THE NATURE OF DAMPED LYMAN-α AND Mg II ABSORBERS EXPLORED THROUGH THEIR DUST CONTENTS

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Received 2014 March 12; accepted 2014 December 5; published 2015 January 29

ABSTRACT

We estimate the abundance of dust in damped Lyman-α absorbers (DLAs) by statistically measuring the excess reddening they induce on their background quasars. We detect systematic reddening behind DLAs consistent with the SMC-type reddening curve and inconsistent with the Milky Way type. We find that the derived dust-to-gas ratio is, on average, inversely proportional to the column density of neutral hydrogen, implying that the amount of dust is constant, regardless of the column density of hydrogen. It means that the average metallicity is inversely proportional to the column density of hydrogen, unless the average dust-to-metal ratio varies with the hydrogen column density. This indicates that the prime origin of metals seen in DLAs is not by in situ star formation, with which $Z \sim N_{H_1}^{0.4}$ is expected from the empirical star formation law, contrary to our observation. We interpret the metals observed in absorbers to be deposited dominantly from nearby galaxies by galactic winds ubiquitous in intergalactic space. When extrapolating the relation between dust-to-gas ratio and H1 column density to lower column density, we find a value that is consistent with what is observed for Mg II absorbers.

Key words: dust, extinction – galaxies: halos – quasars: absorption lines

1. INTRODUCTION

Whether intervening absorbers seen in quasar spectra are aggregates of primordial material or results of the activity in galaxies is an elementary problem. In a previous publication (Ménard & Fukugita 2012; hereinafter MF12), it was advocated that Mg II clouds are likely to be a product of the activity of nearby galaxies with gas exported by galactic winds. This inference is based on the fact that the observed dust abundance of Mg II clouds relative to gas takes a value typical of galactic disks, while the star formation activity is neither observed nor expected in such clouds.

MF12 estimates that the global HI abundance in Mg II clouds is $\Omega_{HI}(\text{Mg} \ II) \approx 1.5 \times 10^{-4}$, which is approximately 3% of the fuel consumed by star formation by the present epoch, or roughly 6% at $z \approx 2$. The amount of matter expelled through galactic winds in actively star-forming galaxies is often inferred to be comparable to the star formation rate (e.g., Heckman et al. 2000; Veilleux et al. 2005; Weiner et al. 2009). The fraction of H I in Mg II absorbers, which is 10%–20% of the gas re-shed by stars as a whole, is not an unreasonable amount as a product resulting from the star formation activity in galaxies. It is also shown that dust in Mg II clouds accounts for half the amount of dust estimated to reside outside galaxies.

The analysis gives the example that the dust abundance, as explored by extinction of light rays passing through the absorbers, provides us with a useful indicator of the heavy element abundance, assuming that photometry is accurate. This suggests that more could be learned from dust studies of other classes of absorbers.

In this paper we focus on damped Lyman-α absorbers (DLAs). The global mass density of H I in DLA clouds has been estimated to be $\Omega_{HI}(\text{DLA}) \approx (4–10) \times 10^{-4}$ at $z \approx 2$ by Prochaska & Wolfe (2009) using the quasar spectroscopic data of Sloan Digital Sky Survey (SDSS) DR5, and more recently by Noterdaeme et al. (2012) using SDSS DR9. This quoted range arises from different treatments of the continuum around the damped Lyman-α line, as well as survey path length and completeness. Whichever value is taken, the DLA mass density is significantly larger than the H I mass density in the Mg II absorbers, which is estimated to be $\Omega_{HI}(\text{Mg} \ II) \approx 1.5 \times 10^{-4}$ (MF12). The H I mass density is clearly larger than that which can be associated with stellar activity.

Studies of individual DLAs have indicated their metallicity [Fe/H] to be in the range $-0.5$ to $-2$ (e.g., Prochaska et al. 2003; Rafelski et al. 2012), an order of magnitude lower than that of galaxies. This contrasts with Mg II absorbers, which MF12 showed to have metallicity of the order of solar. These observations may be taken in favor of the interpretation that there would be two distinct populations of absorbers as to their origin: DLAs belonging to one and Mg II absorbers to another. This also induces the question as to where the metallicity of DLAs arises from.

