ON THE ORIGIN OF THE HIGH COLUMN DENSITY TURNOVER IN THE HI COLUMN DENSITY DISTRIBUTION

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ABSTRACT

We study the high column density regime of the HI column density distribution function and argue that there are two distinct features: a turnover at $N_{\text{HI}} \approx 10^{21}$ cm$^{-2}$ which is present at both $z = 0$ and $z \approx 3$, and a lack of systems above $N_{\text{HI}} \approx 10^{22}$ cm$^{-2}$ at $z = 0$. Using observations of the column density distribution, we argue that the HI-H2 transition does not cause the turnover at $N_{\text{HI}} \approx 10^{21}$ cm$^{-2}$, but can plausibly explain the turnover at $N_{\text{HI}} \gtrsim 10^{22}$ cm$^{-2}$. We compute the HI column density distribution of individual galaxies in the THINGS sample and show that the turnover column density depends only weakly on metallicity. Furthermore, we show that the column density distribution of galaxies, corrected for inclination, is insensitive to the resolution of the HI map or to averaging in radial shells. Our results indicate that the similarity of HI column density distributions at $z = 3$ and $z = 0$ is due to the similarity of the maximum HI surface densities of high-$z$ and low-$z$ disks, set presumably by universal processes that shape properties of the gaseous disks of galaxies. Using fully cosmological simulations, we explore other candidate physical mechanisms that could produce a turnover in the column density distribution. We show that while turbulence within GMCs cannot affect the DLA column density distribution, stellar feedback can affect it significantly if the feedback is sufficiently effective in removing gas from the central 2-3 kpc of high-redshift galaxies. Finally, we argue that it is meaningful to compare column densities averaged over ~ kpc scales with those estimated from quasar spectra which probe sub-arcsecond scales due to the steep power spectrum of HI column density fluctuations observed in nearby galaxies.

1. INTRODUCTION

The statistical distribution of HI column densities is one of the most widely used statistics to describe the statistical properties of atomic hydrogen absorption systems seen in quasar spectra over a wide range of redshifts. Recently, high-resolution HI maps of nearby galaxies have been used to study HI column density distributions of both individual galaxies and statistically for the entire galaxy population (e.g., Zwaan & Prochaska 2006). Current measurements of the column density distribution span almost ten orders of magnitude in column density, $N_{\text{HI}}$, ranging from the highly ionized gas in the intergalactic medium (IGM), $N_{\text{HI}} \sim 10^{22} - 1.6 \times 10^{17}$ cm$^{-2}$, to the predominantly neutral gas associated with the interstellar medium (ISM) of galaxies and their satellites, $N_{\text{HI}} > 10^{21}$ cm$^{-2}$ (e.g., Prochaska et al. 2010). Since physically diverse systems contribute to the distribution, a theoretical understanding of the entire HI column density distribution requires understanding IGM gas as well as gas within galaxies and the circumgalactic medium. As such, the HI column density distribution is a key test of the CDM structure formation paradigm.

Initial measurements of the HI column density distribution were consistent with a single power-law function over the entire column density range (e.g., Fryxell 1987). However, subsequent surveys have found considerably more structure; e.g., flattening at $N_{\text{HI}} \approx 10^{16} - 10^{17}$ cm$^{-2}$ (Petitjean et al. 1993), and steepening of the function at higher column densities corresponding to the damped Lyman $\alpha$ (DLA; $N_{\text{HI}} > 2 \times 10^{20}$ cm$^{-2}$) systems, and in particular, pronounced steepening at $N_{\text{HI}} \gtrsim 10^{21}$ cm$^{-2}$ (Storrie-Lombardi & Wolfe 2000, Prochaska et al. 2005, Wolfe et al. 2005, Noterdaeme et al. 2009). Most recently, Prochaska et al. (2010) found that the HI column density distribution has six different regimes, each approximated by its own power law, which intersect at column densities $N_{\text{HI}} = [10^{14.5}, 10^{17.3}, 10^{19}, 10^{20.3}, 10^{21.75}]$ cm$^{-2}$.

This rich structure is presumably the result of physically distinct populations of absorbers. At the lowest column densities of the Lyman $\alpha$ forest, $N_{\text{HI}} \approx 10^{12} - 10^{17}$ cm$^{-2}$, absorbers arise in the highly ionized intergalactic gas and both the shape of the column density distribution and its evolution with redshift are now fairly well understood (e.g., see Meiksin 2009, for a recent review). At column densities of $N_{\text{HI}} \approx 10^{17} - 10^{20}$ cm$^{-2}$ the absorbers arise in Lyman Limit Systems (LLS). These systems are thought to arise in circumgalactic gas and clouds (e.g., Fumagalli et al. 2011) and are capable of self-shielding against ionizing radiation (Altay et al. 2011), which results in a pronounced flattening of the distribution at these column densities. At the highest column densities of $N_{\text{HI}} \gtrsim 10^{20}$ cm$^{-2}$, DLA absorption lines are thought to arise in the interstellar medium of high-redshift galaxies (e.g., Wolfe et al. 2005). These absorption lines thus directly probe properties of cold gas in high-redshift disks which contain most of the cold gas in the universe.

As we discuss in the next section, modeling the column density distribution and other properties of these DLA systems is both challenging and interesting. It is challenging because the small-scale density and velocity structure of the high-redshift ISM must be reproduced correctly. This same reason makes it interesting since the column density distribution provides a unique way of testing the small-scale gas distribution in theoretical models.

The column density distribution for DLAs has two important features which we will discuss in this paper. First, at
both low and high redshifts there is a pronounced turnover at $N_{\text{HI}} \approx 10^{21} \text{ cm}^{-2}$ (Zwaan et al. 2005; Noterdaeme et al. 2009; Prochaska & Wolfe 2009). The location of this turnover is found by fitting the column density distribution with either a gamma distribution or a double power-law. At low redshift, where observations extend to higher column density, there is an additional feature. We see that there is a transition from HI-H$_2$ at $N_{\text{HI}} \approx 10^{20} \text{ cm}^{-2}$ which leads to a lack of HI systems above this column density (Zwaan et al. 2005; Zwaan & Prochaska 2006). At high redshift this region has not been probed due to insufficient statistics. Previously, these two features were not distinguished but in this paper we will treat them separately since we are interested in differentiating the physical mechanisms which control each of them. In previous works, authors tried to understand the steepening in the column density distribution at high column densities, $N_{\text{HI}} > 10^{21} \text{ cm}^{-2}$. Proposed explanations discussed so far include selection effects due to dust obscuration, conversion of atomic hydrogen to molecular hydrogen, and inclination effects due to randomly oriented galaxies.

Dust obscuration was considered by Fall & Pei (1993) and Vladilo & Péroux (2005), who argued that it could explain the steepening in the DLA regime. The importance of dust obscuration is still a subject of debate (Ellison et al. 2001; Jorgenson et al. 2004; Frank & Péroux, 2010; Kaplan et al. 2010). In particular, Kaplan et al. (2010) and, most recently, Khare et al. (2012) found that a non-negligible fraction of high-metallicity DLAs are significantly reddened. Given that optical quasar samples are constructed using color-based candidate selection, the samples may be biased against significantly reddened QSOs. In the extreme case, when a QSO is completely obscured in the UV and optical range by dust, such a quasar would be missing in radio-selected samples as well because no optical spectrum or redshift would be measured for the radio source. However, we note that although empty-fields have been found in radio-selected samples, these empty-fields were found to contain extended structure in the IR indicating they were not high-redshift quasars (see Jorgenson et al. 2006 for more details).

