that of the injected dust, the radial distribution of dust can significantly differ from uniformity throughout a cluster. Such a non-uniform spatial dust distribution may be found in clusters exhibiting cooling flows. If, as was suggested by Fabian, Nulsen & Canizares (1991), most of the cooled gas remains cold and becomes molecular in cluster cores, then a relatively large amount of dust may also form, resulting in a dust distribution which peaks within the central regions.

We explore the radial dependence of extinction optical depth through a cluster, and the expected deficit in background sources, by assuming that dust is diffusely distributed and follows a spatial density distribution:

$$\rho_{\text{dust}}(R) = \rho(0) \left[1 - \left(\frac{R}{R_c} \right)^2 \right]^{-n}, \quad (9)$$

where R_c is a characteristic radius which we fix and n is our free parameter. Equation (9) with $n = \frac{3}{2}$ is the usual King profile which, with $R_c \simeq 0.25$ Mpc, represents a good approximation to the galaxy distribution in clusters. Thus for simplicity we keep R_c fixed at $R_c = 0.25$ Mpc and vary n . To bracket the range of possibilities in the distribution of intracluster dust, we consider the range $0 < n < \frac{3}{2}$. Here $n = 0$ corresponds to the simple case where $\rho_{\text{dust}}(R) = \rho(0) = \text{constant}$, which may describe a situation where injection of dust is balanced by its destruction by hot gas as discussed above. The value $n = \frac{3}{2}$ assumes that dust follows the galaxy distribution. This profile may arise if grain

destruction by a similar distribution of hot gas were entirely absent.

3.2 Spatial Distribution of Dust Optical Depth and Background Source Deficits

To model the spatial distribution of optical depth, we assume that intracluster dust is distributed within a sphere of radius R_{max} . The central dust mass density $\rho(0)$ in equation (9) is fixed by assuming values for the total dust mass M_{dust} and R_{max} such that

$$M_{dust} = \int_0^{R_{max}} 4\pi R^2 \rho(R) dR. \quad (10)$$

We assume a cluster dust radius of $R_{max} = 1$ Mpc, which represents a radius containing $\gtrsim 90\%$ of the virial mass of a typical dense cluster characterised by galactic velocity dispersion $\sigma_V \sim 800$ km s $^{-1}$ (Sarazin 1986 and references therein). We assume that the total dust mass within $R_{max} = 1$ Mpc is $M_{dust} = 10^{10} M_\odot$. This value is consistent with that derived from extinction measures by Hu et al. (1985), IR emission detections by Wise et al. (1993) and theoretical estimates of the mean intracluster dust density as given by equation (8).

Using equation (10), the B -band optical depth through our spherical intracluster dust distribution at some projected distance r from its centre can be written as

$$\tau_B(r) = \frac{3Q_{ext}}{4a\rho_d} \times \int_0^{2(R_{max}^2 - r^2)^{\frac{1}{2}}} \rho_{dust}([r^2 + R'^2]^{\frac{1}{2}}) dR', \quad (11)$$

where $\rho_{dust}(R)$ is our assumed radial density distribution [equation (9)] and ρ_d the mass density of an individual dust grain. For a uniform dust density [$\rho_{dust}(R) = \rho_{dust}(0) = \text{constant}$], and our assumed values of R_{max} and M_{dust} given above, the radial dependence dust optical depth can be written as

$$\tau_B(r) = \tau_B(0) \left[1 - \left(\frac{r}{R_{max}} \right)^2 \right]^{\frac{1}{2}}, \quad (12)$$

where $\tau_B(0)$ is the optical depth through the centre of our cluster, which with grain properties characteristic of the galactic ISM, will scale as

$$\tau_B(0) \simeq 0.06 \left(\frac{M_{dust}}{10^{10} M_\odot} \right) \left(\frac{R_{max}}{\text{Mpc}} \right)^{-2} \times \left(\frac{a}{0.1 \mu\text{m}} \right)^{-1} \left(\frac{\rho_d}{2 \text{ g cm}^{-3}} \right)^{-1}. \quad (13)$$

This value is about three times lower than estimates of the mean extinction derived from the deficit

of QSOs behind foreground clusters (e.g. Boyle et al. 1988), and that implied by the Balmer decrements of Hu et al. (1985). For a fixed dust mass of $10^{10} M_\odot$, however, we can achieve larger values for the central optical depth by steepening the radial dust-density distribution profile, determined by the slope n in equation (9).