There have been a few attempts to detect reddening of quasars behind DLAs (Fall et al. 1989; Pei et al. 1991; Murphy & Liske 2004; Vladilo et al. 2008; Frank & Péroux 2010; Khare et al. 2011). The results have not always led to positive detections. The difficulty is that the reddening signal is small, of the order of a few hundredths of magnitude, whereas sample variation due to objects is an order of magnitude larger. For photometric studies, one needs to accurately define the mean color of reference quasars. With spectroscopic work one needs accurate sensitivity calibrations over a wide wavelength range.

In this paper we estimate the mean reddening effects induced by DLAs by comparing the broadband flux of the quasar light showing Lyman-α absorptions with damped wings to that without absorbers. We use accurately calibrated SDSS broadband photometry, and we limit the redshift range to minimize the scatter of fiducial quasar colors. We are concerned with a photometric accuracy smaller than 0.1 mag. It turns out that choosing the right range of both quasar and absorber redshifts is important in keeping the errors of colors small.
Specifically, care must be taken so that passbands are away from the Lyman edge or the Lyman $\alpha$ line for absorbers. We study whether the dust-to-gas ratio of DLAs is correlated with their hydrogen column density, and also examine if any difference is seen between Mg II absorbers and DLAs in the metallicity H I column density relation.

2. THE DATA

We use the quasar catalog compiled by Pâris et al. (2012) based on the ninth data release of the SDSS III (hereinafter DR9; Ahn et al. 2012). Noterdaeme et al. (2012) analyzed these 87,822 quasars and identified 12,081 clouds with H I column density $N_{\text{HI}} \geq 10^{20}$ cm$^{-2}$ for redshift $z \geq 1.9$. The column density is estimated using Voigt profile fitting. About 57% of the clouds (6839) have $N_{\text{HI}} \geq 10^{20.3}$ cm$^{-2}$ with damped wings. The quasar sample consists of a union of quasars arisen from different selections. Since accurate photometry and accurate color property are of primary importance for our analysis, we select objects with the flag UNIFORM=1 which produces a homogeneously selected sample of quasars (see Section 4.3 of Pâris et al. 2012). This uniform sample contains 23,499 quasars.

Since we want to detect very small values of reddening, it is of crucial importance to define accurately the reference quasar colors. To do so we first inspect the distribution of quasar colors as a function of redshift and observe that the scatter increases substantially at $z > 3.1$. We therefore restrict our analysis to quasars selected in the redshift range of quasars to $2.3 < z < 3.1$ where the lower limit is motivated by absorber selection, as explained below. In this range, we find that the difference between the mean and median color as a function of redshift is smaller than about 0.01 mag for $z < 3.1$. Using higher-redshift quasars increases the scatter in colors. We therefore do not include them in our analysis.

Zhu & Ménard (2013) identified in the DR9 uniform quasar sample 10,877 Mg II absorbers with rest equivalent widths $W_0 > 0.3$ Å, of which 6635 have $W_0 > 0.8$ Å, in the redshift range $z = 0.36$ and 2.5. We note that no velocity cuts are applied to the Mg II absorbers. We restrict our analysis to the Mg II absorbers with $W_0 > 0.8$ Å, below which the sample completeness drops to $\lesssim 50\%$ (Nestor et al. 2005), although completeness is not important to our analysis.

The DLA and Mg II absorbers overlap in the redshift range $1.9 < z < 2.5$. We restrict our analysis primarily to the range $2.1 < z_{\text{abs}} < 2.3$, avoiding redshift tails of both DLA and Mg II absorber distributions. With this selection we can minimize the effect of Lyman opacity, which contributes to the colors we choose. This overlap allows us to study the relation between the two populations of absorbers. This redshift interval contains in the common quasar sample 1211 DLAs and 680 Mg II absorbers, and 150 among those are common in both samples. These statistics indicate that 12% of DLAs show Mg II absorption lines detected with $W_0 > 0.8$ Å, and conversely 22% of Mg II absorbers are DLAs.

3. DUST REDDENING AND METALLICITY OF DLA

As was done for Mg II absorbers in MF12, we measure mean reddening of background quasars induced by intervening clouds. We estimate the color excess

$$\Delta(g-i)_{\text{obs}} = (g-i) - ((g-i)),$$  

(1)

where the expectation value is computed using a median to avoid largely scattered data points that occasionally happen\textsuperscript{5} rather than the mean.