A physical explanation for the lack of high column density systems above $N_{\text{HI}} \approx 10^{22} \text{ cm}^{-2}$ discussed by a number of authors is the atomic-to-molecular transition (Schaye 2001; Hirashita & Ferrara 2005; Zwaan & Prochaska 2006; Krumholz et al. 2009a; Cen 2012; Altay et al. 2011). The idea is that at large column densities the gas is self-shielded and hence can form H$_2$ if there is sufficient dust. The transition from HI to H$_2$ is expected to occur at a characteristic column density which was monotonically decreasing with some maximum column density at some minimum radius. They considered a universe populated with these disks at random orientations and found that the column density distribution of such a model has a kink at the maximum column density of the radial profile. We will further generalize this model in §5.

In this paper we emphasize the two features in the column density distribution for DLAs. The lack of systems in the local universe above $N_{\text{HI}} = 10^{22} \text{ cm}^{-2}$ can be explained by the HI-H$_2$ transition (Zwaan & Prochaska 2006). However, we will argue that observations show that the turnover at $N_{\text{HI}} \approx 10^{21} \text{ cm}^{-2}$ cannot be explained by the same mechanism. This is because the HI-H$_2$ transition depends on the metallicity and UV radiation of the environment. However, observations show that the turnover at $N_{\text{HI}} \approx 10^{21} \text{ cm}^{-2}$ occurs both in local galaxies, which have metallicities and interstellar UV fields close to those of the Milky Way, and in high-redshift galaxies, which have low metallicities and high UV fluxes. The HI-H$_2$ explanation would predict a transition at a much higher column density at high redshift and therefore a turnover which is not independent of redshift. In addition, we show that the HI column density distribution of individual $z \approx 0$ galaxies all have a similar turnover which does not exhibit a significant dependence on metallicity. Furthermore, we can show that the turnover at $N_{\text{HI}} \sim 10^{21} \text{ cm}^{-2}$ can naturally arise from randomly oriented galaxies.

We present details of the argument against molecular hydrogen formation being the cause of the turnover at $N_{\text{HI}} \sim 10^{21} \text{ cm}^{-2}$ in §3. In §3 we consider the effect of randomly oriented galaxies on the column density distribution and find that they naturally give rise to a turnover in the column density distribution which depends only on the characteristic maximum column density of a galaxy and not on the small-scale features. In §4 we use the column density distribution function of DLAs as a stringent test of the gas distribution in galaxy formation simulations and show that our simulations are discrepant with observational results. In §5 we compare our results to other recent results from galaxy formation simulations by different groups and argue that although current models are quite successful in matching and explaining the column density distribution of HI absorbers over a wide range of column densities, simulation results are generally discrepant or in tension with observations beyond the turnover at $N_{\text{HI}} \gtrsim 10^{21} \text{ cm}^{-2}$.

2. TURNOVER IN THE HI COLUMN DENSITY DISTRIBUTION AND THE HI-H$_2$ TRANSITION

2.1. HI Column Density Distribution

The column density distribution of quasar absorption systems is defined as the number of atomic hydrogen systems, $N$, along a random line of sight per unit column density, $dN_{\text{HI}}$, per unit absorption length, $dX$:

$$f(N_{\text{HI}}, z) = \frac{d^2N}{dN_{\text{HI}} dX},$$

where

$$dX = \frac{H_0}{H(z)} (1 + z)^2 dz.$$  

In this study we focus on the highest column density regime of DLAs, which are associated with the ISM of galaxies hosted by dark matter halos of different mass, $M$. Using the comoving number density of halos per unit halo mass, $n(M, z) dM$, along with the differential HI cross-section associated with such a halo, $d\sigma(M, N_{\text{HI}}, z)/dN_{\text{HI}}$, where $\sigma(M, N_{\text{HI}}, z)$ is the cross-section in proper units for producing absorbers with column densities lower than $N_{\text{HI}}$, we can re-express the column density distribution as

$$f(N_{\text{HI}}, z) = \frac{c}{H_0} \int \frac{d\sigma(M, N_{\text{HI}}, z) d\sigma(M, z)}{dN_{\text{HI}} dM} dM.$$  

This convention emphasizes the physical factors which affect the column density distribution function. The halo number density depends on the physics of halo formation which is...
fairly well understood. However, the differential cross-section in a galaxy with a given halo mass is determined by the surface density distribution on the length scale at which it is being measured. For quasar absorption studies at high redshift, this scale is comparable to the transverse physical size of the quasar emitting region (i.e., $\ll pc$). This distribution will be affected by ISM processes such as turbulence, gravitational instability, gas chemistry, star formation, stellar feedback, etc. Thus, the column density distribution provides a unique high-resolution window into the structure of the ISM of high-redshift galaxies and the processes that shape it.

At the same time, this presents an obvious challenge to the models since the highest resolution galaxy formation simulations have resolutions which are orders of magnitude larger than the scale probed by quasars. Thus, when simulation results are compared to observations, it is implicitly assumed that disparity in scales and unresolved small-scale structure of the ISM does not affect the column density distribution. Although highly non-trivial, as we discuss below this assumption is supported by observations of the column density distribution at different scales in nearby galaxies and is due to the steep power spectrum of HI column density maps.

2.2. Observed Column Density Distribution of DLAs at high and low redshifts

In Figure 1, we plot the column density distribution of systems in the local universe and at $z \approx 3$. As was noted before (Zwaan et al. 2005, Prochaska et al. 2005, Noterdaeme et al. 2009), the column density distribution of DLAs at $z \approx 0$ and $z \sim 3$ are remarkably similar and exhibit a turnover at $N_{HI} \approx 10^{21}$ cm$^{-2}$. At low redshifts, where systems have been measured to higher column densities, this turnover continues to higher column densities and DLAs with $N_{HI} \approx 10^{22}$ cm$^{-2}$ become exceedingly rare. Now we will discuss the physical mechanisms that may be responsible for the steep decrease of the cross-section of high column density gas.

Column densities above $N_{HI} \sim 10^{22}$ cm$^{-2}$ are typical for giant molecular clouds (GMCs) and $f(N_{HI}, z)$ in this regime should probe gas associated with, or fueling formation of, GMCs and star formation in galaxies. For this reason, it is natural to associate the lack of systems above $N_{HI} \sim 10^{22}$ cm$^{-2}$ with the HI-H$_2$ transition. Indeed, Zwaan & Prochaska (2006) showed that for local $z \approx 0$ galaxies the column density distribution of HI smoothly joins onto the column density distribution of molecular gas, with a cross-over at $N_{HI} \sim 10^{22}$ cm$^{-2}$, indicating that the turnover is due to the HI-H$_2$ transition. Recently, the HI-H$_2$ transition was invoked in theoretical studies as a significant factor in steepening the column density distribution at $N_{HI} \sim 10^{22}$ cm$^{-2}$ even for high-$z$ DLAs (Cen 2012, Altay et al. 2011). However, the H$_2$ models used in these studies were calibrated on local galaxies, most of which have solar or super-solar metallicities. The HI-H$_2$ transition, on the other hand, is expected to depend on both the amount of dust and the ambient far UV radiation (e.g., Elmegreen 1993). The dust helps to shield molecular gas from photodissociation and acts as a catalyst for H$_2$ formation. If the dust-to-gas ratio is proportional to the metallicity of the gas, as indicated by observations at $Z \geq 0.1Z_{⊙}$ (e.g., Draine et al. 2007), the HI-H$_2$ transition will correspondingly depend on the metallicity of the absorbing gas. In Schaye (2001), the author developed a theoretical model which predicted the maximum HI column density as a function of metallicity. However, his model predicted that the maximum HI column density scales as $\approx 1/\sqrt{Z}$, in disagreement with local observations of the HI-H$_2$ transition.

