Constraint on intergalactic dust from thermal history of intergalactic medium

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ABSTRACT

This Letter investigates the amount of dust in the intergalactic medium (IGM). The dust photoelectric heating can be the most efficient heating mechanism in the IGM where the density is very small and there are a lot of hard ultraviolet photons. Comparing the observational thermal history of IGM with a theoretical one taking into account the dust photoelectric heating, we can put an upper limit on the dust-to-gas ratio, \( D \), in the IGM. Since the rate of the dust photoelectric heating depends on the size of dust, we find the following results: If the grain size is \( \gtrsim 100 \) \( \AA \), \( D \) at \( z \sim 3 \) is \( \lesssim 1/100 \) Galactic value corresponding to \( \Omega_{\text{dust}} \lesssim 10^{-5} \). On the other hand, if the grain size is as small as \( \sim 10 \) \( \AA \), \( D \) is \( \lesssim 1/1000 \) Galactic value corresponding to \( \Omega_{\text{dust}} \lesssim 10^{-6} \).

Key words: cosmology: theory — dust, extinction — intergalactic medium — quasars: absorption lines

1 INTRODUCTION

There are metals in the intergalactic medium (IGM) even in low density regions such as Lyman \( \alpha \) forest (e.g., Cowie et al. 1996; Telfer et al. 2002). Since metal and dust are relating each other, it is sure that dust grains also exist in the IGM. However, the amount of the intergalactic (IG) dust is still quite uncertain although it seems to be not so abundant. We try to put a new constraint on the amount of the IG dust by using the IGM thermal history suggested by the recent observations of Lyman \( \alpha \) forest (e.g., Schaye et al. 2001).

After the early attempts to estimate the IG extinction (Eggenor 1948; Humason, Mayall, & Sandage 1956; Crane & Hoffmann 1973) have obtained an upper limit on the amount of the IG dust in terms of the density parameter as \( \Omega_{\text{dust}}^{\text{IGM}} (z = 0) \lesssim 10^{-4} \), by comparing the observed spectral energy distribution of distant (but \( z \lesssim 0.5 \)) giant elliptical galaxies with an average spectrum of similar nearby galaxies (see also Nickerson & Partridge 1971; Takas 1972).

Observations of the redshift evolution of the QSOs spectral slope provide us with another approach to the IG dust (Wright 1981; Cheng, Gaskell, & Koratkar 1991). Although Cheng et al. (1991) found no evidence for an appreciable IG reddening up to \( z \sim 2-3 \), this may not be so strict constraint because it is difficult to measure the UV slope of QSOs enough precisely owing to the broad and complex iron band superposing on the continua. Recently, we obtain further constraint on the IG dust from observations of high-z supernovae (SNe) (Riess et al. 1998; Perlmutter et al. 1999). An upper limit of the colour excess by the IG reddening is \( (E_{B-V})_{z=0.5} - (E_{B-V})_{z=0.05} \lesssim 0.03 \) mag.

By the way, Aguirre (1994) suggests that the IG dust can be “gray” by a selection rule in the transfer of grains from the host galaxies to the IGM. This occurs when small \( (\lesssim 0.1 \mu \text{m}) \) grains are destroyed selectively by the thermal sputtering in the hot gas halo of the host galaxies before they reach the IGM. Then, the extinction property becomes “gray” since the relatively large dust survives. Importantly, such “gray” IG dust can avoid the detection by the IG reddening survey like above.

Even if the IG dust is really “gray”, its evidence should be imprinted in the cosmic microwave background (CMB) and infrared background because the dust emits thermal radiation in the wave-band from the far-infrared to submillimetre (submm) (Rowan-Robinson, Nesroponte, & Silk 1974; Wright 1981). According to the current status, COBE data provides us with a rough upper limit on the IG dust (Loeb & Haiman 1997; Ferrara et al. 1997; Aguirre & Haiman 2000). On the other hand, the submm background radiation may give a more strict constraint on the IG dust. The emission from the IG dust expected from the modern cosmic star formation history with the grain transfer mechanism of Aguirre (1994) contributes to a substantial fraction \( (\gtrsim 75\%) \) of the measured background radiation in the submm (Aguirre & Haiman 2000). It is inter-
esting to develop the approach of Aguirre & Haiman (2001) to match a strong constraint by SCUBA whose result of the number count accounts ~ 90% of the submm background (Calzetti 2001) and references therein).

