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Upper limit on dimming of cosmological sources by intergalactic grey dust from the soft X-ray background

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ABSTRACT
Active galactic nuclei (AGN) produce a dominant fraction ($F_{\text{AGN}} \sim 80\text{ per cent}$) of the soft X-ray background (SXB) at photon energies $0.5 < E < 2\text{ keV}$. If dust pervaded throughout the intergalactic medium, its scattering opacity would have produced diffuse X-ray haloes around AGN. Taking account of known galaxies and galaxy clusters, only a fraction $F_{\text{halo}} \lesssim 10\text{ per cent}$ of the SXB can be in the form of diffuse X-ray haloes around AGN. We therefore limit the intergalactic opacity to optical/infrared photons from large dust grains, with radii in the range $a = 0.2–2.0\mu\text{m}$, to a level $\tau_{\text{GD}} \lesssim 0.15(F_{\text{halo}}/10\text{ per cent})(F_{\text{AGN}}/80\text{ per cent})^{-1}$ to a redshift $z \sim 1$. Our results are only weakly dependent on the grain size distribution in this size range or the redshift evolution of the intergalactic dust. Stacking X-ray images of AGN can be used to improve our constraints and diminish the importance of dust as a source of systematic uncertainty for future supernova surveys which aim to improve the precision on measuring the redshift evolution of the dark energy equation-of-state.

Key words: scattering – dust, extinction – intergalactic medium – quasars: general – cosmology: theory – X-rays: diffuse background.

1 INTRODUCTION
The use of Type Ia supernovae as standardized candles provides a powerful measure of the redshift dependence of the luminosity distance, and therefore of the cosmological parameters that shape our Universe (e.g. Riess et al. 2007; Wood-Vasey et al. 2007, and references therein). Historically, supernova surveys provided the first robust evidence for the existence of a positive cosmological constant (Riess et al. 1998; Schmidt et al. 1998). This inference has been confirmed by other independent probes, such as the location of the acoustic peaks in the cosmic microwave background (Dunkley et al. 2009; Komatsu et al. 2009) and galaxy surveys (Eisenstein et al. 2005; Eisenstein 2008), and the observed evolution of the mass function of galaxy clusters (Vikhlinin et al. 2009).

Since supernovae measure the luminosity distance at optical/infrared-infrared wavelengths, they suffer from a systematic uncertainty owing to the possible existence of intergalactic dust. In particular, ‘grey’ dust, which consists of large ($>0.1\mu\text{m}$) grains that may preferentially reside in the intergalactic medium (IGM), can suppress the observed flux while producing little reddening (Aguirre 1999a,b; Goobar et al. 2002; Bianchi & Ferrara 2005). Therefore, the presence of intergalactic grey dust could lead to a systematic overestimation of the luminosity distance, which would in turn modify the inferred values of the cosmological parameters (e.g. Corasaniti 2006). This becomes an important source of systematic uncertainty for future ambitious supernova surveys [performed, e.g., on the Large Synoptic Survey Telescope (LSST),1 or by the Joint Dark Energy Mission (JDEM)2] which are designed to constrain the equation of state parameter of the dark energy, $w(z)$, to an unprecedented (per cent level) precision. A systematic suppression of the supernova flux by a small amount of $+\Delta m$ magnitudes due to grey dust would result in a best-fitting $w$ that is systematically offset by $\Delta w \sim -2\Delta m$ (Zhang 2008). Furthermore, dimming of cosmological sources by grey dust may offset their magnification due to gravitational lensing. Hence, grey dust may limit the accuracy of methods that aim to probe the distribution of matter through gravitational lensing (Zhang & Corasaniti 2007, and references therein).

Probing the grey dust content of the IGM is not only important for the purpose of limiting a source of systematic error for future supernova surveys, it is also related to the fundamental problem of how heavy elements were first produced in galaxies and then dispersed through outflows into the IGM (e.g. Heckman et al. 2000; Aguirre et al. 2001; Furlanetto & Loeb 2003; Bianchi & Ferrara 2005; Scannapieco et al. 2006; Davé & Oppenheimer 2007; Oppenheimer & Davé 2008). A measurement of the intergalactic dust abundance would serve as an important new constraint on theoretical models of the enrichment process of the IGM (e.g. Loeb & Haiman

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1 http://www.lsst.org
2 http://jdem.gsfc.nasa.gov/

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1997; Aguirre & Haiman 2000; Inoue & Kamaya 2004; Petric et al. 2006).

