ON THE ABSENCE OF HIGH METALLICITY-HIGH COLUMN DENSITY DAMPED LYMAN $\alpha$ SYSTEMS: MOLECULE FORMATION IN A TWO-PHASE INTERSTELLAR MEDIUM

MARK R. KRAMHOLZ
Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA

SARA L. ELLISON
Department of Physics and Astronomy, University of Victoria, BC, V8P 5C2, Canada

J. XAVIER PROCHASKA
Department of Astronomy and Astrophysics, University of California, Santa Cruz, CA 95064, USA

JASON TUMLINSON
Space Telescope Science Institute, Baltimore, MD 21218, USA

Submitted to the Astrophysical Journal Letters

ABSTRACT

We argue that the lack of observed damped Lyman $\alpha$ (DLA) systems that simultaneously have high HI column densities and high metallicities results naturally from the formation of molecules in a two-phase atomic medium. In contrast to earlier work, our result applies equally well in diffuse systems where the ultraviolet radiation field is dominated by the extragalactic background and in dense star-forming ones, where the local radiation field is likely to be orders of magnitude higher. We point out that such a radiation-independent model is required to explain the absence of high column density high metallicity systems among DLAs observed using gamma-ray burst afterglows, since these are likely subjected to strong radiation fields created by active star formation in the GRB host galaxy. Moreover, we show that the observed relationship between the maximum atomic gas column in DLAs sets a firm upper limit on the fraction of the mass in these systems that can be in the warm, diffuse phase. Finally, we argue that our result explains the observed lack of in situ star formation in DLA systems.

Subject headings: galaxies: ISM — gamma rays: bursts — ISM: molecules — ISM: structure — quasars: absorption lines — stars: formation

1. INTRODUCTION

Damped Lyman $\alpha$ (DLA) systems are clouds of neutral atomic hydrogen with column densities $N$(H\textsc{i}) $\geq 2 \times 10^{20}$ cm$^{-2}$ that are detected as absorbers against bright background quasars (QSOs) or gamma-ray bursts (GRBs) (Wolfe et al. 2005; Prochaska et al. 2005, 2007, 2008). These systems comprise the bulk of the neutral gas in the universe at redshifts up to at least $z \sim 5$. Because of their ubiquity, the study of DLAs provides vital clues to the distribution of gas and metals, and potentially also star formation, in the universe.

Observations of DLAs show a clear zone of exclusion: none are observed with both high metallicity and high HI column density. One possible explanation for this effect is that lines of sight with large column densities and metallicities produce large dust extinctions that might lead to exclusion of the background QSO from optically-selected samples (Boisse et al. 1998; Prantzos & Boissier 2000). However, statistical analysis of the optically-selected QSO-DLA sample suggests that few DLAs are missed due to extinction (Vladilo & Peroux 2003; Pontzen & Pettini 2009), and radio-selected QSO-DLA samples do not differ significantly from optically-selected ones (Ellison et al. 2001, 2005; Akerman et al. 2005; Jorgenson et al. 2006). Moreover, GRBs can be much brighter than QSOs and thus are less subject to dust bias, and GRB-DLAs appear to respect the same zone of exclusion as QSO-DLAs.

An alternative hypothesis to explain the zone of exclusion is that above some threshold column density, which decreases with increasing metallicity, gas forms molecular hydrogen that is not detectable in Ly $\alpha$ absorption (Schaye 2001; Hirashita & Ferrara 2003; Hirashita et al. 2006). Large amounts of molecular gas are not observed in these DLAs because molecular clouds have a very small covering fraction and are unlikely to be seen along random sightlines (Zwaan & Prochaska 2006), although in some cases trace amounts of molecular gas have been detected (e.g. Ledoux et al. 2003; Noterdaeme et al. 2008). In one GRB-DLA a substantial column of molecular hydrogen has been detected (Prochaska et al. 2009), and, as we show below, this system is unique among DLAs in its high column density and metallicity.