In any current status, the amount of the IG dust is still highly uncertain. Hence, it is worth trying to find a new constraint on the amount of the IG dust. In this Letter, it is demonstrated that we can obtain such a new constraint of the IG dust by comparing the observational IG temperature with a theoretical one if we take into account the dust photoelectric heating in the theoretical model. This is possible because the dust heating is an efficient mechanism in the IG (Nath, Sethi, & Sichikinoto 1999). Interestingly, the effect of the dust photoelectric heating depends on not only the amount but also the size of dust. Therefore, we can put a limit on the amount of the IG dust as a function of the typical size of the IG grains.

2 PHOTOELECTRIC HEATING BY GRAINS

To assess photoelectric effect, we must specify the charge on a grain, \( Z_d \) (in the electron charge unit), which is given by Spitzer (1941):

\[
\sum_i R_i + R_{pe} = 0, \tag{1}
\]

where we have assumed a charge equilibrium because a typical charging time-scale is very short (~ 10\( a/0.1 \mu m \) yr under the UV background radiation dominated by QSO light given in §3). In the equation, \( R_i \) is the collisional charging rate by \( i \)-th charged particle, and \( R_{pe} \) is the photoelectric charging rate. We assume spherical grains for simplicity.

The collisional charging rate is

\[
R_i = \pi a^2 Z_i \cdot m_i \int_{v_{min}}^{v_{max}} \sigma_i(v_i, Z_i, Z_d) v_i f(v_i) dv_i, \tag{2}
\]

where \( Z_i \) is the charge in the electron charge unit, \( m_i \) is the number density, \( a \) is the grain radius, \( v_i \) is the velocity, \( v_{min} \) is the minimum velocity required to collide with a grain, \( \sigma_i \) is the dimensionless collisional cross section depending on both charges and \( v_i \), and \( f(v_i) \) is the velocity distribution function. We simply assume \( s_i \) is always unity. In the above equation, we neglected the effect of the secondary emission.

We can neglect the effect of the “image potential” (Draine & S ignite 1985) on the collisional cross section because the obtained charges are enough large. If we assume the Maxwellian velocity distribution for the particle, the integral in the r.h.s. of equation (2) is reduced to \( (8k_B T/\pi m_i)^{1/2} g(x) \), where \( g(x) = 1 - x \) for \( Z_i Z_d \leq 0 \) and \( g(x) = \exp(-x) \) for \( Z_i Z_d > 0 \), where \( k_B \) is the Boltzmann’s constant, \( T \) is the gas temperature, \( m_i \) is the charged particle’s mass, and \( x = e^2 Z_i Z_d / a k_B T \).

The photoelectric charging rate is given by

\[
R_{pe} = \pi a^2 \int_{v_{min}}^{v_{max}} Q(a, \nu) \cdot Y(a, \nu, Z_d) \frac{4 \pi J_\nu}{h \nu} dv, \tag{3}
\]

where \( Q \) is the absorption coefficient of grains, \( Y \) is the photoelectric yield, \( J_\nu \) is the intensity (averaged for solid angle) of the incident radiation at a frequency \( \nu \), \( h \) is the Plank constant, and \( v_{max} \) is the maximum frequency of the incident rad-

\[
\gamma(a) = \pi a^2 \int_{v_{min}}^{v_{max}} E_{pe}(a, \nu, Z_d) QY \frac{4 \pi J_\nu}{h \nu} dv, \tag{4}
\]

and the cooling rate of the electron capture (recombination) by the grain is \( \lambda(a) = (3/2) k_B T R_i \), where we have assumed the Maxwellian distribution for the gaseous electrons. We also have defined \( E_{pe} \), the mean kinetic energy of photoelectrons that are emitted from a grain with radius \( a \) and charge \( Z_d \) when a photon with energy \( h \nu \) is absorbed. This is determined from the energy distribution function of the photoelectrons, \( f(E) \), which is assumed to be a parabolic function introduced by WD01,¹ and is consistent with a typical energy distribution of photoelectrons in the laboratory experiments. Hence, we estimate