Figure 2a shows the optical depth as a function of projected cluster radius for the cases $n = 0, 0.5, 1$ and 1.5 . The case $n = 0.5$ approximately corresponds to the model of Dwek et al. (1990), which included effects of mild sputtering by hot gas in order to fit the observed IR emission from the Coma cluster. As shown, the case $n = 0$ [$\rho_{dust}(R) = \text{constant}$] predicts that the dust optical depth should be almost independent of projected radius r . Within all projected radii, the optical depths predicted by our diffuse dust model lie in the range $0 < \tau_B < 0.3$. Turning back to the discussion of Section 2, where we show that background obscuration by diffuse dust reaches its maximum for $\tau_B < 1/\beta$, these optical depths satisfy this condition for $\beta \lesssim 2.5$, typical of luminous background galaxies and quasars.

We now explore the effects of these models on background source counts as a function of projected cluster radius. We first give an estimate of the projected radius at which the number of background sources lost from a flux-limited sample is expected to be a maximum. This is determined by investigating the dependence in the differential number of sources missing, dN_{lost} , within an interval $(r, r + dr)$ as a function of projected radius r . From equation (2), this differential number will scale as

$$dN_{lost}(r) \propto r dr [1 - e^{-\beta\tau(r)}], \quad (14)$$

where $\tau(r)$ is given by equation (11). Figure 2b plots dN_{lost}/dr as a function of r for our various models, where we have assumed $\beta = 2.5$. Thus from observations, an identification of the projected radius at which the background source deficit peaks can be used to constrain the spatial distribution of intracluster dust.

The cumulative fraction of background sources missing within a projected cluster radius is given by

$$f_{miss}(<r) = \frac{N_{lost}(<r)}{N_{true}(<r)} = \frac{1}{\pi r^2} \int_0^r 2\pi r' [1 - e^{-\beta\tau(r')}] dr'. \quad (15)$$

This fraction is shown in Figure 2c. As expected, the $n = \frac{3}{2}$ model, which contains the largest amount of dust within the inner few hundred kiloparsecs, predicts the strongest trend with r , while the opposite is predicted if the dust density is completely uniform.

