THE ASTROPHYSICAL JOURNAL, 493:583–594, 1998 February 1

DUST AND ELEMENTAL ABUNDANCES IN DAMPED Lyα ABSORBERS

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Received 1997 May 23; accepted 1997 September 10

ABSTRACT

The effects of the dust on the determination of elemental abundances in damped Lyα (DLA) absorbers are investigated. Relations between the observed abundances measured in the gas phase and the overall abundances (gas plus dust) are derived as a function of dust-to-gas ratio, metallicity, element-to-element abundance pattern, average extinction coefficient of dust grains, and chemical composition of dust grains. A method is presented for determining dust-to-gas ratios, dust-to-metals ratios, and dust-corrected relative abundances in DLA absorbers by assuming dust of Galactic type and constant abundance ratios between iron-peak elements. The method is applied to a sample of 17 DLA absorbers with available Zn, Cr, and/or Fe measurements. The resulting dust-to-gas ratios are mostly distributed between 2% and 25% of the Galactic value, in good quantitative agreement with the results from reddening studies of QSOs with foreground DLA absorption. A correlation is found between dust-to-gas ratio and metallicity in DLA galaxies, with a typical dust-to-metals ratio of ≈60% of the Galactic value. The derived dust-to-metals ratios are then used to correct from the effects of dust the abundance ratios [Si/Fe], [S/Fe], [Ti/Fe], [Mn/Fe], and [Ni/Fe] available for a subsample of nine absorbers. The [α/Fe] ratios corrected from dust do not show the enhancement characteristic of metal-poor Galactic stars, but instead have essentially solar values, within ±0.2 dex. This suggests that the chemical history of DLA absorbers is different from that experienced by the Milky Way. Evidence that points to dwarf galaxies, rather than to spiral galaxies, as important contributors to the DLA phenomenon is summarized.

Subject headings: galaxies: abundances — galaxies: evolution — galaxies: ISM — quasars: absorption lines

1. INTRODUCTION

Damped Lyα (DLA) absorbers are the class of QSO intervening systems with the highest hydrogen column density, $N_{\rm H\,I} \geq 2 \times 10^{20}$ atoms cm^{-2}. Several properties of these absorbers indicate that they are high-redshift progenitors of present-day galaxies (Wolfe et al. 1986, 1995). Spectroscopic observations show, in addition to high H I column densities, metal lines of low ionization and velocity dispersions typical of gas-rich galaxies. Imaging studies of fields around QSOs with foreground DLA absorption at low redshift ($z \leq 1$) reveal the presence of gas-rich galaxies with a variety of morphological types (Le Brun et al. 1997). An independent and remarkable piece of evidence in favor of a galactic origin comes from the behavior of $\Omega_g(z)$, the comoving mass density of neutral gas in DLA absorbers in units of the critical density of the universe. The facts that $\Omega_g(z = 3.5)$ equals the mass density of luminous matter (stars) at the present epoch and that $\Omega_g(z)$ decreases with time are interpreted as evidence of gas consumption due to star formation since $z = 3.5$ to the present time (Wolfe et al. 1995). At high redshift, $\Omega_g(z)$ is at least 10% of the baryonic content of the universe, and therefore understanding the nature of DLA galaxies will give important constraints to cosmological models involving structure formation in the early universe (Klypin et al. 1995). A commonly accepted origin of DLA absorbers is in spiral galaxies, (Wolfe et al. 1995; Prochaska & Wolfe 1997b), but an origin in dwarf galaxies has also been suggested (York et al. 1986; Tyson 1988; Pettini, Boksenberg, & Hunstead 1990; Molaro et al. 1996; Matteucci, Molaro, & Vladilo 1997).

Studies of elemental abundances in DLA systems give important clues for understanding which kind(s) of galaxies are responsible for the absorption. In addition, the study of DLA abundances over a large redshift interval will eventually allow us to trace the chemical evolution of the absorbers over a large interval of look-back time, up to the early stages of galactic nucleosynthesis, providing fundamental tests to models of galactic chemical evolution.

Abundance measurements in DLA systems do not depend critically on ionization corrections, because these absorbers are optically thick to ionizing radiation ($h\nu > 13.6$ eV). As a consequence, species that are dominant in H I regions have negligible ionization corrections, as confirmed by detailed photoionization calculations (Lu et al. 1995; Viegas 1995). Nevertheless, the abundances observed in DLA absorbers may not represent the real chemical composition of the system if part of the elements is removed from the gas to the solid phase (dust grains), as happens in the interstellar medium of our Galaxy where elements with very different dust depletions are known to exist (Jenkins 1987; Savage & Sembach 1996). In DLA absorbers the relative abundances of elements expected to have different dust depletions, such as Zn and Cr, suggest that dust is indeed present, although with a lower dust-to-gas ratio than in the Galaxy (Pettini et al. 1994, 1997a). More direct evidence for dust in DLA systems has been found from reddening studies of QSOs with and without foreground-damped absorption (Pei, Fall, & Bechtold, 1991).

A relatively large number of abundance determinations in DLA absorbers has been collected since it has become possible to observe QSOs at sufficiently high spectral resolution (see the list of references quoted in Table 2). Attempts to interpret the relative abundances (i.e., element-to-element abundance ratios) observed in DLA absorbers have lead, however, to contradictory conclusions. From one side claims have been made that the pattern of relative abundances resembles that of Galactic halo stars, having in common an enhancement of the alpha elements and a deficiency of manganese relative to iron (Lu et al. 1996; Prochaska & Wolfe 1997a). From the other side, evidence has been presented for nearly solar [α/Fe] ratios in spite of the low metallicity level of the absorbers (Molaro et al. 1996; Molaro, Centurión, & Vladilo 1998). These contradictory conclusions are probably due to the fact that the presence of dust in DLA absorbers is not properly taken into account. Several attempts have been made to reproduce the observed abundances by combining different intrinsic abundance patterns with dust-depletion patterns of Galactic interstellar type (Lauroesch et al. 1996; Kulkarni, Fall, & Truran 1997). According to these studies, neither a halo-like nor a solar-like metallicity pattern match the observations perfectly. In the present work the effect of the dust on the determinations of the elemental abundances is studied in detail by deriving equations that take into account the level of metallicity, the dust-to-gas ratio, and the intrinsic abundance pattern of DLA absorbers. As opposed to the analysis performed by Kulkarni et al. (1997), in the present study each individual DLA system is treated separately, and the extinction induced by the dust is taken explicitly into account. The general equations that link observed abundances to real abundances of the absorbers are presented in § 2. Simplified forms of these equations are then used in § 3 to predict possible dust-depletion patterns in DLA systems. In § 4 the method for estimating dust-to-metals ratios, dust-to-gas ratios, and dust-corrected abundances in individual DLA absorbers is presented; the method is applied to available abundance measurements of DLA systems. The relations between dust and metals in DLA absorbers are examined in § 5. The implications for our understanding of the nature of DLA galaxies are discussed in § 6, and the results are summarized in § 7.

2. DEFINITIONS AND BASIC EQUATIONS

The observed abundance ratio by number $(\mathrm{X/H})_{\mathrm{obs}}$ of an element X in a DLA absorber is determined from measurements of the column densities in the gas phase of the system, $N_{\mathrm{X},g}$ and $N_{\mathrm{H}} \simeq N_{\mathrm{H\,I}}$. The observed abundance is usually expressed in logarithmic form relative to solar composition,

$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right]_{\mathrm{obs}} = \log\left(\frac{\mathrm{X}}{\mathrm{H}}\right)_{\mathrm{obs}} - \log\left(\frac{\mathrm{X}}{\mathrm{H}}\right)_{\odot} . \quad (1)$$

However, this is not the real abundance since the column density of atoms in dust, $N_{\mathrm{X},d}$, is not considered in equation (1). The total column density $(N_{\mathrm{X},g} + N_{\mathrm{X},d})$ would instead give the real ratio $(\mathrm{X/H})_{\mathrm{dla}}$ and hence the real abundance

$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right]_{\mathrm{dla}} = \log\left(\frac{\mathrm{X}}{\mathrm{H}}\right)_{\mathrm{dla}} - \log\left(\frac{\mathrm{X}}{\mathrm{H}}\right)_{\odot} . \quad (2)$$

By introducing the fraction in dust of the element X

$$f_{\mathrm{X}} = N_{\mathrm{X},d}/(N_{\mathrm{X},g} + N_{\mathrm{X},d}) \quad (3)$$

it is easy to derive a relation between the observed and the real abundance

$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right]_{\mathrm{obs}} = \left[\frac{\mathrm{X}}{\mathrm{H}}\right]_{\mathrm{dla}} + \log\,(1 - f_{\mathrm{X}}) . \quad (4)$$

To introduce the effect of the dust in the above expression we start by defining the dust-to-gas ratio

$$k = \tau/N_{\mathrm{H\,I}} , \quad (5)$$

where τ is the extinction optical depth in the spectral region of interest in the rest frame of the absorber. The above definition is the same as that of Pei et al. (1991), provided the hydrogen column density $N_{\mathrm{H\,I}}$ is expressed in units of $10^{21}\ \mathrm{cm}^{-2}$. If we call N_{gr} the column density of dust grains per unit area along the line of sight, the optical depth is given by

$$\tau = N_{\mathrm{gr}}\, c_e , \quad (6)$$

where c_e is the average extinction cross section of the grains. For spherical grains of radius a the cross section for extinction is $C_e = \pi a^2 Q_e$, where the efficiency factor for extinction $Q_e(\lambda)$ can be estimated in the framework of the Mie scattering theory (see, e.g., Wickramasinghe 1967). If we call $n_{\mathrm{gr}}(a)da$ the number of grains with radii in the range $(a,\ a+da)$ per unit volume, then it is possible to define $c_e = \langle \pi a^2 Q_e \rangle$ through the relation $\tau = \int \pi a^2 Q_e\, n_{\mathrm{gr}}(a) da = N_{\mathrm{gr}}\, c_e$. We will use, however, the most general form (eq. [6]) to avoid any assumption on the geometry of the grains.