\[
E_{pe} = \int_{0}^{E_{max}} E f(E) dE = \frac{E_{max}(E_{max} - 2 E_{min})}{2(E_{max} - 3E_{min})}, \tag{5}
\]

where \( E_{max} = h \nu - IP \) is the maximum energy of the photoelectrons and \( E_{min} = -e^2(Z_d + 1)/a \) is the minimum energy of the photoelectrons appearing on the grain surface (however falling back into the grain). For the parabolic function adopted here, a typical kinetic energy of the photoelectrons is about half of \( E_{max} \).

To estimate the total photoelectric heating rate, we specify a characteristic grain size in the IGM instead of the size distribution of the IG grains. This is because the size distribution in the IGM is quite unknown. Here we consider three cases for the typical grain size: 0.001 \( \mu m \), 0.01 \( \mu m \), and 0.1 \( \mu m \). The smallest case of 0.001 \( \mu m \) is based on the size of the primary grains produced in the ejecta of SNe II (Todini & Ferrara 2001). It is interesting to obtain an information about the size of the IG dust as well as to put limits on the amount. From the analysis of the case of very small IG dust, we can assess the selection rule of the IG dust suggested by Aguirre (1999).

¹ Our \( f(E) \) is equal to \( f_{E}(E) \) in WD01.
The grain number density is given as \( n(a) = \rho_a / m(a) \), where \( m(a) = (4\pi/3)a^3 \) is the mass of a grain with the radius \( a \), \( g = 2 \text{ g cm}^{-3} \) is the grain material density, and \( \rho_a \) is the volume grain mass density, which is given by \( \rho_a = \mu m_i n_i D \), where \( \mu \) is the mean atomic weight, \( n_i \) is the proton mass, \( n_b \) is the baryon number density, and \( D \) is the dust-to-gas mass ratio. We introduce a relative dust-to-gas ratio, \( \zeta \), defined as \( D = \zeta \Delta N_{\text{MW}} \), where \( \Delta N_{\text{MW}} = 6 \times 10^{-3} \) is the Galactic dust-to-gas ratio (Spitzer 1978), for convenience below. Therefore, the total photoelectric heating rate and electron capture cooling rate per unit volume are \( \Gamma_{\text{pe}} = \gamma(a)n(a) \) and \( \Lambda_{\text{pe}} = \lambda(a)n(a) \), respectively.

The total heating rate is approximately proportional to \( a^{-0.5} \) under the situation considered in the next section. This is because the heating rate per a grain roughly has a dependence of \( a^{-2.5} \), i.e., the grain cross section plus an additional \( a \)-dependence caused by \( J E_{\text{pe}} Q Y d\nu \), whereas the grain number density is proportional to \( a^{-3} \). Therefore, for a fixed dust mass, the photoelectric effect becomes more important as the grain size is smaller. The cooling rate by the electron capture is always about an order of magnitude smaller than the photoelectric heating rate.

3 DUST AND THERMAL HISTORY IN IGM

Suppose an ideal fluid element with the mean density of the IGM. The time evolution of its temperature is governed by (e.g., Hui & Gnedin 1997)
\[
\frac{dT}{dt} = -2HT - \frac{T}{X} \frac{dX}{dt} + \frac{2(\Gamma - \Lambda)}{3\epsilon_b X n_b}
\]
where \( H \) is the Hubble constant, \( n_b \) is the cosmic mean number density of baryon, \( \Gamma \) and \( \Lambda \) are the total heating and cooling rates per unit volume, respectively, \( X \) is the number ratio of the total gaseous particles to the baryon particles, i.e., \( X = \sum n_i / n_b \), where \( n_i \) is the number density of the \( i \)-th gaseous species and we consider \( H \), \( \text{He} \), \( \text{He} \text{ii} \), \( \text{He} \text{iii} \), and electron. Then, we solve equation (6) coupled with the non-equilibrium rate equations for these gaseous particles. For the rate coefficients, we use those compiled by Cerf (1992). The adopted initial conditions are \( T = T_{\text{CMB}}(1 + z) \), \( H \) \( 1/H(\text{total}) = 0.99 \), \( H \) \( 1/\text{He}(\text{total}) = 0.99 \), \( He/\text{He}(\text{total}) = 0.0099 \) at redshift \( z = 10 \), where \( T_{\text{CMB}} = 2.7 \text{ K} \) is the temperature of the CMB radiation at \( z = 0 \). The result is insensitive to the choice of the initial condition if calculation is started at an epoch before \( H \) reionization. We also adopt \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.3 \), \( \Omega_\Lambda = 0.7 \), \( \Omega_b = 0.04 \), and He mass abundance \( Y = 0.24 \).