In this paper, we constrain the abundance of intergalactic grey dust using two facts about the soft X-ray background (SXB): (i) active galactic nuclei (AGN) account for ∼80 per cent of the total SXB (Hickox & Markevitch 2006, 2007b, also see Section 2.4) and (ii) the unresolved SXB component is partially accounted for by the known population of galaxies and X-ray clusters (Moretti et al. 2003; Hickox & Markevitch 2007a, and see Section 2.1). If large dust grain existed in the IGM, they would have scattered X-rays by sufficiently large angles to create extended X-ray haloes around point sources (e.g. Alcock & Hatchett 1978; Miralda-Escudé 1999; Petric et al. 2006, and references therein). The lack of such a halo around any particular point source can be used to limit the grey dust abundance along its line-of-sight. Indeed, the absence of an X-ray halo around a z = 4.3 quasar allowed Petric et al. (2006) to place an upper limit on the intergalactic abundance of dust grains with a radius of a = 1 μm. In this paper, we apply this pioneering approach to the SXB as a whole. The advantage of our methodology is that it does not require knowledge of the surface brightness profile for individual X-ray haloes, which quite strongly depends on the assumed redshift evolution and size distribution of the intergalactic dust grains (see Section 4).

In Section 2, we describe the model used to place upper limits on the intergalactic opacity in grey dust. In Section 3, we present our numerical results, whose implications are further discussed and compared to previous work in Section 4. Finally, we summarize our conclusions in Section 5. Throughout our discussion, we adopt the standard set of cosmological parameters for the background cosmology, (Ωm, ΩΛ, h, σ8) = (0.27, 0.73, 0.042, 0.70, 0.82) (Komatsu et al. 2009).

2 CONSTRAINTS FROM THE SXB

2.1 The composition of the SXB

The total SXB in the 1–2 keV band amounts to 4.6 ± 0.1 × 10^{-12} erg cm^{-2} s^{-1} deg^{-2} (e.g. Hickox & Markevitch 2006, their fig. 15). As already mentioned, discrete sources – most of which are AGN – account for ∼80 per cent of this flux (Hickox & Markevitch 2006, 2007b, also see Section 2.4). Hickox & Markevitch (2007a) showed that starburst and ‘normal’ galaxies that are too faint in X-rays to be resolved account for ∼10–15 per cent of the SXB. Furthermore, as much as ∼6–9 per cent may be accounted for by spatially extended X-ray sources such as clusters (e.g. Wu & Xue 2001; Moretti et al. 2003; Dijkstra, Haiman & Loeb 2004, but see Hickox & Markevitch 2006). Lastly, 1.0–1.7 per cent of the SXB must consist of Thomson scattered X-rays that were originally emitted by AGN (Soltan 2003). Adding up these known contributions could, in principle, account for the full SXB. As a conservative working hypothesis, we therefore assume that X-ray haloes, produced by dust scattering around AGN, cannot account for more than a fraction F_{halo} ≲ 10 per cent of the total SXB.

We do not simply adopt the unresolved X-ray background that has been derived by others;3 (e.g. Hickox & Markevitch 2007a). When Hickox & Markevitch (2007a) measure the flux in the ‘unresolved’ component of the SXB in the Chandra Deep Fields, they exclude regions around detected X-ray sources of radius r_{excl} ≤ 4–9 r_{gal}, in which r_{gal} ∼ 1 + (θ/10^2)" arcsec denotes the radius of the region in which 90 per cent of the flux of a point source is detected, and θ denotes the off-axis angle (Hickox & Markevitch 2006). X-ray haloes that are a result of scattering off intergalactic dust are expected to be ∼0.5–2 arcmin in diameter (see Section 2.2), which can be comparable to the size of the excluded regions. Therefore, a significant fraction of X-rays that were scattered by intergalactic dust would already be excluded from the measurement of the unresolved SXB. On the other hand, when measuring the soft X-ray luminosity from AGN, the X-ray flux from within r_{gal} is used, which contains a negligible fraction of X-rays that were scattered by intergalactic dust.