Dividing the quasar sample into $\Delta z = 0.25$ bins, we set the median of $g-i$ to zero at each bin. As a first test we compare the colors of all quasars with those that do not show DLA signatures. Here, the effect of reddening due to absorbers is diluted by the presence of a larger population that does not show DLA signatures by about 10 times. The difference is smaller than 0.02 mag, which is our current goal in view of the accuracy of photometry. This test, which shows null detection below the noise level and the homogeneity of color, reassures us that we can detect a color change if it is larger than 0.02 mag.

In Figure 1 we show the distributions of $\Delta(g-i)$ for our quasars with and without hydrogen absorbers. Here and hereafter we take the sample down to $N_{\text{HI}} = 10^{20}$ cm$^{-2}$ to include sub-DLA clouds to examine if there is any change in the trend across the DLA threshold\textsuperscript{6} $N_{\text{HI}} = 10^{20.3}$ cm$^{-2}$. The distributions with hydrogen absorbers for three bins of $N_{\text{HI}}$ overlap with each other. When compared to the reference $\Delta(g-i)$ distribution of quasars (thinner black curve), we see that those with Lyman absorption are shifted redward by an amount of about 0.05 mag. The sample dispersion of $\Delta(g-i)$ color is 0.2 mag which indicates that one may detect a reddening signal, say, as small as 0.02 mag only when averaged over 100 or more absorbers. Each measurement, which sometimes gives negative values, does not tell about reddening for individual quasars. Their color shifts are 0.05 mag or smaller, which is buried in much larger scatters, arising from both\textsuperscript{5}

\textsuperscript{5}In MF12 the reference quasar sample is constructed from quasars without detectable absorption lines. In the present work the reference sample includes all quasars. Since the quasar sample is dominated by quasars without absorbers, the difference between the two selections has negligible effects on the mean reference quasar color. We find it to differ by less than $< 3 \times 10^{-3}$ mag, which is undetectable in our analysis. We also note that the quantity $\Delta(g-i)$ given in the DR9 quasar catalog (Pâris et al. 2012) is obtained by taking a mode of the distribution. This differs from our definition (Equation (1)), which uses a median estimate. The difference between the two estimators is of the order of 0.05 mag.

\textsuperscript{6}Where we referred to DLA, the sample is restricted to $N_{\text{HI}} \geq 10^{20.3}$ cm$^{-2}$. 

![Figure 1](http://example.com/Figure1.png)
reddening and by hydrogen Lyman opacity. Figure 2 shows the reddening signal. Averaging over a large sample is needed to detect a meaningful variation among individual quasars and measurement errors. Averaging over a large sample is needed to detect a meaningful reddening signal.

We expect a color excess mainly caused by both dust reddening and by hydrogen Lyman opacity. Figure 2 shows the expected $g - i$ reddening due to Lyman opacity as a function of redshift for specified values of $N_{\text{H}i}$. One sees the first rise due to the Lyman $\alpha$ excitation and the second rise due to the Lyman edge. When the Lyman edge is met, $\Delta(g - i)$ due to hydrogen ionization is larger than that from dust, which is of the order of 0.05 mag (as we see in Figure 3 below). Even away from the Lyman edge, reddening due to the Lyman excitation is non-negligible and must be taken into account. We define reddening due to dust as

$$\Delta(g - i)_{\text{dust}} = \Delta(g - i)_{\text{obs}} - \Delta(g - i)_{\text{H}i}. \quad (2)$$

We note that restricting our analysis to $z \leq 2.3$ has the advantage of significantly reducing the effect of Lyman $\alpha$ opacity in the dust reddening estimate. Figure 3 shows measured reddening $\Delta(g - i)$ as a function of hydrogen column density for absorbers $2.1 < z_{\text{abs}} < 2.3$ for both raw measured value (open circles) and value after hydrogen opacity subtracted (filled circles). As expected from Figure 1 the dependence of $\Delta(g - i)$ on hydrogen column density stays approximately constant at $\approx 0.05$ mag. The color excess due to dust reddening $\Delta(g - i)_{\text{dust}}$ is of order of a few percent and corresponds to a rest-frame reddening value of about $E(B - V) \approx 0.01$, assuming an SMC extinction curve. This is in agreement with Vladilo et al. (2008). We also remark that this level of reddening is consistent with the value reported by Frank & Péroux (2010) when they restrict their analysis to $z < 2.2$.