While the molecule-formation hypothesis avoids the problems of the dust bias explanation, it also has significant weaknesses. In DLAs we can observe only column density and metallicity, so previous authors have been forced to assume values, which may be incorrect, for other quantities such as total gas volume density and radiation field that influence the molecule fraction. For example Schaye (2001) assumes a Lyman-Werner (LW)
radiation field set by the Haardt & Madau (2001) UV background at \( z = 3 \), which is 50 times smaller than the Solar neighborhood value, while the weakest radiation field that Hirashita et al. (2006) consider is 2 times larger than in the Solar neighborhood. Observationally-inferred radiation fields in DLAs span this full range and more (Tumlinson et al. 2007; Wolfe et al. 2008), so neither assumed value works for the full DLA population.

Our goal in this paper is to explain the zone of exclusion using the Krumholz et al. (2008, 2009a, hereafter KMT08 and KMT09) theory of the atomic to molecular transition in galaxies, which does not depend on unobservable quantities such as the gas volume density and UV radiation field. Instead, KMT09 show that to good approximation the molecular fraction in a cloud depends only on its column density and a single dimensionless parameter, which combines the volume density, radiation intensity, \( \mathrm{H}_2 \) formation rate coefficient, and dust opacity, and that the two-phase nature of the atomic interstellar medium imposes strong constraints on the values this parameter can take. This model explains the observed molecular fractions and star formation rates in nearby galaxies (KMT09, Krumholz et al. 2009b), and in §2 we apply it to DLAs. In §3 we demonstrate that the observed zone of exclusion sets strong constraints on the fraction of warm atomic gas in DLAs. Finally, in §4 we discuss the implications of our work.

2. MOLECULE FORMATION AND THE ZONE OF EXCLUSION

2.1. Theoretical Model of \( \mathrm{H}_2 \) Formation

We refer readers to KMT08 and KMT09 for a full derivation of the formalism, and here simply summarize. Consider a spherical cloud of gas immersed in a uniform, isotropic dissociating radiation field. The outer parts are kept predominantly atomic by the radiation, but as one moves inward dissociating photons are absorbed both by \( \mathrm{H}_2 \) molecules and by dust grains. At some depth into the cloud almost all dissociating photons have been absorbed, and there is a sharp transition to predominantly molecular material. The fraction of the cloud radius at which this transition occurs depends only on two dimensionless numbers: \( \tau_0 = N \sigma_d \), the dust optical depth of the cloud, and \( \chi = f_{\text{diss}} \sigma_d c E_0^\prime / (n_{\text{HI}} R) \), the dimensionless strength of the background radiation field. Here \( N \) is the total column density of the cloud including atomic and molecular material, \( \sigma_d \) is the dust cross section per H nucleus to photons in the dissociating LW bands, \( f_{\text{diss}} \approx 0.1 \) is a quantum-mechanical constant describing the approximate probability of dissociation per LW photon absorption, \( E_0^\prime \) is the number density of photons in the LW bands of the background dissociating radiation field, \( n_{\text{HI}} \) is the density of gas in the atomic envelope of the cloud, and \( R \) is the rate coefficient describing formation of hydrogen molecules on the surfaces of dust grains. In the limit \( N \rightarrow \infty \), the H I column density \( N(\mathrm{H}1) \) approaches a finite maximum value that depends only on \( \chi \) and on the dust cross section \( \sigma_d \) (which in turn depends on the metallicity) in the atomic shielding region around the cloud. In effect, a fixed optical depth of material is sufficient to absorb the entire LW photon flux, so any additional material takes the form of molecular rather than atomic gas. This produces the observed zone of exclusion: a metallicity-dependent maximum H I column.