2.2 The scattering cross-section of dust grains

The cross-section for scattering of radiation by a dust grain can be written in the form, \( \sigma_{\text{scat}} = Q_{\text{scat}}a^2 \), where \( a \) is the radius of the grain (assumed to be spherical). Here, \( Q_{\text{scat}} \) denotes the scattering efficiency, which is defined as the ratio between the geometric cross-section and the absorption cross-section of the grain, and is given by (Alcock & Hatchett 1978; Miralda-Escudé 1999)

\[
Q_{\text{scat}} \approx \begin{cases} 
0.7(a/\mu m)^2 (6 \text{ keV}/E)^2 & \text{if } Q_{\text{scat}} < 1; \\
1.5 \text{ otherwise.} 
\end{cases}
\]

The discontinuity at \( Q_{\text{scat}} = 1 \) occurs when the electromagnetic phase shift across the grain reaches unity (Alcock & Hatchett 1978; Miralda-Escudé 1999). For a fixed grain size, equation (1) yields a constant cross-section up to a fixed threshold in photon energy \( E \), after which it declines as \( E^{-2} \). All dust grains with radii \( a \gtrsim 0.16(E/1 \text{ keV})^{-1} \mu m \) are equally likely to scatter all photons of energy less than \( E \). This important result allows us to place tight constraints on intergalactic dust. Equation (1) does not apply to arbitrarily low photon energies, and \( Q_{\text{scat}} \) typically decreases drastically below unity at \( E \lesssim 1(a/0.1 \mu m)^{-1} \text{ eV} \) for grains of radius \( a \) (see e.g. figs 2–4 of Laor & Draine 1993).

X-ray scattering by large dust grains can be described by a phase function of the form \( P(\theta_{\text{scat}}) \propto \exp (-\theta_{\text{scat}}^2/(2\sigma^2)) \), in which \( \sigma = 1.04(a/\mu m)^{-1} (E/\text{keV})^{-1} \text{ arcmin} \) (Mauche & Gorenstein 1986). Furthermore, \( \theta_{\text{scat}} \) denotes the angle between the propagation direction of the photon before and after scattering (i.e. \( k_{in} \cdot k_{out} = \cos(\theta_{\text{scat}}) \)). Hence, dust typically scatters X-ray photons forward into a halo around the source of angular size \( \sim 2\sigma \).

2.3 The fraction of X-rays that is scattered by dust

The fraction of X-ray photons observed at energy \( E \) that is expected to be scattered into X-ray haloes by intergalactic dust is given by

\[
F(E) = \int_0^\infty dz' F(z')[\left[1 - e^{-\tau_{\text{gal}}(E,z')}\right]\int_0^\infty dz' F(z')(2).
\]

where we have defined the function \( F(z') = \mathcal{E}(z)/(1 + z')^2 \mathcal{E}(z) \), in which \( \mathcal{E}(z) = \sqrt{\Omega_m(1+z)^3 + \Omega_k} \), and \( \mathcal{E}(z) \) denotes the X-ray volume emissivity (in erg s^{-1} cm^{-3}) see Section 2.4).

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3 Hickox & Markevitch (2007a) estimate the flux in the unresolved component of the SXB in the Chandra Deep Fields to be \( 3.4 \pm 1.4 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ deg}^{-2} \), which is \( \sim 7 \pm 3 \text{ per cent of the total} \). Similarly Moretti et al. (2003) claim that \( 6 \pm 6 \text{ per cent of the SXB in the energy range } E = 0.5–2 \text{ keV} \) is unresolved.
The redshift evolution of the comoving volume emissivity of AGN in X-rays, $E(z)$ (used in the calculation of the scattered fraction of X-rays in equation 2) is depicted by the solid line. The comoving volume emissivity peaks at $z \sim 2$. The red-dotted line shows the fraction of the total AGN contribution to the SXB that was emitted at redshifts $z > z$. We find that $\sim 50$ per cent (10 per cent) of the total AGN contribution to the SXB originates from AGN at $z \sim 1$ ($z > 2$). This implies that our method is most sensitive to dust at lower redshift (i.e. $z < 2$).

The total optical depth to X-ray scattering by grey dust between redshift 0 and $z$ for an observed photon energy $E$ is given by

$$\tau_{\text{gd}}(E, z) = \frac{c}{P_0} \int_0^z \frac{dn(z') \sigma_{\text{scat}}(E, z')(1 + z')^2}{E(z')} \, dz', \quad (3)$$

where $n(z)$ is the comoving number density of dust grains at a redshift $z$, each having a cross-section $\sigma_{\text{scat}}(E, z) = Q(E \times [1 + z])/\mu a^2$ with $Q_0$ given by equation (1). Equation (3) implicitly assumes that all dust grains are of the same size. For a distribution of grain sizes, equation (3) is generalized to the form,

$$\tau_{\text{gd}}(E, z) = \frac{c}{P_0} \int_0^z \frac{dn(z') \sigma_{\text{scat}}(E, z', a)(1 + z')^2}{E(z')} \, dz', \quad (4)$$

where $\frac{dn}{da}$ denotes the comoving number density of dust grains with radii in the range $a \pm d/2$.

