C II* ABSORPTION IN DAMPED Lyα SYSTEMS. I. STAR FORMATION RATES IN A TWO-PHASE MEDIUM

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ABSTRACT

We describe a technique that for the first time measures star formation rates (SFRs) in damped Lyα systems (DLAs) directly. We assume that massive stars form in DLAs and that the far-ultraviolet (FUV) radiation they emit heats the gas by the grain photoelectric mechanism. We infer the heating rate by equating it to the cooling rate measured by the strength of C II* λ1335.7 absorption. Since the heating rate is proportional to the product of the dust-to-gas ratio, the grain photoelectric heating efficiency, and the SFR per unit area, ψ*, we can deduce ψ* for DLAs in which the cooling rate and dust-to-gas ratio have been measured. We consider models in which the dust consists of carbonaceous grains and silicate grains. We present two-phase models in which the cold neutral medium (CNM) and warm neutral medium (WNM) are in pressure equilibrium. In the CNM model the line of sight passes through CNM and WNM gas, while in the WNM model the line of sight passes only through WNM gas. Since the grain photoelectric heating efficiency is at least an order of magnitude higher in the CNM than in the WNM, most of the C II* absorption arises in the CNM in the CNM model. We use the measured C II* absorption lines to derive ψ* for a sample of ∼30 DLAs in which has been inferred from element depletion patterns. We show that the inferred ψ* corresponds to an average over the star-forming volume of the DLA rather than to local star formation along the line of sight. We obtain the average ψ* and show that ⟨ψ*⟩ = 10^{-2.2} M_☉ yr^{-1} kpc^{-2} for the CNM solution and ⟨ψ*⟩ = 10^{-1.3} M_☉ yr^{-1} kpc^{-2} for the WNM solution. Interestingly, the SFR per unit area in the CNM solution is similar to that measured in the Milky Way interstellar medium.

Subject headings: galaxies: evolution — quasars: absorption lines

1. INTRODUCTION

Star formation is a key ingredient in the formation and evolution of galaxies. The idea that the Hubble sequence is actually a sequence in present-day star formation rates (SFRs) and past star formation histories (Roberts 1963) is supported by results of population synthesis models (Tinsley 1980) and by the use of precise diagnostics of SFRs such as emission-line fluxes (Kennicutt 1983) and UV continuum luminosities. According to this interpretation, late-type Sc galaxies are characterized by low SFRs that are independent of time, while in early-type Sa galaxies an initially high SFR decreases steeply with time (Kennicutt 1998). Star formation may also influence galaxy evolution through feedback. That is, shocks generated by supernova explosions heat gas in protogalaxies, thereby delaying cooling and collapse to rotating disks. This process has been invoked in hierarchical cosmologies in order to prevent the collapse of too many baryons into low-mass dark matter halos and to explain the angular momentum distribution of current galaxy disks (Efstathiou 2000).

A direct measurement of star formation in high-redshift galaxies would provide an independent test of these ideas. Madau et al. (1996) took a crucial first step in this direction when they reconstructed star formation histories by measuring the comoving luminosity density of star-forming galaxies as a function of redshift. While the original “Madau diagrams” exhibited a peak in star formation at z ≈ 1–2, more recent analyses, which are based on larger samples of galaxies and correct for extinction of emitted starlight by dust, show no evidence for such a peak. Rather, the SFR per unit comoving volume, ρ_*, increases by a factor of ~10 in the redshift interval z = [0, 1] and either remains constant out to the highest redshifts confirmed so far (z ≈ 6; Steidel et al. 1999) or keeps increasing to even higher redshifts (Lanzetta et al. 2002). However, the galaxies from which these results are derived are unlikely to be the progenitors of the bulk of the current galaxy population. Whereas the SFR per unit area for the Milky Way is given by ψ* ~ 4 × 10^{-3} M_☉ yr^{-1} kpc^{-2} (Kennicutt 1998), the comoving SFR at z ~ 3 is inferred from the Lyman break galaxies, a highly luminous population of star-forming objects in which ψ* ≥ 1 M_☉ yr^{-1} kpc^{-2} (Pettini et al. 2001). The disk population of the Galaxy was unlikely to be this

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bright in the past, as stellar population studies predict that at \( z \sim 3 \), \( \psi_* \sim 2 \times 10^{-2} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \) for Sb galaxies such as the Milky Way. In fact, only elliptical galaxies are predicted to have \( \psi_* \sim 1 M_\odot \text{yr}^{-1} \text{kpc}^{-2} \) at \( z \sim 3 \) (see Genzel et al. 2001). This is consistent with other independent lines of evidence such as strong clustering (Adelberger et al. 1998), which suggests that the Lyman break galaxies evolve into massive elliptical galaxies in rich clusters. As a result, the published Madau diagrams need not constrain the star formation history of normal galaxies or their progenitors.

This is the first of two papers in which we present a new technique for measuring SFRs in damped Ly\( \alpha \) systems (DLAs). The idea is to infer the SFR from the rate at which neutral gas in DLAs is heated. We determine the heating rate by equating it to the cooling rate; i.e., we assume steady state conditions (see § 4). We estimate the cooling rate from [C ii] 158 \( \mu \text{m} \) emission, the dominant coolant for the Milky Way interstellar medium (ISM; Wright et al. 1991). Specifically, we measure the cooling rate per H atom from the strength of C \( \text{ii} \lambda1335.7 \) absorption. As we shall show, it is plausible to assume that the heating rate is proportional to the mean intensity of far-ultraviolet (FUV) radiation, which is proportional to \( \psi_* \) for a plane-parallel layer. The goal of this paper is to determine the mean SFR per unit physical area, \( \langle \psi_* (z) \rangle \), for a given redshift bin. In the second paper (Wolfe, Gawiser, & Prochaska 2003, hereafter Paper II) we combine \( \langle \psi_* (z) \rangle \) with the incidence of DLAs per unit redshift to obtain \( \rho_* (z) \) for our DLA sample. The advantage of our method is this: because DLAs are not drawn from a flux-limited sample of galaxies, we are able to derive \( \psi_* \) values far below those determined from radiation emitted by objects exhibiting rapid star formation such as Lyman break galaxies. Rather, we will show that our technique is sensitive to \( \psi_* \) as low as \( 1 \times 10^{-4} M_\odot \text{yr}^{-1} \text{kpc}^{-2} \), i.e., to SFRs per unit area below the flux thresholds of detectors on 10 m class telescopes.

A further advantage of our technique is that it probes the physical state of neutral gas at high redshifts. Specifically, from our determination of the heating rate we compute the thermal equilibrium of the neutral gas. By analogy to models for the ISM (here and throughout the paper ISM refers to the interstellar medium of the Milky Way), our calculations predict a two-phase medium comprising a cold (\( T \sim 80 \text{ K} \)) neutral medium (CNM) and a warm (\( T \sim 8000 \text{ K} \)) neutral medium (WNM) in pressure equilibrium with each other. We consider two models: one in which the line of sight to the QSO encounters gas in both CNM and WNM phases, and another in which it encounters only the WNM phase. The WNM model is considered because of recent arguments that DLAs consist only of WNM gas (Norman & Spaans 1997; Liszt 2002; Kanekar & Chengkapur 2001). We find that the technique is insensitive to the masses and sizes of individual DLAs. This has the advantage that the results are not critically dependent on model assumptions such as the mass or length scale of the dark matter mass distribution (e.g., Prochaska & Wolfe 1997; Haehnelt, Steinmetz, & Rauch 1998).

The paper is organized as follows. In § 2 we describe the basic strategy for inferring the SFR per unit area from measurements of C\( \text{ii} \lambda 1335.7 \) absorption lines. We present data for 33 DLAs obtained mainly with HIRES (Vogt et al. 1994) on the Keck I 10 m telescope in § 3. In § 4 we present two-phase models for the neutral gas in DLAs. We explain how radiative excitation causes the [C ii] 158 \( \mu \text{m} \) emission rate to exceed the 158 \( \mu \text{m} \) cooling rate. In § 5 solutions to the transfer equation for FUV radiation are given. We use these solutions to predict heating rates as functions of \( \psi_* \) and dust-to-gas ratio. For each DLA we measure \( \psi_* \) by combining measurements of the heating rate and dust-to-gas ratio with the solutions. We then determine \( \langle \psi_* \rangle \) for two redshift bins drawn from the full sample of 33 DLAs. The significance of these measurements is that they refer to objects representative of the protogalactic mass distribution, i.e., objects likely to evolve into normal galaxies. In § 6 we test the assumptions of our dust models for self-consistency. A summary is presented in § 7.

2. THE IDEA

Our technique is based on the idea that massive stars form out of gas in DLAs. Evidence for this stems from the physical resemblance between DLAs and the neutral gas of the ISM, the presence of heavy elements in DLAs, and the fact that DLAs in the redshift interval \( z = [2, 3] \) contain sufficient baryons in the form of neutral gas to account for all the visible stars in current spiral galaxies (Storrie-Lombardi & Wolfe 2000). Although stars likely form out of molecular rather than atomic gas and molecules are rarely detected in DLAs (Lu, Sargent, & Barlow 1997; Petitjean, Srianand, & Ledoux 2000), the presence of heavy elements argues for the formation of massive stars in DLAs. Such stars emit FUV radiation \( (h\nu = 6-13.6 \text{ eV}) \) that illuminates dust grains known to be present in the gas (Pei & Fall 1995; Prochaska & Wolfe 2002, hereafter PW02). By analogy with the Milky Way ISM, a small fraction of the incident photon energy is transferred to photoejected electrons that heat the gas via Coulomb interactions with ambient electrons (e.g., Bakes & Tielens 1994; Wolfe et al. 1995, hereafter W95). In this case the heating rate per H atom at displacement vector \( r \) is given by

\[
\Gamma_d(r) = 10^{-24} \kappa(r) c G_0(r) \text{ ergs s}^{-1} \text{ H}^{-1}.
\]

In the last equation \( \kappa(r) \equiv k_{\text{D}L} / k_{\text{MW}} \), where \( k_{\text{D}L} \) is the dust-to-gas ratio in the DLA at \( r \) and \( k_{\text{MW}} \) is the dust-to-gas ratio assumed for the present-epoch ISM of the Galaxy (Bakes & Tielens 1994; see discussion in § 4.1). The incident FUV radiation field \( G_0 \) equals \( 4 \pi J \), where \( J \) is the mean intensity integrated between 6 and 13.6 eV, and is in units of Habing’s (1968) estimate of the local interstellar value (\( = 1.6 \times 10^{-3} \text{ ergs cm}^{-2} \text{ s}^{-1} \)). The quantity \( \epsilon \) is the fraction of FUV radiation absorbed by grains and converted to gas heating (i.e., the heating efficiency); \( \epsilon \) is also a function of \( G_0(T/2)/n_e \) (Bakes & Tielens 1994). For a plane-parallel layer, \( J \) is proportional to the source luminosity density projected perpendicular to the plane, i.e., the source luminosity per unit area, which in the case of FUV radiation is proportional to \( \psi_* \). As a result, we can deduce \( \psi_* \) provided that we know \( \kappa \), \( \Gamma_d \), and \( \epsilon \). Because \( \epsilon \) is well determined for a wide range of physical conditions (Bakes & Tielens 1994; Weingartner & Draine 2001b), this reduces to measuring the heating rate and \( \kappa \). Both of these are obtainable from HIRES spectroscopy since the heating rate can be inferred from C\( \text{ii} \lambda 1335.7 \) absorption and \( \kappa \) is determined from the abundance patterns and metallicity of the gas (see § 4.1). Note that to derive equation (1), we assume that \( \epsilon \) in high-\( z \) DLAs is the same as in the ISM. In other words, we assume that quantities determining \( \epsilon \), such as the photoelectric cross...
section, photoelectric ionization yield, kinetic energy partition function, and grain size distribution (Bakes & Tielens 1994), are the same in DLAs and the ISM.

We determine the heating rate by equating it to the cooling rate; i.e., we assume steady state conditions. This is reasonable since the cooling times are \(\approx 10^{3}-10^{6}\) yr, which are short compared to the dynamical timescales for most model protogalaxies (see § 4.3). As a result, we let

\[
\Gamma = n\Lambda ,
\]

(2)

where the total heating rate \(\Gamma\) includes other sources of heat in addition to \(\Gamma_2\) and \(n\) and \(\Lambda\) are the gas density and cooling function. In the ISM, cooling is dominated by \([C\, ii]\) emission, i.e., \(\Delta_{C\, ii}\), with a luminosity \(L_{(C\, ii)} = 5 \times 10^7 L_\odot\) (Wright et al. 1991). The \(158\, \mu m\) line results from transitions between the \(2P_{3/2}\) and \(2P_{1/2}\) fine-structure states in the ground \(2S2P\) term of \(C^+\). Most of the emission from the Galaxy and other nearby spirals arises in the diffuse CNM gas rather than from star-forming regions in spiral arms, or photodissociation regions on the surfaces of molecular clouds (e.g., Madden et al. 1993). The last point is especially relevant for DLAs where molecules are rarely detected (Lu et al. 1997; Petitjean et al. 2000).