We then define the average number of atoms of the element X per dust grain

$$\nu_{\mathrm{X}} = N_{\mathrm{X},d}/N_{\mathrm{gr}} , \quad (7)$$

which is related to the chemical composition of the dust, since the number ratio of two elements X and Y in the dust grains will be $(\mathrm{X/Y})_{\mathrm{gr}} = \nu_{\mathrm{X}}/\nu_{\mathrm{Y}}$.

From equations (5), (6), and (7) it is easy to see that $f_{\mathrm{X}} = k(\mathrm{X/H})_{\mathrm{dla}}^{-1}(\nu_{\mathrm{X}}/c_e)$, where $(\mathrm{X/H})_{\mathrm{dla}} = (N_{\mathrm{X},g} + N_{\mathrm{X},d})/N_{\mathrm{H\,I}}$. By defining the metallicity level of the system as $Z = (\mathrm{Y/H})_{\mathrm{dla}}$, where Y is a suitable reference element, we obtain

$$f_{\mathrm{X}} = \frac{k}{Z}\left(\frac{\mathrm{X}}{\mathrm{Y}}\right)_{\mathrm{dla}}^{-1} \frac{\nu_{\mathrm{X}}}{c_e} . \quad (8)$$

From equations (4) and (8) we obtain a relation between observed and real abundance:

$$\left[\frac{\mathrm{X}}{\mathrm{H}}\right]_{\mathrm{obs}} = \left[\frac{\mathrm{X}}{\mathrm{H}}\right]_{\mathrm{dla}} + \log\left[1 - \frac{k}{Z}\left(\frac{\mathrm{X}}{\mathrm{Y}}\right)_{\mathrm{dla}}^{-1} \frac{\nu_{\mathrm{X}}}{c_e}\right] , \quad (9)$$

where the contributions of dust-to-gas ratio, metallicity level, elemental abundance pattern, dust chemical composition, and dust extinction are clearly separated. A crucial role in the relation is played by the dust-to-metals ratio (k/Z).

2.1. *Scaling to Galactic Quantities*

Equation (9) is not suited for comparing observed and real abundances because it includes several unknown quantities. In order to obtain a more useful relation, it is convenient to normalize the quantities in the DLA absorbers in units of the corresponding Galactic quantities. We indicate such normalized values with a tilde symbol, e.g., $\tilde{k} = k/k_{\mathrm{Gal}}$. By applying equation (8) to DLA systems and to our Galaxy, we derive

$$f_{\mathrm{X}} = \frac{\tilde{k}}{\tilde{Z}} \cdot 10^{-[\mathrm{X/Y}]_{\mathrm{dla}}} \cdot \frac{\tilde{\nu}_{\mathrm{X}}}{\tilde{c}_e} \cdot f_{\mathrm{X,ism}} , \quad (10)$$

where $\tilde{Z} = Z/Z_{\odot} = 10^{[Y/H]_{dla}}$; $10^{[X/Y]_{dla}} = (X/Y)_{dla}/(X/Y)_{\odot}$, since we adopt solar abundances for the Galaxy; and the fraction in dust $f_{X,ism}$ refers to the Galactic interstellar medium.

This expression for the fractions in dust can be written in a simpler form if we require the condition $\nu_X = \nu_{X,ism}$ for any element, which is equivalent to assuming that *the dust has same chemical composition and same average number of atoms per grain as Galactic dust*. This equivalence follows from the fact that the relative abundance of two elements in the dust is $(X/Y)_{gr} = (\nu_X/\nu_Y)$. A constant relative abundance in the dust is consistent with current understanding of grains chemical composition (see, e.g., discussion in §§ 12.2 and 12.3 of Savage & Sembach 1996). In practice, once the chemical composition and the average number of atoms are specified, the grain sizes are also specified. Therefore, the extinction coefficient, which depends on the dielectric properties and geometry of the grains, is also determined; the only degree of freedom left is the exact shape of the grains. Therefore, once the condition $\nu_X = \nu_{X,ism}$ is satisfied, the condition $c_e = c_{e,ism}$ is also virtually satisfied, and hence $\tilde{\nu}_X = \tilde{c}_e = 1$. Equation (10) becomes

$$f_X = \frac{\tilde{k}}{\tilde{Z}} \cdot 10^{-[X/Y]_{dla}} \cdot f_{X,ism} , \tag{11}$$

and from equation (4) we obtain the equation

$$\left[\frac{X}{H}\right]_{obs} = \left[\frac{X}{H}\right]_{dla} + \log\left(1 - \frac{\tilde{k}}{\tilde{Z}} \cdot 10^{-[X/Y]_{dla}} \cdot f_{X,ism}\right) , \tag{12}$$

which can be used to estimate the gas-phase abundances given the real metallicity pattern and a suitable combination of dust-to-gas ratio $\tilde{k}$, and metallicity $\tilde{Z}$. The fractions in dust $f_{X,ism}$ can be considered as input parameters that are known with reasonable accuracy from Galactic interstellar studies, as shown in the next section.

3. DUST-DEPLETION PATTERN IN DLA SYSTEMS

By analogy to the definition of logarithmic dust depletion in the Galactic interstellar medium

$$\delta_{X,ism} = \log\left(\frac{X}{H}\right)_{obs} - \log\left(\frac{X}{H}\right)_{\odot} , \tag{13}$$

we define the dust depletion in DLA systems as

$$\delta_{X,dla} = \log\left(\frac{X}{H}\right)_{obs} - \log\left(\frac{X}{H}\right)_{dla} , \tag{14}$$

where the number ratios $[X/H]_{obs}$ are measured in the gas phase in each case. Since dust depletion and fraction in dust (eq. [3]) are related by the equation

$$\delta_X = \log(1 - f_X) , \tag{15}$$

it follows from equation (11) that for Galactic-type dust

$$\delta_{X,dla} = \log\left(1 - \frac{\tilde{k}}{\tilde{Z}} \cdot 10^{-[X/Y]_{dla}} \cdot f_{X,ism}\right) . \tag{16}$$

We have used this relation to estimate dust-depletion patterns in DLA systems by using the dust-to-metals ratio $(\tilde{k}/\tilde{Z})$ and the abundance pattern $[X/Y]_{dla}$ as free parameters. The results are shown in Table 1, where elements most commonly measured in DLA systems are considered. Iron is used as the zero point for the metallicity level. We have computed the fractions in dust $f_{X,ism}$ from equation (15) by adopting dust depletions typical of Galactic warm disk (Savage & Sembach 1996). More details are given in the notes to Table 1.

The results in columns (4), (5), and (6) are relative to a solar abundance pattern ($[X/Fe]_{dla} = 0$) for dust-to-metals ratios $(\tilde{k}/\tilde{Z}) = 1.00$, 0.75, and 0.50, respectively. By definition, the case S100 is nothing more than the Galactic deple-

TABLE 1

PREDICTED DUST-DEPLETION PATTERNS IN DAMPED Lyα SYSTEMS

Element (1)	$f_{X,ism}$ [a] (2)	$[X/Fe]_{halo}$ [b] (3)	S100[c] (4)	S75[d] (5)	S50[e] (6)	H100[f] (7)	H75[d] (8)	H50[e] (9)
Si........	0.63	+0.27	−0.43	−0.28	−0.16	−0.18	−0.13	−0.08
S	0.12	+0.41	−0.06	−0.04	−0.03	−0.02	−0.02	−0.01
Ti	0.91	+0.22	−1.02	−0.49	−0.26	−0.35	−0.23	−0.14
Mn......	0.88	−0.35	−0.92	−0.47	−0.25	[g]	[g]	−1.82
Cr.......	0.92	−0.07	−1.10	−0.51	−0.27	[g]	−0.72	−0.34
Fe.......	0.94	...	−1.22	−0.53	−0.28	−1.22	−0.53	−0.28
Ni.......	0.97	−0.02	−1.46	−0.56	−0.29	[g]	−0.62	−0.31
Zn	0.35	+0.04	−0.19	−0.13	−0.08	−0.17	−0.12	−0.08

[a] Fractions in dust derived from eq. (15) by adopting the dust depletions representative of Galactic warm disk given by Savage & Sembach 1996; for Zn we adopt the average depletion for sight lines with lowest molecular content from Roth & Blades 1995; for Ti the base depletion is from Jenkins 1987.