### 2.4 The X-ray volume emissivity

Since AGN dominate the SXB, we express the X-ray emissivity in terms of an integral over the AGN luminosity function,

$$L(z) = \int_{L_{\text{min}}}^{L_{\text{max}}} L \psi(L, z) \, d\log L, \quad (5)$$

where $\psi(L, z) \, d\log L$ denotes the comoving number density of AGN with a soft X-ray luminosity [integrated over the photon energy band between $(0.5-2.0) \times (1 + z)$ keV] within the interval $L \pm d\log L/2$. For the X-ray luminosity function, $\psi(L, z) \, d\log L$, we use the fitting formula of Hopkins, Richards & Hernquist (2007) with $L_{\text{min}} = 40.4$ and $L_{\text{max}} = 48.0$. The redshift evolution of the comoving X-ray emissivity, $L(z)$, is shown in Fig. 1, where we have normalized $L(z)$ to the present-day X-ray emissivity at $z = 0$. Fig. 1 shows that the comoving emissivity peaks around a redshift $z \sim 2$. Also shown is the fraction of the total AGN contribution to the SXB that was emitted at redshifts $z$ (red dotted line); for example, we find that $\sim 50$ per cent (10 per cent) of the total AGN contribution to the SXB comes from AGN at $z > 1$ ($z > 2$). This implies that our method is most sensitive to dust at lower redshift (i.e. $z < 2$).

The total SXB in the 0.5–2.0 keV band that one gets by integrating the X-ray emissivity of AGN over redshift is $5.89 \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$ deg$^{-2}$, which accounts for $\sim 80$ per cent of the total background in the 0.5–2.0 keV band, as calibrated by Moretti et al. (2003). Throughout, we shall assume that 80 per cent of the total SXB is accounted for by AGN.

### 3 Constraints from the unresolved SXB

In Section 2.1, we argued that only a small fraction, $F_{\text{halo}} \lesssim 10$ per cent, of the total SXB can be accounted for by X-ray haloes around AGN due to scattering by intergalactic dust. AGN account for $\sim 80$ per cent of the total SXB (Section 2.4), and so we require that $F_{\text{tot}} \equiv \int_{0.5\text{keV}}^{2.0\text{keV}} F(E) S(E) \, dE = \int_{0.5\text{keV}}^{2.0\text{keV}} S(E) \, dE < F_{\text{halo}} \times (100 \text{ per cent}/80 \text{ per cent}) = 13$ per cent, where $F(E)$ is given by equation (2) and where $S(E)$ denotes the spectral energy density of the SXB. For simplicity, we take $S(E) \propto E^{-1}$, but point out that our final results depend only very weakly on this choice. The constraint $F_{\text{halo}} < 10$ per cent translates to a constraint on either $n(z)$ (through equation 3, for a fixed grain size), or on $\frac{dn}{da}(z)$ (through equation 4 for a broad grain size distribution). Once these quantities have been constrained, we apply equations (3) and (4) to constrain the optical depth of the IGM to optical/infrared photons of observed energy $E = 1.5$ eV ($\lambda = 8269$ Å), which characterize supernova surveys. In this last calculation, we do not use just the scattering efficiency factor $Q_{\text{scat}}$ but rather the total efficiency for both scattering and absorption, $Q_{\text{tot}} = Q_{\text{scat}} + Q_{\text{abs}}$. At the wavelengths of interest, the total efficiency for optical/infrared photons is $Q_{\text{tot}} \approx 2$ regardless of the grain composition (provided that $a > 0.1 \mu$m; see figs 2–4 of Laor & Draine 1993).