Pottasch, Wesselius, & van Duinen (1979) used the following expression to estimate the \([C\, ii]\) \(158\, \mu m\) emission per H atom from gas detected in absorption against background sources:

\[
l_c = \frac{N(C\, ii^*) h v_{ul} A_{ul}}{N(H\, i)} \text{ ergs s}^{-1} \text{ H}^{-1} ,
\]

(3)

where \(N(C\, ii^*)\) is the column density of \(C^+\) ions in the \(2P_{3/2}\) state, \(N(H\, i)\) is the H i column density, and \(A_{ul}\) and \(h v_{ul}\) are the coefficient for spontaneous photon decay and energy of the \(2P_{3/2} \rightarrow 2P_{1/2}\) transition. In fact, \(l_c\) is just the density-weighted average along the line of sight of the more fundamental quantity, \(l_c(r)\), the rate of spontaneous emission of energy per H atom at a given displacement vector \(r\). That is,

\[
l_c = \frac{\int_{n_{HI}(s)} n_{C\, ii^*}(s) l_c(r(s)) ds}{\int_{n_{HI}(s)} ds} ,
\]

(4)

where

\[
l_c(r) = \frac{n_{C\, ii^*}(r) A_{ul} h v_{ul}}{n_{HI}(r)} ,
\]

(5)

\(n_{C\, ii^*}\) and \(n_{HI}\) are the volume densities of \(C\, ii^*\) and H i, and \(ds\) is the differential path length along the line of sight. Notice that \(l_c(r) = 4\pi j / n_{HI}\), where \(j\) is the volume emissivity appearing in the radiative transfer equation. We can measure \(l_c\) since \(N(C\, ii^*)\) and \(N(H\, i)\) are measurable: \(N(C\, ii^*)\) from \(C\, ii^*\) \(\lambda 1335.7\) absorption and \(N(H\, i)\) from damped Ly\(\alpha\) \(\lambda 1215.7\) absorption. Note also that \(\Gamma = l_c\) when cooling is dominated by \([C\, ii]\) \(158\, \mu m\) emission.

3. The DATA

We have determined \(l_c\) for 33 DLAs. The results were obtained by measuring \(N(C\, ii^*)\) and \(N(H\, i)\) from accurate velocity profiles. In Table 1 we show \(l_c\) and other properties to be used in subsequent analyses. Column (1) gives the coordinate name of the background QSO, column (2) the absorption redshift of the DLA, column (3) the H i column density, column (4) the \(C\, ii^*\) column density, column (5) the iron abundance relative to solar [where \([Fe/H] = \log_{10}(Fe/Fe) - \log_{10}(Fe/H)\)], column (6) the silicon abundance [\([Si/H]\)], and \(l_c\) is given in column (7). In cases in which Fe absorption lines were not measured, we substituted proxy elements such as Ni, Cr, and Al. In cases in which Si absorption was not measured, we used S or Zn as proxies (see PW02 for a full description of these procedures). The data for 30 of the entries were obtained with HIRES: 23 of these by our group (Prochaska et al. 2001), six by Lu et al. (1997), and one by A. Songaila & L. Cowie (2001, private communication). Data for the remaining three entries were acquired with the UV-Visual Echelle Spectrograph (UVES) on the VLT 8 m telescope (Ellison et al. 2001; Srianand, Petitjean, & Ledoux 2000; Dessauges-Zavadsky et al. 2001).

Figure 1 shows six examples of \(C\, ii^*\) velocity profiles used to derive \(N(C\, ii^*)\) in Table 1 along with corresponding low-ion resonance profiles. While the velocity structures of the two profiles exhibit overall similarity, statistically significant differences exist. These are evident in (1) the DLA toward Q0347−38 (Fig. 1c), where two strong velocity components are detected at \(v = -8\) and \(+12\) km s\(^{-1}\) in Fe \(\lambda 1608\), while only the \(v = +12\) km s\(^{-1}\) component is detected in the \(C\, ii^*\) \(\lambda 1335.7\) profile even though there is sufficient signal-to-noise ratio to detect the \(v = -8\) km s\(^{-1}\) component; and (2) the DLA toward Q2231−00 (Fig. 1f), where absorption in \(C\, ii^*\) \(\lambda 1335.7\) between \(-50\) and \(+20\) km s\(^{-1}\) is not detected in Si \(\lambda 1808\). In Paper II we show these differences to be evidence for a multiphase gas in which \(l_c(r)\) varies along the line of sight.

In Figure 2 we plot \(l_c\) versus \(N(H\, i)\) for the DLAs. There are 16 positive detections (red data points), two lower limits (95% confidence intervals; blue data points), and 15 upper limits (95% confidence intervals; green data points). One purpose of this plot is to illustrate possible systematic effects such as correlations between \(l_c\) and \(N(H\, i)\). No such correlation is evident in the data. However, there is a tendency for the upper limits on \(l_c\) to occur at low \(N(H\, i)\) column densities: 12 of the 15 upper limits on \(N(C\, ii^*)\) occur at \(\log_{10} N(H\, i) \leq 20.6\) cm\(^{-2}\). This suggests that at least some of the null detections with large upper limits result from gas with \(C\, ii^*\) column densities sufficiently low that \(\lambda 1335.7\) is undetectable rather than from low values of \(l_c\). Other upper limits are caused by blending between \(C\, ii^*\) \(\lambda 1335.7\) and Ly\(\alpha\) forest lines (as for the \(z = 2.154\) DLA toward Q2359−02B). However, we cannot exclude the possibility that the remaining upper limits arise from \(l_c\) values substantially below the positive detections. The lower limits correspond to cases in which \(C\, ii^*\) \(\lambda 1335.7\) is saturated.

The second purpose of this plot is to compare \(C\, ii^*\) emission rates in DLAs and in the ISM. Thus, we plot \(l_c\) versus \(N(H\, i)\) pairs derived for representative sight lines through the ISM, which are shown as small blue stars (Pottasch et al. 1979; Gry, Lequex, & Boulanger 1992). While Pottasch et al. (1979) did not report measurement errors, Gry et al. (1992) report 1 \(\sigma\) errors corresponding to \(\approx 0.3\) dex in \(\log_{10} l_c\); data from both surveys are plotted in Figure 2 without error bars. The large star was derived by dividing the total \(158\, \mu m\) luminosity of the Galaxy by the H i mass of the disk (Hollenbach & Tielens 1999); the result corresponds to the density-weighted average of \(l_c(r)\) integrated over the disk of the Galaxy, which we refer to as \(\langle l_c \rangle_{\text{ISM}}\). Comparison between the DLA and ISM data demonstrates that \(l_c\) averaged over the DLA sample, i.e., \(\langle l_c \rangle\), is about 1/30 times...
Because 158 μm emission from DLAs has not been detected, the analogous quantity, which is the density-weighted average of $l_{\nu}(r)$ over the entire H i mass distribution of the DLAs, is unknown. Nevertheless, the data covering 33 sight lines through DLAs strongly suggest the C ii* cooling rate per H atom to be much lower in DLAs than in the ISM. The heating rates are therefore correspondingly lower.

The ratio of the two heating rates is simply explained if the DLA gas is heated by the same mechanism that heats the ISM; i.e., photoejection of electrons from dust grains. If the mean intensities of FUV radiation are the same and the photoelectric efficiencies are the same, equation (1) shows that the ratio of heating rates equals the ratio of dust-to-gas ratios, $k_{DLA}/k_{MW}$. Pettini et al. (1994) set $k_{MW}$ equal to the mean value in the Galaxy and estimate that $k_{DLA}/k_{MW} \approx 1/30$ to 1/20, which approximates the DLA metallicity relative to solar and is remarkably close to the ratio of heating rates. Either this is a chance coincidence, or it means that $G_0$ in DLAs is nearly the same as in the ISM and the paucity of grains accounts for the lower rate of heating in DLAs. Consequently, we shall adopt the grain photoelectric heating mechanism.

### 4. MULTIPHASE STRUCTURE OF THE DLA GAS

To further evaluate the grain photoelectric heating hypothesis, we compute the thermal equilibrium temperature as a function of density for gas subjected to photoelectric grain heating. We adopt the treatment of W95, who calculate the two-phase structure of neutral gas in the ISM. In this calculation the gas is assumed to be mainly atomic and in a state of thermal and ionization equilibrium. We also include heating and ionization due...
to cosmic rays, soft X-rays, and the photoionization of C i by FUV radiation (e.g., W95). Cooling is assumed to arise from fine-structure and metastable transitions in ions of abundant elements, from Lyα, and from radiative recombination of electrons onto grains. Rather than repeat the W95 analysis here, we summarize the important points, emphasizing how the input physics for DLAs differs from that of the ISM.

4.1. Elemental Abundances and Dust-to-Gas Ratios

Elemental abundances affect both the heating and cooling rates in DLAs in different ways. Consider the heating rate. The rate of grain photoelectric heating, $\Gamma_d$, is proportional to the dust-to-gas ratio in DLAs, $k_{DLA}$, which in turn depends on the fraction of extant metals in grains. More specifically, $\Gamma_d$ depends on the grain composition, i.e., on

Fig. 1.—Velocity profiles comparing C ii and selected resonance lines in six DLAs. In each case the resonance transition and C ii column density, $N(C\,\text{ii})$, are specified.
whether grains in DLAs are mainly carbonaceous, as in the Galaxy, or mainly silicates, as in the SMC (see Weingartner & Draine 2001a). Recent evidence suggests that at $z < 1$, grains in DLAs are Galactic. The unambiguous detection of the $\lambda$2175 graphite absorption feature and the overall shape of the reddening curves suggest that a known DLA at $z = 0.524$ (Junkkarinen et al. 2002) and a DLA detected in a gravitationally lensed galaxy at $z = 0.83$ (Motta et al. 2002) contain Galactic dust. On the other hand, a search for the $\lambda$2175 feature in five DLAs with mean redshift $\approx 2$ (Pei, Fall, & Bechtold 1991) resulted in null detections with upper limits on the $\lambda$2175 optical depth significantly below predictions based on the relative reddening of QSOs with foreground DLAs. To account for this result, Pei et al. (1991) suggested that dust in DLAs resembles SMC dust that does not exhibit the $\lambda$2175 feature, presumably because it is composed mainly of silicates.

For these reasons we shall consider a “Gal” model in which dust in DLAs consists of carbonaceous grains and PAHs and an “SMC” model in which the dust in DLAs consists of silicate grains. The “Gal” model assumes that small (4–10 Å) carbonaceous dust grains dominate the heating as they do in the Galaxy, and we shall use the heating efficiency for Galactic regions rich in small carbonaceous grains computed by Bakes & Tielens (1994). We infer the abundance of carbonaceous grains (per H atom) from the relative dust-to-gas ratio, $\kappa$, where $\kappa = k_{\text{DLA}}/k_{\text{MW}}$ and $k_{\text{MW}}$ is the dust-to-gas ratio in the Galaxy. We determine $\kappa$ from the observed depletion of Fe in each DLA (see derivation in the Appendix). Our method assumes that the number of C atoms depleted onto dust grains per depleted Fe atom is the same in DLAs as in the Galaxy, i.e.,

$$\frac{n_{\text{C, depleted}}^\text{DLA}}{n_{\text{Fe, depleted}}^\text{DLA}} = \frac{n_{\text{C, depleted}}^\text{MW}}{n_{\text{Fe, depleted}}^\text{MW}} .$$

This is a reasonable assertion because Fe tracks C in metal-poor stars (Carretta, Gratton, & Sneden 2000). Indexing the C depletion to the Fe depletion is necessary because the C abundance typically cannot be measured in DLAs and Fe is the only element for which the depletion level is known (by comparison with Si). We also assume that the size distribution of the carbonaceous grains containing the depleted C atoms follows that of Bakes & Tielens (1994). As a result, the grain photoelectric heating rate equals $\Gamma_{\phi}$ computed for pure carbonaceous grains and solar composition multiplied by $\kappa$ (eq. [1]).

The “SMC” model assumes that silicate grains dominate the heating. The absence of a 2175 Å bump in the typical SMC dust extinction curve and deficit of 12 µm emission indicate a lack of small carbonaceous grains (Sauvage & Vigroux 1991), so it is the remaining small silicate grains that dominate the heating. Therefore, we use the heating efficiency calculated by Weingartner & Draine (2001b) for regions that lack small carbonaceous grains. We infer the abundance of silicate grains from the dust-to-gas ratio determined from the observed depletion of iron analogous to the equation for carbon shown above. This assumes that the number of depleted Si atoms per depleted Fe atom is the same in DLAs as in the Galaxy, making the SMC model a hybrid of SMC and Galactic conditions. Observations of [Fe/Si] in DLAs will allow us to check this assumption against reality. In calculating the gaseous carbon abundance and using [Fe/Si] to determine $\kappa$, we assume that C and Si are nearly undepleted. The possible contradiction of using the heating efficiency of carbonaceous or silicate grains while assuming C and Si to be undepleted will be discussed in § 6.