To add to the photoelectric heating and the electron capture cooling by grains, we consider the following heating/cooling mechanisms: For cooling, we use the recombination cooling, collisional ionization/excitation cooling, bremsstrahlung cooling, and Compton cooling compiled by Cerf (1992). For heating rates, to take account of the radiative transfer effect (Abel & Haehnelt 1994), we multiply usual photoionization heating rates by a correction factor of \( (1 + C_{\text{RT}} f_i) \), where \( f_i \) is the fractional abundance of \( \text{H} \), \( \text{He} \), and \( \text{He} \text{ii} \) relative to total number of \( \text{H} \) and \( \text{He} \). This factor mimics the situation that atoms are ionized by higher energy photons when the optical depth is large (i.e., \( f_i \) is nearly unity) relative to the optically thin limit. The coefficient \( C_{\text{RT}} \) is a parameter determined by solving the cosmological radiative transfer. The metal line cooling is negligible because we consider only the case that metallicity is less than 1/100 solar value and temperature is less than a few \( 10^4 \text{ K} \) (see e.g., Sutherland & Dopita 1993).

We need to give the UV background radiation and the cosmic reionization history to obtain the temperature evolution. We adopt, for UV background, \( J_\nu = J_{\nu} \nu^{-\alpha} \), where \( J_{\nu} \) is the mean intensity at the Lyman limit of \( \text{H} \) in unit of \( 10^{-21} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1} \text{ Hz}^{-1} \) and its evolution is given by equation (3) in Kitayama et al. (2001). We assume the spectral index to be \( \alpha = 1 \) as a QSO dominated background radiation. For the reionization history, we assume, for simplicity, a sudden reionization of \( \text{H} \) (and \( \text{He} \text{ii} \)) at \( z = 6.0 \) (Becker et al. 2001)\(^2\); there is no UV photon before this redshift. To mimic the \( \text{He} \text{ii} \) reionization at \( z \approx 3.4 \) (Theuns et al. 2002), we set the maximum photon energy of the UV background to be 54.4 eV (\( \text{He} \text{ii} \) Lyman limit) for \( z > 3.4 \) and to be 1.24 keV for \( z \lesssim 3.4 \) (i.e., a sudden \( \text{He} \text{ii} \) reionization). Other choice of \( \alpha \) will be discussed later.

We compare our theoretical thermal history at the mean density of the IGM with the observational one obtained by Schaye et al. (2001). They observe the Ly\( \alpha \) forest clouds with the column density of \( 10^{13-15} \text{ cm}^{-2} \) (i.e., slightly over density regions), and then they convert the temperature at this density range estimated from the minimum \( b \) (Doppler) parameters into that at the mean density of the IGM by using the observed equation of state of the IGM. Thus, we can compare both thermal histories directly.

In Figure 1, we show the IGM thermal history obtained for no dust cases and dusty cases of \( \zeta = 1/100 \) (silicate grains). For no dust cases (three dotted curves), the calculated thermal histories are consistent with the data points of Schaye et al. (2000) if \( \zeta_{\text{Cen}} \approx 3.0-7.0 \). For dusty cases (solid [\( a = 0.1 \text{ \mu m} \)], dash-dotted [\( a = 0.01 \text{ \mu m} \)], and dashed curves [\( a = 0.001 \text{ \mu m} \)], we observe, especially after the \( \text{He} \text{ii} \) reionization, temperature enhancement by the dust photoelectric effect. In Table 1, we summarize the temperature enhancement factors at some redshifts for some sets of dust size and dust-to-gas ratio. All calculations do not include the evolution of the dust-to-gas ratio, for simplicity.