Broadband reddening effects due to the presence of metal lines was studied by Ménard & Fukugita (2012) using both calculations and measurements. In this study we showed that the combination of Mg $\text{II}$ and Fe $\text{II}$ lines (some of the strongest absorption features in the UV) induce magnitude changes at a level below one percent and we were able to detect this effect using strong Mg $\text{II}$ absorbers spanning the range $0.5 < z < 2$. Pieri et al. (2014) presented composite spectra of Lyman-$\alpha$ absorbers. Their results show that the metal lines that would fall in the $g$ and $i$ bands would be weaker than the combination of Mg $\text{II}$ and Fe $\text{II}$ lines. The presence of metal lines is therefore not expected to appreciably affect the measured color excess of quasars behind absorbers in the current analysis.

Having both reddening and Lyman-$\alpha$ absorption measurements we estimate the average dust-to-gas ratio of the systems as measured by $\Delta(g - i)_{\text{dust}}/N_{\text{H}i}$. Figure 4 shows this ratio as a function of $N_{\text{H}i}$ for absorbers at $2.1 \leq z_{\text{obs}} < 2.3$. Circles are median estimates and the error bars are computed from bootstrap resampling. We show the dust-to-gas ratio separately for clouds showing Mg $\text{II}$ features and those that do not. We observe that the two trends are parallel. The median is well represented by

$$\frac{\Delta(g - i)_{\text{dust}}}{N_{\text{H}i}} \propto N_{\text{H}i}^{-1.0\pm0.2}. \quad (3)$$

for DLAs showing Mg $\text{II}$ features, and

$$\frac{\Delta(g - i)_{\text{dust}}}{N_{\text{H}i}} \propto N_{\text{H}i}^{-1.3\pm0.3}. \quad (4)$$

for DLAs without Mg $\text{II}$ features, both indicating $\Delta(g - i)_{\text{dust}}/N_{\text{H}i} \propto 1/N$. This means that the total metal abundance along the column hardly depends on the hydrogen column density of the cloud, as we noted in Figures 1 and 3 above. For this redshift range the contribution from Lyman-$\alpha$ opacity is small, as mentioned, which is anyway subtracted out (if not the power appears more like $N_{\text{H}i}^{-0.8}$). We do not see any break beyond the error in this correlation for the range $N_{\text{H}i} = 10^{20.0-10^{21.8}}$ cm$^{-2}$.

We note that the two curves in Figure 4, one with Mg $\text{II}$ signature and the other without, obey parallel relations, meaning that all DLAs are dusty, regardless of whether they show significant Mg $\text{II}$ absorption or not. Those that show Mg $\text{II}$ absorption have somewhat larger metallicity, approximately by a factor of 3. Whether a system shows Mg $\text{II}$ absorption depends solely on the total Mg $\text{II}$ abundance in the relevant column. When the total abundance of Mg $\text{II}$ exceeds some threshold (roughly $N_{\text{Mg} II} \approx 3 \times 10^{15}$ cm$^{-2}$), the clouds are identified as Mg $\text{II}$ absorbers with $W_0 > 0.8$ Å.
One data point added below our analysis threshold log \( N_{\text{H}} < 20 \) refers to Mg ii clouds in the \( W_0 > 0.8 \) Å sample in MF12. The \( \text{H} \text{i} \) column density is not directly measured for these absorbers. We infer it by invoking the \( W_0 - N_{\text{H}} \) relation (Ménard & Chelouche 2009), taking account of the redshift dependence, to obtain \( (\log N_{\text{H}}) \approx 19.8 \) (MF12), however, with a large scatter around the \( W_0 - N_{\text{H}} \) relation in mind. The mean metallicity of Mg ii clouds is about solar within a factor of two. We observe that Mg ii absorption systems are on the metallicity versus hydrogen column density relation for DLAs. There seems to be no discontinuity in this relation between Mg ii and DLA absorbers; the total abundances of magnesium along the column in both absorbers are about the same.