To estimate $\kappa$, we compute the fraction of Fe in grains. To estimate this fraction, we need to determine the intrinsic abundance of Fe and compare it to its gas-phase abundance. Although previous workers used Zn to estimate intrinsic Fe, we shall use Si because (1) the median ratio $\langle [\text{Si}/\text{Zn}] \rangle = 0.03 \pm 0.05$ for a sample of 12 DLAs indicates that Si traces Zn (implying that Zn may trace α-enhanced elements rather than Fe peak elements; PW02), (2) there is only one case of Si depletion to date (Petitjean, Srianand, & Ledoux 2002), and (3) Si abundances have been measured to $z = 4.5$ whereas Zn is rarely measured at $z > 3.3$. In the Appendix we show that in the case of grains composed of Fe,

$$\kappa = 10^{\log_{10}(10^{[\text{Fe}/\text{Si}]_{\text{int}}} - 10^{[\text{Fe}/\text{Si}]_{\text{gas}}})} .$$

In the last equation the abundance ratios $[X/Y] = \log_{10}(X/Y) - \log_{10}(X/Y)_{\odot}$, and the subscripts “int” and “gas” refer to intrinsic and gas-phase abundance ratios.

Since $\kappa$ is sensitive to the level of depletion, we test two models. In the minimal depletion model we make use of
abundance patterns of DLAs deduced by PW02. Although they derived the median value \( \langle [\text{Fe}/\text{Si}]_{\text{int}} \rangle = -0.3 \) from the abundance pattern of metal-poor DLAs that are not expected to have significant dust depletion, we shall adopt the more conservative value of \(-0.2\). This is consistent with \( \alpha \) enhancement expected from Type II supernovae that dominate nucleosynthesis at high \( z \). We then let \([\text{Fe}/\text{Si}]_{\text{gas}}\) equal the observed ratio and use equation (7) to derive \( \frac{1}{2} \). No. 1, 2003 C

\[ \text{Fe} \]

\[ \text{C} \]

\[ \text{O} \]

\[ \text{Si} \]

\[ \text{Fe} \]

First, we equate the abundances of these elements in each DLA. Because the value of \([\text{Fe}/\text{Si}]_{\text{int}}\) is not yet well established, we consider a second, maximal depletion model in which we derive \( \kappa \) by assuming \([\text{Fe}/\text{Si}]_{\text{int}} = 0 \); i.e., we assume that the observed deviations of the Fe/Si ratios from the solar value are caused only by depletion. In both models we assume \([\text{Si}/\text{H}]_{\text{int}} = [\text{Si}/\text{H}]_{\text{gas}}\) because of evidence that Si is nearly undepleted. In cases in which only observational limits exist on \([\text{Si}/\text{H}]_{\text{gas}}\) or \([\text{Fe}/\text{H}]_{\text{gas}}\) we substitute elements such as S or Zn for Si and Ni, Cr, or Al for Fe. One could also consider the prescription of Pei, Fall, & Hauser (1999), who let the dust-to-gas ratio equal the observed Fe abundance, i.e., \( \kappa = 10^{0.2 [\text{Fe}/\text{H}]_{\text{int}}} \), but that turns out to be intermediate between the two models considered below; the minimal depletion model yields the smallest values of \( \kappa \), and the maximal depletion model yields the largest values of \( \kappa \).

The abundances of the elements C, O, Si, and Fe in the gas phase affect the cooling rate since transitions of \( \text{C}^+ \), \( \text{O}^0 \), \( \text{Si}^+ \), and \( \text{Fe}^+ \) are the major coolants. In our models we use the following prescription to compute gas-phase abundances of these elements in each DLA. First, we equate the intrinsic abundance of Si to its measured gas-phase abundance, i.e., \([\text{Si}/\text{H}]_{\text{int}} = [\text{Si}/\text{H}]_{\text{gas}}\), where the latter are listed in Table 1. Oxygen resembles silicon as it is undepleted and an \( \alpha \)-enhanced element. As a result, we assume that \([\text{O}/\text{H}]_{\text{gas}} = [\text{Si}/\text{H}]_{\text{gas}}\). While we assume that carbon is undepleted, we are aware that this poses a potential contradiction with the “Gal” dust model in which the depletion level of C is assumed proportional to the depletion level of Fe, and we mention this in \( \S 6 \). In any case C is not an \( \alpha \)-enhanced element but rather is likely to trace Fe since \([\text{C}/\text{Fe}] \approx 0\) in stars of all metallicities (e.g., Carretta et al. 2000). Therefore, we assume \([\text{C}/\text{H}]_{\text{gas}} = [\text{Fe}/\text{H}]_{\text{int}}\), where \([\text{Fe}/\text{H}]_{\text{int}} = [\text{Fe}/\text{Si}]_{\text{int}} + [\text{Si}/\text{H}]_{\text{int}}\). For consistency with the other model abundances we compute \([\text{Fe}/\text{H}]_{\text{gas}}\) from \([\text{Fe}/\text{H}]_{\text{int}}\) rather than equate it to the observed DLA Fe abundance. In this case \([\text{Fe}/\text{H}]_{\text{gas}} = [\text{Fe}/\text{H}]_{\text{int}} + \log_{10}(1 - \kappa \times 10^{-0.4 [\text{Fe}/\text{H}]_{\text{int}}} \text{). The results are summarized in Table 2.}

4.2. Heating and Cooling

In this subsection we discuss the sources of heating and cooling in DLA gas. Specifically, we consider a gas layer subjected to heating by grain photoelectric emission, cosmic-ray ionization, X-ray ionization, and photoionization of C I. We also discuss cooling by important emission lines from abundant elements and show how direct excitation by CMB photons and indirect excitation due to pumping by FUV fluorescence photons cause the spontaneous emission rate to deviate from the cooling rate. Similar discussions that did not include optical pumping were given by Norman & Spaans (1997) and subsequently by Liszt (2002).

4.2.1. Heating

The heating rate is given by

\[ \Gamma = \Gamma_d + \Gamma_{CR} + \Gamma_{XR} + \Gamma_{CI}, \]

where \( \Gamma_d \) is given by equation (1) and \( \Gamma_{CR} \), \( \Gamma_{XR} \), and \( \Gamma_{CI} \) are the heating rates due to cosmic rays, X-rays, and photoionization of C I by the FUV radiation field, \( G_0 \). We ignore heating due to the integrated background from galaxies and QSOs as it is negligible compared to \( \Gamma_d \) for the range of SFRs considered in \( \S 5 \). I.e., \( \log_{10} \psi_\star > 4.0 \ M_\odot \text{yr}^{-1} \text{kpc}^{-2} \). We compute \( \Gamma \) by adopting expressions and parameters used by W95 to model the ISM, but where appropriate we extrapolate to physical conditions pertaining to DLAs. Thus, in the case of “Gal” dust we compute \( \Gamma_d \) by adopting the Bakes & Tielens (1994) expression for the photoelectric efficiency, since we assume that the DLAs have the same relative distribution of small grains and PAHs as the ISM. In the case of “SMC” dust we compute \( \Gamma_d \) by adopting the Weingartner & Draine (2001b) expression for photoelectric efficiency in the case of pure silicates, blackbody FUV radiation, and selective extinction \( R_e = 3.1 \). On the other hand, there is no a priori reason why \( G_0 \) in DLAs should equal 1.7, the widely accepted value for the ISM (Draine 1978). As we show in \( \S 5 \), \( G_0 \propto \psi_\star \) and the SFRs per unit area in DLAs need not equal the Milky Way rates. Moreover, the transfer of FUV radiation depends on the dust optical depth, which should be lower in DLAs than in the ISM. We use the inferred optical depths to determine a self-consistent solution for \( \psi_\star \), which reveals the SFR per unit area (see \( \S 5.2 \)).

To compute \( \Gamma_{CR} \), we assume \( \Gamma_{CR} = \zeta_{CR} E_0(E) \), where expressions for \( \zeta_{CR} \), the primary cosmic-ray ionization rate, and \( E_0(E) \), the energy deposited for each primary electron of energy \( E \), are given by W95. These authors find \( \zeta_{CR} = 1.8 \times 10^{-17} \text{s}^{-1} \) in the Galaxy. We scale this result to DLAs by assuming

\[ \zeta_{CR} = 1.8 \times 10^{-17} \left( \frac{\psi_\star}{10^{-2.4} \ M_\odot \text{yr}^{-1} \text{kpc}^{-2}} \right) \text{s}^{-1}. \]

where we have used \( \log_{10} \psi_\star = -2.4 \ M_\odot \text{yr}^{-1} \text{kpc}^{-2} \) for the disk of the Galaxy (Kennicutt 1998).

| Element | \( \log_{10}(X/H)_{\odot} \) | \( \log_{10}(X/H)_{\text{gas}} - \log_{10}(X/H)_{\odot} \) |
|--------|----------------|-------------------------------|
| He     | -1.00          | 0                             |
| C      | -3.44          | \([\text{Si}/\text{H}]_{\text{int}} + [\text{Fe}/\text{Si}]_{\text{int}}\) |
| O      | -3.34          | \([\text{Si}/\text{H}]_{\text{int}}\) |
| Si     | -4.45          | \([\text{Si}/\text{H}]_{\text{int}}\) |
| Fe     | -4.45          | \([\text{Si}/\text{H}]_{\text{int}} + [\text{Fe}/\text{Si}]_{\text{int}} + \log_{10}(1 - \kappa \times 10^{-0.4 [\text{Fe}/\text{H}]_{\text{int}}} \) |
To compute the effects of soft X-rays, we use the W95 expressions for the heating rate, \( \Gamma_{\text{XR}} \), and primary and total ionization rates, \( \zeta_{\text{XR}} \) and \( \xi_{\text{XR}} \). We again scale to DLAs by assuming that all these quantities are proportional to \( \psi_\star \). W95 assume that soft X-rays (photon energies exceeding 0.2 keV) are emitted by thermal and nonthermal components. The thermal component comprises the hot \((T \approx 10^6 \, \text{K})\) coronal phase of the ISM. The nonthermal component consists of extragalactic power-law radiation. These X-rays penetrate the outsides of CNM clouds, heating the gas to form the WNM (e.g., Heiles 2001). W95 assume that the incident X-rays are attenuated by a WNM layer of gas with hydrogen column density \( \log_{10} N_H = 20 \, \text{cm}^{-2} \). For our analysis we must assume \( \log_{10} N_H = 20 \, \text{cm}^{-2} \) instead. This is because low-density \((n \sim 0.1 \, \text{cm}^{-3})\) WNM gas cannot remain neutral at \( T \) hydrogen column densities \( \log_{10} N_H > 20.3 \, \text{cm}^{-2} \) as a result of the background ionizing radiation field, which is about 100 times more intense at high redshifts than at \( z = 0 \) (e.g., Prochaska & Wolfe 1996). Had we assumed \( \log_{10} N_H = 19.0 \, \text{cm}^{-2} \), the total column density of neutral plus ionized gas would exceed \( \log N = 20.0 \, \text{cm}^{-2} \) and it is the total column density that is crucial for determining X-ray opacity. Furthermore, Vladilo et al. (2001) present strong arguments that gas in DLAs is mostly neutral. Thus, our limit is conservative. Another reason for adopting the larger WNM column density is our model assumption that a significant fraction of the \( T \) hydrogen column density in each DLA consists of WNM gas. The result of these model assumptions is that cosmic rays will be a more important source of heating and ionization than X-rays.

Notice that we have assumed that \( G_\theta \), \( \Gamma_{\text{CR}} \), and \( \Gamma_{\text{XR}} \) are all proportional to \( \psi_\star \). While unproven for \( \Gamma_{\text{CR}} \) and \( \Gamma_{\text{XR}} \), we believe that this assumption is reasonable as all three quantities are ultimately driven by the formation rate of massive stars. This is because cosmic rays are thought to be accelerated in supernova remnants, and much of the soft X-ray emission is thought to arise in hot gas located behind supernova shocks (McKee & Ostriker 1977).

