Invited Review

Ly-α and Mg II as Probes of Galaxies and Their Environment

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ABSTRACT. Lyα emission, Lyα absorption, and Mg II absorption are powerful tracers of neutral hydrogen. Hydrogen is the most abundant element in the universe and plays a central role in galaxy formation via gas accretion and outflows, as well as being the precursor to molecular clouds, the sites of star formation. Since 21 cm emission from neutral hydrogen can only be directly observed in the local universe, we rely on Lyα emission, and Lyα and Mg II absorption to probe the physics that drive galaxy evolution at higher redshifts. Furthermore, these tracers are sensitive to a range of hydrogen densities that cover the interstellar medium, the circumgalactic medium, and the intergalactic medium, providing an invaluable means of studying gas physics in regimes where it is poorly understood. At high-redshift, Lyα emission line searches have discovered thousands of star-forming galaxies out to z = 7. The large Lyα scattering cross-section makes observations of this line sensitive to even very diffuse gas outside of galaxies. Several thousand more high-redshift galaxies are known from damped Lyα absorption lines and absorption by the Mg II doublet in quasar and GRB spectra. Mg II, in particular, probes metal-enriched neutral gas inside galaxy haloes in a wide range of environments and redshifts (0.1 < z < 6.3), including the so-called redshift desert. Here, we review what observations and theoretical models of Lyα emission and Lyα and Mg II absorption have told us about the interstellar, circumgalactic, and intergalactic medium in the context of galaxy formation and evolution.

Online material: color figures

1. INTRODUCTION

In the modern picture of galaxy formation, primordial gas from the intergalactic medium (IGM) falling into the gravitational potential well of dark-matter haloes can accrete onto galaxies to feed the interstellar medium (ISM) and fuel star formation. Feedback mechanisms powered by supernovae and active galactic nuclei (AGN) are able to heat surrounding gas and reprocess material from the galaxy into the circumgalactic medium (CGM) in the form of galactic winds.

As the most abundant element in the universe, hydrogen is a unique tracer of the formation and evolution of galaxies, and its neutral atomic form (H I) can probe gas at various scales (ISM, CGM, and IGM). Much of what we know about neutral hydrogen in the ISM comes from 21 cm observations of the Milky Way, local galaxies, and the low-redshift Universe (z ≤ 0.05). Future surveys with the Square Kilometer Array (SKA) pathfinders, such as the Australian SKA Pathfinder (ASKAP; Johnston et al. 2008), the Karoo Array Telescope (MeerKAT; Booth et al. 2009), and APERture Tile In Focus (APERTIF; Verheijen et al. 2008), will be restricted to redshifts less than one, which will not allow H I surveys to be carried out at earlier epochs, i.e., when galaxies were forming stars at the highest rate (z ≥ 1.5−2). Until the large field of view and high sensitivity of the SKA become available, other tracers of the hydrogen gas are then needed at high redshift.

The Lyman Alpha (Lyα) line offers an invaluable insight into the gas physics that drive galaxy formation. The Lyα line results from a transition between the 22P state and the 12S (ground) state in hydrogen atoms (λ = 1215.67 Å) that can be observed from the ground at z ≥ 2, both in emission or in absorption. In star-forming galaxies, intense Lyα emission lines can be produced in the ISM as the result of the photoionization and the subsequent recombination of hydrogen by massive, short-lived stars. Lyα emission features are commonly observed in high-redshift galaxies, and thousands of so-called Lyα emitters (LAEs) have been detected at z = 2−7 (e.g., Hu et al. 1998; Rhoads et al. 2000; Ouchi et al. 2008; Cassata et al. 2011). A major uncertainty in the interpretation of the data comes from the resonant scattering of Lyα photons by H I atoms in the
interstellar, circumgalactic, and intergalactic medium. Indeed, it has been observationally shown that the emergent $Ly\alpha$ line profile and $Ly\alpha$ spatial extent can be highly affected by the kinematics, geometry, and ionization state of the gas in and around galaxies (e.g., Shapley et al. 2003; Ostlin et al. 2009; Steidel et al. 2010).

In absorption, the large cross-section for the $Ly\alpha$ transition makes it the most sensitive method for detecting baryons at any redshift (e.g., Rauch 1998). Close to 7000 absorption systems with $z > 2.15$ have been detected with H I column densities $N_{HI} > 2 \times 10^{20}$ cm$^{-2}$, suggestive of the ISM of galaxies.