We focus on four different models, in which we assume either a single grain radius of $a = 1 \mu$m, or a continuous size distribution of the form $\frac{dn}{da} \propto a^{-3.5}$ with $a_{\text{min}} = 0.2 \mu$m and $a_{\text{max}} = 2 \mu$m, as implied by interstellar extinction within the Milky Way galaxy (Mathis, Rumpl & Nordsieck 1977). Our constraints are most effective for $a \gtrsim 0.2 \mu$m, since the scattering efficiency drops rapidly for smaller grains at X-ray energies $\gtrsim 0.5$ keV (for which $Q_{\text{scat}} \propto a^{-2}$ in equation 1). On the other hand, grains larger than $a = 2 \mu$m scatter X-rays into compact haloes with angular sizes much smaller than $2\sigma \lesssim 1(a/2\mu m)(E/\text{keV})^{-1}$ arcmin. Especially photons with an observed energy of 2 keV that were scattered by these grains at higher redshift (say $z \gtrsim 2$) would be scattered into haloes of radius $< 8$ arcsec. Hence, a significant fraction of the flux in these scattered X-ray haloes may have already been included in the measurement of the AGN flux. In addition, we consider either a constant comoving dust density, or a comoving dust density that decreases with increasing redshift. In the evolving case, we assume that the comoving dust density traces the stellar mass density in the Universe, since dust is a by-product of star formation. In this case, the comoving dust density is proportional to the integrated star formation rate density, $n(z) \propto \int_{0}^{z} \frac{dn}{dz} \frac{1}{\mu(a_{\text{min}})} \, dz$, where we use the fitting formula for $\rho_*(z)$ that was derived by Hernquist & Springel (2003, their equation 51).

Below we discuss our four models individually:

**Model 1.** $a = 1 \mu$m and $n$ constant. Fig. 2 shows our upper limit on the opacity of the IGM to optical/infrared photons of observed energy $E = 1.5$ eV ($\lambda = 8269$ Å) out to a redshift $z$, $\tau_{\text{gd}}(z)$. The solid line shows our upper limit for $F_{\text{halo}} = 10$ per cent, while the blue dashed lines (red dotted line) correspond to
the critical mass density $\rho$ pressed as an upper limit on the density parameter in dust (in units $10^{-3}$). Our upper limit on the IGM opacity can be also expressed (in the observer’s frame) out to redshift $z$. Figure 3. Upper limits on the opacity of the IGM to optical/infrared radiation (in the observer’s frame) out to redshift $z$. The solid line shows the constraint that is obtained when we assume that a fraction $F_{\text{halo}} = 10$ per cent of the total SXB is accounted for by X-ray haloes around AGN due to intergalactic dust scattering. Blue dashed (red dotted) lines show the upper limits for $F_{\text{halo}} = 5$ per cent ($F_{\text{halo}} = 15$ per cent).

Our upper limits on the IGM opacity to optical/infrared photons appears to be robust, and exhibits only a mild dependence on the details of the underlying model.

$F_{\text{halo}} = 5$ per cent ($F_{\text{halo}} = 15$ per cent). Fig. 2 implies that $\tau_{\text{GD}}(z = 0.5) \lesssim 0.04(F_{\text{halo}}/10\text{ per cent})$ and $\tau_{\text{GD}}(z = 2.0) \lesssim 0.2(F_{\text{halo}}/10\text{ per cent})$. Our upper limit on the IGM opacity can be also expressed as an upper limit on the density parameter in dust (in units of the critical mass density $\rho_{\text{crit}} = 1.88 \times 10^{-26} h_{70}^{-2}$ g cm$^{-3}$) of $\Omega_d \equiv [n(\frac{4\pi}{3}) \rho_p]/\rho_{\text{crit}} \lesssim 10^{-4}(F_{\text{halo}}/10\text{ per cent}) (\rho_p/3\text{ g cm}^{-3})$, where $\rho_p$ denotes the material density within the dust grains$^4$ (e.g. Omel$\bar{\text{e}}$ 2008, and references therein).

Model II. $dn/da \propto a^{-3.5}$ and $n = \text{constant}$. The red dotted line in Fig. 3 shows the upper limit on $\tau_{\text{GD}}(z)$ obtained by requiring that $F_{\text{halo}} = 10$ per cent. Our constraints on this model are weaker because the total opacity is now dominated by the smaller grains

$^4$This upper limit on $\Omega_d$ is significantly higher than the upper limit quoted by Petric et al. (2006). However, our constraints on $\tau_{\text{GD}}$ are comparable (see Section 4). This discrepancy arises because Petric et al. (2006) used $Q_{\text{scat}} \propto a^2 E^{-2}$ for all values of $Q_{\text{scat}}$, which significantly boosts the grain opacity per unit mass.

which are less efficient in scattering X-rays. Therefore, the overall number density of grains needs to be increased in order to produce the same opacity to X-ray photons; this in turn boosts the allowed opacity to optical/infrared photons. In this case, we get $\Omega_d \lesssim 7 \times 10^{-3} (F_{\text{halo}}/10\text{ per cent}) (\rho_p/3\text{ g cm}^{-3})$.