[b] Average values in Galactic halo stars at a metallicity level $Z/Z_{\odot} = 0.1$; Si, Ti, Mn, Cr, and Ni are estimated from the midmean vector defined by Ryan et al. 1996; S is from Francois 1988 corrected by −0.2 dex (Lambert 1988); Zn is from Sneden et al. 1991.

[c] Predicted depletion pattern in DLA systems $\delta_{X,dla}$ assuming solar relative abundances, dust-to-metals ratio $\tilde{k}/\tilde{Z} = 1.00$, and Galactic-type dust with fractions in dust as in col. (2).

[d] Same as in previous column, except for dust-to-metals ratio $\tilde{k}/\tilde{Z} = 0.75$.

[e] Same as in previous column, except for dust-to-metals ratio $\tilde{k}/\tilde{Z} = 0.50$.

[f] Predicted depletion pattern in DLA systems $\delta_{X,dla}$ assuming halo-like abundance as in col. (3), dust-to-metals ratio $\tilde{k}/\tilde{Z} = 1.00$, and Galactic-type dust with fractions in dust as in col. (2); iron depletion is the same as in the case of solar-like abundances because iron is used as a reference for the metallicity level.

[g] Solution not allowed.

tion pattern for low-density lines of sight (Galactic warm disk). By comparing this pattern with the cases S75 and S50 one can see that the absolute values of the depletions decrease when the dust-to-metals ratio is reduced. However, *the scaling law of the differential depletion is not linear*, contrary to what assumed in previous works (see, e.g., Lauroesch et al. 1996). Rather, *the differential depletion between pairs of elements tends to vanish as the dust-to-metals ratio decreases*. This implies that elements moderately depleted in the Galaxy can still have a nonnegligible depletion when less dust is present. As an example, Si depletion decreases by only 0.3 dex, compared to a decrease of 1 dex of Fe, when $(\tilde{k}/\tilde{Z})$ is reduced from 1.0 to 0.5.

More surprising results are found when an abundance pattern different from the solar one is considered. In columns (7), (8), and (9) we give the depletions expected for an intrinsic abundance pattern typical of Galactic halo stars, again for dust-to-metals ratios $(\tilde{k}/\tilde{Z}) = 1.00$, 0.75, and 0.50, respectively. The adopted values of halo-star abundances are taken from Francois (1988), Sneden, Gratton, & Crocker (1991), and Ryan, Norris, & Beers (1996), at a metallicity level $Z/Z_\odot = 0.1$, which is characteristic of DLA absorbers; refer to the notes in Table 1 for more details. The very small deviations from the solar pattern found for [Cr/Fe] and [Ni/Fe] are treated here as real to show how even small deviations can affect the dust-depletion pattern. From the results shown in Table 1 one can see that *inversions in the differential depletion pattern may appear if the DLA abundance pattern is not solar*. For instance, underabundant elements such as Mn and Cr are more depleted than Fe in halo-like models, contrary to what is found in Galactic interstellar gas. Overabundant elements tend, on the other hand, to be less depleted. As an example, Ti depletion is quite modest in halo-like models, while it is comparable to iron depletion in Galactic gas. It is also interesting to note that no solutions are allowed for underabundant elements with a high fraction in dust ($f_{\rm X,ism} \simeq 0.9$) unless the dust-to-metals ratio is sufficiently low. This apparently peculiar result is due to the fact that one cannot use any combination of input parameters one chooses, because by definition equation (3) must be $f_{\rm X} \leq 1$ and therefore $(\tilde{k}/\tilde{Z}) \leq (10^{[{\rm X/Y}]_{\rm dla}}/f_{\rm X,ism})$, otherwise there will be not enough atoms available to form the required amount of dust. As an example, there are no solutions for Mn in the models H100 and H75, while there is a solution for H50, when the dust-to-metals ratio becomes half the Galactic value.

4. ANALYSIS OF ABUNDANCE MEASUREMENTS

Instead of using equation (12) to estimate the effect of a given DLA abundance pattern on the observed abundances, we will follow the opposite approach of deriving the real abundance pattern starting from the observed ratios. By applying equation (12) to the elements X and Y and combining the resulting equations, it is possible to find the real abundance ratio

$$10^{[{\rm X/Y}]_{\rm dla}} = 10^{[{\rm X/Y}]_{\rm obs}} + \frac{\tilde{k}}{\tilde{Z}} \cdot (f_{\rm X,ism} - f_{\rm Y,ism} \cdot 10^{[{\rm X/Y}]_{\rm obs}}) \quad (17)$$

from the observed abundance ratio. This equation still depends on the dust-to-metals ratio, which is unknown. However, if two elements X and Y trace each other over the chemical history of the system, i.e., if $[{\rm X/Y}]_{\rm dla} = 0$ at any time, then it is easy to derive from equation (17) the expression

$$\frac{\tilde{k}}{\tilde{Z}} = \frac{10^{[{\rm X/Y}]_{\rm obs}} - 1}{f_{\rm Y,ism} \cdot 10^{[{\rm X/Y}]_{\rm obs}} - f_{\rm X,ism}}, \quad (18)$$

which allows one to compute the dust-to-metals ratio from observed abundances by using the Galactic interstellar fractions in dust as input parameters. Once the dust-to-metals content is determined from a given pair of elements, equation (17) can be applied to other elements for deriving their intrinsic abundance. This method can be applied to individual DLA systems for which suitable abundances measurements are available. In the following sections we describe the results of the application of this procedure to currently available measurements.

4.1. *Dust-to-Metals Ratios from Iron-Peak Elements*

In order to determine the dust-to-metals ratio from equation (18) we need at least two elements for which $[{\rm X/Y}]_{\rm dla} = 0$ in DLA systems. Studies of metal-poor stars in the Galaxy indicate that iron-peak elements generally trace each other down to metallicities comparable to those found in DLA absorbers (see col. [3] of Table 1 and references quoted therein). A relatively large amount of observations of iron-peak elements are available for DLA systems, as can be seen in the updated summary of measurements presented in Table 2. The use of iron-peak elements is therefore the most natural choice to determine the dust-to-metals ratio. However, a few caveats have to be considered. From one side, observed DLA [Mn/Fe] ratios show an underabundance that is difficult to understand in terms of dust depletion (Lu et al. 1996). In addition, some deviations from solar ratios are found in metal-poor stars for [Cr/Fe], [Mn/Fe], and [Co/Fe] (Ryan et al. 1996), and for [Cu/Fe] (Sneden et al. 1991). For Cr, however, these deviations are significant only at $[{\rm Fe/H}] < -2.5$ and are negligible at the metallicity level typical of DLA systems. Also taking into account the number of available measurements, this leaves Zn, Fe, and Cr as the best candidates for using equation (18). Thanks to the long-standing observational effort of Pettini et al. (1994, 1997a), a relatively large number of Zn and Cr measurements are available. These overlap in many cases with Fe (and sometimes Ni) determinations based on Keck observations (Lu et al. 1996 and references therein). The form of the denominator of the right-hand side of equation (18) indicates that the use of any pair of elements with similar fractions in dust and gas-phase abundances must be avoided, because a small observational error would lead to a large error in the dust-to-metals ratio. This precludes the use of Cr and Fe, as can be seen in Tables 1 and 2. Since Zn has a much smaller fraction in dust than Cr and Fe, we have determined the dust-to-metals ratio from (18) by using Zn as the element X and Cr or Fe as the element Y.

Table 2 includes the 17 DLA systems for which a Zn measurement exists, rather than an upper limit, together with a Cr or Fe determination. The resulting dust-to-metals ratios are shown in Table 3. In eight cases the determinations are obtained independently from [Zn/Cr] and [Zn/Fe] ratios. We do not find a systematic difference between the eight results in common, the average percent difference being $-0.06\% \pm 0.19\%$. This agreement gives us confidence on the method adopted and on the assumption that these elements indeed trace each other in DLA systems, at least down to the level of metallicity of the present

TABLE 2

IRON-PEAK ABUNDANCE DETERMINATIONS IN DLA SYSTEMS[a,b]

QSO	z_{abs}	[Zn/H]	References	[Cr/H]	References	[Fe/H]	References	[Ni/H]	References	[Mn/H]	References
0056+014......	2.777	−1.23	1	−1.35	1	...		...		...	
0100+130......	2.309	−1.55	2	−1.79	2	−1.99	3	−2.13	2	...	
0112+029......	2.422	−1.15	4, 1	−1.65	4, 1	...		...		...	
0201+363......	2.462	−0.26	5	−0.90	5	−0.80	5	−1.00		...	
0302−223......	1.009	−0.51	6	−0.90	6	...		...		...	
0454+039......	0.859	−0.83	7, 1	−1.02	7, 1	−0.97	8	...		−1.22	8
0458−020......	2.039	−1.23	4, 1	−1.59	4, 1	...		−1.90	9	...	
0528−250......	2.811	−0.76	8	−1.23	8	−1.23	8	−1.56	8	...	
0841+129......	2.374	−1.35	1	−1.64	1	...		...		...	
0935+417......	1.372	−0.80	10, 1	−0.90	10, 1	−0.96	10	...		−1.24	10
1104−180......	1.661	−0.80	11, 1	−1.29	11, 1	...		...		...	
1151+068......	1.773	−1.56	1	−1.64	1	...		...		...	
1223+175......	2.465	−1.68	4, 1	−1.82	4, 1	...		...		...	
1328+307......	0.692	−1.21	12, 1	−1.66	12, 1	−1.80		...		...	
1331+170......	1.776	−1.27	8	−2.10	8	−2.03	8	−2.20		...	
2206−199......	1.920	−0.38	13	−0.58	13	−0.68	13	−1.01	13	...	
2231−001......	2.066	−0.88	8	...		−1.14	8	−1.53	8	...	