\subsection*{4.2.2. Cooling}

The cooling rate (ergs cm\(^{-3}\) s\(^{-1}\)) is given by

\[ \Lambda = \Lambda_{\text{FS}} + \Lambda_{\text{AMS}} + \Lambda_{\text{Ly}\alpha} + \Lambda_{\text{GR}}. \]  

(10)

At \( T < 3000 \, \text{K} \), cooling is dominated by the fine-structure term, \( \Lambda_{\text{FS}} \). The leading contributors are emission by the fine-structure lines [C \( \text{ii} \)] 158 \( \mu \text{m} \), which typically dominates at \( T < 300 \, \text{K} \), and [O \( \text{i} \)] 63 \( \mu \text{m} \), which is comparable to 158 \( \mu \text{m} \) emission only at \( T > 300 \, \text{K} \). Following W95, we also include fine-structure cooling from other transitions in \( \text{O}^0 \) (i.e., neutral oxygen) and from transitions in \( \text{Si}^+ \) and \( \text{Fe}^+ \). At \( T > 3000 \, \text{K} \), the term \( \Lambda_{\text{AMS}} \) becomes important. This arises from excitation of metastable transitions of \( \text{C}^+ \), \( \text{O}^0 \), \( \text{Si}^+ \), and \( \text{S}^+ \). At higher temperatures, the Ly\( \alpha \) cooling term, \( \Lambda_{\text{Ly}\alpha} \), starts to dominate along with \( \Lambda_{\text{GR}} \), the grain recombination rate. We computed \( \Lambda_{\text{GR}} \) by adopting the Bakes & Tielens (1994) expression for cooling due to radiative recombinations of electrons onto polycyclic aromatic hydrocarbons (PAHs) and grains. Note that we have not included cooling by transitions in the neutral species \( \text{C}^0 \), \( \text{Fe}^0 \), \( \text{Mg}^0 \), and \( \text{Si}^0 \) considered by W95 as their contribution to \( \Lambda \) is negligible.

By definition the cooling rate of the gas equals the net loss of thermal kinetic energy per unit time. In the case of line cooling this is the product of (1) the difference between the collisional excitation and de-excitation rates and (2) the energy of the atomic transition. The former equals the spontaneous emission rate, provided that collisions are the dominant source of excitation and de-excitation. As a result, \( n_{\text{AC}} = \lambda_{\text{LR}} \) in the ISM, where \( \lambda_{\text{LR}} \) is the spontaneous emission rate per \( \text{H} \) atom of the \( 2P_{3/2} \to 2P_{1/2} \) transition. However, this equality can break down in DLAs since radiative excitation can be important. At high \( z \) the CMB contributes significantly to the rate at which the \( 2P_{1/2} \) and \( 2P_{3/2} \) states are populated. Moreover, for large values of \( G_\theta \), these ground-term fine-structure states can be populated indirectly through FUV excitation of higher energy states, i.e., through optical pumping (termed “fluorescence” by Silva & Viegas 2002). When radiative excitations are important, we have

\[ \lambda_{\text{LR}} = n_{\text{AC}} + (\lambda_{\text{pump}} + \lambda_{\text{CMB}}), \]  

(11)

where \( (\lambda_{\text{pump}} + \lambda_{\text{CMB}}) \) are the spontaneous energy emission rates in the limits of pure optical pumping and CMB excitation. In deriving the last equation we used the condition \( 1 - z \ll \nu_{\text{CMB}} / kT_{\text{CMB}} = 33 \), where \( \nu_{\text{CMB}} \) is the excitation energy corresponding to the \( 2P_{3/2} \to 2P_{1/2} \) transition in \( C^+ \) and \( T_{\text{CMB}} = 2.728 \, \text{K} \) is the current temperature of the CMB. We find that

\[ \lambda_{\text{pump}} = \left( \frac{C}{H} \right) \Gamma_B h \nu_{\text{ul}} \]  

\[ \lambda_{\text{CMB}} = 2 \left( \frac{C}{H} \right) A_{\text{lu}} h \nu_{\text{ul}} \exp\left[ -\frac{\nu_{\text{ul}}}{k(1+z)T_{\text{CMB}}} \right], \]  

(12)

where \( (C/H) \) is the carbon abundance and \( A_{\text{lu}} \) is the rate of spontaneous emission for the \( 2P_{1/2} \to 2P_{3/2} \) transition. The quantity \( \Gamma_B \) is the net rate at which state \( l \) pumps state \( u \) (see Silva & Viegas 2002). We calculated \( \lambda_{\text{GR}} \) using standard expressions for excitations due to collisions and CMB radiation. We used the Silva & Viegas (2002) code, POPRATIO, to compute the rate at which the \( 2P_{1/2} \) and \( 2P_{3/2} \) states are populated by optical pumping. We considered indirect excitation of the \( 2P_{3/2} \) and \( 2P_{1/2} \) states through transitions to eight higher levels. For consistency we used the spectral form advocated by Draine (1978) for the FUV radiation field, normalized such that \( G_\theta = 4 \pi J_d \nu_d / (1.6 \times 10^{-3} \, \text{ergs cm}^{-2} \, \text{s}^{-1}) \). However, this procedure ignores the effects of line opacity, which can effectively suppress the pumping rate when the gas is optically thick to transitions such as \( \text{C}^+ \lambda 1334.5 \) and 1036.3 (Sarazin, Rybicki, & Flannery 1979; Flannery, Rybicki, & Sarazin 1979, 1980). Because the values of \( G_\theta \) resonance-line optical depth, and collisional excitation rates are required to evaluate the suppression of optical pumping, we shall reevaluate our “optically thin” solutions for self-consistency in § 5.2.2.

\subsection*{4.3. Phase Diagrams for DLAs}

In this subsection we compute the two-phase structure of neutral gas in DLAs. We find that if the gas is CNM, the SFRs per unit area deduced for local disk galaxies (Kennicutt 1998) generate [C \( \text{ii} \)] spontaneous emission rates similar to those observed in DLAs for typical DLA metallicities. If the gas is WNM, the required SFR per unit area must be at least a factor of 10 higher.

We solved the equations of thermal and ionization equilibrium for gas at constant density with the numerical
techniques and iterative procedures outlined in W95. We checked our technique by computing solutions for ISM conditions. In that case we assumed \( G_0 = 1.7, [\text{Si}/\text{H}]_{\text{int}} = 0, \) log_{10} \( \kappa = [\text{Fe}/\text{H}], \) and the same density-dependent depletion formulae advocated by W95. The results are in good, although not exact, agreement. Most importantly, the \( \lambda_{\text{cr}} \) versus \( n \) curves are in excellent agreement with the W95 results except at \( \log_{10} n < -0.5 \) cm\(^{-3} \) where optical pumping effects ignored by these authors cause \( \lambda_{\text{cr}} \) to deviate significantly above \( n_{\text{CR}}. \)

To illustrate the behavior of two-phase media with DLA conditions, we let \([\text{Si}/\text{H}]_{\text{int}} = -1.3,\) the mean Si abundance found for DLAs (PW02). We assume the “Gal” model and use maximum depletion to find log_{10} \( \kappa = -1.5. \) We assume an ISM radiation field, \( G_0 = 1.7, \) and adopt the mean redshift of the DLA sample, \( z = 2.8, \) to compute the CMB temperature. We compute the cosmic-ray and X-ray heating rates from equation (9) by assuming the ISM SFR log_{10} \( \psi_\ast = -2.4 \) M_\odot kpc\(^{-2} \) yr\(^{-1}. \) The resulting equilibrium curves shown in Figure 3 exhibit the same two-phase equilibria found by W95 for the ISM. In a plot of pressure, \( P/k, \) versus density, \( n \) (see Fig. 3a), the regions of thermal stability occur where \( \partial (\log P)/\partial (\log n) > 0 \) (in the case of constant \( \Pi \)). Thus, a two-phase medium in which a WNM can remain in pressure equilibrium with a CNM can be maintained between \( P_{\min}/k \approx 460 \) K cm\(^{-3} \) and \( P_{\max}/k \approx 1750 \) K cm\(^{-3}. \) An example in which \( P = (P_{\min}P_{\max})^{1/2} \) is shown as the horizontal line connecting the WNM and CNM. The intercepts with the \( P(n) \) curve in the WNM and CNM correspond to thermally stable states: a WNM with \( T \approx 7600 \) K and \( \log_{10} n \approx -1 \) cm\(^{-3} \) in pressure equilibrium with a CNM with \( T \approx 80 \) K and \( \log_{10} n \approx +1 \) cm\(^{-3}. \) Gas with densities \(-0.6 \) cm\(^{-3} < \log_{10} n < 0.0 \) cm\(^{-3} \) is thermally unstable and evolves to either WNM or CNM states. Figure 3b shows the fractional ionization as a function of density.

Figure 3c plots the heating rates, \( \Gamma \) (magenta curves), cooling rates, \( n\Lambda \) (green curves and dotted blue curve in the case of C \( \Pi \)), and the spontaneous emission rate \( \lambda_{\text{cr}} \) (solid blue curve). It is evident that grain photoelectric heating dominates in the CNM while cosmic ray heating dominates in the WNM (see W95). By contrast to the ISM, cosmic rays dominate X-ray heating in DLAs for all densities, as a result of the higher X-ray opacity of the H \( \Pi \) column density assumed for DLAs. The dominant coolant in the CNM is \([\text{C} \Pi] 158 \mu \text{m} \) radiation, which is insensitive to density at \( 0.5 \) cm\(^{-3} < \log_{10} n < 4.0 \) cm\(^{-3}. \) This breaks down at \( \log_{10} n > 4.5 \) cm\(^{-3} \) (not shown) where C \( \Pi \) photoionization heating dominates the heating.

![Figure 3](image-url)

Fig. 3.—Two-phase diagrams for gas heated by grain photoelectric emission plus cosmic rays and soft X-rays, where the SFR per unit area log_{10} \( \psi_\ast = -2.4 \) M_\odot yr\(^{-1} \) kpc\(^{-2}, \) metallicity \([\text{C}/\text{H}] = -1.5, \) and dust-to-gas ratio log_{10} \( \kappa = -1.7. \) (a) Pressure vs. density. The S-shaped curve is indicative of a two-phase medium. Labels and horizontal line in the \( (n, P) \)-plane are explained in the text. (b) Fractional ionization vs. density. Magenta curves in (c) show grain photoelectric heating (PE), cosmic-ray heating (CR), X-ray heating (XR), and C \( \Pi \) photoionization heating rate vs. density. The dotted blue curve is the \([\text{C} \Pi] 158 \mu \text{m} \) cooling rate, and green curves are \([\text{O} \Pi], [\text{Si} \Pi], \text{Ly}_\alpha, \) and grain recombination cooling rates. The solid blue curve is the \([\text{C} \Pi] 158 \mu \text{m} \) spontaneous energy emission rate. The black curve (\( \Gamma \)) is the total heating rate. (d) Temperature vs. density.
rate and the cooling rate increases rapidly with density. On the other hand, [C ii] 158 μm emission comprises less than 10% of the cooling in the WNM. Furthermore, owing to CMB excitation and optical pumping, the population of the $^2P_{3/2}$ state of C$^+$ is larger than in the case of collisional excitations and de-excitation alone. As a result, at log$_{10} n < 0.0$ cm$^{-3}$ the spontaneous emission rate, $l_{cr}$, will exceed the cooling through 158 μm emission (see eq. [11]). Notice that $l_{cr}$ is insensitive to density in the CNM where $l_{cr} \rightarrow \Gamma_0$ and in the WNM where $l_{cr} \rightarrow (l_{cr})_{pump}$ (see eq. [12]). This reduces the uncertainty in estimating $l_{cr}$ in the models discussed in $\S$ 5. In any case the spontaneous emission rate in the CNM, log$_{10} l_{cr} \approx -26.6$ ergs s$^{-1}$ H$^{-1}$, is comparable to the mean $l_c$ for the DLA sample in Figure 1. Stated differently, the hypothesis of grain photoelectric heating can account for the mean [C ii] cooling rate of DLAs provided that (1) heating occurs in CNM gas with a low dust-to-gas ratio and (2) heating is driven by an FUV radiation field comparable to that inferred for the ISM. On the other hand, the observed $l_c$ could also arise in WNM gas (e.g., Norman & Spaans 1997; Kanekar & Chengalur 2001), provided that $G_0$ is about a factor of 30 or more higher. We will address this further in $\S$ 5.

In our models the heating rates for DLAs were inferred from the cooling rates by assuming steady state conditions. To determine whether this assumption is valid, consider the cooling time of gas in pressure equilibrium,

$$t_{cool} = \frac{(5/2)(1.1 + x)kT}{n\Lambda}$$

(see eq. [10] in W95). We find that $n\Lambda = 3 \times 10^{-27}$ ergs s$^{-1}$ H$^{-1}$ is required for CNM gas to match the inferred [C ii] emission rate. Since $T \approx 50$ K, we have $t_{cool} \approx 3 \times 10^5$ yr. If the DLA gas is in the WNM phase, then $n\Lambda = 3 \times 10^{-26}$ ergs s$^{-1}$ H$^{-1}$ is required to explain the observed $l_c$. In that case $T \approx 8000$ K and $t_{cool} \approx 5 \times 10^5$ yr. Because these time-scales are comparable to the dynamical time-scales of individual interstellar clouds, the assumption of thermal balance may break down on the spatial scales of typical interstellar clouds. However, the measured quantity for DLAs is $l_{cr}$ which is the density-weighted average of the [C ii] spontaneous emission rate, $l_{cr}(r)$, along the sight line through a typical DLA. In this case the relevant dynamical timescale is that of a typical protogalaxy which in any scenario is large compared to $5 \times 10^5$ yr. Stated differently, the fluctuations of heating and cooling rates integrated over the length scales of typical DLAs average out so that the mean rates are equal. As a result, the assumption of thermal and ionization balance should be an excellent approximation for DLAs.