Gillen et al. (2006) measured the transition in the Milky Way and Tumlinson et al. (2002) measured the transition in the Small Magellanic Cloud (SMC) and Large Magellanic Cloud (LMC; see also a compilation of archival measurements in the SMC, LMC and Milky Way by Welty et al. 2012). The transition in the Milky Way occurs at a column density of $N_{HI} \approx 10^{20.4} - 10^{20.7}$ cm$^{-2}$, depending on whether the line of sight is at high latitude or along the disk. This difference is expected due to a higher H$_2$-dissociating UV field in the disk plane. The transition in the LMC ($Z \approx 0.3Z_{⊙}$) occurs at $N_{HI} \geq 10^{21.3}$ cm$^{-2}$ and the transition in the SMC ($Z \approx 0.15Z_{⊙}$) occurs at $N_{HI} \geq 10^{22}$ cm$^{-2}$. Thus, the transition column density in these galaxies scales as $\approx 1/Z$ or even more strongly.

In light of the expected metallicity dependence of the HI-H$_2$ transition, the similarity of the low and high-$z$ HI column density distribution turnover at $N_{HI} \sim 10^{21}$ cm$^{-2}$ in Figure 1 is remarkable and strongly disfavors the HI-H$_2$ transition as the physical origin of the turnover. While the low-redshift systems have metallicities of $[Z/H] \sim -0.5$ (Zwaan et al. 2005), high-redshift DLAs have typical metallicities of $[Z/H] \leq -1$ (Noterdaeme et al. 2009, Prochaska & Wolfe 2009), and we would thus expect the turnover in the high-$z$ $f(N_{HI}, z)$ to occur at least $0.5$ dex higher in column density. Yet, the column density distributions of these systems exhibit turnovers at similar column densities. This indicates that the origin of the turnover is not due to the phase transition from atomic to molecular gas, but rather due to the overall density structure of interstellar gas in galaxies. Remarkable similarity of the low- and high-redshift distribution indicates that some universal and metallicity independent process is likely responsible for this structure.

This result is consistent with the distribution of DLAs in the $N_{HI}-Z$ plane which has been used to argue that there is a metallicity dependent maximum $N_{HI}$ (e.g., Krumholz et al. 2009a). In Krumholz et al. (2009a), the authors present a compilation of observations of high-redshift DLAs and show that the distribution of DLAs in the $N_{HI}-Z$ plane is consistent with being bounded by a metallicity dependent maximum $N_{HI}$ which is due to the HI-H$_2$ transition. Binning this data in $N_{HI}$ gives the column density distribution of the compiled sample which displays a turnover at $N_{HI} \sim 10^{21}$ cm$^{-2}$. This binning exercise can be used to show that the feature is primarily due to the density of points in the $N_{HI}-Z$ plane rather than the cutoff in the plane due to the HI-H$_2$ transition, and hence that the turnover at $N_{HI} \sim 10^{21}$ cm$^{-2}$ is not primarily due to the HI-H$_2$ transition.

2.3. Column Density Distribution within the ISM of $z \approx 0$ Galaxies in the THINGS Sample

If the shape of the overall HI column density distribution is related to some universal features of the HI surface density distribution in individual galaxies, it would be interesting to explore whether such universality is indeed observed in individual galaxies. To this end, we use galaxies from the THINGS sample (Walter et al. 2008), in which HI surface density maps are measured for 34 local galaxies using 21-cm observations. The physical resolution of the maps ranges from $\sim 100$ to $\sim 500$ pc depending on the distance to the galaxy. We use the robust weight data cubes of the galaxies since they have the highest resolution. We have omitted three galaxies from consideration: M81 DwA, NGC 3031, and IC
For each THINGS galaxy that we use, we compute the column density distribution:

\[ f(N_{\text{HI}}) = \frac{\Delta N(N_{\text{HI}})}{\Delta N_{\text{HI}} \Delta X} \]  

(4)

where \( \Delta N(N_{\text{HI}}) \) is the number of resolution elements with column density in the range \( N_{\text{HI}} \) to \( N_{\text{HI}} + \Delta N_{\text{HI}} \) and \( \Delta X \) is the absorption length for each galaxy, which is arbitrary. In terms of the formalism from §2, \( f(N_{\text{HI}}) \) is proportional to the differential cross-section of the galaxy,

\[ f(N_{\text{HI}}) \propto \frac{c}{H_0} \frac{\partial \sigma(M, N_{\text{HI}})}{\partial N_{\text{HI}}} . \]  

(5)

Since we are just comparing the differential cross-sections and shapes of the column density distributions in different galaxies, we have adjusted the normalization by choosing \( \Delta X \) such that all column density distributions coincide with the column density distribution of local galaxies from \( \text{Zwaan et al. (2005)} \) at \( N_{\text{HI}} = 10^{20} \, \text{cm}^{-2} \).

The resulting column density distributions for the THINGS galaxies are plotted in Figure 2 in which each colored line represents the distribution of an individual galaxy with color indicating the galaxy’s metallicity (taken from \( \text{Walter et al. (2008)} \), as shown by the color bar. Although the THINGS sample consists of a wide range of systems, from dwarf irregulars to spirals, with metallicities varying by more than 1.5 dex, the HI column density distributions of these galaxies are quite similar and the scatter is surprisingly small. There is no clear correlation of the shape of the distribution with metallicity; all galaxies have a turnover at column density \( N_{\text{HI}} \approx 10^{21} \, \text{cm}^{-2} \).

This is shown more quantitatively in Figure 3, where we plot the turnover column density versus galaxy metallicity. We determine the turnover column density by performing a double power-law fit to the deprojected (face-on) column density distribution of each galaxy; we define the turnover column density as the column density where the two power laws intersect. To deproject the column density maps we just rescale the column densities in individual pixels by \( \cos \theta \), where \( \theta \) is the inclination angle of a particular galaxy. The figure shows that there is at best only a weak correlation between turnover column density. The correlation coefficient for the shown points is \( -0.40 \pm 0.14 \), where the error is computed from 10000 bootstraps. Although a weak correlation is present, we do not observe any strong correlation which would be expected if the turnover was caused by the HI-H2 transition. The weak correlation that may be present could be due to the fact that the column density distribution depends weakly on the mass of the galaxy, which would also imply a weak correlation with metallicity due to the metallicity-stellar mass relation. In addition, we note that the two galaxies with the highest characteristic column densities in Figure 3 (SMC, NGC 1569) are galaxies showing signs of strong tidal interactions with their neighbors and have associated bursting star formation. Their higher than average column densities may thus be due to the tidally-induced inflow of gas into their central regions.

As a check of this weak correlation, we performed two additional tests. First, we did the analysis in Figure 3 using more recent metallicities for the 23 galaxies in THINGS which have updated metallicities in \( \text{Moustakas et al. (2010)} \). We used the metallicities derived using the empirical calibration from \( \text{Pilyugin & Thuan (2005)} \) and found that the correlation func-

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6 M81 DwA is a low-mass dwarf irregular galaxy and, as such, likely has a low metallicity of \( [Z/H] \sim -1 \). Nevertheless, HI column density within this galaxy does not exceed \( N_{\text{HI}} = 5 \times 10^{20} \, \text{cm}^{-2} \) (\( \text{Walter et al. (2007)} \)).
tion became $-0.39 \pm 0.14$, indicating that the effect of using the updated metallicities is small. Second, we performed a KS test on the inclination corrected column density distributions. We separated the galaxies into quartiles based on their metallicities and then performed KS tests between all pairs of galaxies with one drawn from the bottom quartile and the other drawn from the top quartile. The result was that 90% of such pairs had a KS probability greater than 0.01 of being drawn from the same distribution. Thus, in addition to the result in Figure 3 we have a non-parametric test which shows that the column density distribution of the THINGS galaxies show little metallicity dependence.