Let us now suppose that gas in Mg ii clouds has properties similar to a typical ISM. In this case, we expect that 30% of heavy elements condense into dust grains, which corresponds to the case when all silicate and a substantial fraction of graphite (15%–50%) condense into dust grains (e.g., Weingartner & Draine 2001). We also assume that the relation between \( E(B-V) \) and \( N_{\text{H}} \) for the Milky Way (MW) holds up when scaled by metallicity (Bohlin et al. 1978). It then implies that dust reddening and hydrogen column density can be used to estimate metallicity \( Z \). Numerically, this is given by the relation

\[
Z/Z_\odot = \frac{(\Delta g - i)_{\text{dust}}}{0.30 \times 10^{-21} k(z_{\text{abs}}) N_{\text{H}}},
\]

where \( k(z) \) is the “\( K \)-correction” for the dust extinction curve for the \( g - i \) color. There are typically two types of extinction curves, MW type and SMC type. The two extinction curves differ little in the optical region, and Equation (5) holds for both curves up to a 20% difference. In the UV region the two curves differ significantly, and it has been shown that dust in Mg ii clouds obeys the SMC-type extinction curve (e.g., York et al. 2006; Ménard et al. 2008; MF12). Which extinction curve works for DLAs is part of the task given to our study.

The most conspicuous difference between the MW extinction curve and the SMC curve is the presence of a hump in the former at 2175 Å. The \( K \)-correction for MW extinction in the \( g - i \) band wildly varies as a function of redshift for \( z > 0.8 \) when the feature enters the \( g \) band until it goes away from the \( i \) passband for \( z > 2.8 \). The \( K \) correction even becomes negative for \( z = 2.2-2.6 \), which is close to the redshift of absorbers that concern us. This does not agree with the reddening we observed\(^7\), supporting the validity of the SMC-type extinction law for DLAs. The MW-type extinction, which would lead to very small reddening or bluing instead, is excluded. With the SMC-type extinction curve (Weingartner & Draine 2001), we have \( k(z_{\text{abs}}) = 2.1 \) ≃ 3.0 to \( k(z_{\text{abs}}) = 2.3 \) ≃ 3.2.

We use Equation (5) as a proxy to estimate metallicity. Here we assume that the dust-to-metal ratio does not vary with the hydrogen column density. The inferred metallicity values can be read in the right axis of the Figure 4. To assess whether our mean metallicity estimate is reasonable, i.e., valid within a factor of a few, we also plot spectroscopic metallicity estimates compiled by Neeleman et al. (2013). From their list, we select DLAs centered around the mean redshift of our sample (\( \bar{z} = 2.2 \)) and with a somewhat wider redshift range of ±0.3 in order to have enough systems. We then compute the median metallicity as a function of hydrogen column density and show the results as green points in the figure. The errors are estimated by bootstrapping the sample. It shows that our estimate of metallicity inferred from dust reddening is consistent with spectroscopic estimates. We note that, from the spectroscopic measurements alone, the current data set does not allow us to obtain a statistically significant anticorrelation between metallicity and hydrogen column density. This overall consistency validates the assumption that, within a factor of a few, the median dust-to-metal ratio does not depend much on hydrogen column density in the range of values considered in this analysis. In addition, this agreement between the two estimates reassures that our procedure is not affected by substantial errors\(^8\).

The lack of DLA in the upper right plane (high \( Z \), high \( N_{\text{H}} \)) in Figure 4 above has been noticed in the past in spectroscopic samples (e.g., Boissé et al. 1998; Péroux et al. 2003; Khare et al. 2007). In particular, Meiring et al. (2009) showed that the metallicity of DLAs is bound by \( [Zn/H] \lesssim -0.8 \log N_{\text{H}} \) + constant. This lack, however, has been ascribed to a selection effect against heavily reddened quasars, or to sometimes more complicated atomic effects (Krumholz et al. 2009). With only the spectroscopic sample one cannot conclude as to the cause.

\(^7\) We observe approximately constant reddening induced by DLAs in a wide range of redshift with \( z \lesssim 4 \).

\(^8\) We here remark on the trend noted by De Cia et al. (2013) that the median value of the dust-to-metal ratio decreases by a factor of a few when \( N_{\text{H}} \) increases from about \( 10^{20} \) to \( 10^{22} \) \( \text{cm}^{-2} \). Such an effect, if any, would have only a modest impact on the overall trends of the estimated metallicity as a function of column density seen here.
At somewhat higher redshift we noted, with a larger error, that the reddening trend does not change much from what we observed for our $2.1 < z < 2.3$ sample. The 2175 Å hump goes off the $i$ band for $z > 2.8$, and the MW extinction curve should lead to negative reddening. The fact that we do not see a change in the reddening of DLAs with redshift from $z \approx 2.1$ to higher $z$ is consistent with the shape of the SMC extinction curve but not with that of the MW.