On the other hand, the assumption of pressure equilibrium is not well established empirically. Accurate Arecibo 21 cm measurements of H i spin temperatures in the ISM reveal strong evidence for CNM gas with $T = 25-50$ K but no evidence for WNM gas with $T > 7000$ K. Rather, a significant fraction of the warm gas lies in the thermally unstable regime with $T = 500-5000$ K (Heiles 2001). While these measurements do not rule out multiphase models for the ISM, they bring to mind alternative scenarios. Specifically, Vazquez-Semadeni, Gazol, & Scalo (2000; see also Gazol et al. 2001) compute two-dimensional numerical simulations in which the dynamics of ISM clouds is dominated by turbulence rather than thermal instability. In this scenario the boundaries of dense CNM clouds are accretion shocks comprising thermally unstable gas rather than quiescent contact discontinuities separating disparate phases at constant pressure. Moreover, the unstable gas is found to comprise a significant fraction of the ISM mass (although higher resolution three-dimensional numerical simulations by Kritsuk & Norman 2002 show the fraction to be less than 15%). However, as stressed by Vazquez-Semadeni et al. (2000), the cooling times in the thermally unstable gas are shorter than the dynamical timescales, and as a result, the thermally unstable gas evolves quasi-statically through a sequence of thermal equilibrium states. For these reasons, the cooling curves shown in Figure 3c also apply to the "turbulence scenarios." Although $n\Lambda_{CII}$ and $l_c$ increase as $T$ decreases from 7500 to 1000 K, both quantities are still small compared to the total heating rate, $\Gamma$. As a result, relatively large SFRs are required for scenarios in which C $^+$ absorption occurs in warm neutral gas (as discussed in Paper II), whether or not that gas is in pressure equilibrium with the CNM. It is this property that ultimately rules out the WNM models. We conclude that the possible breakdown of pressure equilibrium has little effect on our results.

5. THE STAR FORMATION RATE PER UNIT AREA

We now estimate the SFR per unit area for each of our sample of DLAs. We first solve the transfer equation for the mean intensity of FUV radiation corresponding to the $\kappa$ derived for each DLA and for a wide range of $\psi_*$. For each DLA we assign appropriate gas-phase abundances and then combine equation (1) with the steady state assumption of equation (2) to compute $l_{cr}$. We compare the computed $l_{cr}$ with the observed $l_c$ to deduce $\psi_*$ for each DLA in both the CNM and WNM models. As we shall show, these SFRs are global in nature as they correspond to $\psi_*$ averaged over the entire DLA.

5.1. Solutions to the Transfer Equation

Assume that the gas, dust, and stars comprising DLAs are uniformly distributed throughout plane-parallel disks with half-width $h$ and radius $R$. A disk is a reasonable approximation for DLAs because dissipative collapse of gas in all galaxy formation scenarios, including protogalactic clump formation predicted by CDM numerical simulations (Haehnelt et al. 1998), occurs along a preferred axis, resulting in configurations resembling plane-parallel layers. Although uniformity is a highly idealized assumption, we shall show that the results do not differ qualitatively when this assumption is relaxed (see Paper II). We compute the mean intensity, $J_\nu$, at the center and midplane location of the uniform disk and find

$$J_\nu = \frac{2}{4\pi} \int_0^{2\pi} d\phi \left( \int_0^\theta \int_0^{h \sec \theta} r^2 \sin \theta \, d\theta \, dr \, \rho_\nu \frac{e^{-k_\nu r}}{4\pi r^2} + \int_\theta^{\pi/2} \int_0^{R \sec \theta} r^2 \sin \theta \, d\theta \, dr \, \rho_\nu \frac{e^{-k_\nu r}}{4\pi r^2} \right),$$

where we have ignored scattering of photons and $k_\nu$ is the
absorption opacity of dust at frequency $\nu$. The quantity $\rho_d$ is the luminosity density of the uniform disk, $\theta_c = \tan^{-1}(R/h)$, and the extra factor of 2 out front comes from having $\theta$ run from 0 to $\pi/2$. After integration we find that

$$J_\nu = \frac{1}{2} \left( \frac{\Sigma_\nu}{4\pi} \right) \left[ 1 - \frac{h}{\sqrt{h^2 + R^2}} \exp(-k_\nu R) \right] - \int_1^{\sqrt{h^2 + R^2}/h} \frac{dx}{x} \exp(-k_\nu hx) \right]. \quad (15)$$

Note that we obtained equation (15) by assuming that the radial distance to the edge of the disk equals $R$ for $\theta_c < \pi/2$.

To compute $J_\nu$, it is necessary to evaluate the quantities $k_\nu h$ and $k_\nu R$, i.e., the dust optical depths perpendicular and parallel to the plane of the disk. Define the optical depth, $\tau_\nu$, to be that of an average line of sight through the disk. At an average inclination angle of 45° we find that

$$k_\nu h = \frac{\tau_\nu}{2\sqrt{2}}. \quad (16)$$

To compute $\tau_\nu$, we follow Fall & Pei (1989), who derived the following expression:

$$\tau_\nu = \frac{A(\lambda)}{A(4400 \, \AA)} k_{\rm DLA} \left[ \frac{N(H \, i)}{10^{21} \, \text{cm}^{-2}} \right], \quad (17)$$

where $k_{\rm DLA} = \kappa_{\rm MW}$ for “Gal” dust and $k_{\rm DLA} = \kappa_{\rm SMC} \times 10^{-8}[\text{Si}/\text{H}]_{\text{SMC}}$ for “SMC” dust, and $A(\lambda)$ is the extinction at wavelength $\lambda = \epsilon/\nu$. The $[\text{Si}/\text{H}]_{\text{SMC}}$ term is the silicon abundance of the SMC and appears because $\kappa$ is normalized with respect to Galactic dust. The photons responsible for photoelectric grain heating in DLAs have energies between $\epsilon = 6$ eV and the Lyman limit cutoff at 13.6 eV. At the characteristic energy $\epsilon = 8$ eV (corresponding to $\lambda = 1500$ Å) we find that $k_{\rm MW}$ and $A(1500 \, \AA)/A(4400 \, \AA)$ equal 0.79 and 2.5, respectively, for the “Gal” model and $k_{\rm SMC}$ and $A(1500 \, \AA)/A(4400 \, \AA)$ equal 0.05 and 5.0, respectively, for the “SMC” model. We determine $\tau_\nu$ by assigning the appropriate $\kappa$ for each DLA and by using the median of our sample distribution of H $\, i$ column densities, $N(H \, i) = 0.48 \times 10^{21} \, \text{cm}^{-2}$. For each DLA we use the sample median rather than the measured value of $N(H \, i)$ because $N(H \, i)$ along a single line of sight is unlikely to represent the H $\, i$ column encountered by most of the FUV radiation; since $\tau_\nu \ll 1$, the FUV radiation that heats the grains is transported across the entire DLA. Consequently, $\tau_\nu \approx 0.01$ for values of $\kappa$ typifying our sample.

These estimates of $\tau_\nu$ imply the condition $k_\nu h \ll 1$ in every case. For reasonable aspect ratios, $R/h$, we find that $k_\nu R \ll 1$ in most DLAs, but in metal-rich objects the condition $k_\nu R > 1$ may hold. Therefore, in the limits corresponding to most models, $J_\nu$ takes on the following simple form:

$$J_\nu = \frac{1}{2} \left( \frac{\Sigma_\nu}{4\pi} \right) \left[ \left[ 1 + \ln \left( \frac{R}{h} \right) \right] - k_\nu R + O(k_\nu R)^{2} \ldots \right]$$

$$k_\nu h \ll k_\nu R \ll 1,$$

$$k_\nu h \ll 1, \quad k_\nu R \gg 1,$$

$$J_\nu = \frac{1}{2} \left( \frac{\Sigma_\nu}{4\pi} \right) \left[ \left[ 1 - \ln(k_\nu h) + 0.5k_\nu h + O(k_\nu h)^{2} \ldots \right] \right]$$

where $\Sigma_\nu (= 2\rho_d h)$ is the luminosity density projected along the rotation axis of the disk, i.e., the luminosity per unit area, and $\gamma$ is Euler’s constant. Equation (18) shows the mean intensity to vary linearly with the source luminosity per area but to be weakly dependent on metallicity, reddening curve, and aspect ratio. To illustrate the parameter dependence of $J_\nu$, we solved equation (14) for (1) the “Gal” and “SMC” dust assumptions, (2) the maximal and minimal depletion models, and (3) aspect ratios in the range predicted by current models of galaxy formation. The results are shown in Figure 4, where we plot mean intensity versus $[\text{Si}/\text{H}]$. As expected, for fixed values of $R/h$, $J_\nu$ increases with decreasing $[\text{Si}/\text{H}]$ until the disk becomes optically thin in the radial direction. At lower values of $[\text{Si}/\text{H}], J_\nu$ equals a constant that increases with increasing $R/h$. At higher values of $[\text{Si}/\text{H}], J_\nu$ decreases with increasing $[\text{Si}/\text{H}]$, becoming insensitive to $R/h$ as the disk becomes optically thick: this is because $J_\nu \propto \Sigma_\nu/\tau_\nu$ in the optically thick limit. Figure 4 also plots results for a uniform sphere that, while unrealistic, provide a lower limit to the strength of the radiation field. For our standard model we shall adopt a disk with an aspect ratio $R/h = 10$. From Figure 4 we see that for a measured $[\text{Si}/\text{H}]$ the uncertainties in $R/h$ and dust composition cause uncertainties in $J_\nu$ for the disk models that do not exceed $\sim 30\%$. When the spherical model is included, these remain less than $50\%$.

The grain heating rate is determined by $J$, i.e., $J$ integrated between photon energies $\epsilon = 6$ and 13.6 eV. Assuming the Draine (1978) UV spectrum, we find that $J_\nu = 10^{-19}$ ergs cm$^{-2}$ s$^{-1}$ sr$^{-1}$ Hz$^{-1}$ at $\epsilon = 8$ eV (i.e., 1500 Å) results in $4\pi R^2 = 1.6 \times 10^{-3}$ ergs cm$^{-2}$ s$^{-1}$, which equals Habing’s (1968) estimate of the UV interstellar radiation field.

Therefore, we shall assume

$$G_0 = \left( \frac{J_\nu}{1 \times 10^{-19} \, \text{ergs cm}^{-2} \, \text{s}^{-1} \, \text{sr}^{-1} \, \text{Hz}^{-1}} \right), \quad \lambda = 1500 \, \text{Å}. \quad (19)$$

To relate $G_0$ to the rate of star formation, we use the Madau & Pozzetti (2000) calibration. In that case

$$\Sigma_\nu = 8.4 \times 10^{-16} (\psi_*/M_{\odot} \, \text{yr}^{-1} \, \text{kpc}^{-2}) \, \text{ergs cm}^{-2} \, \text{s}^{-1} \, \text{Hz}^{-1}. \quad (20)$$

By combining equations (14), (19), and (20), we can convert $\psi_*$ into $G_0$. To see whether our technique reproduces the ISM radiation field, we solved for $G_0$ assuming $R = 20$ kpc, $h = 0.125$ kpc, $k_{\odot} = 0$, and $\log_{10} \psi_*/M_{\odot} \, \text{yr}^{-1} \, \text{kpc}^{-2}$. We found that $G_0 = 1.6$, which is in excellent agreement with the Draine (1978) value of $G_0 = 1.7$.

Before changing topics, we wish to emphasize several points. First, for typical metallicities the DLAs will be
optically thin to FUV radiation in every direction. In the uniform disk approximation, sources at all distances contribute roughly equally to $J_r$. As a result, the SFRs per unit area inferred from the C II absorption profiles are representative of stars distributed throughout the entire DLA, not just in regions adjacent to the line of sight. This is in contrast to the ISM, where the high dust opacity results in SFRs with only local significance. Second, we computed $J_r$ for midplane points displaced from the center of the disk; i.e., we computed $J_r(r, Z)$ at cylindrical coordinates $(r, 0)$. When $R/h = 10$, we found $J_r(r, 0)/J_r(0, 0)$ to slowly decrease from 1 at $r = 0$ to equal 0.9 at the median radius $r = R/\sqrt{2}$, 0.75 at $r = 0.9R$, and 0.5 at $r = 0.98R$; when $R/h = 100$, $J_r(r, 0)/J_r(0, 0)$ was 0.94 at $r = R/\sqrt{2}$, 0.85 at $r = 0.9R$, and 0.7 at $r = 0.98R$. Therefore, radiation fields computed from equation (15) result in heating rates representative of sight lines selected to have arbitrary impact parameters. Third, we computed $J_r(0, Z)$ at distance $Z$ above the midplane of the uniform disk and then averaged the result along sight lines through the disk. This is a more realistic simulation of the dependence of the heating rate on mean intensity than estimating $J_r$ at midplane. It is encouraging that the resulting mean intensities differed by less than 10% from the solution in equation (15) for dust-to-gas ratios, $-3.0 < \log_{10} \kappa < 0.0$. We also considered Draine’s (1978) solution for $J_r(R, Z)$ in which the radiation sources are confined to a uniform thin sheet at $Z = 0$. The same averaging process led to results in excellent agreement with equation (15) except when $\log_{10} \kappa > -0.5$ where the Draine expression fell significantly below our result. This occurs because Draine (1978) excluded sources within a critical radius in the disk location below the field point in order to avoid a singularity in his solution. Fourth, in realistic models of DLAs, $\psi_*$ is not constant throughout a uniform disk with constant gas density but rather is a function of $r$ in a system in which gas density also changes with $r$. We shall examine the implications of this in Paper II.