The lack of strong correlation between the turnover column density and the gas metallicity shown in Figure 2 and Figure 3 is in contrast with the strong correlation that would be expected if the HI-H$_2$ transition was shaping the turnover. In this respect, we can also note that although the column density distribution of molecular hydrogen extends the HI distribution smoothly in $z \approx 0$ galaxies (Zwaan & Prochaska 2006), H$_2$ only affects the shape of the total hydrogen distribution for $N_{\text{HI}} \geq 10^{21.7}$ cm$^{-2}$ and $f(N_{\text{HI}}) \leq 10^{-26}$. This limit comes from computing how many HI and H$_2$ lines of sight there are above a given column density, which is just the integral of the column density distribution. Above the column density of the turnover, $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$, there are more than 10 times as many HI lines of sight as H$_2$ lines of sight.

With this argument in mind, we see that the HI-H$_2$ transition does not cause the turnover of the column density distribution at $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$ in the local universe. Furthermore, although the HI-H$_2$ transition can help explain the paucity of HI absorbers with $N_{\text{HI}} > 10^{22}$ cm$^{-2}$ for relatively metal-rich galaxies at $z \approx 0$, such an explanation would not work for higher-redshift DLAs. These DLAs have considerably smaller metallicities and for low metallicities the transition is expected to occur at much higher column densities (see observations of the transition in the Milky Way, SMC, and LMC discussed in § 2.4 and theoretical predictions shown in Fig. 4 below). This reasoning predicts a tail out to high $N_{\text{HI}}$ in the high-redshift column density distribution which is not present in the local universe.

The similarity of the column density distributions of the galaxies in THINGS, despite a wide range of metallicities, sizes, star formation rates, total HI masses, and absolute luminosities (Walter et al. 2008), implies that the shape of the column density distribution at high column densities may be due to some universal physical mechanism. In the next section we will explore the connection between the column density distribution of a single galaxy and the column density distribution measured for a statistical sample.

3. COLUMN DENSITY DISTRIBUTION OF RANDOMLY ORIENTED GALAXIES

In the previous section, we presented arguments that the HI-H$_2$ transition cannot explain the turnover at $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$. Here we investigate the origin of this turnover by examining how the column density distribution within individual galaxies contributes to the overall statistical column density distribution probed by quasar lines of sight. The inclination angle of a galaxy can affect the column density distribution since it affects both the number of absorption lines through a galaxy and the column density of those lines due to projection.

The effect of inclination angle was investigated in studies by Milgrom (1988), Fall & Pei (1993), and Wolfe et al. (1995), in which the authors considered column density distributions arising from randomly oriented thin disks with fixed radial surface density profiles. They assumed that the radial column density profiles are monotonically decreasing, with a maximum column density at some minimum radius. Under these assumptions, they showed that the column density distribution has a kink at the maximum column density of the galaxy viewed face-on. Above this column density, all sight lines are due to projection effects and the column density distribution behaves as a power-law with an exponent of $-3$, independent of the specific radial profile. Below the critical column density, the column density distribution depends on the details of the radial profile.

First, we would like to note that this result can be extended to surface density profiles that are not axially symmetric. To prove this we consider a galaxy which, when viewed face-on, has a column density distribution given by $f_\theta(N_{\text{HI}})$, where $N_{\text{HI}}$ is the column density as measured for the face-on galaxy. Next, we rotate this galaxy so it has an inclination angle $\theta$ with respect to the observer and consider the column density distribution, denoted by $f_\theta(N_{\text{HI}}^\theta)$. We make the assumption that the galaxy is thin in the $z$ direction which allows us to relate the inclined column density, $N_{\text{HI}}^\theta$, to the face-on column density, $N_{\text{HI}}^\parallel$, via $N_{\text{HI}}^\theta = N_{\text{HI}}^\parallel f_\cos \theta$. Furthermore, when we incline the galaxy, the number of lines of sight piercing the galaxy decreases by $\cos \theta$ due to projection effects. Therefore, the number of lines of sight between $N_{\text{HI}}^\theta$ and $N_{\text{HI}}^\parallel + dN_{\text{HI}}^\parallel$ is

![Figure 2](image_url)
Given by
\[ f_\theta(N_{HI})dN_{HI} = \cos \theta f_L(N_{HI})dN_{HI}, \]  
(6)
thus we get
\[ f_\theta(N_{HI}) = \cos^2 \theta f_L(N_{HI}). \]  
(7)
Finally, we average this distribution over all possible inclination angles to get the column density distribution of randomly oriented galaxies:
\[ f(N_{HI}) = \int_0^{\pi/2} d\theta \sin \theta f_\theta(N_{HI}) \]
\[ = \int_0^{\pi/2} d\theta \sin \theta \cos^2 \theta f_L(N_{HI}/\cos \theta) \]
\[ = \frac{1}{N_{HI}^3} \int_0^{N_{HI}} dN_{HI} N_{HI}^2 f_L(N_{HI}). \]  
(8)
While equation (8) has appeared in the literature (e.g. Wolfe et al. 1995; Wolfe & Chen 2006), previously it was derived for column density distributions arising from galaxies with monotonically decreasing radial profiles. Now we see that the result is more generic and applies to any two dimensional structure, not simply disks. We would like to note that equation (8) implies that the column density distribution has a tail which extends to arbitrarily large column densities. This is due to the relation between the inclined and face-on column density, \( N_{HI}^w = N_{HI}^f/\cos \theta \), which implies that arbitrarily large column densities can be reached as we approach an edge-on inclination. Of course, the real maximum is given by the maximum edge-on column density. Therefore, even the randomly inclined column density distribution naturally has a maximum column density. More precisely, this inclination model starts to break down for large inclination angles when the lines of sight pierce uncorrelated regions in the galaxy.

As we see from equation (8), if the face-on galaxy has a maximum column density, or if the face-on galaxy column density distribution becomes steeper than \( N_{HI}^f \) above some column density, then above this column density the column density distribution will behave as a power-law with an exponent of \(-3\). Note that the high column density tail seen in Figure 1 is consistent with this \(-3\) exponent.

With this idea in mind, we return to the plots we have above regarding the column density distribution of the THINGS galaxies. As we can see in Figure 2, individual galaxies have steeper distributions than the local column density distribution. This effect is further emphasized in Figure 3 where we include inclination corrections and determine the turnover column density by fitting a double power-law to the face-on corrected column density distribution of each galaxy. Above the turnover column density, the column density distributions of individual galaxies have slopes steeper than \(-3\). From equation (5) we see that inclination averaging wipes away the precise details of the column density distribution above this turnover column density because the integral in equation (8) is relatively insensitive to steep column density distributions.

Now we can use this intuition to understand which systems are most important for the column density distribution. Since inclination averaging wipes away information beyond the turnover of an individual galaxy, the systems with column densities above this turnover are not important for the global column density distribution, as measured for a statistically large sample. These systems are necessarily small in size (< few 100 pc) since they contribute relatively few lines of sight. Thus, we are arguing that the small-scale features in column density maps are not important for the global column density distribution whose high end tail is determined by projection effects of the bulk of the gas in a galaxy.

To give further evidence to support this assertion, we consider the galaxy NGC 2403 from the THINGS sample. In Figure 4 we display the face-on corrected column density distribution of NGC 2403 computed using maps with pixels of different size (indicated in the legend). In addition, we compute the column density distribution as derived from the radial average surface density profile of NGC 2403. As we can see, the column density distribution is quite insensitive to the averaging scale of the map. As we average over progressively larger scales we simply lose the relatively rare highest column density regions, while at lower column the distribution is insensitive to the averaging scale. This insensitivity is due to the steep power spectrum of HI maps, as noted in §. As a result, the turnover of the column density distribution is almost identical over a wide range of scales. In addition, the column density distribution derived from the radial profile has a similar turnover. As a quantitative measure of this insensitivity to resolution, we fit double power-laws to the distributions in Figure 4 and found that the turnover column density changed by 0.05 dex as we changed the resolution from 93 pc to 372 pc, and by another 0.05 dex as we changed the resolution from 372 pc to 1.49 kpc. This indicates that the scatter due to resolution effects in Figure 3 should be quite small.