4. DUST IN DLA AND Mg II CLOUDS

We attempt to estimate the hydrogen and cosmic dust budget among quasar line absorbing clouds. We must bear in mind that there may be systematic effects arising from the treatment as to the selection of the absorption system. The numbers given below (summarized in Table 1) should be taken with reservations for the errors that may not be properly estimated. We consider, nevertheless, that it is worthwhile to envisage a global picture as to the distribution of hydrogen and dust in intergalactic objects.

With the SDSS DR9 catalog Noterdaeme et al. (2012) estimated the H i mass density $\Omega_{H i} \approx 1.0 \times 10^{-3}$ at $z \approx 2$. We obtain with the uniform quasar sample of DR9 $\Omega_{H i} \approx 8.6 \times 10^{-4}$, using the DLA identification of Noterdaeme et al. This value is two times larger than the H i abundance at $z = 0$, $\Omega_{H i} \approx 4.2 \times 10^{-5}$ (Zwana et al. 2003), meaning that the H i mass density further decreases toward $z = 0$. We remark, however, that Prochaska & Wolfe's (2009) estimate at $z \approx 2$, is lower, $4 \times 10^{-4}$. DLAs identified by Prochaska & Wolfe are fewer. The difference seems to arise largely from the different treatment of the continuum around Lyman-$\alpha$ in the identification of DLAs, as well as survey path length and completeness. We adopt here the more recent Noterdaeme et al. catalog without referring to this problem further.

The slope of the cloud abundance as a function of the hydrogen column density is a matter of argument (e.g., Prochaska et al. 2005; Péroux et al. 2003) in sub-DLA column density, i.e., around the Lyman limit system, LLS: $10^{17.3} < N_{H i} < 10^{20.3}$. Adopting the slope $\alpha = -1.0$ of Prochaska et al. (2005, 2014) for this column density range, we extrapolate the DLA abundance to the LLS region to obtain $\Omega_{H i}(LLS) \approx 2-4 \times 10^{-4}$, which is less than half the DLA H i mass density.

For our DLA sample, we estimate the incidence of Mg ii absorption to be approximately 10%. The fraction of clouds that show Mg ii absorption with $W_0 > 0.8$ Å is shown in Figure 5.

![Figure 5](https://example.com/f5.png)

**Figure 5.** Fraction of clouds that show Mg ii absorptions with $W_0$(Mg ii) $> 0.8$ Å as a function of the hydrogen column density.

It stays roughly constant, at 10%, independent of the hydrogen column density above $10^{20}$ cm$^{-2}$.

To account for the total incidence of Mg ii absorbers, however, we are led to guess that the fraction should go up to 40% in the LLS regime. Adding DLAs that show Mg ii absorption, Mg ii clouds amounts to $\Omega_{H i}(Mg ii) \approx 2.1 \times 10^{-4}$, in our estimate based on the H i sample. This value is not inconsistent with our previous estimate based on the Mg ii line-selected sample, $1.5 \times 10^{-4}$ (MF12), if errors from the sample selection are considered. Taking the fraction of Mg ii clouds in DLAs, we estimate the mass density of Mg ii clouds in DLAs to be $0.12 \times 8.6 \times 10^{-4} \approx 1 \times 10^{-4}$. Subtracting this from the H i mass density in Mg ii clouds, we estimate that the H i mass density in Mg ii clouds in the LLS regime is $\approx 1 \times 10^{-4}$. Comparing this with $\Omega_{H i}(LLS)$ above, we infer that there may be more clouds (roughly up to 3 times more) in the LLS regime that do not show Mg ii lines, i.e., are metal poor.

In MF12 we estimate that $\Omega_{dust}(Mg ii) \approx 2.3 \times 10^{-6}$. For the DLA sample, we obtain $\Omega_{dust}(DLA&Mg ii) \approx 1.6 \times 10^{-7}$, which should be included in the MF12 estimate. More dust, however, is associated with non-Mg ii DLAs, which is estimated to be $\Omega_{dust}(DLA non-Mg ii) \approx 5.0 \times 10^{-7}$. Dust in DLA as a whole, $\Omega_{dust}(DLA) \approx 7 \times 10^{-7}$ is still three times less than that in Mg ii clouds, namely it is only some modest addition to the global dust budget in absorption clouds.