5.2. Determining $\psi_*$ in a DLA

5.2.1. Technique

The next step is to infer $\psi_*$ for each DLA from determinations of $l_\lambda$ and $\kappa$. To do this, we need an additional assumption about the physical state of the gas since $l_\lambda$ is not a unique function of the other two variables. Indeed, for fixed [Si/H], $\kappa$, and $\psi_*$ the computed [C II] emission rate per H atom, $l_{c2}$, varies with density (as shown in Fig. 3e). Therefore, to infer $\psi_*$ from observations, we need to know the density of the gas. We address this problem by assuming the gas to be a two-phase medium with stable CNM gas in pressure equilibrium with stable WNM gas. In that case the gas pressure $P$ is restricted to lie between the local minimum

Fig. 4.—Solutions to transfer equation given in eq. (15). The resultant mean intensity, $G_1 \equiv J_r/(10^{-19} \text{ergs cm}^{-2} \text{s}^{-1} \text{sr}^{-1} \text{Hz}^{-1})$, is plotted vs. [Si/H] assuming $\Sigma_\nu$ corresponding to an SFR, $\log_{10} \psi_\delta = -2.4 \, \text{M}_\odot \, \text{yr}^{-1} \text{ kpc}^{-2}$. In (a) we assume “Gal” dust and show results for various aspect ratios, $R/h$, and for the maximal and minimal dust depletion models. (b) Same as (a), except that “SMC” dust is assumed. Spherical solutions are also shown.
and maximum of the pressure field, i.e., $P_{\text{min}} < P < P_{\text{max}}$ (see Fig. 3a). For a given $\psi_*$, $l_{c r}$ in the CNM is at least 10 times larger than $l_{c r}$ in the WNM. Our first model, referred to as CNM, assumes that the typical DLA sight line encounters comparable H I column densities in the CNM and WNM. Because the empirical quantity $l_c$ is the density-weighted average of $l_c(r)$ along the line of sight (eq. [4]), $l_c$ will thus be dominated by contributions from $l_c(r)$ in the CNM. As a result, $l_c$ will be insensitive to density, as can be seen in Figure 3c, which shows $l_c$ to vary by less than 0.1 dex for $1 \text{ cm}^{-3} < \log_{10} n < 4 \text{ cm}^{-3}$, i.e., in the density range of the CNM.

This insensitivity to density is a generic trait of CNM gas, as shown in Figure 5, where $P$ and $l_{c r}$ are plotted against $n$ for a grid of SFRs. The results for the Q0458–02 and Q1346–03 DLAs are shown in Figures 5a and 5b and Figures 5c and 5d, respectively. These were chosen to compare results for a low-z metal-rich DLA and a high-z metal-poor DLA. As $\psi_*$ increases, $P_{\text{min}}$ and $P_{\text{max}}$ increase in magnitude and shift to higher densities (see W95). We shall assume that the pressure of the two-phase medium equals the geometric mean of $P_{\text{min}}$ and $P_{\text{max}}$, i.e., $P_{\text{eq}} = (P_{\text{min}}P_{\text{max}})^{1/2}$. In principle, $P_{\text{eq}}$ could assume any value between $P_{\text{min}}$ and $P_{\text{max}}$. We were guided by Zeldovich & Pikelner (1969), who used stability arguments to derive unique solutions for $P_{\text{eq}}$. Recent numerical simulations tend to support these conclusions and show that $P_{\text{eq}}$ is closer to $P_{\text{min}}$ than $P_{\text{max}}$ (Kritsuk & Norman 2002), in approximate agreement with our criterion. But given all the uncertainties, we shall not pursue the stability approach here. As discussed in § 3, the intersection between $P_{\text{eq}}$ and the equilibrium curve $P(n)$ results in two thermally stable roots: $n = n_{\text{CNM}}$ in the high-density CNM and $n = n_{\text{WNM}}$ in the low-density WNM (see also Fig. 3). The steeply rising black solid curves in Figures 5b and 5d connect the $n_{\text{CNM}}$ and $l_{c r}(n_{\text{CNM}})$ pairs determined for each $\psi_*$ of the SFR grid, where $l_{c r}(n_{\text{CNM}})$ represents $l_{c r}$ evaluated at the density $n_{\text{CNM}}$ determined for a given $\psi_*$. The intersections between these curves and the observed $l_c$ (horizontal lines) determine $n_{\text{CNM}}$ and $\psi_*$ for each DLA. These are denoted by “C” in Figures 5b and 5d, as are the corresponding locations in the $(P, n)$-plane. The unique $l_{c r}(n)$ curves passing through the intersection point “C” are shown as solid blue curves and correspond to $\log_{10} \psi_* = -1.90$ and $-2.75 \Msun \text{ yr}^{-1} \text{ kpc}^{-2}$ for Q0458–02 and Q1346–03, respectively. In most cases the precise location of $n_{\text{CNM}}$ is unimportant as the $l_{c r}$ versus $n$ curves are so

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Fig. 5.—Two-phase diagrams plotting $P/k$ and $l_{c r}$ vs. density. Results are shown for DLAs toward (a) and (b) Q0458–02 and (c) and (d) Q1346–03. The dot-dashed curves in (a) and (c) depict $P(n)$ equilibrium solutions for the SFR grid $\log_{10} \psi_* = -4, -3, \ldots, 0 \Msun \text{ yr}^{-1} \text{ kpc}^{-2}$. Dot-dashed curves in (b) and (d) depict $l_{c r}(n)$ equilibrium solutions for the same SFR grid. The solid and dashed black curves cutting across these solutions correspond to $l_{c r}(n_{\text{CNM}})$ and $l_{c r}(n_{\text{WNM}})$, respectively, for the SFR grid, where $n_{\text{CNM}}$ and $n_{\text{WNM}}$ are thermally stable densities for which the pressure $P = (P_{\text{min}}P_{\text{max}})^{1/2}$. The intersections between these curves and the observed $l_c$ (horizontal line) yield $n_{\text{CNM}}, n_{\text{WNM}}$, and the corresponding $\psi_*$ for each DLA. The intersections, denoted by “C” and “W,” are also shown in the $P(n)$ solutions. The two solid blue curves in (b) and (d) are the unique solutions passing through the intersections.
flat in the CNM. Therefore, the SFRs we derive are relatively insensitive to expressions for $P_{eq}$ (see discussion in Paper II). As discussed in § 5.1, the heating rates averaged along the line of sight equal the heating rates at midplane to an accuracy better than 10%. It follows from our steady state assumption that the same is true for the cooling rates, and it is this that justifies the approximation $I_c = I_{C}$.

Figure 5 also illustrates why Norman & Spaans (1997) suggested that all high-$z$ DLAs comprise neutral gas only in the WNM phase. Suppose that $I_c$ for the metal-poor DLA toward Q1346–03 ([Si/H] = −2.332) were increased to the lower limit placed on $I_c$ for the more metal-rich DLA toward Q0458–02 ([Si/H] = −1.785). In that case the SFR implied for the Q1346 DLA would be $I_{C0} = −1.2 M_\odot$ yr$^{-1}$ kpc$^{-2}$, which is 5 times the SFR implied by the same $I_c$ for the Q0458 DLA. The pressure inferred for the Q1346–03 DLA would increase from $3 \times 10^{12}$ to $10^{13}$ K cm$^{-3}$. The Norman & Spaans (1997) models required high pressures at high redshifts, since they assumed metallicity to decline rapidly with redshift. They concluded that the gravitational fields generated by low-mass galaxy progenitors in CDM models could not supply hydrostatic pressures as high as $10^9$ K cm$^{-3}$ at $z \sim 3$. To solve this problem, these authors concluded that all the neutral gas in high-redshift DLAs must be low-pressure matter in which $P_{eq} < P_{min}$, i.e., the gas is a pure WNM. Although recent studies show that the metallicities of high-$z$ DLAs are not as low as assumed by Norman & Spaans (see PW02), there are other, independent arguments for DLAs comprised of pure WNM gas. Specifically, the failure to detect 21 cm absorption in high-$z$ DLAs with large H 1 column densities led Kanekar & Chengalur (2001) to invoke high spin temperatures as the explanation. Moreover, Liszt (2002) claimed the large C n/C I ratio detected in many DLAs as evidence for WNM gas.

For these reasons we consider the alternative hypothesis that C n absorption in DLAs originates in the WNM. More specifically, we suppose that all low-ion transitions in DLAs, such as Ly$\alpha$ 1215, Si II 1527, Fe ii 1608, etc., are in low-density gas with $T_e \approx 8000$ K. According to the Norman & Spaans (1997) hypothesis, this occurs because $P < P_{min}$, i.e., CNM gas does not exist in high-$z$ DLAs. However, the detection of 21 cm absorption with spin temperatures $T_s < 600$ K in Q0458–02 (Wolfle et al. 1985) and $T_s < 1200$ K in Q1331+17 (Wolfle & Davis 1979; Chengalur & Kanekar 2000) rules out a pure WNM and is consistent with the presence of CNM in some cases. As a result, we retain the two-phase hypothesis but assume that the CNM covering factor is so low that many sight lines miss the CNM phase and encounter only the WNM phase. Because we assume $P = P_{eq}$, the density of the WNM would be given by this thermally stable root $n_{WNM}$ discussed above. In this case, the steeply rising dashed curves in Figures 5b and 5d connect the $n_{WNM}$, $I_{C}(n_{WNM})$ pairs, and their intersections with the observed $I_c$ are denoted by “W.” Proceeding by analogy with the CNM model, we find that $\log_{10} n = -0.90$ and $-1.75 M_\odot$ yr$^{-1}$ kpc$^{-2}$ for the Q0458–02 and Q1346–03 DLAs, respectively. Because the $I_{C}$ versus $n$ curves are flat at densities below our solution for $n_{WNM}$, the precise location of $n_{WNM}$ is not essential in this case either. Note that the shapes of the $I_{C}$ versus $n$ curves are flat in the WNM because at low densities the UV radiation field dominates the population of the $^2P_{3/2}$ and $^2P_{1/2}$ fine-structure states in C II through optical pumping. The increase of $I_{C}$ with $n_{WNM}$ is due to the increase in the pumping rate caused by the increase in FUV radiation. By contrast, the high gas densities in the CNM cause $I_{C}$ to equal the heating rate. Hence, in that case $I_{C}$ increases with $n_{WNM}$ because the heating rate rises with increasing $n_{WNM}$. The effects of CMB radiative excitations should be recognizable at low $n_{WNM}$, where pumping is negligible, and at high $n_{WNM}$, where the CMB intensity is high. They are evident in the $(n, I_{C})$-plane for the Q1346–03 DLA as the sharp flat cutoff at $\log_{10} I_{C} < 28$ erg s$^{-1}$ Hz$^{-1}$.
measurement of \([\text{Si}/\text{H}]\) or of a relevant proxy exists. We threw out the DLAs toward Q1759+75 and Q2343+12 because of evidence that \(C^+/C < 1\) and \(H^0/H < 1\); i.e., the gas causing damped \(\text{Ly}\alpha\) absorption is significantly ionized (Prochaska et al. 2002; Dessauges-Zavadsky 2003). This is in contrast to most DLAs, where \(H^0/H \approx 1\) (Vladilo et al. 2001). As a result, the maximal depletion subsample comprises the remaining 27 DLAs. For the minimal depletion sample we also excluded the DLAs toward Q0201+11 and Q2344+12 because the observed \([\text{Fe}/\text{Si}]\) exceeds the assumed “nucleosynthetic ceiling” value of \([\text{Fe}/\text{Si}]_{\text{int}} = -0.2\). Consequently, the minimal depletion subsample comprises the remaining 25 DLAs. The DLAs excluded from the subsamples are noted in Table 1.