Our constraint on $\Omega_d$ is slightly tighter in this model for the following reason. Consider the simplest case in which $Q_{\text{scat}} = 1.5$ for all grain sizes of interest. The total mass that is required to produce a given $\tau_{\text{GD}}$ would then scale as $\rho/\tau_{\text{GD}} \propto \int d\alpha^3 \alpha^2 \propto a_{\text{crit}}^{1.5} a^{1/2}$ (where we assumed that $a_{\min} \ll a_{\max}$). Therefore, decreasing $a_{\min}$ decreases the mass in dust that is required to produce a given $\tau_{\text{GD}}$. In reality, $Q_{\text{scat}} \propto a^2$ for grain size smaller than some threshold value that depends on the energy of the X-ray photons (equation 1), which makes the $a_{\min}$ dependence of our constraint on $\Omega_d$ a bit more complicated.

Model III. $a = 1\mu m$ and $n(z) \propto \int_{z}^{z_0} dz' \rho_{\text{c}}(z')/a_{\text{min}}^2$. In this model, the number density of grains decreases with increasing redshift. For example, the number density of grains at $z = 1 (z = 2, z = 3) = 0.7 (0.5, 0.3)$ times its value at $z = 0$. For this reason, the IGM becomes increasingly transparent with increasing redshift compared to Model I, and $\tau_{\text{GD}}(z)$ increases more moderately towards higher redshifts than in Model I. For this model, we find that $\Omega_d(z = 0) < 1.5 \times 10^{-4} (F_{\text{halo}}/10\text{ per cent}) (\rho_p/3\text{ g cm}^{-3})$. The redshift dependence of our upper limit on $\Omega_d$ scales as $n(z)$.

Model IV. $dn/da \propto a^{-3.5}$ and $n(z) \propto \int_{z}^{z_0} dz' \rho_{\text{c}}(z')/a_{\text{min}}^2$. The differences between this model and Model III are similar to the differences between Model I and Model II. We find that $\Omega_d(z = 0) \lesssim 9 \times 10^{-5} (F_{\text{halo}}/10\text{ per cent}) (\rho_p/3\text{ g cm}^{-3})$.

4 DISCUSSION

We next translate our upper limits on the opacity of intergalactic dust grains to an upper limit on the increase in the apparent $R$- and $I$-band magnitude of optical/IR sources, $\Delta m(z) = 1.086\tau_{\text{GD}}(z)$. The black solid lines in Fig. 4 show our upper limit on $\Delta m(z)$ for $F_{\text{halo}} = 10$ and 5 per cent, in comparison to the effective dimming of sources as a result of a departure in the value of the luminosity distance from that predicted in the standard $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology.

Figure 4. Upper limit on the allowed increase in the apparent magnitude of optical/infrared sources, $\Delta m(z)$, due to intergalactic grey dust for $F_{\text{halo}} = 10$ per cent and 5 per cent (black solid lines). We also consider the effective dimming of sources as a result of a departure in the value of the luminosity distance from that predicted by the standard $\Lambda$CDM cosmology, and compare the allowed deviation from dust to that caused by different choices of the equation of state of the dark energy, $w = -0.8$ and $-0.9$ as well as an $\Omega_{\text{m}} = 1$, $\Omega_{\Lambda} = 0$ cosmology.
cosmology. We compare our upper limit to the difference in the distance modulus (defined as the difference between the apparent and absolute magnitude of a source) for different cosmological models.\footnote{Our constraint on $\tau_{\text{GD}}$ actually depends weakly on the assumed cosmology. Suppose that the equation of state of dark energy is measured to be $w = -1$ or $w = -0.8$ or $w = -0.9$ relative to the standard $\Lambda$CDM. At $z < 1$, our upper limit on the intergalactic opacity with $F_{\text{halo}} = 10$ per cent is comparable to the difference in the distance modulus for models with $w = -0.8$ and $w = -1$.

Fig. 4 suggests that at $z < 1$ or $< 0.5$ the systematic uncertainty that is introduced by grey dust with $F_{\text{halo}} = 10$ per cent is smaller than the boost in the distance modulus for a model with $w = -0.8$ or $w = -0.9$, respectively. At higher redshifts, the possibility that dust mimics the behaviour of dark energy with $w = -0.8$ or $w = -0.9$ for a Universe in which $w = 1.0$ is not ruled out yet. Also shown for completeness is our upper limit on the amount of attenuation by grey dust if $F_{\text{halo}} < 5$ per cent, which implies that $\tau_{\text{GD}} < 0.05$ at $z < 1$.