[a] All abundances have been normalized to the solar values by Anders & Grevesse 1989: $\log(\mathrm{Zn/H})_{\odot} = -7.35$, $\log(\mathrm{Cr/H})_{\odot} = -6.33$, $\log(\mathrm{Ni/H})_{\odot} = -5.75$, $\log(\mathrm{Mn/H})_{\odot} = -6.61$, with the exception of iron, taken from Hannaford et al. 1992: $\log(\mathrm{Fe/H})_{\odot} = -4.52$.

[b] Typical errors of these abundance determinations are in the order of 0.1 dex; we refer to the references below for exact error determinations in individual cases.

REFERENCES.—(1) Pettini et al. 1997a; (2) Wolfe et al. 1994; (3) Molaro et al. 1998; (4) Pettini et al. 1994; (5) Prochaska & Wolfe 1996; (6) Pettini et al. 1997b; (7) Steidel et al. 1995; (8) Lu et al. 1996; (9) Meyer & Roth 1990; (10) Meyer, Lanzetta, & Wolfe 1995; (11) Smette et al. 1995; (12) Meyer & York 1992; (13) Prochaska & Wolfe 1997a.

sample. For these eight cases we adopt the average of the two independent determinations as the final dust-to-metals ratio. For the other cases we adopt the individual result, being confident that Fe versus Cr systematic effects should be negligible. An attempt to derive the dust-to-metals ratio using [Zn/Ni] leads to values systematically higher by about 20% than the values derived from [Zn/Cr] and [Zn/Fe]. This suggests that a weak deviation from solar iron-peak relative composition may be present for Ni, even though the suspicion has been advanced that Ni abundances could be affected by uncertainties in the Ni II oscillator strengths (Lu et al. 1996). For these reasons, dust-to-metals ratios determined from [Zn/Ni] ratios are not considered here.

The typical random error of the dust-to-metals ratio derived in this way can be estimated by neglecting the contribution of $f_{\mathrm{Zn,ism}}$ in the denominator of the right-hand side of equation (18). The error of the dust-to-metals ratio equals that of the [Zn/Y] measurement, which is typically 0.1 dex, although in some cases it can be as low as 0.05 dex. In addition to this random error, systematic errors are introduced through the Galactic fractions in dust used in equation (18). To quantify this effect we computed the dust-to-metals in two cases: (1) zinc completely undepleted, i.e., $f_{\mathrm{Zn,ism}} = 0$, and (2) zinc mildly depleted, with $f_{\mathrm{Zn,ism}} = 0.35$. The resulting dust-to-metals ratios, also shown in Table 3, are systematically lower by $\simeq 20\%$ in the first case than in the second case. Uncertainties in Fe and Cr fractions in dust

TABLE 3

DUST-TO-METALS RATIOS, DUST-TO-GAS RATIOS, AND METALLICITIES IN DAMPED Lyα SYSTEMS

QSO	z_{abs}	$\frac{\tilde{k}}{\tilde{Z}}$ Zn, Cr[a]	$\frac{\tilde{k}}{\tilde{Z}}$ Zn, Cr[b]	$\frac{\tilde{k}}{\tilde{Z}}$ Zn, Fe[a]	$\frac{\tilde{k}}{\tilde{Z}}$ Zn, Fe[b]	$\tilde{k}_{\mathrm{Zn,Cr}}$[b]	$\tilde{k}_{\mathrm{Zn,Fe}}$[b]	$\log \tilde{k}$[b,c]	$\log \tilde{Z}$[b,c]
0056+014......	2.777	0.26	0.37	...	...	0.025	...	−1.60	−1.17
0100+130......	2.309	0.46	0.59	0.68	0.78	0.021	0.030	−1.60	−1.43
0112+029......	2.422	0.74	0.85	...	...	0.085	...	−1.07	−1.00
0201+363......	2.462	0.84	0.92	0.76	0.85	0.747	0.667	−0.15	−0.10
0302−223......	1.009	0.64	0.76	...	...	0.323	...	−0.49	−0.37
0454+039......	0.859	0.38	0.51	0.29	0.40	0.092	0.070	−1.09	−0.75
0458−020......	2.039	0.61	0.74	...	...	0.059	...	−1.23	−1.10
0528−250......	2.811	0.72	0.83	0.70	0.81	0.203	0.196	−0.70	−0.61
0841+129......	2.374	0.53	0.65	...	...	0.038	...	−1.42	−1.23
0935+417......	1.372	0.22	0.32	0.33	0.44	0.057	0.083	−1.13	−0.73
1104−180......	1.661	0.73	0.84	...	...	0.189	...	−0.72	−0.65
1151+068......	1.773	0.18	0.27	...	...	0.008	...	−2.09	−1.52
1223+175......	2.465	0.30	0.41	...	...	0.010	...	−2.00	−1.61
1328+307......	0.692	0.70	0.81	0.79	0.88	0.070	0.078	−1.13	−1.06
1331+170......	1.776	0.93	0.98	0.88	0.94	0.081	0.076	−1.11	−1.09
2206−199......	1.920	0.40	0.53	0.53	0.65	0.271	0.354	−0.50	−0.28
2231−001......	2.066	...	...	0.48	0.60	...	0.101	−0.99	−0.78

[a] Values derived by assuming zinc completely undepleted in Galactic interstellar gas, i.e., $f_{\mathrm{Zn,ism}} = 0$.

[b] Values derived by assuming zinc mildly depleted in Galactic interstellar gas, with $f_{\mathrm{Zn,ism}} = 0.35$.

[c] Adopted value in computing the relation between dust-to-gas ratio and metallicity.

would yield a much smaller systematic error since $f_{\mathrm{Fe,ism}} \simeq f_{\mathrm{Cr,ism}} \simeq 0.9$ for the current range of Fe and Cr dust depletions observed in Galactic interstellar clouds.

4.2. *Relative Abundances Corrected from Dust Effects*

Having derived the $(\tilde{k}/\tilde{Z})$ ratio for individual DLA systems we can now use equation (17) to estimate relative abundances corrected from dust effects. In Table 4 we list additional abundance measurements available for the DLA systems of the sample shown in Table 3. Dust-corrected relative abundances are given in Table 4 below each gas-phase determination and are shown in a synoptic view in Figure 1. Internal errors of the corrected relative abundances are quite low, as estimated from the dispersion of the five [Si/Fe] measurements, ± 0.09 dex, and of the seven [Ni/Fe] measurements, ± 0.04 dex. By applying error propagation to equation (17) one can see that the total random error of the dust-corrected ratios is typically $\simeq 0.15$ dex, but can be as low as $\simeq 0.05$ dex for the most precise measurements. In addition, systematic errors related to the uncertainty of the $f_{\mathrm{X,ism}}$ and $f_{\mathrm{Y,ism}}$ parameters should be taken into account. The use of dust-to-metals ratios derived by assuming zinc completely undepleted would systematically reduce the dust corrections; however, the net effect on the corrected ratios is in most cases less than 0.05 dex.

A first result that is clear from Figure 1 is that the spread of the dust-corrected relative abundances for any given [X/Fe] ratio is generally within the range of the expected errors, suggesting that *the sample of DLA systems investigated is chemically homogeneous over the range of metallicities from nearly solar down to* -1.5 dex.

The most important result visible in Figure 1, however, comes from the analysis of the element-to-element abundance pattern. If the intrinsic abundances of DLA systems were similar to metal-poor Galactic halo stars, the ratios shown in Figure 1 should deviate from the solar pattern, with the only exception of [Ni/Fe]. Quite surprisingly, the dust-corrected ratios are remarkably close to solar. Errors due to uncertainties of the fractions in dust $f_{\mathrm{X,ism}}$ and $f_{\mathrm{Y,ism}}$ should produce different effects for any given pair of elements X and Y, and would tend to destroy the solar-like pattern.