We determined \(\psi_\star\) for each DLA in these subsamples. Figure 6 shows the resulting \(\psi_\star\) plotted against redshift for both the CNM and WNM models in the case of minimal dust-to-gas ratios and “Gal” dust composition. For either the CNM or WNM models the results are qualitatively similar for all four combinations of maximal or minimal dust-to-gas ratios and “Gal” or “SMC” composition. As a result of the lower fraction of cooling carried by \([\text{C}\ ii]\) 158 \(\mu\text{m}\) emission in the WNM, the SFRs are at least 10 times higher for the WNM model than for the CNM model. Although the positive detections exhibit an apparent decrease in \(\psi_\star\) with redshift in the interval \(z = [3, 4]\), no statistically significant evidence for redshift evolution exists. A Kendall \(\tau\) test using only positive detections shows \(\tau = -0.26\), while the probability for the null hypothesis of no correlation is \(p_{\text{Kendall}} = 0.26\). Since there is no empirical evidence that the DLAs with limits are physically distinct from those with measured \(\psi_\star\), we shall assume that all systems are drawn from the same underlying population. The lowest upper limits on \(\psi_\star\) at \(z = 3.608\) and 4.080 are possible exceptions to this rule, as these points are outliers with \(\psi_\star\) systematically below the range of the main population. A self-consistent interpretation we shall explore is that the underlying population of DLAs consists of two-phase media with \(\log_{10} \psi_\star\) ranging between \(-3\) and \(-2\) \(M_\odot\) yr\(^{-1}\) kpc\(^{-2}\). In most cases the sight lines pass through CNM and WNM gas. However, the sight lines through the two “outliers” (the DLAs toward Q1108+07 and Q2237−06) pass only through WNM gas, in which case the SFRs fall within the range of the underlying population (see Fig. 6b). If future observations reduce the upper limits on \(N(\text{C} \ ii)\) significantly, we would reject this hypothesis and attribute virtually all of \(l_{\text{cr}}\) in these two systems to excitation by the CMB (see Paper II).

Finally, we evaluated the pumping parameter, \(\xi\), for the 25 DLAs in the minimal depletion “Gal” sample. For \(\text{C} \ ii\) \(\lambda\lambda 1036.3\) and 1334.5 we found that the WNM solutions for \(\psi_\star\) resulted in \(\xi < 0.4\) for the 11 cases of positive \(\text{C} \ ii\)
SFRs inferred from flux-limited samples of galaxies for multiple redshift bins. Therefore, \( l_c(\mu) \) is likely to be lower in the WNM and approach the cooling rate \( n_A C_\mu \) (Fig. 3c, dotted blue curve). When we recomputed \( \psi_* \) in the absence of optical pumping, we found that \( \psi_* \) for the WNM increased between 0.2 and 0.3 dex above the values shown in Figure 6b. While a more realistic treatment of optical pumping (see Flannery et al. 1979, 1980) is necessary to compute accurate values of \( \psi_* \) in the WNM, it is obvious that the true values for \( \psi_* \) lie somewhere between the values shown in Figure 6b and those computed in the limit of zero pumping rates. In what follows we adopt the “optically thin” solutions with pumping shown in Figure 6b. We shall reexamine the effects of negligible pumping in Paper II, where we compute the bolometric background radiation generated by the WNM solutions.

5.3. The Average SFR per Unit Area, \( \langle \psi_* (z) \rangle \)

We now determine the average SFR per area \( \langle \psi_* \rangle \) from our sample distribution of \( \psi_* \). This is an important statistic since, as we show in Paper II, the SFR per unit comoving volume is proportional to \( \langle \psi_* \rangle \). Our goal is to determine \( \langle \psi_* \rangle \) in as many redshift bins as possible. This is because we wish to determine the star formation history of DLAs and because we wish to compare our results with comoving SFRs inferred from flux-limited samples of galaxies for multiple redshift bins (e.g., Steidel et al. 1999). We find that dividing the data into more than two redshift bins results in statistical errors in \( \langle \psi_* \rangle \) that exceed the systematic errors. As a result, we split the data set at the median redshift, \( z = 2.7 \), and determine \( \langle \psi_* \rangle \) in two redshift bins with redshift intervals \( z_1 = [1.6, 2.7] \) and \( z_2 = [2.7, 4.6] \).

While positive measurements of \( \psi_* \) were inferred for many DLAs with detected \( l_c \), upper limits on \( \psi_* \) were set for an even larger number of DLAs with upper limits on \( l_c \), and lower limits were set on \( \psi_* \) for a single DLA with a lower limit on \( l_c \). The numbers for the minimal and maximal depletion subsamples are 11 and 12 positive measurements, 13 and 14 upper limits, and a single lower limit, respectively. The presence of large numbers of limits among the data sets presents a challenge in estimating \( \langle \psi_* \rangle \). The arithmetic mean is particularly sensitive to possible large values in the system for which only a lower limit could be measured. As discussed in § 5.2, we do not have useful evidence that the systems with measured limits are physically distinct from those where the SFR has been detected. We therefore proceed from the assumption that the points with limits have been drawn from the same underlying distribution of SFRs as the detections. We use the detections to model this distribution empirically, as there is no consensus physical model for SFRs in DLAs at this redshift. We then treat the upper and lower limits as being drawn randomly from this empirical distribution truncated at the observed limit value. The mean value of the remaining probability distribution function is assigned to the data point, and the arithmetic mean of the full data set including upper and lower limits is then calculated. We have performed this calculation in two ways, using (1) the observed distribution of the detections and (2) a Gaussian in \( \log_{10} \psi_* \) fitted to this observed distribution as our probability density function, which is then truncated by the observed limit. The second approach is designed to include a reasonable probability of high-valued outliers to which the mean is particularly sensitive, although the mean derived by this method does not differ strongly from the first method, and indeed neither mean differs strongly from the simple arithmetic mean of the detections alone. The uncertainty in the mean of our sample is then calculated using bootstrap resampling (e.g., Efron & Tibshirani 1993). The bootstrap errors are larger than a nominal propagation of the errors on the individual detections because of significant scatter in the \( \psi_* \).

We computed \( \langle \psi_* \rangle \) with the two truncation approaches, as well as assuming it to be the arithmetic mean of the positive detections. The results of the three techniques agree within the 1 \( \sigma \) errors indicating that \( \langle \psi_* \rangle \) is a robust statistic. As a result, we henceforth assume \( \langle \psi_* \rangle \) to be given by the mean of the positive detections. Table 3 shows \( \langle \psi_* \rangle \) and the 1 \( \sigma \) errors adopted for the CNM and WNM models in the two redshift bins, for the assumptions of maximal and minimal depletion, and “Gal” and “SMC” dust composition. The errors are the quadratic sums of the bootstrap errors and errors of individual detections. Obviously the final uncertainty in \( \langle \psi_* \rangle \) is dominated by the systematic variation of the mean among the models. Averaging over the

| Table 3 |

| Average SFR per Unit Area |
|---------------------------|
| \( \langle \psi_* \rangle \) (M_\odot yr^{-1} kpc^{-2}) |
| **Dust Model** | **CNM** | **WNM** |
| \( z = 2.15 \) | \( z = 3.70 \) | \( z = 2.15 \) | \( z = 3.70 \) |
| “Gal,” max | \( 3.29 \pm 0.71 \times 10^{-3} \) | \( 2.23 \pm 0.40 \times 10^{-3} \) | \( 3.39 \pm 0.66 \times 10^{-2} \) | \( 2.50 \pm 0.45 \times 10^{-2} \) |
| “Gal,” min | \( 7.93 \pm 1.60 \times 10^{-3} \) | \( 4.52 \pm 1.12 \times 10^{-3} \) | \( 6.47 \pm 1.21 \times 10^{-2} \) | \( 4.38 \pm 0.86 \times 10^{-2} \) |
| “SMC,” max | \( 9.29 \pm 1.97 \times 10^{-3} \) | \( 4.45 \pm 1.02 \times 10^{-3} \) | \( 4.94 \pm 0.99 \times 10^{-2} \) | \( 3.34 \pm 0.57 \times 10^{-2} \) |
| “SMC,” min | \( 1.32 \pm 0.27 \times 10^{-2} \) | \( 6.39 \pm 1.79 \times 10^{-3} \) | \( 7.96 \pm 1.61 \times 10^{-2} \) | \( 4.84 \pm 0.99 \times 10^{-2} \) |

\( ^a \) Entries are SFRs per unit area.
\( ^b \) Mean redshift of low-z bin.
\( ^c \) Mean redshift of high-z bin.
\( ^d \) Carbonaceous “Gal” dust.
\( ^e \) Maximal model where \( \kappa = 10^{\mathrm{Si/H_i}} (10^{\mathrm{Fe/Si}} - 10^{\mathrm{Fe/Si}}} \), \( [\mathrm{Fe/Si}]_{\mathrm{int}} = 0 \).
\( ^f \) Minimal model where \( \kappa = 10^{\mathrm{Si/H_i}} (10^{\mathrm{Fe/Si}} - 10^{\mathrm{Fe/Si}}} \), \( [\mathrm{Fe/Si}]_{\mathrm{int}} = -0.2 \).
\( ^g \) Silicate “SMC” dust.
6. CONSTRAINTS ON DUST COMPOSITION IN DLAs

The heating rate, \( \Gamma_{dc} \), is proportional to \( \epsilon G_0 n_{\text{grain}}/n_{\text{H}} \), the product of the photoelectric heating efficiency of the dust grains, the FUV radiation intensity, and the abundance of the dust grains that dominate the heating. In §4.1 and the Appendix we use the dust-to-gas ratio \( \kappa \) to determine the abundance of grains that dominate the heating for both the Gal and SMC models. Our analysis implicitly assumes that the number of depleted C or Si atoms per depleted atom of Fe is the same in DLAs as in the Milky Way (see eq. [6]). We will now test this assumption for consistency with the lack of evidence of Si depletion in DLAs and with our assumption that Si and C are undepleted when calculating \( \kappa \) and the gaseous carbon abundance.

The depletion of Fe was determined by assuming that Si was undepleted. In that case the depleted ratio \( [\text{Fe}/\text{Si}]_{\text{depleted}} = 10^{[\text{Fe}/\text{Si}]_{\text{int}} - [\text{Fe}/\text{Si}]_{\text{gas}} - [\text{Fe}/\text{Si}]_{\text{int}}^{-1}} \), where the intrinsic ratio \( [\text{Fe}/\text{Si}]_{\text{int}} = 0 \) in the case of maximal depletion and \( [\text{Fe}/\text{Si}]_{\text{int}} = -0.2 \) in the case of minimal depletion. Since \( [\text{Fe}/\text{Si}]_{\text{gas}} \) typically equals \(-0.3\), we have \( [\text{Fe}/\text{Si}]_{\text{depleted}} = -0.3 \) for maximal depletion and \( [\text{Fe}/\text{Si}]_{\text{depleted}} = -0.9 \) for minimal depletion. Comparison with the abundance of Zn and S implies that Si cannot typically be depleted by more than 0.1 dex (PW02). Over the range of \( [\text{Fe}/\text{Si}] \) observed, this implies that measuring the relative abundance of Fe versus a nonrefractory element with the same nucleosynthetic history as Si such as S would generate values of \( [\text{Fe}/\text{Si}] \) about 0.1 dex lower than those observed for \( [\text{Fe}/\text{Si}] \). This implies that our technique of using Si as an undepleted element results in an underestimate of the dust-to-gas ratio. This is because the ratio of \( \kappa \) based on Si to \( \kappa \) based on S is given by

\[
\frac{n_{\text{Si}}}{n_{\text{S}}} = 10^{[\text{Si}/\text{S}]} \left( \frac{1 - 10^{[\text{Fe}/\text{Si}]_{\text{gas}} - [\text{Fe}/\text{Si}]_{\text{int}}^{-1}}{1 - 10^{[\text{Fe}/\text{Si}]_{\text{gas}} - [\text{Fe}/\text{Si}]_{\text{int}}^{-1}}} \right)^2,
\]

where we assumed \( [\text{Fe}/\text{Si}]_{\text{int}} = [\text{Fe}/\text{Si}]_{\text{int}} \) since Si and S are both \( \alpha \)-enhanced elements. Assuming \( [\text{Si}/\text{S}] = -0.1 \), we find that we have underestimated the dust-to-gas ratios by factors between 1.5 (maximal depletion) and 2.2 (minimal depletion), offering the possibility of reducing the SFRs by a factor of 2 in both the Gal and SMC models (since our estimate of \( \kappa \), i.e., \( \kappa_{\text{Si}} \), is used to predict the dust grain abundance in both models).

For the purposes of determining the gaseous carbon abundance in DLAs, we assumed that carbon was undepleted and set \( [\text{C}/\text{H}]_{\text{gas}} = [\text{Fe}/\text{H}]_{\text{int}} \). In the Gal model, however, we are relying on carbonaceous grains to dominate the heating, so carbon must be \textit{somewhat} depleted. Empirical determinations of the C abundance in DLAs are not available since all detectable C II resonance lines are saturated (except in one system). In our Galaxy, it appears that at least half of the C atoms are depleted at all densities (Meyer 1999). If this is also true in DLAs, it would reduce the gaseous C abundance by half and alter our thermal balance solutions such that \( \langle \psi_{\text{c}} \rangle \) is reduced by \( \approx 0.2 \) dex; this is a mild change in our results that leads to no qualitative differences in our conclusions. It seems more likely that the overall carbon depletion level is lower in DLAs as a result of the reduced metallicity. In particular, the SMC model has a reduction in the abundance of carbonaceous grains; therefore, it is likely that the vast majority of carbon is gaseous.