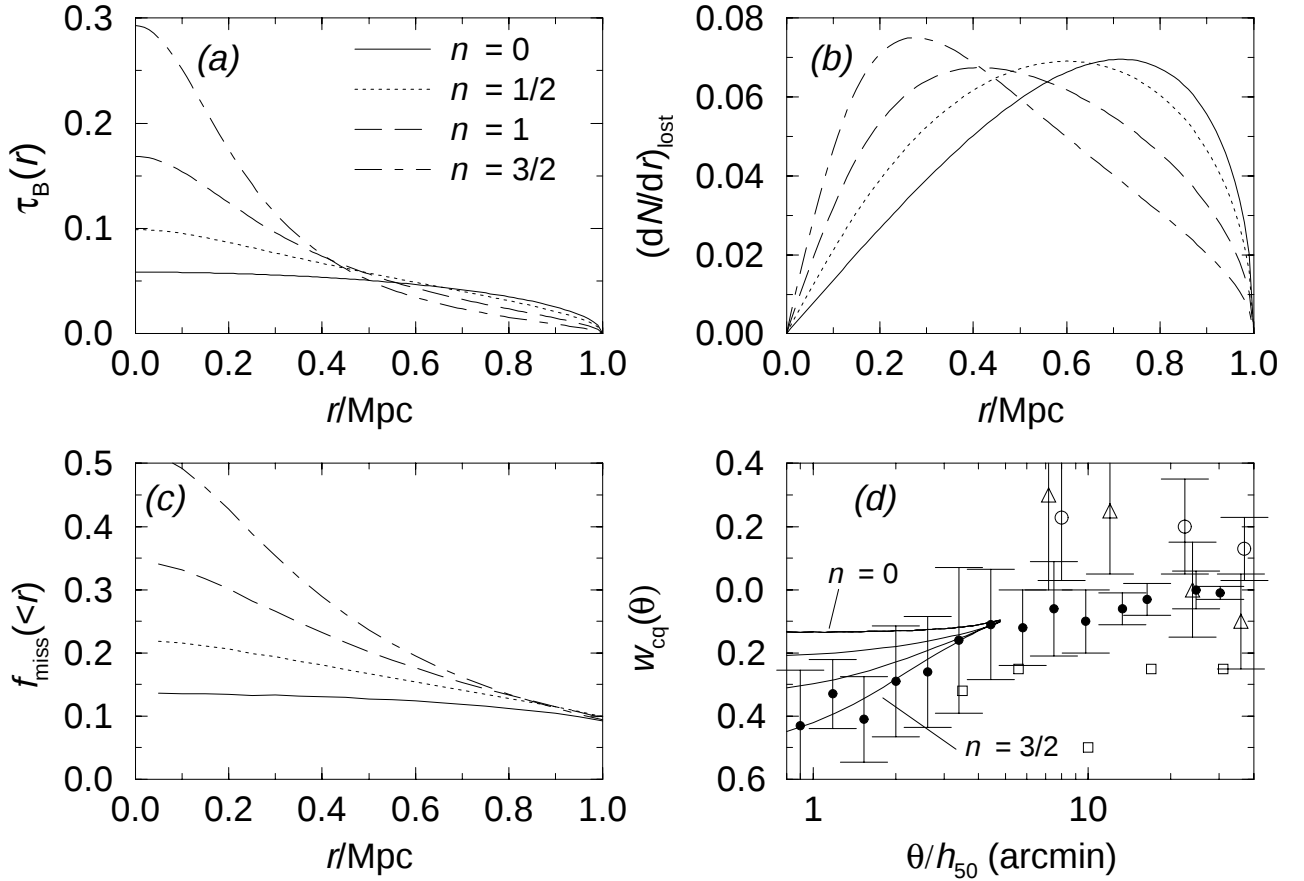


Figure 2—(a) Optical depth as a function of projected cluster radius for various dust density distributions as parametrised by equation (9). (b) Differential number of background sources lost from a flux-limited sample (arbitrary scale). (c) Total fraction of background sources missing to some r . (d) Cluster–QSO two-point angular correlation function: filled circles, Boyle et al. (1988); squares, Romain & Maoz (1992); open circles, Rodrigues-Williams & Hogan (1994); triangles, Rodrigues-Williams & Hawkins (1995).

These predictions can be compared with a number of existing studies of the observed two-point angular correlation function between clusters and optically selected QSOs. This function is usually defined as

$$w_{cq}(\theta) = \frac{\langle N_{obs}(<\theta) \rangle}{\langle N_{ran}(<\theta) \rangle} - 1, \quad (16)$$

where $\langle N_{obs}(<\theta) \rangle$ is the average number of observed cluster–QSO pairs within an angular radius θ and $\langle N_{ran}(<\theta) \rangle$ is that expected in a random distribution. For our purposes, $\langle N_{ran}(<\theta) \rangle$ can be replaced by the ‘true’ number of cluster–QSO pairs expected in the absence of dust, and hence, we can rewrite equation (16) as

$$w_{cq}(\theta) \equiv -\frac{\langle N_{lost}(<\theta) \rangle}{\langle N_{true}(<\theta) \rangle} = -f_{miss}(<\theta). \quad (17)$$

We compare our models with a number of studies of $w_{cq}(\theta)$ for optically selected QSOs in Figure 2d. These studies differ considerably from each other in the selection of the QSO and cluster samples, and as seen, both anticorrelations and correlations

on different angular scales are found. The former have been interpreted in terms of extinction by intracluster dust, the latter with reference to the GL phenomenon. In most cases the reported overdensities are too large to be consistent with GL models, given our current knowledge of cluster masses and QSO distributions.