In Figure 5 we show the inclination averaged column density distribution computed using the face-on column density distribution from Figure 4 and equation (8). We see that the inclination averaged column density distribution is very similar to the local column density distribution from Zwaan et al. 2006.
we repeated this procedure for the other galaxies in THINGS and got similar results. In addition, we note that the inclination averaged column density distribution is even less sensitive to the resolution than the face-on column density distribution. This is due to the fact that equation (8) is insensitive to the steepest parts of the face-on column density distribution and hence insensitive to the small-scale structures in the HI map. As a result, even the average radial surface density profile of HI is sufficient to produce an inclination averaged distribution that is similar to that obtained from the highest resolution HI map. Note that the high-\(N_{\text{HI}}\) tail of the column density distribution, \(N_{\text{HI}} > 10^{22} \text{ cm}^{-2}\), can still be sensitive to the small-scale structures in the map because even an edge-on galaxy will have some maximum column density.

From Figure 3 we see that the turnover column density is relatively similar for all galaxies in the THINGS sample and depends only weakly on metallicity. Through inclination effects, this turnover column density within each galaxy gives rise to the turnover in the column density distribution for a statistical sample of galaxies. In light of this idea, we can now better understand the universality of the column density distribution as seen in Figure 1. The similarity in turnover of the column density distribution at low and high redshift indicates that the galaxies at low and high redshifts have similar maximum column densities of HI. We argue that this universal maximum is not due to the HI-H\(_2\) transition since this would imply a dependence on metallicity which is not seen. The exercise described in this section also indicates that this maximum column density does not arise in the small-scale structure of the HI distribution, shaped, for example by turbulent cascades, but is present in the large-scale structure of the HI disk. It is present, for example, in the average radial HI surface density profile of disks. It thus appears to be related to the global processes that set properties of galactic disks rather than the small-scale dynamics of the ISM.

In principle, simulations of galaxy formation should also reproduce such universal behavior if the physical processes shaping the surface density structure of galaxies are modeled correctly. In the following section we will compare the observational results discussed in this section to the results of cosmological galaxy formation simulations.

4. SIMULATIONS

In this section we will utilize our simulations in two ways. First, we will use the observations described in the previous section as a stringent test of our simulations. Second, we will use the simulations as a testing ground to investigate the effects of various physical mechanisms on the column density distribution. This will teach us which of these physical mechanisms are most relevant for the turnover.

In this paper we use several sets of related simulations performed with the Adaptive Refinement Tree (ART) code (Kravtsov 1999; Kravtsov et al. 2002; Rudd et al. 2008), which uses adaptive mesh refinement for both gas and dark matter, thus achieving a large dynamic range in spatial scale.
These simulations follow one or more regions of interest, typically selected as Lagrangian regions of five virial radii around typical dark matter halos. Regions of interest are embedded into a coarsely resolved cosmological cubic volume with periodic boundary conditions. In all simulations used here the maximum spatial resolution inside regions of interest is about 260 comoving pc (65 pc at $z = 3$) which is the result of 9 levels of adaptive mesh refinement. The highest dark matter mass resolution is $1.3 \times 10^6 M_\odot$ and the baryonic mass resolution varies from $\sim 10^3 M_\odot$ to $\sim 10^6 M_\odot$ depending on cell size and density.

All our simulations include three-dimensional radiative transfer of UV and ionizing radiation from stars formed during the simulation, as well as the cosmic background. This is done with the OTVET approximation (Gnedin & Abel 2001). Radiative transfer is especially important for the column density distribution since it correctly models the local radiation flux which can ionize neutral hydrogen regions. Finally, these simulations include the non-equilibrium chemical network of hydrogen and helium described in Gnedin & Kravtsov (2011). This network includes molecular hydrogen and, in particular, the formation of H$_2$ in both the primordial phase and on dust grains. We note that the H$_2$ model in Gnedin & Kravtsov (2011) is calibrated against observations of the Milky Way, LMC, and SMC. Therefore, we expect the model to be valid over a range of metallicities and radiation fields which extend to at least the values characterized by the SMC.

Our fiducial run is a fully cosmological simulation with a box size of $6h^{-1}$ comoving Mpc and a single region of interest around a Milky-Way type galaxy (the simulation called “cosmo II” in Gnedin & Kravtsov 2011) The computational box outside the region of interest is covered with a uniform $6^3$ grid. The cosmological parameters used in the fiducial run are similar to the WMAP1 parameters: $\Omega_m = 0.3, \Omega_\Lambda = 0.7, \sigma_8 = 0.9$, and $h = 0.7$.

In addition to the fiducial run, we use a larger run with a $25h^{-1}$ comoving Mpc box and $256^3$ root grid, focusing on 5 Lagrangian regions around halos with masses between $10^{12}$ and $10^{13} M_\odot$, with exactly the same physics and mass and spatial resolution as in the fiducial run. We use this simulation to test the robustness of our results and for better statistics of halo based properties.

We also used the “fixed ISM” runs of Gnedin & Kravtsov (2011), in which the dust-to-gas ratio and the overall normalization of the radiation field at 1000Å were fixed to constant values. These are useful when we want to compare particular galaxies to models with exactly the same dust-to-gas ratio and interstellar UV field. For example, as a model for the ISM of the SMC we can use a “fixed ISM” simulation with a dust-to-gas ratio corresponding to a metallicity of $Z \approx 0.1Z_\odot$ and a radiation field which is $10 - 100$ times larger than that in the Milky Way.

4.1. Computing the Simulated Column Density Distribution

In order to compare our simulations to the observations in §2.2, we need to compute the column density distribution. The procedure is similar to the one discussed for the THINGS galaxies in §2.3.

Since the DLAs are rare in our simulation, we expect to find at most one DLA along a random line of sight. Therefore, we project our simulated box separately along each axis to get the projected column densities for the box. On the boundary we use a grid whose cell size is the same as the smallest cell in our simulation. For the 6 comoving $h^{-1}$ Mpc box we project onto a grid consisting of $(64 \times 2^3)^3$ pixels which corresponds to a resolution of 65 pc at $z = 3$. Given this projected map, we can compute the column density distribution using equation (4). To improve our statistics, we average the column density distribution over the three cartesian projections. We have verified that the column density distribution has converged at this resolution for column densities below $N_{HI} \approx 10^{23} cm^{-2}$.

In addition, when we project the box onto the boundary grid as described above, we also save the location of the highest HI density cell along each hypothetical line of sight. This is useful since we can subsequently project the HI density along a shorter segment which is centered on the maximum HI density cell. We have verified that if we integrate along a 27 comoving kpc segment about each of these maxima and compute the column density distribution, we have converged to the full-box column density distribution above $N_{HI} = 10^{19} cm^{-2}$. This is useful when we post-process the simulation since then we can save computational time by integrating along these relatively short lines of sight.

Note that the column density distributions considered in this study were extracted from Lagrangian regions around progenitors of massive galaxies and therefore they may not be fully representative of the mean distribution in a large random volume of the universe. However, we focus on qualitative features of the column density distribution and do not attempt to make detailed quantitative comparisons. Given that the discrepancies we identify can be traced to the internal density distribution in galaxies of a wide range of masses, we believe our results and conclusions are representative and generic.