Without much knowledge of the composition of dust outside our own Galaxy, it is difficult to estimate the systematic uncertainty introduced by our assumption that the number of depleted Si and C atoms per depleted Fe atom is the same in DLAs as in the Milky Way. If there really is a base level of C depletion independent of density and metallicity, this implies that using \( \kappa \) underestimates the true number of depleted carbon atoms. However, this may still give a reasonable estimate of the small carbonaceous grains that dominate the heating but do not appear to be part of the base depletion in our Galaxy (Sauvage & Vigroux 1991). The uncertainty in the abundance of small carbonaceous grains is bracketed by the range of models for the size distribution of dust grains in Weingartner & Draine (2001a). The fraction of depleted C atoms in small carbonaceous grains could be a factor of 2 lower than implied by the extrapolated size distribution used by our adopted Bakes & Tielens (1994) model, which would reduce the photoelectric heating efficiency by a factor of 2 and thereby increase our inferred SFRs by a factor of 2. Reducing the overall number of depleted C atoms could make the SFRs even higher, but reducing the small carbonaceous grain population by more than a factor of 3 makes silicate grains dominate the heating, in which case the Gal model becomes the SMC model. Alternatively, the fraction of depleted C atoms contained in small grains could be increased by up to a factor of 4. If this is the case, or if indexing \( \kappa \) to Fe has underestimated the carbon depletion, small carbonaceous grains could be more abundant than our assumptions imply, leading to higher heating efficiency, reduced SFRs, and a stronger 2175 Å bump. Observational limits on the strength of the 2175 Å bump in DLAs make it difficult for small carbonaceous grains to be more than a factor of a few more abundant than we have supposed (Pei et al. 1991). Tighter observational limits on (and possibly detection of) the 2175 Å bump in DLAs are of the utmost importance in reducing the systematic uncertainties in the nature of dust at these redshifts.

In the SMC model, we suppose the complete absence of small carbonaceous grains as inferred from the lack of the 2175 Å bump. This allows one to lower the depletion level of Si considerably and still have silicate grains dominate the heating. Since Fe is almost completely depleted in diffuse regions of the Milky Way, we are likely to overestimate the ratio of \( n_{\text{Fe}}^{\text{depleted}}/n_{\text{Fe}}^{\text{int}} \) in a lower metallicity region, since our prescription for computing \( n_{\text{Fe}}^{\text{depleted}} \) in the Appendix would be an underestimate. This appears to be the case for the SMC, where absorption by clouds along the lines of sight to Sk 108 and Sk 155 shows \( [\text{Si}/\text{Zn}] = 0 \), implying a lack of silicon depletion, but \( [\text{Si}/\text{Fe}] = 0.5 \), indicating that iron is significantly depleted (Welty et al. 1997, 2001). In the diffuse regions of the Galaxy modeled by Weingartner & Draine (2001a), 75% of the Si atoms and 95% of the Fe atoms are depleted, but in the SMC it appears that no more than 20% of the Si atoms are depleted even though 70% of...
the Fe atoms are. This implies that indexing \( \kappa \) to the Fe depletion overestimates the number of depleted Si atoms by at least a factor of 3 if DLAs are like the SMC. This uncertainty is somewhat balanced by the uncertainty in the fraction of Si atoms contained in small (\(<15\) Å) grains. In the models of Weingartner & Draine (2001a), this varies from the fraction we have assumed up to a factor of 3 higher. Therefore, the abundance of small silicate grains dominating the heating is unlikely to be more than a factor of 3 higher than we have assumed; if it were, the DLA SFRs for the SMC model would be less than or equal to our current Gal model results. It is possible, on the other hand, to decrease the amount of Si depletion by an arbitrary amount, which would increase the inferred DLA SFRs. For the WNM solution, this would worsen the conflict with observational limits on the integrated background light discussed in Paper II. For both WNM and CNM solutions, it exacerbates the general problem of overproduction of metals in DLAs discussed in Paper II. Hence, the integrated background light constraints the abundance of small silicate grains in DLAs to be at least half of that of the Milky Way.

7. SUMMARY

The conventional view of DLAs is that they are high-\( z \) neutral gas layers with low metallicities, low dust content, and quiescent velocity fields. In this paper we have developed a new technique providing a more complete picture. Using the \( C^{m+} \) absorption method, we find that rather than being passive objects transmitting light from background QSOs, DLAs are the sites of active star formation and that neutral gas in DLAs is likely to be a two-phase medium. At this stage of our analysis it is unclear whether \( C^{m+} \) absorption arises in the CNM or WNM phase. Our conclusions are summarized as follows:

1. Our technique assumes that massive stars forming out of neutral gas in DLAs emit FUV radiation that heats the gas by ejecting photoelectrons from dust grains known to be present in the gas. We can infer the heating rate since in steady state conditions it equals the cooling rate that is directly measurable. This is because cooling is dominated by [C \( \equiv \)] 158 \( \mu m \) emission if the gas is a CNM, and [C \( \equiv \)] 158 \( \mu m \) emission per H atom can be obtained by measuring \( C^{m+} \lambda 1335.7 \) absorption arising from the \( 2P_{3/2} \) excited fine-structure state in the ground term in \( C^{+} \). The heating rate equals the product of the dust-to-gas ratio, the mean intensity of FUV emission, \( G_0 \), and the grain photoelectric heating efficiency, \( \epsilon \). We can measure \( G_0 \) since the cooling rate is inferred directly from the column density \( N(C^{m+}) \), the dust-to-gas ratio can be computed from element abundance patterns, and \( \epsilon \) is well determined provided that the gas is a CNM. By measuring \( G_0 \), we measure the SFR per unit area, \( \psi_* \), since \( \psi_* \propto G_0 \) in a plane-parallel layer.

2. We have measurements of \( C^{m+} \lambda 1335.7 \) absorption in 33 DLAs; 16 of these are positive detections, 15 are upper limits, and two are lower limits. We use these data to infer the spontaneous energy emission rate per H atom, \( l_* \), from the ratio \( N(C^{m+})/N(H \equiv) \). We find that \( l_* \) in DLAs is typically about 1/30 times \( l_* \) measured for the ISM of the Galaxy. Because \( l_* \) equals the cooling rate in the CNM, in our model \( l_* \) equals the heating rate, which is proportional to \( \kappa G_0 \), where \( \kappa \) is the dust-to-gas ratio in DLAs relative to the ISM. Since \( \kappa \) is also about 1/30, the implication is that \( G_0 \) in DLAs is similar to that in the ISM. In other words, \( \psi_* \) in DLAs is similar to the local \( \psi_* \) in the ISM, provided that \( C^{m+} \) absorption arises in a CNM.

3. We compute thermal equilibria of gas subjected to grain photoelectric heating and standard cooling processes. Since the dust content of DLAs is not well determined, we consider a “Gal” model, in which the grains are mainly carbonaceous and heating is dominated by small (\(<15\) Å) grains and PAHs, and a SMC model, in which heating is dominated by small silicate grains. We compute \( \kappa \) from the observed depletion of Fe in each DLA and assume that the number of C or Si atoms depleted onto grains per depleted Fe atom is the same in DLAs as in the Galaxy. We also consider models with minimal and maximal depletion to account for the uncertainties in the Fe depletion levels. We include heating and ionization due to cosmic rays and soft X-rays. When computing cooling rates, we account for excitation of the \( C^{+} \) fine-structure levels by CMB radiation. We also account for excitation due to optical pumping by FUV radiation but find that optical pumping may not be significant as a result of the high opacity in the \( C^\circ \) resonance lines. Equating heating and cooling rates, we find the resulting equilibrium curves of pressure versus density to exhibit a maximum pressure, \( P_{\text{max}} \), and minimum pressure, \( P_{\text{min}} \). A two-phase medium in which a dilute WNM is in pressure equilibrium with a dense CNM is possible if the equilibrium pressure, \( P_{\text{eq}} \), satisfies the constraint \( P_{\min} < P_{\text{eq}} < P_{\text{max}} \). Therefore, \( C^{m+} \) absorption can occur in the WNM or the CNM. Because \( l_* \) equals the cooling rate in the CNM but is a small fraction of the cooling rate in the WNM, the SFRs implied from a measured \( l_* \) are much higher in the WNM than the CNM.

4. We calculate \( \psi_* \) for selected subsets of our DLA sample corresponding to “Gal” or “SMC” dust and to minimal or maximal depletion. We first solve the transfer equation for sources of FUV (\( \approx15000 \) Å) radiation (OB stars) uniformly distributed throughout a plane-parallel disk. Using standard reddening curves for “Gal” and “SMC” dust, we find the disks to be optically thin parallel to the plane for most of our sample DLAs. As a result, the \( \psi_* \) inferred from \( C^{m+} \) absorption are representative of the entire DLA rather than just regions along the QSO sight line. To infer \( \psi_* \) from measurements of \( l_* \) and \( \kappa \), we assume the equilibrium pressure, \( P_{\text{eq}} = (P_{\min}P_{\text{max}})^{1/2} \). As expected, we find two solutions: one in which \( C^{m+} \) absorption occurs in the WNM, and the other in which \( C^{m+} \) absorption occurs in the CNM. For the CNM solution we find \(-3.0 \) \( M_{\odot} \) yr\(^{-1} \) kpc\(^{-2} \) \( < \log_{10} \psi_* < -2.0 \) \( M_{\odot} \) yr\(^{-1} \) kpc\(^{-2} \), and for the WNM solution we find \(-2.0 \) \( M_{\odot} \) yr\(^{-1} \) kpc\(^{-2} \) \( < \log_{10} \psi_* < -1.0 \) \( M_{\odot} \) yr\(^{-1} \) kpc\(^{-2} \). Neither case shows evidence for redshift evolution in the interval \( z = 1.6, 4.5 \). In Paper II we discriminate between these models by deriving cosmological constraints such as the bolometric background radiation.

5. Our assumptions that C and Si are undepleted in determining the gaseous C abundance and the dust-to-gas ratio are reasonable and do not create serious contradictions with the heating being dominated by carbonaceous or silicate grains because the C and Si depletion levels in DLAs appear to be quite low. Varying the size distribution of carbonaceous grains and the number of depleted C atoms per...
depleted Fe atom could make the SFRs reported for the Gal model as high as those of the SMC model, but one cannot lower the SFRs too far since the 2175 A bump has not been observed in high-redshift DLAs. Varying the number of depleted Si atoms per depleted Fe atom could make the SFRs reported for the SMC model as high as allowed by the integrated background limits, and varying the size distribution of silicate grains could make the SFRs a factor of 3 lower.

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APPENDIX
DUST-TO-GAS RATIO

Consider a box containing $N_{Fe}^{tot}$ iron atoms. If $N_{Fe}^{gas}$ atoms are in the gas phase and $N_{Fe}^{dust}$ atoms are locked up in grains, then

$$N_{Fe}^{dust} = N_{Fe}^{tot} - N_{Fe}^{gas}.$$  \hspace{1cm} (A1)

Because we cannot measure $N_{Fe}^{tot}$ as a result of depletion of Fe atoms onto grains, we shall use Si as a proxy as Si is essentially undepleted in DLAs (see PW02). Therefore, we assume $N_{Si}^{tot} = N_{Si}(Fe/Si)_{int}$, where $N_{Si}$, the total number of Si atoms, also equals the number of gas-phase Si atoms and $(Fe/Si)_{int}$ is the intrinsic (i.e., undepleted) ratio of Si to Fe. Let the dust-to-gas ratio $k \equiv N_{Fe}^{dust}/N_{H}$. As a result,

$$k = \frac{N_{Si}(Fe/Si)_{int}}{N_{H}} - \frac{N_{Fe}^{gas}}{N_{H}}.$$  \hspace{1cm} (A2)

where $N_{H}$ is the number of H atoms. Since $k \equiv k/k_{MW}$, where $k_{MW}$ is the dust-to-gas ratio of the current Milky Way, and assuming that $k_{MW} = (Fe/H)_{\odot}$, since Fe is almost entirely depleted, we find

$$k = \frac{(Si/H)(Fe/Si)_{int}}{(Fe/H)_{\odot}} - \frac{(Fe/H)^{gas}}{(Fe/H)_{\odot}}.$$  \hspace{1cm} (A3)

Factoring Fe/H = (Fe/Si)(Si/H), we find

$$k = \frac{(Si/H)(Fe/Si)_{int}}{(Si/H)_{\odot} (Fe/Si)_{\odot}} - \frac{(Si/H)(Fe/Si)_{int}}{(Si/H)_{\odot} (Fe/Si)_{\odot}}.$$  \hspace{1cm} (A4)

As a result,

$$k = 10^{(Si/H)_{int}} \left(10^{[Fe/Si]_{int}} - 10^{[Fe/Si]_{gas}}\right).$$  \hspace{1cm} (A5)

where we assume $[Si/H] = [Si/H]_{int}$.

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