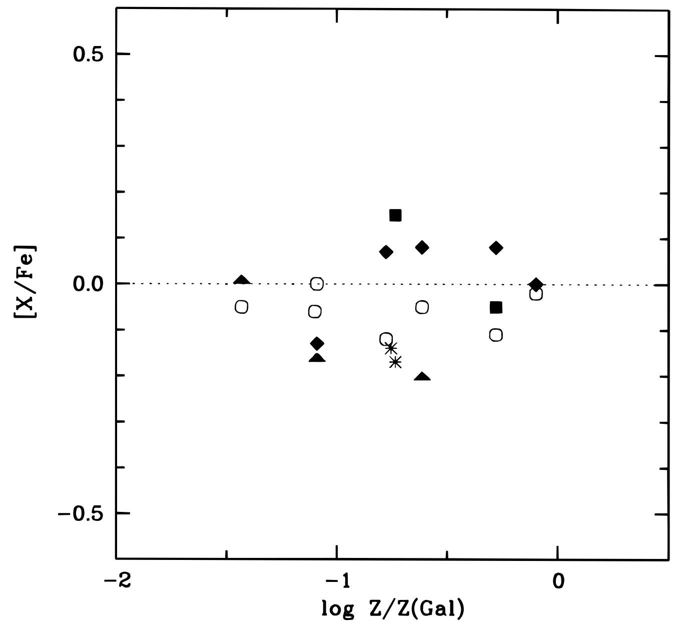

FIG. 1.—Dust-corrected relative abundances vs. metallicity for the sample of DLA absorbers shown in Table 4. *Dotted line:* solar reference abundance. *Filled diamonds, triangles, and squares:* [Si/Fe], [S/Fe], and [Ti/Fe] ratios, respectively. *Asterisks:* [Mn/Fe] ratios. *Open circles:* [Ni/Fe] ratios. Typical random errors of the ratios are of about ± 0.15 dex.

Of course, as we discuss in detail in the following paragraphs, the relative abundances are not exactly solar. It is also important to note here that departures from solar ratios in DLA systems are found when nitrogen abundances are considered (L. Lu 1997, private communication; Vladilo, Molaro, & Matteucci 1997b). However, owing to

TABLE 4

OBSERVED AND DUST-CORRECTED RELATIVE ABUNDANCES[a,b]

QSO	z_{abs}	[Si/Fe]	References	[S/Fe]	References	[Ti/Fe]	References	[Mn/Fe]	References	[Ni/Fe]	References
0100+130……	2.309	…		+0.45	1	…		…		−0.18	2, 1
		…		+0.03		…		…		−0.05	
0201+363……	2.462	+0.42	3	…		…		…		−0.20	3
		0.00		…		…		…		−0.02	
0454+039……	0.859	…		…		…		−0.25	4	…	
		…		…		…		−0.14		…	
0458−020……	2.039	…		…		…		…		(−0.67)[c]	5, 6
		…		…		…		…		−0.06	
0528−250……	2.811	+0.48	4	+0.35	4	…		…		−0.33	4
		+0.08		−0.20		…		…		−0.05	
0935+417……	1.372	…		…		+0.23	7	−0.28	7	…	
		…		…		+0.15		−0.17		…	
1331+170……	1.776	+0.18	4	+0.76	4, 8	…		…		−0.17	4
		−0.13		−0.16		…		…		0.00	
2206−199……	1.920	+0.27	9	…		−0.10	9	…		−0.34	9
		+0.08		…		−0.05		…		−0.11	
2231−001……	2.066	+0.26	4	…		…		…		−0.39	4
		+0.07		…		…		…		−0.12	

[a] For each damped absorber we give the observed gas-phase abundance in the first row and the dust-corrected abundance in the second row.

[b] Abundances are relative to the solar photospheric values by Anders & Grevesse 1989: $\log(\mathrm{Si/H})_\odot = -4.45$, $\log(\mathrm{S/H})_\odot = -4.79$, $\log(\mathrm{Ti/H})_\odot = -7.01$, $\log(\mathrm{Ni/H})_\odot = -5.75$, $\log(\mathrm{Mn/H})_\odot = -6.61$, with the exception of iron, taken from Hannaford et al. 1992: $\log(\mathrm{Fe/H})_\odot = -4.52$.

[c] [Ni/Zn] used instead of [Ni/Fe], which is not available; the resulting [Ni/Zn] corrected for dust is, however, equal to [Ni/Fe], since the intrinsic [Zn/Fe] ratio is solar.

REFERENCES.—(1) Molaro et al. 1998; (2) Wolfe et al. 1994; (3) Prochaska & Wolfe 1996; (4) Lu et al. 1996; (5) Pettini et al. 1997a; (6) Meyer & Roth 1990; (7) Meyer et al. 1995; (8) Kulkarni et al. 1995; (9) Prochaska & Wolfe 1997a.

the complex galactic chemical evolution of this element, the study of nitrogen abundances is deferred to a subsequent paper (Centurión et al. 1998). We discuss now in more detail specific (groups of) elements.

4.2.1. *Nickel*

Nickel is expected to trace iron at least down to a metallicity $Z/Z_{\odot} \simeq 0.01$, even though there is some indication for a very mild underabundance ($\simeq -0.02$ dex) at $Z/Z_{\odot} \simeq 0.1$ from the data by Ryan et al. (1996). The seven dust-corrected measurements available yield $\langle[\mathrm{Ni/Fe}]\rangle = -0.06 \pm 0.05$, consistent both with Ni tracing Fe or with a mild underabundance. Even if this result is not particularly surprising, it shows already the importance of the correction from dust effects. In fact the gas phase [Ni/Fe] measurements yield values around -0.2 dex, which have lead Lu et al. (1996) to suspect the presence of a constant offset between stellar and DLA measurements. Our results can be explained instead in terms of the expected trends of iron-peak elements.

4.2.2. *Alpha Elements*

The ratios of alpha elements to iron-peak elements is the best indicator of halo-like metallicity pattern. In the early stages of chemical evolution the products of Type II SNs, rich in alpha elements, are expected to dominate the observed abundances and to produce the overabundance of the [α/Fe] ratio that is observed in Galactic metal-poor stars. At later stages, the contribution of Type Ia SNs reduces the [α/Fe] ratio to the typical values observed in Galactic stars of solar metallicity (see, e.g., Matteucci et al. 1997). At a metallicity $Z/Z_{\odot} \simeq 0.1$ Galactic halo stars show [Si/Fe] $= +0.27$ dex (Ryan et al. 1996) and [S/Fe] $= +0.4$ dex (Francois 1988; including a correction of -0.2 dex proposed by Lambert 1988). Ti behaves similarly to an alpha element with [Ti/Fe] $= +0.22$ at $Z/Z_{\odot} \simeq 0.1$ (Ryan et al. 1996). If the chemical history of DLA systems was similar to that of the Galaxy, we would expect to find similar overabundances of the [α/Fe] ratios. This is not the case for any of the elements considered here. The five dust-corrected measurements of Si yield $\langle[\mathrm{Si/Fe}]\rangle = +0.02 \pm 0.09$ (internal error of the average). Even assuming a total random error as high as 0.15 dex, the result is still inconsistent at 2 σ from the [Si/Fe] $\simeq +0.3$ dex expected for a halo-like abundance pattern. Also, the three dust-corrected measurements of [S/Fe] do not show evidence of overabundance. As noted by Molaro et al. (1998), in all three of these cases the observed [S/Zn] ratio is solar. Since dust depletion is modest for both S and Zn, this result confirms the validity of the correction applied to the observed [S/Fe] ratios. Of the two dust-corrected measurements of [Ti/Fe], one is clearly not overabundant, and the other is consistent, within an error bar of $\pm$ 0.15 dex both with a solar-like abundance and with the mild overabundance observed in Galactic halo stars. Finally, we note also that the [Mg/Fe] upper limit derived by Molaro et al. (1998) for the $z = 2.309$ absorbers toward PHL 957 is inconsistent with a halo-like pattern.

4.2.3. *Manganese*

Gas-phase measurements of the [Mn/Fe] ratio in DLA systems systematically yield negative values (Lu et al. 1996). The [Mn/Fe] ratio is believed to be a good discriminant between Galactic halo and Galactic interstellar abundance patterns. In the first case Mn is underabundant ([Mn/Fe] $= -0.35$ dex; Ryan et al. 1996) while in the latter case Mn is overabundant ([Mn/Fe] $\simeq +0.3$; Savage & Sembach 1996) as a consequence of differential dust depletion. However, as we have shown in § 3, even a mild underabundance of the [Mn/Fe] ratio can lead to an inversion of the dust-depletion pattern, with manganese becoming more depleted than iron. This explains why the dust correction can increase the observed [Mn/Fe] ratio, as happens in the two cases shown in Table 4. The dust-corrected ratios indicate in fact a modest underabundance of manganese. This underabundance is smaller than expected for a halo-like chemical composition, and the [Mn/Fe] ratio is marginally consistent with a solar composition. We note that this conclusion does not depend on the adopted cosmic abundance for manganese. For consistency with the results of Ryan et al. (1996) we have renormalized the DLA measurements by adopting solar photospheric abundance for Mn, instead of the solar meteoric value used by Lu et al. (1996). Should we adopt the meteoritic value, we would find a [Mn/Fe] lower by 0.14 dex in the DLA systems, but also the [Mn/Fe] ratio for Galactic halo stars should be decreased, down to [Mn/Fe] $= -0.49$ dex, and the dust-corrected ratios would still be in between the solar-like and the halo-like case.