KMT09 point out that \( \chi \) cannot vary strongly between galaxies. Both \( \sigma_d \) and \( R \) measure the total surface area of dust grains in the gas, so \( \sigma_d / R \) is insensitive to changes in dust abundance or size distribution, and thus varies little with environment. Moreover, in a two-phase atomic medium, the H I density \( n_{\text{HI}} \) that determines when molecules form is the density of the cold neutral phase, \( n_{\text{CNM}} \). This is because the effective LW opacity of a fluid element provided by \( \mathrm{H}_2 \) absorption, which usually dominates, is proportional to its density (cf. equation 8 of KMT08). Thus the low density of the warm phase guarantees that it provides negligible shielding compared to the cold gas, and we care almost exclusively about \( n_{\text{CNM}} \). The ratio \( E_0^\prime / n_{\text{CNM}} \) is tightly constrained by the thermodynamics of the gas and the requirement of pressure balance between the two phases (Wolff et al. 2003; a reasonable approximation is \( E_0^\prime / n_{\text{CNM}} \approx (1 + 3.12^{0.365})/93 \) cm\(^3\), where \( Z' \) and \( E_0^\prime \) are the metallicity and FUV radiation intensity \( E_0^\prime \) normalized to their values in the Solar neighborhood.\(^1\) Together, with the invariance of \( \sigma_d / R \), this (weak) dependence of \( E_0^\prime / n_{\text{CNM}} \) on \( Z' \) gives a dimensionless radiation intensity \( \chi \approx 0.77 (1 + 3.1 Z'^{0.365}) \) that depends only on the metallicity of the gas.

The implication of this result is that, for a two-phase ISM, the dimensionless radiation strength \( \chi \) that controls when molecules form does not depend on the absolute FUV radiation field in a galaxy. Any change in the radiation intensity induces a countervailing change in the CNM density. This is the fundamental reason that there is a zone of exclusion for all DLAs despite the huge range in radiation intensities inferred within them. To calculate this effect quantitatively, if we assume that dust opacity \( \sigma_d \) scales with metallicity, then in the KMT formalism the molecular mass fraction becomes solely a function of \( N_c \) and \( Z' \), which is approximately given by

\[
\phi_{\text{mol}}(N_c, Z') \approx 1 - \left[ 1 + \left( \frac{3}{4} \frac{s}{1 + \delta} \right)^{2/3} \right]^{-1/5},
\]

where \( N_c \) is the column density of cold gas (i.e. including CNM and molecular gas, but excluding warm atomic gas), \( s = \ln(1 + 0.6 \chi)/(0.045 N_{20} Z') \), \( N_{20} = N_c / [10^{20} \text{ H nuclei cm}^{-2}] \), and \( \delta = 0.0712 (0.1 s^{-1} + 0.675)^{-2/3} \). (Note that this approximation is slightly different than the one given in KMT09: the two agree to within a few percent for clouds that are substantially molecular, but this one is more accurate at low values of \( f_{\text{H}_2} \) – McKee et al., 2009, in preparation.) The corresponding covering fraction of the molecular region is

\[
f_{\text{H}_2}(N_c, Z') \approx \left[ 1 - \phi_{\text{mol}} (1 - f_{\text{H}_2}^{\text{ol}}) \right]^{-2/3},
\]

where \( \phi_{\text{mol}} \) is the ratio of the mass densities of the molecular and cold atomic gas. KMT09 show that \( \phi_{\text{mol}} \approx 10 \) is typical.

For a given metallicity \( Z' \) it is trivial to numerically invert equation 2 to calculate the total cold gas column density \( N_c \) for which the molecular covering fraction

\(^1\) Following Draine (1978), we take the LW radiation intensity in the Solar neighborhood to have a value that produces a free-space dissociation rate of \( 5.43 \times 10^{-11} \text{ s}^{-1} \); this is 1.6 times the Habing (1968) field.
Fig. 1. — H i column density $N$(H i) versus normalized metallicity $Z'$ for molecular covering fractions from $c_{H_2} = 0.01 - 1$. We also show lines of constant $H_2$ covering fraction $c_{H_2}$ (blue lines, larger $c_{H_2}$ at larger $N$(H i)), lines of constant color excess $E(B-V)$ (green dotted lines, larger $E(B-V)$ at larger $N$(H i)), a sample of QSO-DLAs from Herbert-Fort et al. (2009), Kaplan et al. (2009, in preparation), and Dessauges-Zavadsky et al. (2009, in preparation) (black circles), a sample of GRB-DLAs without H2 detections (red diamonds; Prochaska et al. 2007), and the GRB080607 DLA with an $H_2$ detection (purple diamonds connected by line; Prochaska et al. 2009). For the QSO-DLAs, filled circles indicate detections of metals and open circles indicate the 1σ upper limits on metallicity. See the main text for discussion of the data.