In addition to $Ly\alpha$, metal lines, such as the Mg II $\lambda \lambda 2796, 2803$ doublet, provide a direct tracer of neutral hydrogen column densities, $10^{16} \lesssim N_{HI} \lesssim 10^{22}$ cm$^{-2}$ (Churchill et al. 2000a; Rigby et al. 2002) and can be observed in a redshift range much of which cannot be accessed in $Ly\alpha$ from the ground ($0.1 < z < 6.3$). These metal lines can be used to study the H I when it is not directly detected or can be used in tandem to determine the origins of the gas.

A particularly important motivation for this review is the ability of $Ly\alpha$ and the Mg II $\lambda \lambda 2796, 2803$ doublet to shed light on the circumgalactic medium, roughly defined as the 100–300 kpc region around a galaxy, distinct from the stellar system but within the virial radius of its halo. The CGM has been the subject of intense theoretical study in recent years, as it is where accretion (cold and hot) and feedback (supernovae and AGN) meet. Bahcall & Spitzer (1969) were the first to suggest that quasar absorption lines are caused by “tenuous gas in extended haloes of normal galaxies.” Together, $Ly\alpha$ scattering and emission and $Ly\alpha$ and metal line absorption hold great potential to learn about gas in galaxies and their surroundings and the mechanisms that govern their formation and evolution.

Here, we review observations and models of neutral hydrogen in and around galaxies in the high-redshift universe. § 2 will examine $Ly\alpha$ in absorption, focusing on observations and simulations of damped $Ly\alpha$ absorption systems (DLAs). § 3 will examine the Mg II $\lambda \lambda 2796, 2803$ doublet and how it is used to trace the processes that shape the CGM. § 4 will consider $Ly\alpha$ in emission: the physics of its production and scattering, observations and models of $Ly\alpha$-emitting galaxies, and its illumination of the wider cosmological context of galaxy formation.

### 2. $Ly\alpha$ IN ABSORPTION

$Ly\alpha$ photons are strongly scattered by H I. There are no other states between the $2^2P$ state and the ground state in an H I atom; thus, when the probability of collisional deexcitation is negligible (as it almost always is in astrophysical contexts), the absorption of a $Ly\alpha$ photon by an H I atom is almost immediately ($A_{21}^1 = 1.6 \times 10^{-9}$ s) followed by the reemission of a $Ly\alpha$ photon. This can be thought of as a scattering process. A $Ly\alpha$ photon (at line center) passing through an H I region with column density $N_{HI}$ and temperature $T$ encounters an optical depth of

$$\tau_\alpha \approx 0.59 \left(\frac{T}{10^4 \text{ K}}\right)^{-1/2} \left(\frac{N_{HI}}{10^{17} \text{ cm}^{-2}}\right). \quad (1)$$

$Ly\alpha$ in absorption is observed in the spectra of quasars and gamma-ray bursts (Fig. 1). Three classes of absorbers are distinguished by their neutral hydrogen column density, $N_{HI}$. $Ly\alpha$ forest absorbers have $N_{HI} < 10^{13}$ cm$^{-2}$, making them optically thin to ionizing radiation. Lyman limit systems (LLS) have $10^{17} \text{ cm}^{-2} < N_{HI} < 2 \times 10^{20}$ cm$^{-2}$. Damped $Ly\alpha$ absorption systems (DLAs) are the highest column density systems, with $N_{HI} > 2 \times 10^{20}$ cm$^{-2}$. Damped $Ly\alpha$ absorption profiles are characterized by their Lorentz or damping wings: at such high column densities, unit optical depth occurs in the damping wings of the profile function, beyond the inner Doppler core. The equivalent width of the line is independent of the velocity and temperature structure of the absorber. The column density $N_{HI} = 2 \times 10^{20}$ cm$^{-2}$ also fortuitously separates the predominantly ionized LLS population from DLAs, in which the hydrogen is mainly neutral due to self-shielding. We will focus here on the properties of DLAs, believed to probe galaxies and their immediate surroundings.