4.3. *Dust-to-Gas Ratios*

The basic assumption of the present work is that dust affects the observed abundances in DLA absorbers. We can test this assumption by comparing the dust-to-gas ratios derived from the observed abundances with dust-to-gas ratios obtained from reddening determinations. For any two elements X and Y with similar nucleosynthetic history it is possible to estimate the dust-to-gas ratio by means of the expression

$$\tilde{k} = \frac{10^{[\mathrm{Y/H}]_{\mathrm{obs}}} - 10^{[\mathrm{X/H}]_{\mathrm{obs}}}}{f_{\mathrm{X,ism}} - f_{\mathrm{Y,ism}}} , \qquad (19)$$

which can be derived by applying equation (12) to X and Y and by combining the resulting relations with the condition $[\mathrm{X/Y}]_{\mathrm{dla}} = 0$. This method is conceptually similar to that originally used by Pettini et al. (1994) for estimating the dust-to-gas ratio from Cr and Zn abundances.

On the basis of what was discussed in § 4.1 we have used the [Zn/H] and [Cr/H] ratios and the [Zn/H] and [Fe/H] ratios to derive $\tilde{k}$ from equation (19) for our sample of 17 DLA systems. The results are shown in Table 3. In the eight cases with available independent determinations we do not find a systematic difference between the results based on the [Zn/H] and [Cr/H] ratios and the results based on the [Zn/H] and [Fe/H] ratios. The average percent difference between the two cases is $-0.07\% \pm 0.23\%$. By applying random error propagation to equation (19), keeping fixed the Galactic fractions in dust $f_{\mathrm{X,ism}}$ and $f_{\mathrm{Y,ism}}$, one finds errors about twice as large as those in the case of the equation (18). This is not surprising since two independent measurements are required to determine $\tilde{k}$ from equation (19) and only one to determine $(\tilde{k}/\tilde{Z})$ from equation (18). Systematically lower dust-to-gas ratios by about -0.2 dex would be derived by assuming zinc completely undepleted.

The resulting dust-to-gas ratios span a wide interval, from about 1% to 75% of the Galactic value, without a concentration around a particular value. The logarithmic average yields $\langle\log \tilde{k}\rangle = -1.12 \pm 0.52$, which implies that the most probable interval lies between 2% and 25% of the Galactic value. This result is in good agreement with the most probable range found by Pei et al. (1991) in their study of QSOs with and without foreground DLA absorbers, which is between 5% and 20%. The combined sample used by these authors includes 22 QSOs with foreground DLA absorber, seven of these systems being in common with the present sample. The quantitative agreement between the two independent extinction estimates supports the validity of the assumption that dust is responsible for the apparent deviations of the [Zn/Cr] and [Zn/Fe] ratios from solar composition. By assuming zinc completely undepleted, our results indicate a most probable range from 1% up to 16% of the Galactic value. Even if this interval still overlaps with the best range of Pei et al. (1991), the mild zinc depletion adopted here yields a better agreement.

4.4. *Metallicities Corrected by Dust Effects*

Once we have determined the dust-to-gas ratio, the metallicity corrected by dust can be determined from the relation

$$\tilde{Z} = 10^{[\mathrm{Y/H}]_{\mathrm{obs}}} + \tilde{k} \cdot f_{\mathrm{Y,ism}} , \qquad (20)$$

which results by applying equation (12) to the element used as the reference for the metallicity level. The dust-corrected metallicities of our sample are shown in Table 3. Since Fe, Cr, and Zn trace each other, equivalent results are obtained by using any of the three elements in equation (20). In practice we have used the [Zn/H] ratios for which the correction term is smaller. On the average the corrected metallicities differ by only $\simeq +0.12$ dex from the observed [Zn/H] ratios, which would represent the real metallicity if zinc were completely undepleted. Owing to the small amount of the correction, the use of the dust-corrected metallicities in Table 3 does not affect significantly the values of metallicities derived for DLA absorbers. It is worth noting, however, that even a small amount of zinc depletion in the Galaxy still implies a small but measurable amount of depletion in DLA absorbers. This can be understood from our previous discussion in § 3.

5. CORRELATION BETWEEN DUST AND METAL CONTENT IN DLA ABSORBERS

An important by-product of the present investigation is the determination of dust-to-gas ratios and metallicities in individual DLA systems. We start by analyzing the dust-to-metals ratio $\tilde{k}/\tilde{Z}$, which is less affected by error propagation than the dust-to-gas ratio $\tilde{k}$. The logarithmic average yields $\langle \log (\tilde{k}/\tilde{Z}) \rangle = -0.21 \pm 0.16$, which implies a typical value around 62% and the most probable range between 42% and 89% of the Galactic dust-to-metals content. An attempt to find correlations of $(\tilde{k}/\tilde{Z})$ with metallicity or with redshift gives negative results. We conclude that in the present sample of 17 DLA systems *the dust-to-metals ratio is approximately constant and lower than in the Galaxy*. The average dust-to-metals ratio that we find is comparable with the value $\tilde{k}/\tilde{Z} \simeq 50\%$ obtained by Pettini et al. (1997a) by assuming zinc completely undepleted.

The constancy of the $\tilde{k}/\tilde{Z}$ ratio implies that the dust-to-gas ratio and metallicities are correlated in DLA systems. This can be seen in Figure 2, where we plot $\tilde{k}$ versus metallicity $\tilde{Z}$ for our sample of 17 DLA systems. Filled diamonds represent the eight systems with most accurate measurements, based on two independent $\tilde{k}$ determinations in each case. The other systems, with one single $\tilde{k}$ determination, are indicated with open diamonds. The linear regression

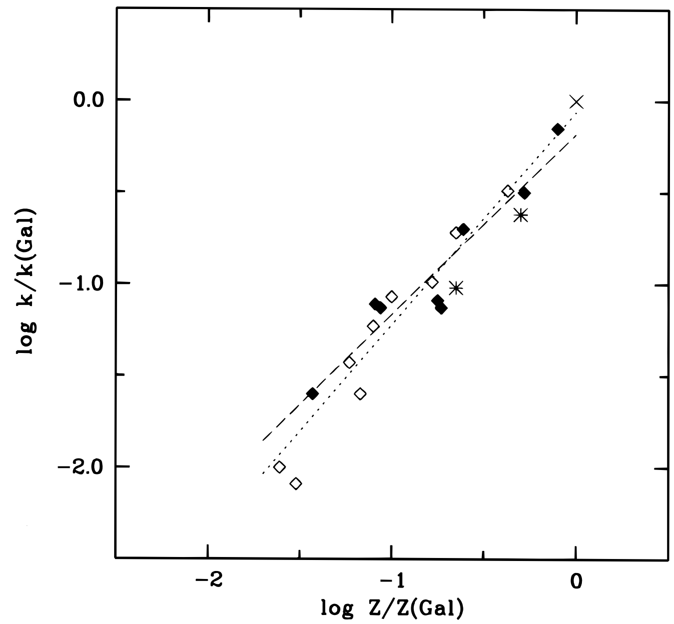

FIG. 2.—Dust-to-gas ratios vs. metallicities normalized in Galactic units for the sample of DLA absorbers shown in Table 3 (*diamonds*), the Magellanic Clouds (*asterisks*) and the Galaxy (*cross*). *Dashed line:* linear regression through the full sample of 17 DLA absorbers. *Dotted line:* linear regression through the eight filled diamonds, representing the DLA absorbers with most precise measurements of the dust-to-gas ratio.

through the 17 DLA data points confirms the existence of a correlation, with slope 1.16 and correlation coefficient $r = 0.95$ (Fig. 2, *dotted line*). By using only the eight systems with most accurate measurements, we find a correlation with slope 0.98 and $r = 0.95$ (*dashed line*). The slope is therefore 1 within the errors, as expected for a constant $\tilde{k}/\tilde{Z}$ ratio.

The fact that the dust content follows the metal content gives fresh support to the idea that DLA systems are originated in galaxies: dust would be produced in the diffuse medium following the injection of metals from the stellar component. The constancy of the $\tilde{k}/\tilde{Z}$ ratio has important implications in the framework of the model of cosmic chemical evolution developed by Pei & Fall (1995). In fact, in that model it is assumed that the dust-to-metals ratio is constant in DLA absorbers. Our study shows that this basic assumption of the model is essentially correct. The range of redshifts investigated here is probably insufficient to detect variations of the dust-to-metals content that may be expected in the course of the cosmic evolution.