It is interesting to note that the studies which have reached the smallest angular scales ($\lesssim 5'$) are also those in which anticorrelations between QSOs and foreground clusters have been reported. This can be understood in terms of a larger dust concentration and hence extinction towards cluster centres. These studies, however, may not be free of selection effects, such as in the detection of QSOs from the visual inspection of objective prism plates. From a cross-correlation analysis of galactic stars with their cluster sample, however, Boyle et al. (1988) found that such selection effects are minimal.

The maximum dust radial extent assumed in our models, $R_{max} = 1$ Mpc, corresponds to angular scales $\sim 5'$ at the mean redshift of the clusters ($\langle z_c \rangle \sim 0.15$) used in these studies. Thus, as shown

in Figure 2d, our model predictions only extend to $\sim 5'$. As shown in this figure, the $n = \frac{3}{2}$ model, which corresponds to the case where the dust density is assumed to follow the galaxy distribution, provides the best fit to the Boyle et al. (1988) data. We must note that this is the only existing study performed to angular scales $\sim 1'$ with which we can compare our models. Further studies to such scales are necessary to confirm the Boyle et al. result, and/or provide a handle on any selection effects.

3.3 Summary

To summarise, we have shown that for a plausible value of the dust mass in a typical rich galaxy cluster, obscuration of background sources will be most effective if dust is diffusely distributed on scales ~ 1 Mpc. This conclusion is based on our predicted optical depths ($\tau_B < 0.3$) satisfying our condition for ‘maximum’ obscuration: $\tau_B < 1/\beta$ (see Section 2), where typically $\beta \lesssim 2.5$ for luminous background galaxies and QSOs.

We have explored the spatial distribution in dust optical depth, and the background source deficits expected through a typical rich cluster, by assuming different radial dust density profiles. These predictions can be used to constrain cluster dust properties. A dust density distribution with $n = \frac{3}{2}$ [equation (9)] appears to best satisfy the ‘small-scale’ cluster–QSO angular correlation study of Boyle et al. (1988).

4 Diffuse Intergalactic Dust?

There have been a number of studies claiming that the bulk of metals in the local universe had already formed by $z \sim 1$ (e.g. Lilly & Cowie 1987; White & Frenk 1991; Pei & Fall 1995). Similarly, models of dust evolution in the galaxy show that the bulk of its dust content was formed in the first few billion years (Wang 1991). These studies suggest that the global star formation rate peaked at epochs $z \gtrsim 2$ when the bulk of galaxies were believed to have formed. Supernova-driven winds at early epochs may thus have provided an effective mechanism by which chemically enriched material and dust were dispersed into the IGM. As modelled by Babul & Rees (1992), such a mechanism is postulated to be crucial in the evolution of the ‘faint blue’ galaxy population observed to magnitudes $B \sim 28$. Nath & Trentham (1997) also showed that this mechanism could explain the recent detection of metallicities $Z \sim 0.01Z_\odot$ in low-density Ly- α absorption systems at $z \sim 3$. Another source of diffuse IGM dust may have been provided by an epoch of population III star formation associated with the formation of galactic haloes (e.g. McDowell 1986).

What effects on background sources would be expected if all dust formed to the present day was completely uniform and diffuse throughout the IGM?

In this section, we show that such a component would have a low optical depth and an insignificant effect on the colours of background sources, but would be sufficient to significantly bias their number counts in the optical.