3 Although Kogut et al. (2003) find a higher-\( z \) \( \text{H} \) reionization, our constraint of the IG dust dose not change because it is determined mainly from the IGM temperature after the \( \text{He} \text{ii} \) reionization.

\(^2\) This is determined by the maximum frequency in the data of grain absorption coefficient.
the radiative transfer effect. The dashed, dash-dotted, and solid curves are no dust cases; bottom: optically thin case, middle: $C_{\text{RT}} = 3.0$ case, top: $C_{\text{RT}} = 7.0$ case, where $C_{\text{RT}}$ is the correction factor of the radiative transfer effect. The dashed, dash-dotted, and solid curves are cases of grain radius $a = 0.001$, 0.01, and 0.1 $\mu$m, respectively. For these dusty cases, the dust-to-gas mass ratio is set to be 1/100 Galactic value, $C_{\text{RT}} = 3.0$ is assumed, and the grain type is silicate. The middle dotted curve in $z > 3.4$ is almost superposed on the solid curve.

For the case of very small ($\sim 0.001$ $\mu$m) grains, the photoelectric heating is always dominant when $\zeta \gtrsim 1/100$. Especially, this heating exceeds the He II photoionization heating by a factor of 10 after the He II reionization. Then the temperature enhancement factor becomes about 2 at $z = 2$ (dashed curve in Figure 1). Thus, the thermal histories of these cases are consistent with that obtained by Schaye et al. (2000) when $C_{\text{RT}} = 3.0$ is adopted.

For the case of very small ($\sim 0.001$ $\mu$m) grains, the photoelectric heating is always dominant when $\zeta \gtrsim 1/100$. Especially, this heating exceeds the He II photoionization heating by a factor of 10 after the He II reionization. Then the temperature enhancement factor becomes about 2 at $z = 2$ (dashed curve in Figure 1). Thus, the thermal history in this case may be inconsistent with the data from Schaye et al. (2000). This means that if the typical grain size in the IGM is $\sim 0.001$ $\mu$m, the dust-to-gas mass ratio in the IGM should be much less than 1/100 Galactic value.

### Table 1. Temperature enhancement by IG dust.

| $a$, $D/D_{\text{MW}}$ | $z = 5$ | 4 | 3 | 2 |
|------------------------|--------|---|---|---|
| 0.001 $\mu$m, 1/1000  | 1.01   | 1.02| 1.04| 1.09 |
| 0.001 $\mu$m, 1/100   | 1.07   | 1.21| 1.35| 1.88 |
| 0.01 $\mu$m, 1/1000  | 1.00   | 1.00| 1.01| 1.04 |
| 0.01 $\mu$m, 1/100   | 1.01   | 1.04| 1.13| 1.37 |
| 0.1 $\mu$m, 1/100    | 1.00   | 1.00| 1.04| 1.12 |

### Table 2. Amount of the IG dust at $z \gtrsim 2$.

| $a$ | $D/D_{\text{MW}}$ | $\Omega_{\text{IGM}}$ |
|-----|-------------------|---------------------|
| 0.001 $\mu$m | $<10^{-3}$ | $<7 \times 10^{-7}$ |
| 0.01-0.1 $\mu$m | $<10^{-2}$ | $<7 \times 10^{-6}$ |