4.2. Comparing the Simulated Column Density Distribution to Observations

A comparison of the observed column density distribution to simulation results is shown in Figure 6 for both the 6 and $25h^{-1}$ comoving Mpc boxes. Note that we have normalized the column density distributions to match the observed column density distribution at $N_{HI} = 10^{20.3} cm^{-2}$.

From Figure 6 we see that the simulated column density...
distribution turns over at a higher column density than the observed column density distribution. Since we have a large simulation volume which includes many galaxies, this result has already taken into account the effect of random orientations which we described in §3. Furthermore, since our simulations have metallicities and radiation fields which are consistent with Lyman Break galaxies over a variety of redshifts (see Fig. 2 in Gnedin & Kravtsov 2010) and our HI-H2 model is consistent with observations, we should be correctly reproducing the effect of the HI-H2 transition. The fact that our HI column density distribution is turning over at such a high column density indicates that our galaxies have face-on column density distributions which extend to high column density. This indicates that we are not correctly modeling the surface density distribution of the individual galaxies in the simulation. Below we will investigate how this can be remedied and what it tells us about the physics which shapes the column density distribution.

4.3. Effect of Metallicity and Radiation Field on the Column Density Distribution

A large part of our argument in §2 was based on the effect of metallicity and UV field on the HI-H2 transition and the corresponding effect this would have on the column density distribution. Since our simulations model molecular hydrogen, we can test this directly in the simulations using the fixed-ISM runs. We considered SMC-like ISM parameters: $Z = 0.1 Z_{\odot}$ and a UV radiation field, denoted by $U$, which is 10 times stronger than the fields in the Milky Way, $U = 100 U_{MW}$; and Milky Way-type ISM parameters: $Z = Z_{\odot}$ and $U = U_{MW}$. Finally, we consider an intermediate model with $Z = 0.1 Z_{\odot}$ and $U = U_{MW}$. The column density distributions of these three model ISMs are presented in Figure 7.

As we can see from Figure 7, an increase in the metallicity shifts the turnover to lower column density. This is expected due to the metallicity dependence of the HI-H2 transition. As we argued above, the observed turnover at $N_{\text{HI}} \sim 10^{21} \text{ cm}^{-2}$ does not depend strongly on metallicity (Fig. 1 and Fig. 2) and thus is not due to HI-H2 transition. As a check that the difference in Figure 7 is indeed due to the HI-H2 transition and not some process which is blowing all the high density gas away, we can compare HI column density distribution to the neutral hydrogen column density distribution, which includes both atomic and molecular gas. Such distributions are very similar for all of the metallicity and radiation field configurations in Figure 7, which indicates that the trend shown is indeed due to the metallicity dependence of the HI-H2 transition.

4.4. Systems Responsible for the High Column Density Discrepancy

In order to understand which physical process are missing or incorrectly modeled in our simulations, it is helpful to know which systems are contributing the most to the high column density lines of sight. This is accomplished by associating the HI systems with their host halo and determining which halos give rise to the high column density systems. First, we consider the cross-section above a fixed column density versus the virial mass which is plotted in Figure 8. In terms of the quantities in §2.1 the cross-section for a halo of mass $M$ above a HI column density of $N_{\text{HI}}$ is given by

$$ \sigma_{N_{\text{HI}}}(M, z) = \int_{N_{\text{HI}}}^{\infty} \frac{d\sigma(M, N'_{\text{HI}} \mid z)}{dN'_{\text{HI}}} dN'_{\text{HI}}. \quad (9) $$

From Figure 8 we can see how the cross-section of a galaxy above a fixed column density increases with increasing halo mass. Although the more massive halos have larger cross-sections, we must weight the cross-sections by the number density of their associated halos in order to know the relative importance of each galaxy type.

One way to describe the importance of each mass range is to compute the column density distribution of systems associated with each mass range. This is shown in Figure 9.
can see, the shape of the column density distribution is fairly similar for all mass ranges. While the dwarf galaxies, with halo masses in the range $10^4 M_\odot < M < 10^{11} M_\odot$, give the largest contribution at all column densities, none of the mass ranges have column density distributions which are consistent with observations. Therefore, we see that we need to include physics which is efficient at removing high density gas from both dwarf galaxies and Milky Way-like galaxies.

4.5. Additional Physical Mechanisms which can Affect the Column Density Distribution

Now that we understand which systems are giving rise to the discrepancy, we can try to understand what additional physics we need to correctly model these systems.

Looking back to equation (3), we recall that we must correctly model the differential cross-section, or equivalently the surface density distribution, of each galaxy to get the correct column density distribution. We are already modeling the HI-H_2 transition using the model of Gnedin & Kravtsov (2011) and observational evidence indicates that this transition does not play an important role for these systems. As a check we have also post-processed our gas with the H_2 model of Krumholz et al (2008, 2009), McKee & Krumholz (2010), which leads to only a small decrease in the column density distribution function at large N_HI. The small difference between our model and the model of Krumholz et al is not surprising, given that Krumholz & Gnedin (2011) showed that these two H_2 models agree well for metallicities greater than $Z/Z_\odot = 0.1$.

4.5.1. Sub-grid Models for Turbulence and Self-gravitation

While the observed column density distribution at high redshift is probing the gas at scales significantly smaller than 1 pc, the highest resolution of our simulations is only 65 pc at $z = 3$. Therefore it is possible that the discrepancy between observed and simulated column density distributions is due to different column density structure on small scales. Indeed, quasar lines of sight probe the column density distribution on sub-parsec scales, while the smallest resolved scales in simulations are $\sim 100$ pc. It is not guaranteed \textit{a priori} that column density distributions measured at such different scales should match. As an extreme example, consider a toy model in which the HI gas on small scales is in tiny $\sim 1$ pc size clouds. For a sparse scattering of clouds measured at a resolution of 1 pc or smaller, most lines of sight would pierce no clouds and a few would pierce the cloud giving rise to two peaks in the column density distribution. In contrast, at a significantly coarser resolution, say 100 pc, the column density distribution would depend on the spatial distribution of these clouds. If they are uniformly spread out then the column density distribution would have a single peak at the average column density with a width given by the central limit theorem. However, in general, different regions could have different column densities when averaged over 100 pc, giving rise to a very broad column density distribution. In principle, the column density distribution measured at different scales can look very different.

We can attempt to model the effect of a physically plausible small-scale density distribution using the results of turbulence simulations on GMC scales. Turbulence leads to compression and rarefaction of the gas, which can affect the column density of the gas and generically predicts a log-normal distribution for densities. While we do not know the exact nature of DLAs systems at high redshift, observations of the local universe indicate that the highest column density systems are in structures like giant molecular clouds (GMCs). The gas density PDF in such clouds has been studied and is known to be log-normal (see McKee & Ostriker 2007, Kritsuk et al. 2007, for a review). Interestingly, the column density PDF also obeys a log-normal distribution in GMCs (Ostriker et al. 2001; Goodman et al. 2009). In Ostriker et al. (2001), the authors simulated GMCs using magnetohydrodynamics and found that the column densities obeyed a log-normal PDF which indicated that the gas density was correlated along lines of sight due to coherent structures on larger scales. This was followed up by observational results in Goodman et al. (2009) where the authors observed the column density distribution of nearby GMCs. The observed column densities satisfied a log-normal PDF with similar variance to that of Ostriker et al. (2001).