#### 2.1. Observed Properties of DLAs

Wolfe (1986) conducted the first DLA survey, using quasar spectra to detect neutral gas in absorption in the disks of high-redshift galaxies. To identify a DLA, one must distinguish a single absorption line, broadened by damping, from an absorption feature caused by the blending of Doppler-broadened, low column density systems. The $Ly\alpha$ forest also generates confusion noise, contaminating the damping wings. The Sloan Digital Sky Survey (SDSS; Prochaska & Bertone-Fort 2004; Prochaska et al. 2005) overcame these problems using high-quality, good spectral resolution ($R \sim 2000$) that does not require higher-resolution follow-up spectroscopy to accurately fit Voigt profiles to the data. Using such methods, around 10,000 DLAs have been observed. The largest DLA survey to date is the Baryon Oscillation Spectroscopic Survey (BOSS; Dawson et al. 2013), part of the Sloan Digital Sky Survey (SDSS) III (Eisenstein et al. 2011). The full sample, based on SDSS Data Release 9, contains over 150,000 quasar spectra over the redshift range $2.15 < z < 3.5$ and has discovered 6839 DLAs, which is an order-of-magnitude larger than SDSS II.

The statistical properties of the DLA population can be summarized by its distribution function: the number of absorbers ($d^2N$) along a random line-of-sight in the redshift range $(z, z + dz)$ that have H I column densities in the range $(N_{HI}, N_{HI} + dN_{HI})$ is

$$d^2N = n_{N_{HI}}(N_{HI}, z) \sigma_{DLA}(z)(1 + z) \frac{dz}{dz} dN_{HI}dz \quad (2)$$

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\[ f(N_{HI}, X) \, dN_{HI} \, dX, \]  

(3)

where \( n_{HI} \, dN_{HI} \) is the comoving number density of DLAs within \( (N_{HI}, N_{HI} + dN_{HI}) \), \( \sigma_{DLA} \) is the DLA absorption cross-section, \( dl_c/dz = c/[H(z)(1 + z)] \) is the ratio of proper distance interval to redshift interval, and the so-called absorption distance \( X \) is defined by 

\[ dX \equiv \frac{H_0}{H(z)(1 + z)^2} \, dz. \]

Figure 2 shows the results of Noterdaeme et al. (2012b), derived from 5428 DLA systems observed as part of the BOSS survey.

The function \( f(N_{HI}, X) \) can be approximated by a double power law. The distribution has a low-\( N_{HI} \) dependence of \( f \propto N_{HI}/C_0^2 \), and drops more steeply above \( N_{HI} = 10^{21.2} \text{ cm}^{-2} \), which has been attributed to the high-mass turnover of the halo mass function, the impact of stellar feedback, and the formation of molecular hydrogen in the highest column density clouds. A similar turnover is seen in the \( \text{H}_1 \) column density profiles of local THINGS (The HI Nearby Galaxy Survey) galaxies, which Erkal et al. (2012) show is not strongly correlated with gas metallicity. This suggests that the \( \text{H}_1-\text{H}_2 \) transition is not the primary driver of this feature of \( f(N_{HI}, X) \).

The zeroth moment of \( f(N_{HI}, X) \) gives the number of DLAs encountered along a line of sight per unit absorption distance \( dX \), i.e., the line density of DLAs:

\[ l_{DLA}(X) \, dX = \int_{N_{DLA}}^{\infty} f(N_{HI}, X) \, dN_{HI} \, dX, \]  

(4)

where \( N_{DLA} = 2 \times 10^{20} \text{ cm}^{-2} \). Alternatively, we can define this quantity in terms of \( dz \), \( l_{DLA}(z) = dN/dz \) is often referred to as the DLA covering fraction per unit redshift. Prochaska & Wolfe (2009), using SDSS Data Release 5, show that \( l_{DLA}(X) \) drops from 0.08 at \( z \sim 3-4 \) to 0.05 at \( z \sim 2.2 \), at which point it is consistent with the present-day value estimated from 21 cm observations (Ryan-Weber et al. [2003]; Zwaan et al. [2005]; note, however, Braun [2012]). This indicates surprisingly little evolution in galactic \( \text{H}_1 \) gas for the last \( \sim 10 \text{ Gyr} \).

The first moment of \( f(N_{HI}, X) \) can be related to the mass density of gas associated with DLAs:

\[ \Omega_g^{DLA}(X) = \frac{\mu m_H H_0}{c \rho_{crit}} \int_{N_{DLA}}^{\infty} N_{HI} \, f(N_{HI}, X) \, dN, \]  

(5)

where \( \mu \) is the mean molecular mass of the gas; see Prochaska et al. (2005) for a discussion of the limits of the integral, and the contribution of LLSs to the mass density of gas associated with \( \text{H}_1 \) atoms. DLAs dominate the neutral gas content of the universe in the redshift interval \( z = 0-5 \). Further, DLAs between \( z \sim 3.0-4.5 \) contain sufficient neutral hydrogen to account for a significant fraction of the gas mass in stars in present-day galaxies. DLAs plausibly contain or are related to the reservoirs of...
gas needed to fuel star formation for much of the history of the universe (Wolfe et al. 2005).