reaches a particular value $c_{H_2}$. Assuming the bulk of the atomic gas is in the cold phase, the mean atomic column density is then $N$(H i) = $(1 - f_{H_2}) N_c$. This defines a locus of points in the $(N$(H i), $Z'$)-plane corresponding to the specified $c_{H_2}$. The maximum possible H i column density corresponds to the limit $c_{H_2} \to 1$.

2.2. Comparison of Models and Observations

In Figure 1 we plot our derived values $N$(H i) versus $Z'$ for molecular covering fractions from $c_{H_2} = 0.01 - 1$. We also show lines of constant $E(B-V)$, computed using a Draine (2003) $R_V = 3.1$ extinction curve scaled by metallicity, giving $E(B-V) / N$(H i) = $1.65 \times 10^{-22} Z'$ cm$^{-2}$ and $A_V / N$(H i) = $5.32 \times 10^{-22} Z'$ mag cm$^{-2}$. We compare to observed QSO- and GRB-DLAs from Herbert-Fort et al. (2009), Prochaska et al. (2005, 2009), Kaplan et al. (2009, in preparation), and Dessauges-Zavadsky et al. (2009, in preparation). For the Dessauges-Zavadsky et al. sample we derive metallicities based on zinc abundances: $\log Z' = [Zn/H] = \log(Zn/H) - \log(Zn/H)_{⊙}$, where $\log(Zn/H)_{⊙} = 12.463$ (Lodders 2003). For all other data we use the metallicity reported by the authors. To avoid possible issues arising from either ionization correction or metallicity correction with redshift, we exclude DLAs with $N$(H i) < 20 and redshift $z < 1.7$.

As the Figure shows, the zone at high $N$(H i) and $Z'$ where no DLAs lie (except that associated with GRB080607, which we discuss below), corresponds extremely well to the zone of exclusion predicted by the KMT formalism. The plot also explains why large molecular column densities have not been detected in these systems. The molecular covering fraction declines very sharply away from the $c_{H_2} = 1$ line, so only six DLAs systems lie above $c_{H_2} = 0.01$, and all but GRB080607 lie below $c_{H_2} = 0.06$. This is consistent with the results of Zwaan & Prochaska (2000), who conclude that detection of true molecular clouds in DLAs is extremely unlikely because, in the range of volume densities probed by DLAs, molecular material covers a tiny fraction of a galaxy’s area. Trace amounts of molecular hydrogen have been discovered in some DLAs (e.g. Ledoux et al. 2003; Noterdaeme et al. 2008), but these low molecular column densities almost certainly correspond to $H_2$ spatially mixed with cold atomic gas, rather than true molecular clouds. The KMT formalism does not apply to these cases, since it is based on the approximation of a sharp transition between mostly atomic and mostly molecular regions, and we defer discussion of what can be learned from these detections to future work.

2.3. The DLA Associated with GRB080607

The DLA associated with GRB080607 (Prochaska et al. 2009) is unique in that it shows a clear detection of significant columns of $H_2$ and CO, and that it lies well within the zone of exclusion. We plot this detection at two metallicities derived in different ways. One value at $\log Z' = -0.2$ corresponds to the oxygen abundance [O/H]. The other at $\log Z' = -0.94$ is derived using the observed visual extinction $A_V \approx 3.2$ and $H_2$ column densities $N$(H i) = 22.7 and $N$(H2) = 21.2, and adopting the same metallicity-dependent $A_V / N$(H i) ratio as in §2.2. Since the molecular fraction depends on metals in solid form that can catalyze $H_2$ formation and absorb LW photons, the latter estimate is probably the relevant one. The solid content of the atomic gas may be even lower if a disproportionate share of the observed extinction comes from the molecular material.