These studies found that the area-weighted column density PDF of a cloud with a mean column density of $\overline{N}$ is given by

$$P(y) = \frac{1}{\sqrt{2\pi\sigma^2}} \exp \left( -\frac{1}{2\sigma^2} (y - \mu)^2 \right),$$  \hspace{1cm} (10)$$

where $y = \ln(N/N)$ and $\mu = \sigma^2/2$, as required for normalization. Ostriker et al. (2001) and Goodman et al. (2009) found that the log-normal distribution is a good fit to the simulated and observed distributions with $\sigma \in (0.25, 0.55)$ depending on the conditions in the gas, ie mach number and magnetic field. In comparison to these GMCs, the DLAs consist of mostly atomic hydrogen, which can be expected to have a smoother spatial distribution. Therefore, the column density PDFs described above will serve as an overestimate of the variance in DLAs. In light of this, we have tested a large range of parameters, $\sigma \in (0.1, 5)$, to see if there is any large effect on the column density distribution.

We implement the log-normal PDF on a cell-by-cell basis. In each cell, along each line of sight, we take the HI column density and multiply it by a realization of the log-normal PDF.
This important grid mechanism that can affect these high column density systems is self-gravitation. Observations of molecular clouds and simulations have indicated that self-gravitation gives rise to a power-law tail in the column density PDF at high column densities (Kritsuk et al. 2011). We can include this effect by implementing the same procedure as for the log-normal PDF but also including a power-law tail. Since we do not know the exact power-law behavior that will be present in high redshift DLAs we once again test a variety of parameters. For realistic power-law tails similar to the ones in Kritsuk et al. (2011), we find no significant change in the column density distribution. This is expected from cross-sectional arguments since the regions in which the power-law behavior develops, GMCs, will be very small and hence very rare in a cross-section weighted sample.

As a final comment, we note that the results of the log-normal PDF model described above are consistent with an independent, observation-based argument mentioned in § 2.3. There we noted that observations of nearby galaxies show that the HI column density power spectra can be described by a steep power-law over a wide range of scales, ranging from ~ 0.1 pc up to ~ 10 kpc (Stanimirovic et al. 1999; Elmegreen et al. 2001; Miville-Deschênes et al. 2003; Dutta et al. 2009 etc.), with slopes of the power spectra ranging from ~ −1.5 to ~ −3.5. Such steep power-law behavior indicates that the HI maps do not have large-amplitude fluctuations on small scales and hence the column density distribution cannot be a strong function of averaging scale. This argument hinges on observations of local galaxies. However, if the origin of steep power-law spectra is due to some universal process, such as turbulence, it is reasonable to expect that ISM giving rise to DLAs will have similarly steep power spectra.

4.5.2. Toy Model for Feedback Effects

Since DLAs are associated with the ISM of galaxies, they can be greatly affected by the physical processes which occur in the central regions of these galaxies where the star formation rate is highest and effects of feedback can be expected to be strongest. Due to high densities and star formation rates, the centers of these galaxies will be affected by feedback effects like supernovae and radiation pressure. Some of these effects have been included in recent works (see Altay et al. 2011; Fumagalli et al. 2011). While we have included the effects of supernovae, this feedback scheme is inefficient in driving outflows and does not change the distribution of gas appreciably.

To explore the impact of a much stronger feedback, we consider a simple toy model. Since feedback mechanisms are most relevant for the high densities in the inner parts of galaxies, we can set an upper limit of their effect by removing the inner parts of these disks when we calculate the column density distribution. If this overestimate of the feedback effect is compatible with the observed column density distribution, then it is plausible that feedback can bring our simulation into agreement with observations.

Figure 11 shows the column density distribution with regions of radius 1 and 3 kpc from the parent halo center removed. We see that removing a region of radius 3 kpc is sufficient to bring the simulations into agreement with observations. It remains to be seen if realistic star formation and feedback models can account for such a substantial removal of gas from the central regions of high-redshift galaxies.

5. COMPARISON TO RECENT SIMULATIONS

A number of recent studies have presented column density distributions from simulations and compared them to observations (e.g. Razoumov et al. 2006; Pontzen et al. 2008; Cen 2012; Nagamine et al. 2010; Altay et al. 2011; Fumagalli et al. 2011). Some of the simulations in these studies have successfully reproduced the column density distribution while others were discrepant. Since the observed column density distribution is a sub-parsec scale probe of atomic hydrogen at high redshift, it provides a stringent test of simulations. In fact, since the resolutions found in cosmological simulations are at best hundreds of parsecs, it is surprising that any simulation can match observations without delving into the sub-grid physics. In this section we will try and understand the reasons behind the success and failures of these
Simulations. Such insight will help us understand what additional physical processes are needed in future simulations to obtain the observed column density distribution. Razoumov et al. (2006) used an adaptive mesh refinement simulations with a set of physical processes similar to our simulations. Their simulations include detailed gas chemistry for all species of hydrogen and helium, radiative transfer above the Lyman limit, UV background, but no star formation and no H₂ model for HI-H₂ transition. They simulated a variety of box sizes ranging from $2 - 8h^{-1}$ comoving Mpc with resolution at $z = 3$ varying from 93 pc for the smallest box, to 1.5 kpc for the largest box. In addition, they ran their $8h^{-1}$ comoving Mpc box with a variety of resolutions from 190 pc to 1.5 kpc. Razoumov et al. (2006) found a power-law column density distribution in their simulations that extends to $N_{\text{HI}} \sim 10^{22.5} \text{ cm}^{-2}$ without any sign of a turnover. We find a similar behavior which extends to even higher column densities due to the higher resolution of our simulation.

Cen (2012) used an adaptive mesh refinement code with a zoom-in simulation on a $120h^{-1}$ comoving Mpc box onto a cluster and a void of sizes approximately $20h^{-1}$ comoving Mpc and $30h^{-1}$ comoving Mpc respectively. The grid resolution is $460h^{-1}$ pc. The simulations include a Haardt/Madau UV background, neutral hydrogen self-shielding, metallicity dependent radiative cooling, star formation, supernova feedback, and a molecular hydrogen model based on a solar metallicity HI-H₂ transition. They find a column density distribution at $z = 3$ which is similar to observations. The key difference of our simulations is that we include a model for HI-H₂ transition, which takes into account the dependence on metallicity. The model used by Cen (2012), on the other hand, is based on observations of the HI-H₂ transition in the Milky Way. As a check of the effect of their H₂ model, we have reprocessed our neutral hydrogen with the H₂ model used by Cen (2012) and found that we also get a similar agreement with observations. However, this agreement is artificial because a solar metallicity model for the HI-H₂ transition is not applicable to $z \sim 3$ DLAs, which have metallicities $Z \lesssim 0.1Z_\odot$. Therefore, we can conclude that the HI column density distribution in simulations of Cen (2012) actually disagrees with observations.

Altay et al. (2011) used the set of the OWLS simulations, run with Gadget SPH code with subgrid models for star formation, chemodynamics, galactic winds, cooling in the presence of a uniform UV background, and a Milky Way-type H₂ model. They consider column density distribution in a box of size $25h^{-1}$ comoving Mpc with a gravitational softening length of $2.79$ comoving kpc. With this set of physical processes, Altay et al. (2011) were able to approximately reproduce the column density distribution at $z = 3$ across many decades in column density, $N_{\text{HI}} \sim 10^{12.5} - 10^{22} \text{ cm}^{-2}$. Notably, they get the correct turnover in the column density distribution at $N_{\text{HI}} \approx 10^{21.5} \text{ cm}^{-2}$. One potential caveat to this result is the relatively low resolution of the OWLS simulations. However, we have re-run our simulations at a similar resolution, a minimum cell size of 520 pc at $z = 3$, and found that such a decrease in resolution does not lead to a better agreement with the observed column density distribution. In addition, the OWLS simulations use a star formation prescription which relies on a rigid equation of state which can, in principle, prevent the formation of high density regions within the ISM. Interestingly, Altay et al. (2011) find that the HI-H₂ transition affects the HI column density distribution only at $N_{\text{HI}} \gtrsim 10^{21.5} \text{ cm}^{-2}$, which is consistent with our findings. However, since their H₂ model is based on an empirical calibration of the molecular fraction by Blitz & Rosolowsky (2006), which used local galaxies, the resulting calibration may thus not be applicable to low-metallicity ($Z/Z_\odot \lesssim 0.1$), high-redshift DLA systems Fumagalli et al. (2011). Indeed, although the galaxy sample studied by Blitz & Rosolowsky (2006) included two galaxies with metallicities of $\sim 0.2Z_\odot$, the majority of galaxies in their sample have metallicities close to solar. As we noted before, strong dependence of the HI-H₂ transition on metallicity is both expected theoretically and is actually observed in measurements of molecular fraction along stellar lines of sight in the Milky Way, LMC, and SMC (Tumlinson et al. 2002; Gillmon et al. 2006; Wolfire et al. 2008).