In Section 3, we inferred that $\Omega_{\text{IGM}} < 10^{-4} (\rho_{\text{gr}}/3 \text{ g cm}^{-3})$ for all models, which is comparable to the intergalactic dust density that is predicted for certain models (Aguirre 1999b; Heckman et al. 2000). Suppose that we can constrain the intergalactic dust abundance down to a level of $\Omega_{\text{IGM}} < 10^{-3}$, then this would allow us to put valuable constraints on models of the enrichment of the IGM. Furthermore, constraints at this level would greatly reduce the systematic uncertainties introduced by grey dust to a level of $\tau_{\text{GD}}(z = 2) < 0.02$. One way to get better constraints on the intergalactic dust abundance from X-ray observations is to put upper limits on the total X-ray flux in the haloes surrounding individual X-ray point sources (as in Petric et al. 2006). Petric et al. (2006) obtained an upper limit on $\tau_{\text{GD}}(z = 4.3) < 0.18$ (assuming $a = \text{constant}$ and $a = 1 \mu \text{m}$, which corresponds to our Model 1), which is a factor of $\sim 3$ tighter than our constraint. However, in difference from our constraints, this result depends strongly on the assumed grain size (e.g. Mathis & Lee 1991): for example, grains with $a = 0.5 \mu \text{m}$ ($a = 0.25 \mu \text{m}$) would scatter the X-rays over an area that is four (16) times larger, which would weaken the upper limit by a corresponding factor of $\sim 4$ ($\sim 16$). This technique is nevertheless powerful and can be applied to individual AGN at lower redshifts. For example, the observed flux from an equally luminous X-ray source at $z = 1$ is $\sim 30$ times larger. Therefore, with an equally long X-ray observation one would be able to constrain the surface brightness of the scattering halo to a level that is $\sim 30$ times lower, thus greatly reducing the upper limit on $\tau_{\text{GD}}(z = 1)$. Stacking of the X-ray images of luminous nearby sources may reduce this upper limit even further.

We note that scattering of X-rays by smaller dust grains in the haloes hosting the X-ray sources can also produce haloes around sources (Priedhorsky et al. 1991; Priedhorsky & Schmitt 1995). Furthermore, X-rays may also be scattered by large dust grains in our own galaxy. However, as long as X-ray haloes are not observed, these additional opacities only render our upper limits more conservative. The absence of X-ray haloes around individual AGN may therefore also constrain the opacity of the dust in spatially extended (several tens of kpc) winds that may surround quasars. On the other hand, if X-ray haloes are detected there might be degeneracies in their interpretation.

Our constraint that $\tau_{\text{GD}}(z = 1) < 0.15$ is among the tightest in the literature. Aguirre & Haiman (2000) showed that the unresolved fraction of the Far-Infrared Background (at $\lambda = 850 \mu \text{m}$) can be used to constrain the intergalactic grey dust opacity to a level $\tau_{\text{GD}}(z = 0.5) < 0.15$. Their upper limit applies to dust grains with radii $a_{\text{min}} > 0.1 \mu \text{m}$. Mörtsell & Goobar (2003) were able to put an upper limit on the total dimming by grey dust at the level $\Delta m(z = 1) = \tau_{\text{GD}}(z = 1) < 0.2$ (99 per cent confidence level) by investigating the colour evolution in the spectra of 2740 quasars at $0.5 < z_{\text{qso}} < 2.0$. Furthermore, More, Bovy & Hogg (2009) constrained the intergalactic dust opacity to $\tau_{\text{GD}}(z = 0.35) = \tau_{\text{GD}}(z = 0.20) < 0.13$ (95 per cent confidence level. Note that the subscript ‘D’ emphasizes that this constraint refers to dust in general rather than grey dust) by comparing the luminosity distance to the angular diameter distance inferred from baryonic acoustic oscillations. This upper limit is significantly weaker than the upper limit derived in this paper. However, More et al. (2008) anticipate their upper limit to improve by a factor of $\sim 10$ within the next few years (also see Avgoustidis, Verde & Jimenez 2009, who already obtain an order of magnitude improvement in the constraint on $\tau_{\text{D}}(z)$, which makes their upper limit comparable to ours). The advantage of their test is that it works regardless of the composition of intergalactic dust (but this may be a disadvantage if one would like to constrain the physical properties of the intergalactic dust).