While it is gratifying that the only DLA in the zone of exclusion is also the only one that shows significant molecular material, we must still explain why its column is only 6% molecular. Molecule dissociation by the GRB afterglow is unlikely to be the explanation. The hard spectrum of the afterglow illuminating a molecular cloud produces nearly coincident ionization and dissociation fronts with little neutral, atomic hydrogen between them (Draine & Haq 2002), and excited $H_2$ just outside a dissociation front should produce strong absorption features in the DLA that are not observed (Prochaska et al. 2009; however, see Sheffer et al., 2009, in preparation). Observations instead suggest that the molecular cloud is at least 100 pc away from the GRB, so our line of sight must pass through the host galaxy’s disk at a glancing angle. In this configuration we expect a majority of the material along the line of sight to be warm atomic gas that is unrelated to the molecular cloud, and, as discussed in §2.1, provides no shielding to it.

Quantitatively, let the DLA sightline contain warm material with column density $N_w$ and cold material (including both cold atomic and molecular gas) with column density $N_c$. In this case the molecular column will be

$$1.8 N(H_2) = f_{H_2}(N_c, Z') N_c,$$

where the factor of 1.8 accounts for the difference in mean number of particles per unit mass between atomic and molecular gas. For $\log Z' = -0.94$ and the observed molecular column density $log N(H_2) = 21.2$, solving this equation yields $log N_c = 22.0$, which implies $f_{H_2} = \ldots$
We emphasize, however, that our constraint on the warm gas fraction is only statistical. There cannot be many DLAs with high column density, high metallicity, and large warm gas fraction, but any individual DLA can be dominated by warm gas provided that it does not also have high NV(H1) and Z′. Thus our results are consistent with the conclusion of Kanekar et al. (2009), who find high H1 spin temperatures and thus large values of fω for the DLAs shown by the green points in Figure 2. Significantly, all of these points are at least 1.6 dex to the left of the fω = 0 line. Thus they have large fω but small NV(H1) and Z′, and do not violate our constraint on the non-existence of systems where fω, NV(H1), and Z′ are all large.

4. SUMMARY AND DISCUSSION

We show that the absence of high column density, high metallicity DLAs results from the conversion of atomic into molecular gas. We have done so with a model that does not depend on the radiation environment within the DLA due to the way that atomic gas responds to variations in radiation field in a two-phase medium. The maximum metallicity and column density do depend on the fraction of the atomic gas that is cold and dense, so that it can shield against dissociating Lyman-Werner photons. The observed distribution of DLAs is inconsistent with the existence of a significant population of high NV(H1) DLAs that are dominated by warm gas.

Given our conclusion that high column density DLAs must host significant amounts of cold gas, one might ask, as pointed out by Wolfe & Chen (2006), most DLAs cannot host significant in situ star formation. The answer is that the presence of cold gas is a necessary but not sufficient condition for star formation. Although DLAs populate the NV(H1), Z′ plane up to the point where the molecule fraction becomes large, the vast majority of them are found at much lower column densities and metallicities, where they are not expected to have any significant amount of molecular gas. If stars form exclusively in molecular gas, as numerous observations now seem to suggest, then the vast majority of DLA columns should be inert as far as star formation is concerned.

This is not to say that DLA systems do not host any star formation. Indeed, indirect measures of the radiation fields in some QSO-DLAs show strong evidence for the presence of a local heat source that is likely to be star formation (Wolfe et al. 2008), and in GRB-DLA systems there is obviously evidence for ongoing star formation. Our result simply suggests that the star formation must be taking place in other parts of these galaxies, which have significantly higher column densities and molecular contents than the sightlines we most commonly observe as DLAs.