It is worth noting that the constancy of the dust-to-metals ratio could have been predicted from the remarkably small scatter of the abundances measured in different DLA systems. In fact, each one of the ratios [Si/Fe], [Cr/Fe], and [Ni/Fe] from the compilation by Lu et al. (1996) has dispersion <0.2 dex, the most remarkable case being [Si/Fe] with $\sigma = 0.11$ dex in 12 DLA systems. The compilation of [Zn/Cr] data by Pettini et al. (1997a) gives $\sigma = 0.18$ dex for 14 systems. Within the typical measurement error the observed abundances in the gas phase are essentially constant. This remarkable result cannot be explained only by assuming that DLA systems have equal intrinsic abundances and equal dust-grains properties. Even in this case the fractions in dust, and therefore also the observed abundances, are expected to depend on the dust-to-metals ratio, as can be seen from equation (9). Since metallicity and dust content can significantly vary among DLA systems, the only way to explain the constancy of the observed abundances is that k/Z is roughly constant in different absorbers, as we indeed find.

6. DISCUSSION

6.1. *The Elemental Abundance Pattern of DLA Absorbers*

Taken at face values, the positive [Si/Fe] and [S/Fe] ratios and the negative [Mn/Fe] ratios observed in DLA systems suggest an abundance pattern similar to that found in the Galactic halo (Lu et al. 1996). However, this interpretation requires that dust is completely absent from the absorbers and is unable to explain why the iron-peak ratios [Zn/Fe] and [Ni/Fe] are different from zero. This inconsistency, together with the agreement between direct and indirect estimates of the dust-to-gas ratios discussed in § 4.3, suggests that any interpretation of the observed abundances must take into account the presence of dust.

In principle, the dust in DLA absorbers could differ from the dust in the Galaxy, and an overall halo-like abundance pattern could be hidden by the peculiar properties of the dust. Equation (9) shows that one can obtain a halo-like pattern from the observed quantities by playing with the chemical composition of the dust. Nevertheless, since the condition $f_X = (k/Z)(X/Y)^{-1}{}_{\rm dla}(\nu_X/c_e) \leq 1$ must be satisfied, one will be obliged to play with other parameters also, such as c_e, in order to obtain meaningful results (it is possible to see that this is in fact the case for Mn). Therefore, only by invoking a set of ad hoc requirements on the chemical composition and on the extinction properties of the dust grains is it possible to argue that the intrinsic abundances follow a halo-like pattern. By contrast, the results shown in Figure 1 have been derived without any fine tuning of the input parameters, i.e., the Galactic fractions in dust, which are known from Galactic interstellar studies.

Our results indicate that all the DLA systems for which good quality abundance determinations are available show an elemental abundance pattern approximately solar, within at most ± 0.2 dex (see however the comments on nitrogen in § 4.2). The absorbers included in this sample span a wide range of metallicities $[-1.4 \leq \log (Z/Z_\odot) \leq -0.1]$ and redshifts ($1 \leq z_{\rm abs} \leq 2.5$). Even if Table 4 includes only five [Si/Fe] determinations, the remarkably similar [Si/Fe] values reported by Lu et al. (1996) in other systems without Zn measurement, together with the approximately constant dust-to-metals ratio (§ 5), suggest that the lack of [α/Fe] enhancement is common to all the 12 absorbers with observed [Si/Fe] ratio. Similarly, the mild [Mn/Fe] underabundance ($\simeq -0.15$ dex) is probably present in all 10 systems for which measurements are available and not only in the two systems shown in Table 4.

Future measurements for a statistically significant number of systems are required to see how general the solar-like ratios are. As mentioned in § 4.2, nitrogen observations do show deviations from solar relative abundances. In addition, DLA systems with intrinsically enhanced [α/Fe] ratios might be hidden by selection effects. For instance, damped absorbers with high dust content could systematically obscure the background QSO (Pei & Fall 1995), and this fact could affect the probability of detecting cases with enhanced [α/Fe] ratios.

6.2. *DLA Absorbers as Dwarf Galaxies*

Similarities between properties observed in DLA absorbers and in gas-rich dwarf galaxies, including the presence of large amounts of gas, the low level of metallicity, and the complexity of the line profiles, had already been pointed out by York et al. (1986). Pettini et al. (1990) noted, in addition, a similarity in the star formation rate and suggested that DLA absorbers might arise predominantly in dwarf galaxies whose properties have not changed significantly from $z = 2.5$ to the present epoch. According to Tyson (1988) the frequency of detection of DLA absorbers can be naturally explained by dwarf galaxies with no need to invoke extremely large H I diameters for the progenitors of present-day spiral galaxies. Recent studies of the luminosity function of galaxies based on deep field observations (Campos 1997; Zucca et al. 1997) indicate a steepening of the faint end of the luminosity function consistent with that suggested by Tyson (1988).

In addition to the above arguments, we note here that (1) the general lack of detection of molecules in DLA absorbers (see Levshakov et al. 1992 and references therein) is consistent with the low molecular content apparently typical of dwarf galaxies (Israel, Tacconi, & Baas 1995), and (2) the lack of the extinction bump at $\simeq 2175$ Å in DLA absorbers (Pei et al. 1991) is characteristic of the extinction curves of the Magellanic Clouds. Finally, we note that the high fraction of metal-poor stars predicted for the descendant of DLA absorbers by Lanzetta, Wolfe, & Turnshek (1995) is consistent with most DLA absorbers being metal-poor dwarf galaxies. The high fraction of metal-poor stars predicted by the model of Lanzetta et al. (1995) is not seen in the Milky Way, and this inconsistency is known as the "cosmic G dwarf problem." To solve this problem it has been suggested that a large fraction of the gas in DLA absorbers is consumed in forming stars in galactic bulges and spheroids rather than in galactic disks. However, this explanation conflicts with the low mass fraction of the halo and of the bulge (Bahcall & Soneira 1980; Rich 1992) relative to the total mass of the Milky Way, and is not supported by the range of abundances recently found in the Galactic bulge (Rich 1992). If DLA absorbers are predominantly dwarf galaxies, then there is no "cosmic G dwarf problem," because the stars of the descendant of DLA absorbers do have low metallicities. We will now discuss the observational evidence concerning the nature of DLA galaxies related to the results of the present work.

6.2.1. *Elemental Abundance Pattern*

The present results suggest that DLA galaxies commonly show a nearly solar [α/Fe] ratio at a low level of metallicity. This property does not show evolution over a wide range of metallicities $[-1.4 \leq \log (Z/Z_\odot) \leq -0.1]$ and redshifts ($1 \leq z_{\rm abs} \leq 2.5$). The lack of evolution up to high levels of metallicity might suggest that the population of absorbers is essentially unevolved to the present time. This possibility, however, can only be investigated by studying a sample of low-redshift DLA absorbers.

The nearly solar [α/Fe] ratios do not support an origin in spiral galaxies like the Milky Way, where the enhancement of the [α/Fe] ratio is found not only in halo stars (Ryan et al. 1996), but also in metal-poor stars of the disk (Edvardsson et al. 1993). It is unlikely therefore that DLA absorbers arise in massive protogalactic disks.

Galaxies with low metallicities and without [α/Fe] enhancement are known to exist, as demonstrated, for instance, by abundance studies of the Magellanic Clouds (Wheeler, Sneden, & Truran 1989, p. 315). Models of chemical evolution developed to explain the elemental abundances observed in blue compact and dwarf irregular galaxies show that it is possible to obtain low [α/Fe] ratios at low metallicities when many episodes of star formation and differential galactic winds are assumed (Marconi, Matteucci, & Tosi 1994). Similar models have been applied to explain the abundances observed in some DLA systems (Matteucci et al. 1997).

6.2.2. *Metallicity*

From a recent analysis, Pettini et al. (1997b) have concluded that the metallicity distribution of DLA absorbers is different from that found in the stellar populations of the Milky Way. As we mentioned in § 4.4, the dust-corrected metallicities derived here are essentially equal to the direct [Zn/H] measurements and therefore the conclusions of Pettini et al. (1997b) are unchanged.

6.2.3. *Dust Content*

The dust-to-metals ratios of DLA absorbers are systematically lower than in the Milky Way (§ 4.1), even at metallicities comparable to that attained by the Galactic disk. Similarly low dust-to-metals ratios are instead found in the Magellanic Clouds. This can be seen by combining the typical metallicities of the LMC and SMC, [Fe/H] = −0.30 and −0.65, respectively (Wheeler et al. 1989; p. 315), with their typical gas-to-dust ratios, $N_{\rm H\,I}/E(B-V) = 2 \times 10^{22}$ and 5×10^{22} cm^{-2} mag^{-1}, respectively (Lequex 1989). These last ratios yield $\tilde{k} = 0.24$ and 0.096, respectively, once normalized to the standard Galactic value $N_{\rm H\,I}/E(B-V) = 4.8 \times 10^{21}$ cm^{-2} mag^{-1}. The Magellanic ratios follow remarkably well the behavior typical of DLA systems, as we show in Figure 2, and this is consistent again with an origin of DLA absorbers in dwarf galaxies.