Lastly, we point out that our calculations have assumed that $F_{\text{AGN}} < 80$ per cent of the total SXB is accounted for by AGN, which was based on the most recent compilation of measured quasar luminosity functions at $0 < z < 5$ in the soft X-ray band (observer’s frame, see Section 2.4). Because these quasar luminosity functions involve (educated) extrapolations down to luminosities that lie below current detection thresholds, the number $F_{\text{AGN}}$ is subject to some uncertainty.\footnote{We calculated in Section 2.4 that AGN account for $\sim 80$ per cent of the total SXB. The actual observed AGN account for a slightly lower fraction. As mentioned in Section 2.1 however, discrete observed sources account for $\sim 80$ per cent of the SXB and at least 10 per cent can be attributed to known low luminosity sources. Our assumption that $F_{\text{halo}} < 10$ per cent of the SXB can be in the form of X-ray haloes produced by intergalactic grey dust remains conservative.} Our constraints depend only weakly on $F_{\text{AGN}}$: quantitatively, we may express our upper limits as $\tau_{\text{GD}} < 0.15 (F_{\text{halo}}/10 \text{ per cent}) (F_{\text{AGN}}/80 \text{ per cent})^{-1}$ to $z < 1$.

5 CONCLUSIONS

Scattering by dust grains in the IGM produces diffuse X-ray haloes around AGN, with a surface brightness that is typically too faint to be detected. Taking account of the X-ray emission by star-forming galaxies and galaxy clusters leaves only a fraction $F_{\text{halo}} < 10$ per cent of the SXB to be possibly associated with these diffuse X-ray haloes.
The SXB constrains the opacity of the intergalactic ‘grey’ dust, which consists of large grains ($a \gtrsim 0.1 \mu m$) that produce little reddening at optical/infrared wavelengths (Aguirre 1999a). Thus, grey dust is a source of systematic uncertainty for supernova surveys that aim to improve the precision on measuring the redshift dependence of the luminosity distance, in an attempt to constrain the cosmic evolution of the equation of state of the dark energy.

Our analysis placed an upper limit on the dust opacity of the IGM to optical/infrared photons (with energy $E \gtrsim 1$ eV) of $\tau_{GD}^z \lesssim 0.15( F_{\text{halo}} / 10 \text{ per cent}) ( F_{\text{AGN}} / 80 \text{ per cent})^{-1}$ to $z \sim 1$ (and $\tau_{GD}^z \lesssim 0.4( F_{\text{halo}} / 10 \text{ per cent}) ( F_{\text{AGN}} / 80 \text{ per cent})^{-1}$ to $z \sim 2$; see Fig. 2). Here, $F_{\text{AGN}}$ denotes the fraction of the total SXB that is accounted for by AGN. Our constraints are most effective for large dust grains with radii in the range $a = 0.2–2.0 \mu m$. Our quoted upper limits are only weakly sensitive to the assumed size distribution of the dust grains within this size range, or to the precise redshift evolution of the overall dust content (see Fig. 3).

Significantly improved constraints may be obtained by stacking X-ray point sources in the redshift interval $z = 0–2$. This approach has the potential to eliminate one systematic source of uncertainty for future supernova surveys which aim to determine the redshift dependence of the dark energy equation of state at the per cent level of precision. Combining the constraints from X-ray observations with constraints from the unresolved Far-Infrared Background (Aguirre & Haiman 2000), the reddening $^7$ (Mőrtsell & Goobar 2003; Ménard et al. 2009) and comparing the luminosity and angular diameter distances (More et al. 2009) may constrain further the properties of intergalactic dust. In addition, these techniques might also be used to search for spatial fluctuations in the intergalactic dust abundance.

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$^7$ After the submission of our paper, Ménard et al. (2009) reported a detection of the reddening of quasars by intergalactic dust out to a few Mpc around galaxies at $z = 0.3$ (also see Chelouche, Koester & Bowen 2007, for a detection of reddening of quasars behind clusters). The observed reddening implies a slope of the extinction curve, $R_V = 3.9 \pm 2.6$, which is consistent with that of interstellar dust (for which $R_V = 3.1$). For $R_V = 3.1$ the observed reddening corresponds to a cosmological dust opacity of $\tau_D(z = 0.5) = 0.03$ and $\tau_D(z = 1.0) = 0.05–0.09$. The reported uncertainty on $R_V$ allows for a contribution of a grey dust component to the intergalactic dust opacity of comparable magnitude.

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