4.1 Comoving Dust Mass Density

To explore the effects of a diffuse intergalactic dust component, we need to assume a value for the mean mass density in dust in the local universe. This density must not exceed the total mass density in heavy metals at the present epoch. An upper bound for the local mass density in metals (hence dust) can be derived from the assumption that the *mean* metallicity of the local universe is typically $Z \sim \Omega_{\text{metals}}/\Omega_{\text{gas}} \sim 0.01$ (i.e. the ratio of elements heavier than helium to total gas mass), as found from galactic chemical evolution models (e.g. Tinsley 1976) and abundance observations (Grevesse & Anders 1991). Combining this with the upper bound in the baryon density predicted from big-bang nucleosynthesis (Olive et al. 1990), where $\Omega_{\text{gas}} \lesssim \Omega_{\text{baryon}} < 0.06h_{50}^{-2}$, it is apparent that

$$\Omega_{\text{metals}}(z=0) < 6 \times 10^{-4} h_{50}^{-2}. \quad (18)$$

Let us now compute the total mass density in dust used in previous studies that modelled the effects of dust in individual galaxies on background quasars. Both Heisler & Ostriker (1988) and Fall & Pei (1993) modelled these effects by assuming that dust in each galaxy was distributed as an exponential disk with scale radius $r_0 \simeq 30$ kpc and central face-on optical depth $\tau_B = 0.5$. The comoving mean mass density in dust (relative to the critical density) in these studies, given a comoving galaxy number density $n_0 = 0.002h_{50}^3 \text{ Mpc}^{-3}$, can be shown to be

$$\begin{aligned} \Omega_{\text{dust}0} \simeq & 7.3 \times 10^{-6} h_{50} \left(\frac{n_0}{0.002 \text{ Mpc}^{-3}} \right) \\ & \times \left(\frac{r_0}{30 \text{ kpc}} \right)^2 \left(\frac{\tau_B}{0.5} \right) \end{aligned} \quad (19)$$

(see Masci 1997). This is consistent with the constraint in equation (18). Thus, as a working measure, we assume the comoving mass density defined by equation (19) in the calculation that follows.

4.2 Obscuration by Diffuse Intergalactic Dust

If the dust mass density given by equation (19) is assumed to be uniformly distributed and constant on comoving scales to some redshift, the *B*-band optical depth through a dust sheet of width dl at redshift z in an observer’s frame can be written [see equation (3)]

$$d\tau_B \simeq 7.2 \times 10^{-6} h_{50} \left(\frac{\Omega_{dust0}}{7.3 \times 10^{-6}} \right) \left(\frac{a}{0.1 \mu\text{m}} \right)^{-1} \times \left(\frac{\rho_d}{2 \text{ g cm}^{-3}} \right)^{-1} \left(\frac{dl}{\text{Mpc}} \right) (1+z), \quad (20)$$

where for simplicity, we have assumed dust properties characteristic of the galactic ISM. The factor $(1+z)$ is due to our assumption of a $1/\lambda$ dependence for the dust extinction law. This arises from the fact that light received in the B -band corresponds to light of wavelength $\lambda_B/(1+z)$ at redshift z , which consequently suffers greater extinction. Although a $1/\lambda$ law is not fully representative of that observed in the galactic ISM, which includes the strong 2200 Å feature, this is a good on-average relation for the dust laws in many external galaxies (e.g. Jansen et al. 1994). Such an assumption greatly simplifies the redshift dependence of extinction in an observer's frame. With $dl/dz = 6000 h_{50}^{-1} (1+z)^{-5/2}$ Mpc (for a $q_0 = 0.5$ and $\Lambda = 0$ cosmology), the total mean optical depth to some redshift in an observer's B -band will scale as

$$\tau_B(z) \simeq 0.1 \left(\frac{\Omega_{dust0}}{7.3 \times 10^{-6}} \right) \left(\frac{a}{0.1 \mu\text{m}} \right)^{-1} \times \left(\frac{\rho_d}{2 \text{ g cm}^{-3}} \right)^{-1} [1 - (1+z)^{-1/2}]. \quad (21)$$

This represents the total optical depth if all dust in the intervening galaxy model of Heisler & Ostriker (1988) is assumed uniformly distributed throughout the universe.