We thank C. F. McKee for helpful discussions. Support for this work was provided by the Alfred P. Sloan Foundation (MRK), by NASA, as part of the Spitzer Theoretical Research Program, through a contract issued by the JPL (MRK), by the National Science Foundation through grants AST-0807739 (MRK) and AST-0709235 (JXP), and by an NSERC Discovery Grant (SLE).
REFERENCES

Akerman, C. J., Ellison, S. L., Pettini, M., & Steidel, C. C. 2005, A&A, 440, 499

Boisse, P., Le Brun, V., Bergeron, J., & Deharveng, J.-M. 1998, A&A, 333, 841

Draine, B. T. 1978, ApJS, 36, 595

—. 2003, ARA&A, 41, 241

Draine, B. T., & Hao, L. 2002, ApJ, 569, 780

Ellison, S. L., Hall, P. B., & Lira, P. 2005, AJ, 130, 1345

Ellison, S. L., Yan, L., Hook, I. M., Pettini, M., Wall, J. V., & Shaver, P. 2001, A&A, 379, 393

Haardt, F., & Madau, P. 2001, in Clusters of Galaxies and the High Redshift Universe Observed in X-rays, ed. D. M. Neumann & J. T. V. Tran

Habing, H. J. 1968, Bull. Astron. Inst. Netherlands, 19, 421

Herbert-Fort, S., Prochaska, J. X., Dessauges-Zavadsky, M., Ellison, S. L., Howk, J. C., Wolfe, A. M., & Prochter, G. E. 2006, PASP, 118, 1077

Hirashita, H., & Ferrara, A. 2005, MNRAS, 356, 1529

Hirashita, H., Shibai, H., & Takeuchi, T. T. 2006, A&A, 452, 481

Jorgenson, R. A., Wolfe, A. M., Prochaska, J. X., Lu, L., Howk, J. C., Cooke, J., Gawiser, E., & Gelino, D. M. 2006, ApJ, 646, 730

Kanekar, N., Lane, W. M., Momjian, E., Briggs, F. H., & Chengalur, J. N. 2009, MNRAS, 394, L61

Krumholz, M. R., McKee, C. F., & Tumlinson, J. 2008, ApJ, 689, 865 (KMT08)

—. 2009a, ApJ, 693, 216 (KMT09)

—. 2009b, ApJ, in press, arXiv:0904.0009

Ledoux, C., Petitjean, P., & Srianand, R. 2003, MNRAS, 346, 209

Lodders, K. 2003, ApJ, 591, 1220

Noterdaeme, P., Ledoux, C., Petitjean, P., & Srianand, R. 2008, A&A, 481, 327

Pontzen, A., & Pettini, M. 2009, MNRAS, 393, 557

Prantzos, N., & Boissier, S. 2000, MNRAS, 315, 82

Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007, ApJ, 666, 267

Prochaska, J. X., Chen, H.-W., Wolfe, A. M., Dessauges-Zavadsky, M., & Bloom, J. S. 2008, ApJ, 672, 59

Prochaska, J. X., Herbert-Fort, S., & Wolfe, A. M. 2005, ApJ, 635, 123

Prochaska, J. X., et al. 2009, ApJ, 691, L27

Schaye, J. 2001, ApJ, 562, L95

Tumlinson, J., Prochaska, J. X., Chen, H.-W., Dessauges-Zavadsky, M., & Bloom, J. S. 2007, ApJ, 668, 667

Vladilo, G., & Péroux, C. 2005, A&A, 444, 461

Wolfe, A. M., & Chen, H.-W. 2006, ApJ, 652, 981

Wolfe, A. M., Gawiser, E., & Prochaska, J. X. 2005, ARA&A, 43, 861

Wolfe, A. M., Prochaska, J. X., Jorgenson, R. A., & Rafelski, M. 2008, ApJ, 681, 881

Wolfe, M. G., McKee, C. F., Hollenbach, D., & Tielens, A. G. G. M. 2003, ApJ, 587, 278

Zwaan, M. A., & Prochaska, J. X. 2006, ApJ, 643, 675