We estimate dust in LLS showing Mg ii absorption to be $2.1 \times 10^{-6}$. We are not able to estimate dust in non-Mg ii absorbing LLS from our samples. It could bear an amount comparable to that in Mg ii clouds with the LLS hydrogen density, $\Omega_{dust}(LLS, non-Mg ii) \approx 2 \times 10^{-6}$ if we assume one-third the metallicity of Mg ii clouds, as we found for DLA. On the other hand, non-Mg ii LLS could be metal poor (hence dust poor) or dominantly pristine with negligible dust, as has been uncovered by Fumagalli et al. (2011) for their examples.

Adding all, we estimate the amount of dust in all intergalactic absorbers $\Omega_{dust} \approx 3-5 \times 10^{-6}$. This larger value agrees with what we infer from reddening of rays passing in the vicinity of galaxies (Ménard et al. 2010, hereinafter MSFR; Fukugita 2011). When dust in galaxies ($4 \times 10^{-6}$) (Fukugita & Peebles 2004) is added, there seems to be, at least, no obvious missing dust in view of the present error, when compared with the
amount that ought to be produced in the history of the galaxy (Fukugita 2011). This consideration shows that dust observed is consistent with the amount that is produced in stars in galaxies \((10 \times 10^{-6})\), allowing for a possibility of some amount (say \(\leq 20\%–30\%\)) still missing, or destructed.

5. INTERPRETATION AND IMPLICATIONS

The low metallicity of DLAs indicates that they are primarily aggregates of primordial gas, rather than gas processed by stars ass with Mg II clouds. Metallicity of DLAs, however, is non-vanishing. They are enriched in some way. A notable feature is that metallicity is inversely proportional to the hydrogen column density.

We can think of two possibilities to enrich DLA with metals, star formation activity in DLA themselves and the contamination from outside via winds from other galaxies. For nearby galaxies it is established that star formation rate is proportional to a power of hydrogen column density, known as the Schmidt (1959)–Kennicutt (1998) law, \(N_{\text{H}}\) above the hydrogen column density threshold, \(N_{\text{H}} \approx (0.5–1) \times 10^{21} \text{ cm}^{-2}\). Below this column density, the star formation efficiency drops sharply. This has also been confirmed in a more recent study for low surface brightness galaxies (Wyder et al. 2009).

The Schmidt–Kennicutt law leads us to expect that the column density of star formation, hence the heavy element and dust production, when divided by \(N_{\text{H}}\), is proportional to \(N_{\text{H}}^{-0.4}\) above some threshold. This is contrary to the trend in our analysis, \(N_{\text{H}}^{-1}\). We do not detect any threshold in the metallicity versus hydrogen column density relation around \(N_{\text{H}} \approx (0.5–1) \times 10^{21} \text{ cm}^{-2}\), which is known from Kennicutt’s work. This leads us to conclude that the observed characteristics do not agree with the idea that dust is produced via in situ star formation in DLA, at least, as far as the dominant part of dust is concerned. A number of studies have characterized the level of star formation rate associated with \(z \approx 2\) DLAs from continuum emission (Rafelski et al. 2011) or emission line (Noterdaeme et al. 2014) measurements and also found that the dependence on hydrogen column density does not follow the Schmidt–Kennicutt law. We note that, in contrast, at low redshift it is known that some DLAs are parts of galaxies of a variety of morphological types (e.g., Le Brun et al. 1997; Rao et al. 2003).

We argued that gas and dust in Mg II clouds are likely to be transported by stellar activity in nearby galaxies via galactic winds (MF12). This hypothesis may also apply to DLA. We expect that intergalactic objects may receive deposit from intergalactic gas at the same amount per unit area of the surface. This means that the average metallicity should be inversely proportional to the hydrogen column density, in agreement with what is observed here. From the dust distribution that extends to very large scales around galaxies (MSFR; Fukugita 2011), we may infer that galactic winds are ubiquitous throughout the universe. In our earlier publication (MSFR) we have shown that the abundance ratio of dust to dark matter stays approximately constant to a scale larger than a few Mpc away from galaxies. Knowing that the mean dark matter distribution obeys a power law, roughly as \(r^{-2.4}\), to far beyond the virial radius of the galaxy (Masaki et al. 2012), we infer that dust also follows a similar power law without cutoff to a few Mpc scale.