Assuming that dust is uniformly distributed to $z = 2$, the *observed* B -band optical depth from equation (21) will be of order

$$\tau_B(\text{U})(z=2) \simeq 0.04. \quad (22)$$

Using a galactic extinction law (Pei 1992), this corresponds to an extinction in $B-R$ colour of $E_{B-R} \sim 0.02$ mag. Thus, if background faint field galaxies and QSOs are observed through a uniform intergalactic dust distribution, their observed colours are not expected to be significantly affected. We now show, however, that the numbers of sources missing at such redshifts could be significantly greater than those claimed by previous studies, which assume all dust to be associated with massive galaxies alone.

If dust to some distance D covers an area of sky A and hence has covering factor $C_d = A/4\pi D^2$, the number of background sources lost from a flux-limited sample can be estimated from equation (2). In general, the number of background sources at some redshift lost from an area of sky with dust covering factor C_d will scale as

$$N_{lost}(\tau, z) \propto C_d f_{miss}(\tau, z), \quad (23)$$

where $f_{miss} \equiv 1 - e^{-\beta\tau_B(z)}$ is the fraction of sources missing per unit area. For a completely uniform dust distribution, $C_d(\text{U}) = 1$, and to redshift $z = 2$, $f_{miss} \simeq 10\%$ for $\beta = 2.5$.

If dust is confined to individual galaxies along the line of sight, however, the covering factor, assuming that they follow a Poisson distribution is typically $C_d \simeq \bar{N}_z \exp(-\bar{N}_z)$, where $\bar{N}_z$ is the mean number of absorber intersections to redshift z :

$$\bar{N}_z \simeq 0.01 h_{50}^2 \left(\frac{n_0}{0.002 \text{ Mpc}^{-3}} \right) \left(\frac{r_0}{30 \text{ kpc}} \right)^2 \times [(1+z)^{1.5} - 1] \quad (24)$$

(see Heisler & Ostriker 1988). We have scaled to the nominal parameters assumed in the intervening galaxy model of Heisler & Ostriker (1988) (hereafter HO). In this model, we find a covering factor of only $C_d(\text{HO}) \simeq 0.04$ to $z = 2$. We can estimate the mean effective optical depth *observed* in the B -band through an individual absorber to $z \simeq 2$ in the HO model by using the formalism of Section 2. For a *fixed* mass of dust, equation (4) implies that the product of the area (or covering factor) and optical depth of a dust distribution, $\tau \times C_d$, is a constant, depending on grain properties and dust mass alone. Using this relation, the *observed* effective absorber optical depth to $z \simeq 2$ in the HO model, $\tau_B(\text{HO})$, can be estimated by scaling from our values of $\tau_B(\text{U})$ and $C_d(\text{U})$ above for uniformly distributed dust:

$$\tau_B(\text{HO}) \simeq \tau_B(\text{U}) C_d(\text{U}) / C_d(\text{HO}) = \frac{0.04 \times 1}{0.04} = 1. \quad (25)$$

Using this value, the fraction of background sources missed by obscuration from an individual absorber is 'effectively' $f_{miss} = 1 - \exp(-2.5 \times 1) \simeq 91\%$. Combining these results, we find using equation (23) that the number of sources missing at $z \simeq 2$ due to a uniform foreground dust distribution is greater by a factor of $(1 \times 0.1 / 0.04 \times 0.91) \sim 3$ than that predicted by Heisler & Ostriker (1988).

We must note that this estimate makes no allowance for possible evolution in dust content. Effects of foreground diffuse dust on source counts at $z > 2$ may be significantly reduced if appreciable evolution has occurred. Effects of models where the dust content evolves have been explored by Masci & Webster (1998).

4.3 Summary

We conclude that the existence of a significant amount of diffusely distributed dust (e.g. with mass density on comoving scales of order that observed in local galaxies) can enhance the number of background

sources missing in optical samples. Due to its relatively large covering factor, diffuse dust predicts a reduction in optical counts at $z > 2$ about three times greater than that claimed in previous studies.