In Fumagalli et al. (2011) the authors utilize an old version of the ART code, which differs from the version we use in its implementation of star formation, cooling, and, stellar feedback. The resolution of their simulations is $\sim 35 - 70$ pc depending on redshift. Fumagalli et al. (2011) show that their simulations successfully reproduce the turnover in the column density distribution function. One potential reason for this match is their aggressive star formation prescription and supernova feedback. The star formation efficiency in their simulations is 20-50 times higher than the efficiency we use and the efficiency that is estimated for real molecular clouds. Likewise, their feedback includes processes that overestimate the actual amount of energy that should be injected into the ISM. Their aggressive star formation thus likely disrupts regions of high HI column density gas and may be responsible for their agreement with the observed column density distribution function. Although we consider the star formation and feedback model employed in these simulations extreme, the results do indicate that the discrepancy in column density distribution between observations and our simulations is likely related to the inefficient feedback of our simulations. In their appendix, these authors show that inclusion of the $H_2$
model of [Krumholz et al. (2008, 2009b), McKee & Krumholz (2010)] is only important above $N_{\text{HI}} \sim 10^{22}$ cm$^{-2}$, once again in agreement with our argument that the HI-H$_2$ transition is not relevant for the turnover in the column density distribution.

As we can see from this section, several different mechanisms can lead to the correct column density distribution. Even if we doubt the physical applicability of these mechanisms, we can still learn a lot from them. Clearly, star formation and feedback have a large effect on the column density distribution, while the HI-H$_2$ transition is unimportant for the turnover at $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$. Therefore, future efforts to correctly model the column density distribution will require correctly modeling star formation and feedback and, more generally, the density structure of turbulent galactic disks. We plan to explore physical processes that affect the density structure of the ISM using high-resolution simulation models of the ISM in a future study.

6. CONCLUSIONS AND FUTURE DIRECTIONS

In this study, we have argued that there are two features in the column density distribution at high HI column density systems. First, there is a turnover at $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$ which is present in both $z = 0$ and high-redshift HI column density distributions. Second, at low redshifts there is also a lack of high column density systems above $N_{\text{HI}} \sim 10^{22}$ cm$^{-2}$. This second turnover can be plausibly explained by the HI-H$_2$ transition. At this point, however, it is not clear whether a similar high-column density turnover exists in the high-$z$ distribution as probing this regime would require orders of magnitude larger absorber samples. In this study we have focused on the universal turnover at $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$.

In §2.2 we argued that the HI-H$_2$ transition does not contribute significantly to the turnover. This was supported by a comparison of observational evidence at both high and low redshift which showed an identical turnover. This is in contrast to what is expected from a HI-H$_2$ induced turnover which would be strongly metallicity dependent. Furthermore, we showed that even in the local universe, the column density distributions within nearby galaxies exhibit a universal shape similar to that of the overall column density distribution and show little dependence on metallicity. Altogether, this observational evidence led us to conclude that the turnover is due to some universal properties of HI distribution in galaxies, presumably shaped by global processes that set overall structure of gaseous disks during their formation.

In the following section, §3 we revisited the idea of deriving the column density distribution from randomly oriented disks which was originally considered in Milgrom (1988), Fall & Pei (1993), Wolfe et al. (1995). We extended this idea to randomly oriented two dimensional structures in equation (8). This extension allows us to take the face-on column density distribution of a single galaxy and then average it over inclination angles to produce a statistical column density distribution. As we saw from Figure 5 this inclination averaged column density distribution is remarkably similar to the local column density distribution as measured in Zwaan et al. (2005). Furthermore, we showed that this inclination averaged column density distribution is insensitive to the averaging scale of the HI map, indicating that the local column density distribution itself is fairly insensitive to small-scale features. This implies that the turnover at $N_{\text{HI}} \sim 10^{21}$ cm$^{-2}$ is not due to the small-scale features in a galaxy, but rather due to the large-scale structure of the HI distribution or, equivalently, the radial profile of the galaxy.

Next, we turned to comparisons of the HI column density distribution in our simulations and in observations, which showed that our simulations severely overpredict the frequency of high column density systems, especially above $N_{\text{HI}} \sim 10^{22}$ cm$^{-2}$. Since the column density distribution depends on a variety of physical processes, our failure to match the observed distribution teaches us about the shortcomings of our simulations. We used the simulations to explicitly show how a HI-H$_2$ induced turnover depends on metallicity. We also showed that dwarf galaxies at $z \sim 3$ provide a dominant contribution to the column density distribution, but Milky Way-sized galaxies also contributed some high column density sight lines. We showed that the discrepancy is not alleviated by increasing resolution.

We then checked the effect of two important pieces of sub-grid physics on the column density distribution: small-scale ISM turbulence and gravitational collapse within GMCs. Both of these were included through their known effect on the column density PDF. We found that for physically realistic parameters, they have a negligible effect. In addition, we showed that simulations can be brought in agreement with observations if a region of radius 3 kpc around centers of all galaxies is removed. This exercise shows that the discrepancy is due to excessively high densities in the centers of our simulations. Presumably this excess gas should be removed by stellar feedback. However, it remains to be seen if realistic models of stellar feedback can remove such a large amount of gas.

Finally, we compared our results to the results of several recent papers which presented simulation predictions for the HI column density distribution. Although some of the simulations in these studies were successful in reproducing the high column density part of the distribution, we believe that this success may partially be due to the extreme feedback models employed. Despite this, their success indicates the sensitivity of the column density distribution to these mechanisms and indicates that the high-$N_{\text{HI}}$ tail of the DLA column density distribution is a sensitive probe of both gas dynamics in high-redshift disks and effects of stellar feedback. Future work can therefore fruitfully focus on detailed modeling of these aspects of forming high-$z$ galaxies.

Shortly after the submission of this manuscript, Braun (2012) considered the effect of 21cm HI self-absorption on the column density distribution. He claims that the column density distribution is sensitive to both resolution, in contradiction with our argument in §2.3 and Figure 4 and opacity corrections. In Figure 6 of Braun (2012) he compares the HI column density distribution of a large sample of nearby galaxies (Zwaan et al. 2005), which made use of $\sim 1.5$ kpc to $\sim 3$ kpc-scale maps, to the column density distribution of a weighted combination of three local galaxies (M31, M33, and LMC) corrected for self-absorption, which made use of $\sim 100$ pc-scale maps. While these column density distributions have a significant difference below $N_{\text{HI}} = 10^{21}$ cm$^{-2}$, opacity corrections are not important at such low column densities. This indicates that the difference is due to the fact that M31, M33, and LMC do not form a representative sample. Above $N_{\text{HI}} = 10^{21}$ cm$^{-2}$ the differences are small but since the sample used to make the opacity corrected column density distribution is not representative, it is not clear how significant this difference is.
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