This result is at variance with the claim by Roth & Blades (1997) that the Magellanic dust-to-metals ratios are closer to Milky Way than to DLA values. The claim is based on three measurements of the Magellanic [Cr/Zn] ratio, two of which are in fact consistent, within the error bars, with DLA values. The third measurement, toward Sk −68°73, gives a [Cr/Zn] ratio lower than in DLA systems, but in this case the Magellanic Zn II and Cr II column densities are exceptionally high, not only compared to the other two Magellanic lines of sight, but even compared to the 20 Galactic lines of sight observed with the *Hubble Space Telescope* (*HST*) GHRS (Roth & Blades 1995). The LMC path toward Sk −68°73 is clearly atypical and might hide an exceptional amount of dust. The few available Magellanic [Cr/Zn] measurements, therefore, do not contradict our conclusion that Magellanic dust-to-metals ratios are comparable to DLA ratios.

6.2.4. *Imaging of Foreground Galaxies*

A direct answer on the morphology of DLA galaxies can be obtained, in principle, from imaging observations of the close environment of QSOs showing DLA absorption. A study of this kind has been performed by Le Brun et al. (1997) for eight absorbers at $z \leq 1$ in seven fields observed with the *HST* WFPC2. The candidate absorbing galaxies display a variety of morphological types, including three compact galaxies, two low surface brightness (LSB) galaxies, and three spiral galaxies. Our sample of Table 3 includes four of the absorbers studied by Le Brun et al. (1997): three are compact galaxies and one is an LSB galaxy. The sample of dust-corrected elemental abundances (Table 4) includes two of these absorbers, and both are compact galaxies. Therefore, also the available imaging data are consistent with an origin in dwarf galaxies of the absorbers of the present sample.

6.2.5. *Kinematics*

The kinematics also gives important clues for understanding the nature of DLA galaxies. The velocity spread of the absorption components seen through a randomly oriented galaxy along the line of sight is in fact expected to be higher for a quickly rotating spiral galaxy than for a slowly rotating dwarf galaxy. Nevertheless, there is evidence of dwarf galaxies with velocity spreads higher than expected from a slow rotation. For instance, velocity spreads of ≈100 km s^{-1} are found both from stellar (Westerlund 1990) and interstellar (Blades et al. 1988; Songaila et al. 1986) studies of the Magellanic Clouds. The compact galaxies identified by Le Brun et al. (1997) as the $z = 0.859$ absorber toward QSO 0454+039 and the $z = 1.766$ absorber toward QSO 1331+170 have velocity spreads of 150 km s^{-1} and 100 km s^{-1}, respectively (see Lu et al. 1996). Such relatively high velocity widths could be due to the presence of flows or systematic motions superposed to the low rotation pattern of dwarf galaxies (see, e.g., Sahu & Blades 1997). Six out of the nine absorbers in our sample of Table 4 have velocity spreads of at most 100–150 km s^{-1} and are therefore consistent with an origin in dwarf galaxies. The remaining three absorbers ($z = 2.462$ in QSO 0201+363, $z = 2.811$ in QSO 0528−250, and $z = 1.920$ in QSO 2206−199) show instead velocities of 200 km s^{-1} or even higher (Lu et al. 1996; Prochaska & Wolfe 1996, 1997a). Such a high velocity width is quite unlikely for a single dwarf galaxy, but is not conclusive evidence for a quickly rotating disk, since multiple intervening galaxies at similar redshift can also produce a broad absorption profile. In fact, Lu, Sargent, & Barlow (1997) present circumstantial evidence that the large velocity width of the $z = 2.811$ system toward QSO 0528−250 can be due to the presence of more than one galaxy or subgalactic fragment along the line of sight. In our sample we do not see systematic differences in the elemental abundance patterns between the cases with moderate and large velocity spread. It is possible that the few cases with high velocity spread are due to the superposition of low-mass intervening galaxies. From a statistical analysis of a sample of 17 DLA absorbers, Prochaska & Wolfe (1997b) claim that models of slowly rotating dwarf galaxies ($V_{\rm rot} = 50$ km s^{-1}) are excluded at 97% confidence level, while models with rapidly rotating disks ($V_{\rm rot} \simeq 250$ km s^{-1}) are consistent with the data at high confidence level. These authors do not exclude, however, that some of the cases with higher velocity spreads might arise from multiple intervening galaxies of low mass. An inspection of the velocity profiles of their sample reveals that the radial velocity spread is ≤100 km s^{-1} in 10 systems, between ≃100 and ≃150 km s^{-1} in two systems, and ≥200 km s^{-1} in only five systems.

7. CONCLUSIONS

In the present work the general equations that link elemental abundances observed in the gas phase with real abundances of DLA absorbers (gas plus dust) have been presented. By assuming that dust is of Galactic type, simplified equations have been obtained in which the observed abundances are expressed as a function of the dust-to-metals ratio, metallicity, element-to-element abundance pattern, and of Galactic interstellar dust parameters, namely the fractions in dust of the elements of interest.

The behavior of the dust depletions in DLA absorbers has been investigated for different sets of element-to-element abundances and of dust-to-metals ratios. The dust-depletion pattern does not scale linearly in logarithm with the Galactic pattern of depletion, contrary to what was assumed in some previous works. Instead, the differential depletion between pairs of elements tends to vanish as the dust-to-metals ratio decreases. In addition, inversions in the differential depletion pattern may appear if the DLA abundance pattern is not solar.

A method has been presented for determining dust-to-metals ratios and dust-to-gas ratios in individual DLA absorbers from the abundances of elements with similar nucleosynthetic history. This method has been applied to a sample of 17 DLA absorbers with available Zn, Cr, and Fe measurements, assuming that these iron-peak elements trace each other down to the metallicities of DLA systems, as they do in metal-poor stars of the Galaxy. The resulting dust-to-gas ratios are mostly distributed between 2% and 25% of the Galactic value, in good agreement with the most probable range of dust-to-gas ratios obtained by Pei et al. (1991) from their reddening study of QSOs with foreground DLA absorption.

Dust-to-gas ratio and metallicity are found to be correlated in DLA galaxies, with a typical dust-to-metals ratio $\simeq 60\%$ of the Galactic value. This suggests that the metals injected from the stellar component are systematically removed from gas to dust with an efficiency approximately constant but lower than in the Milky Way. The correlation between dust-to-gas ratio and metallicity is relevant to models of cosmic chemical evolution of the type investigated by Pei & Fall (1995). The approximate constancy of the dust-to-metals ratio explains why the element-to-element abundances observed in DLA systems are remarkably constant in spite of the variable amount of dust in the absorbers.

The resulting dust-to-metals ratios have been used to correct from dust effects the element-to-element abundances measured in a subsample of nine DLA absorbers. The dust-corrected [α/Fe] ratios do not show evidence of the enhancement characteristic of metal-poor Galactic stars, but have instead solar values within ± 0.2 dex. The [Mn/Fe] ratio shows a mild underabundance, less marked than that found in metal-poor Galactic stars. The [Ni/Fe] ratio is essentially solar, with weak evidence for a modest underabundance. These results rely on the assumption that dust in DLA absorbers has the same chemical composition as Galactic interstellar dust. The available measurements of the [S/Zn] ratio, a proxy of the [α/Fe] ratio virtually unaffected by dust, support the validity of the dust correction applied here (Molaro et al. 1997).

The abundance pattern of DLA absorbers does not show evidence of evolution in the range of redshifts $1 \leq z_{\rm abs} \leq 2.5$ and of metallicities $-1.4 \leq \log\,(Z/Z_{\odot}) \leq -0.1$ investigated. Studies of low-redshift absorbers are required to establish whether evolution is present or not closer to the present time (Vladilo et al. 1997a).

The dust-corrected pattern of abundances indicates that the chemical history of a large fraction of DLA galaxies is different from that experienced by the Milky Way halo or disk. The results of the present work are consistent with DLA absorbers being predominantly dwarf rather than spiral galaxies. Evidence in this sense comes from a wide spectrum of observational properties that include, in addition to the abundance pattern, the dust-to-metals ratio and the morphological type of the intervening galaxies at $z \leq 1$. The kinematics of the absorbers is in most cases consistent with an origin in dwarf galaxies, even though an origin in spiral galaxies gives a more natural explanation of the highest observed velocity spreads.

It is necessary to study a larger sample of DLA systems by means of spectroscopic and imaging techniques in order to determine with statistical accuracy the fraction of spiral galaxies in this class of QSO absorbers. At the same time, it is important to understand whether the low fraction of identified spiral galaxies is real or, instead, is due to some selection effect or to a peculiar dust composition that would alter the conclusions of the present work. If the fraction of spiral galaxies is confirmed to be low, a mass of DLA galaxies lower than expected for protospiral objects would help to reconcile cold plus hot dark matter (CHDM) cosmology with observed properties of high-redshift absorbers (see Klypin et al. 1995 and references therein).

The interpretation of this work has benefited from important discussions with P. Molaro. I wish to thank P. Bonifacio and M. Centurión for their critical reading of the manuscript. Discussions with S. Bardelli, S. Borgani, F. Matteucci, and S. Ortolani have helped to clarify specific topics of this work. I also thank the referee, L. Lu, for his constructive remarks and for anticipating some of his results in advance of publication.

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