The colours of background sources are not expected to be significantly affected. This implies that the use of background populations to measure a diffuse IGM dust component will be extremely difficult.

5 Discussion

In this section we discuss some further uncertainties and implications regarding the existence of diffuse dust in the universe.

First, the effects of intracluster dust on background sources critically depend on the amount of dust present, and its spatial distribution. Regardless of the mechanism by which grains are injected into the intracluster medium from galaxies, it is possible that a significant fraction is destroyed in the injection process. Significant amounts of hot gas are also believed to exist in the ISM of cluster ellipticals (e.g. Forman, Jones & Tucker 1985). This gas is expected to destroy grains on timescales $\lesssim 10^8$ yr (Draine & Salpeter 1979), much shorter than injection timescales. Such destruction mechanisms can thus prevent the formation of significant quantities of dust.

It is possible that the spatial distribution of intracluster dust is not ‘diffuse’ and uniformly distributed, but inhomogeneous. For example, Fabian et al. (1991) proposed that if most of the cooled gas resulting from cluster cooling flows remains cold and becomes molecular, then this may provide suitable conditions for large amounts of dust to form. A clumpy dust distribution that follows cooling-flow filaments may result, reducing the effective dust covering factor and hence the background source deficit. These issues need to be addressed before attributing such deficits to extinction by dust.

The existence of a smooth IGM dust component also remains a major uncertainty. Due to a deep gravitational potential, Margolis & Schramm (1977) showed that it is unlikely for supernovae-driven winds to expel significant quantities of dust from a massive galaxy to large scales. For low mass galaxies however (e.g. dwarfs), Babul & Rees (1992) showed that this mechanism could be effective. Such systems are believed to comprise a majority of the ‘faint-blue population’, which show an excess ~ 20 – 30 times that predicted from non-evolving galaxy models for $B > 24$ (e.g. Tyson 1988). Simulations based on star formation rates that assume yields in metallicity from local observations predict that the amount of metals (and hence dust, assuming that a fixed fraction of metals condenses into grains at a constant rate) produced from such a population would be smaller than local estimates by an order

of magnitude (e.g. White & Frenk 1991). If the only source of IGM dust was from these ‘low-mass’ galaxies, then the total optical depth to $z \gtrsim 2$ would be insignificant, and effects on the background universe would be minimal.

6 Conclusions

In this paper we have shown that dust is more effective at obscuring background sources when diffuse or extended. We find that obscuration of background sources by a given dust distribution with optical depth τ_B will be most effective when $\tau_B < 1/\beta$, where β is the cumulative luminosity function slope of the sources.

We have explored the effects of diffuse dust from, first, galaxy clusters and, second, a hypothesised uniform IGM component. By assuming different radial dust density profiles in a typical rich cluster, we have predicted the optical depth and background source deficit as a function of projected cluster radius. These predictions can be compared with future observations to constrain the properties of intracluster dust. Our predicted optical depth measures ($\tau_B \lesssim 0.3$) satisfy the above criterion ($\tau_B < 1/\beta$) for background luminous QSOs and galaxies. Existing studies claiming anticorrelations in the distribution of QSOs with foreground clusters down to scales $\sim 1'$ are consistent with a dust density profile that follows the galaxy distribution.

As a further illustration, we have explored the effects of a diffuse IGM dust component with cosmic mass density equal to that observed in local galaxies. Assuming this density to be constant on comoving scales to $z = 2$, we find a deficit in background sources about three times greater than that predicted assuming dust in normal galaxies alone.

The ‘diffuseness’ of the dust is the key parameter which we claim determines the effectiveness of obscuration of the background universe. Although such dust distributions may be difficult to detect, we must not neglect their possible presence. Further studies of spatial dust distributions, preferably via the counts and colours of background sources, will be essential in confirming our predictions.

Acknowledgments

I am grateful to Paul Francis and Rachel Webster for many illuminating discussions and suggestions. I also acknowledge support from an Australian Postgraduate Award.

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