### 4 DISCUSSION

In Table 2, we summarize the obtained upper limits of the amount of the IG dust at $z \gtrsim 2$. Let us compare these limits with the IG dust amount estimated from a possible cosmic star formation history (e.g., Madau, Pozzetti, & Dickinson 1998). Once we assume a cosmic star formation history, the cosmic metal amount can be estimated. Roughly, we find $\Omega_{\text{metal}} \sim \text{a few } \times 10^{-5}$ at $z \sim 3$ (e.g., Aguirre 1999). If we postulate $\sim 0.5$ as the metal depletion to dust grains, which number is suitable for the Milky Way, we obtain $\Omega_{\text{dust}} \sim 10^{-7}$ as the total cosmic dust amount at the redshift. We show in Table 2 the upper limits in terms of the density parameter converted from the dust-to-gas ratios by $\Omega_{\text{dust}}^{\text{IGM}}(z) = \zeta D_{\text{MW}} \Omega_{\text{dust}}(z)$. For the larger grain models, we obtain an upper limit, $\Omega_{\text{dust}}^{\text{IGM}} \sim 7 \times 10^{-6}$ which is comparable to $\Omega_{\text{dust}}$. This means that our upper limit may not deny the possibility that most of the dust grains produced in galaxies before $z \sim 3$ escape to the IGM as an extreme case. For very small (0.001 $\mu$m) grain case, we obtain $\Omega_{\text{dust}}^{\text{IGM}} \lesssim 7 \times 10^{-7}$. Thus, a small fraction ($\lesssim 10\%$) of such very small grains can escape from the host galaxies to the IGM because of $\Omega_{\text{dust}}^{\text{IGM}}/\Omega_{\text{dust}} \lesssim 0.1$. The latter conclusion is consistent with
the suggestion by Aguirre (1999), who proposes that the IGM is very difficult to be polluted by the very small grains.

The obtained values of the heating rate by the dust photoelectric effect are consistent with those in Nath et al. (1999). It indicates that our result is robust against uncertainties of the adopted efficiency factor $Q$, photoelectric yield $Y$, and energy distribution function of the photoelectrons, etc., because these are somewhat different between our model and Nath et al. (1999). If we consider only graphite grains, the photoelectric heating rate is found to be about 70% of that of only silicate grains, i.e., silicate grains can be more efficient heating source. The temperature in the graphite case is lower than that in the silicate case, while the decrement is $\lesssim 10\%$. These results are also consistent with Nath et al. (1999).

We shall comment some uncertainties of our analysis. First, the effect of the spectral index of $\alpha$ is examined. As shown in Zheng et al. (1997), for example, a softer spectrum than $\alpha = 1$ is still compatible with observations. If $\alpha = 1.5$, the heating rates by dust at $z = 3$ decrease by a factor of 0.25 ($a = 0.1 \mu m$)–0.5 ($a = 0.001 \mu m$) relatively to our case of $\alpha = 1$. If $\alpha = 2$ is used, the heating rates at $z = 3$ decrease by a factor of 0.1 ($0.1 \mu m$)–0.25 ($0.001 \mu m$). In these calculations, $\zeta = 1/100$ and $C_{\text{ICR}} = 3.0$ are assumed. As the dust heating becomes less efficient, a more abundant IG dust is allowed. Then the upper limits for the IG dust amount at $z > 3$ can be more efficient heating source. The temperature in the graphite case is lower than that in the silicate case, while the decrement is $\lesssim 10\%$. These results are also consistent with Nath et al. (1999).

It might be possible to take very large $\alpha$. For example, we consider a background radiation field dominated by only galaxies (e.g., $\alpha = 5$). In this case, the dust heating rates at $z = 3$ become 1/100 ($0.1 \mu m$)–1/10 ($0.001 \mu m$) of those in $\alpha = 1$. However, the thermal histories with $\alpha = 5$ never reproduce a steep rise of the observed temperatures at the He II reionization. In addition, the transfer correction should be smaller as the spectrum is softer (Abel & Haehnelt 1999). Therefore, the background spectrum is unlikely to be as soft as $\alpha = 5$ after the He II reionization. We should assume a harder index.

A caveat against our results is in the correction factor of the transfer effect. Indeed, the effects of the photoelectric heating and the transfer correction can be offset. Thus, we should check this point by solving the cosmological radiative transfer in the future work.

The current work may give a hint for the origin of the large $b$ region of the observed IGM clouds. There is a possibility that the large $b$ regions are localized. If the very small grains are located at the restricted areas, a systematic heating owing to the dust photoelectrons may explain the large-$b$ at the localized region. The principal role of the photoelectric heating in the IGM temperature also indicates that the theoretical equation of state in the IGM should be reconstructed by including the photoelectric heating effect. All of these works are being developed by the authors.

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