The total global amount of dust in galaxies and absorbers is consistent with what is ought to be produced in star formation in galaxies. This implies that the effective lifetime of dust, including its possible regeneration, is of the order of the age of the universe. It is somewhat puzzling to note that a clear discontinuity is not observed between Mg II absorbers and DLAs in their metallicity distributions, while the dust to gas ratio in Mg II clouds implies that they are predominantly of galactic activity origins: they should not be diluted much with pristine gas.

The amount of dust deposited to each cloud should vary: it would depend on the distance to and on the dust producing activity of nearby galaxies. We expect DLAs lying closer to galaxies to have, statistically, a higher metal column density.

6. CONCLUSIONS

We have studied the dust-to-gas ratio of DLAs and used it as a metallicity indicator. The advantage is that the dust abundance can be estimated passively from the extinction of light, provided that care is taken to measure a small value of reddening. To keep the accuracy controlled we limited our analysis to carefully chosen redshift ranges for both quasars and absorbers. Using the fact that 30% of heavy elements condense into dust grains, metallicity can be estimated from reddening in broadband photometry. This requires averaging over a large data set and well-controlled photometry that does not suffer from arbitrary errors. The advantage is that the estimate of metallicity, using only passive measurements, does not use the temperature, or does not depend on the environment such as the radiation field. Our central conclusion is that average metallicity is inversely proportional to the column density of the DLA, as \(Z \propto N_{\text{H}}^{-1}\), or in other words, the metal column density stays constant independent of the hydrogen column density.

We argued that in situ star formation should lead to \(Z \approx N_{\text{H}}^{-0.4}\), which is in contrast to the observation of the inverse correlation. We have not observed any threshold in the hydrogen column density that is known for the law of star formation (Kennicutt 1998; Wyder et al. 2009). These aspects lead us to conclude that it is unlikely to ascribe the origin of the bulk of dust in DLAs to in situ star formation. We argued that, instead, dust in DLAs is deposited from intergalactic space through stellar activity in the neighborhood of the cloud. In this case, we expect, on average, the same amount of dust deposited per surface area of intergalactic clouds regardless of the column density. It then follows that \(Z \approx N_{\text{H}}^{-1}\). We discussed that this view does not bring a problem into the dust budget consideration.

About 10% of DLAs show Mg II absorption features at \(z \approx 2\). DLAs that do not show strong Mg II absorption features harbor one-third the amount of dust compared with those that show strong Mg II absorption. As a result, dust in DLAs as a whole resides more in those that do not show Mg II absorption features. The global amount of dust in DLAs, however, is still one-third the amount in Mg II clouds, which is mostly at lower, LLS column densities.

A corollary result from our study is that dust in DLA shows reddening consistent with the SMC-type extinction curve. For the redshift we chose \((z \approx 2.2)\) the MW-type extinction would lead to no color excess or even bluing in \(g - i\) color in the presence of dust due to the 2175 Å feature. We detected reddening when DLA is present in the foreground, and metallicity derived using the SMC-type extinction curve agrees statistically with spectroscopic estimates. This rules out MW-type extinction for the DLA.

DLAs seem to be aggregates of primarily unprocessed gas with small amounts of deposits from galaxy activity in their vicinity. In contrast, Mg II clouds are consistent with sec-
ondary products of galaxies, weakly diluted with pristine gas. However, there seems to be no clear dichotomy in the metallicity–hydrogen column density relation between the two populations. Mg$\ii$ clouds should thoroughly be contaminated, or even dominated by galactic wind, if they are of the primordial origin. There seems to be a significant population of hydrogen clouds with hydrogen column density comparable to Mg$\ii$ clouds but do not show Mg$\ii$ lines: they seem to be a population similar to DLAs at a lower column density extension. How Mg$\ii$ clouds formed remains an interesting problem.

M.F. thanks the W.M. Keck Foundation (2013) and Ambrose Monell Foundation (2014) at the Institute for Advanced Study, and received in Tokyo a Grant-in-Aid (No. 23540288) from the Ministry of Education. B.M. is supported by NSF Grant AST-1109665. He also acknowledges the hospitality of the Institute for Advanced Study.

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