2.2. DLA Kinematics

An important clue as to the nature of DLAs comes from the velocity profiles of associated metal lines. Because unit optical depth occurs outside the Doppler core, the observed Lyα absorption profiles of DLAs contain no information about the velocity structure of the gas. Observers have used high-resolution spectroscopy to study so-called low-ionization metals (or low-ions). For example, Mg I (Mg II) has an ionization potential of 7.65 eV (15.04 eV) (Dopita & Sutherland 2003). Thus, in a region where neutral hydrogen is self-shielded from photons with energies above its ionization potential (13.6 eV), the dominant ion of magnesium will be Mg II. Other low-ions include Si II, Fe II, and Ni II, while N I and O I have ionization potentials that are greater than 13.6 eV and are thus predominantly neutral in a self-shielded H I region (Viegas 1995). Thus, absorption features from low-ionization metals at the same redshift as the DLA give us crucial information about the kinematics of the neutral gas.

The most common statistic used to characterize the width of a low-ion metal absorption feature is \( \Delta v_{90} \), defined by Prochaska & Wolfe (1997) in their pioneering survey as the velocity interval encompassing 90% of the total integrated optical depth. (We will often use the more compact notation \( v_{90} \).) Figure 3 shows the observations of Prochaska et al. (2008). The mean redshift of the DLA sample is \( z = 3 \); Pontzen et al. (2008) and Neeleman et al. (2013) note that there is negligible redshift evolution of the distribution. DLAs velocity widths range from 15 km s\(^{-1}\) to several hundred kilometers per second with a median of \( \approx 80 \) km s\(^{-1}\). The high-velocity tail has been the subject of much theoretical attention, following the claim by Prochaska & Wolfe (1997) that it conflicts with the predictions of hierarchical structure growth within cold dark matter (CDM) cosmologies (see § 2.6).

An important low-redshift insight into DLA kinematics comes from 21 cm emission from H I in local galaxy disks. Zwaan et al. (2008) use high-quality H I 21 cm data to measure the distribution of \( \Delta v_{90} \) for local galaxies with \( N_{\text{HI}} > 2 \times 10^{20} \) cm\(^{-2}\). The observed distribution peaks sharply at around 30 km s\(^{-1}\), with a FWHM of \( \approx 20 \) km s\(^{-1}\) and a shallow tail out to \( \approx 200 \) km s\(^{-1}\). This distribution is very different than that shown in Figure 3 for high-redshift DLAs—the median is smaller by more than a factor of 2. Zwaan et al. (2008) conclude that the low-redshift observation is consistent with a cold dark matter cosmology, while the high-redshift observation is not.

![Figure 2](https://example.com/fig2.png)

**Figure 2.**—Left: Column density distribution function \( f(N_{\text{HI}}, X) \) at \( z = 2.5 \) from Noterdaeme et al. (2012b). Horizontal bars represent the bin over which \( f \) is calculated, and vertical error bars represent Poissonian uncertainty. The double-power-law and \( \Gamma \) function fits to the DR7 distribution of Noterdaeme et al. (2009) at \( z = 2.9 \) are shown as red dashed lines. The function \( f(N_{\text{HI}}, X)(z=0) \) is taken from Braun (2012; purple) and Zwaan et al. (2005; green). Right: Cosmological mass density of neutral gas in DLAs as a function of redshift [Z05: Zwaan et al. (2005); B12: Braun (2012); R06: Rao et al. (2006); PW09: Prochaska & Wolfe (2009); DR9: Noterdaeme et al. (2012b)]. Credit: Noterdaeme et al. (2012b), reproduced with permission © ESO.

![Figure 3](https://example.com/fig3.png)

**Figure 3.**—Histogram of the velocity width, \( \Delta v_{90} \), of low-ions associated with the sample of DLAs found in Prochaska et al. (2008). The sample shows velocity widths ranging from 15 km s\(^{-1}\) to several hundred kilometers per second with a median of \( \approx 80 \) km s\(^{-1}\). The mean redshift of the DLAs is \( z = 3 \); Pontzen et al. (2008) and Neeleman et al. (2013) note that there is negligible redshift evolution of the distribution.
that gas kinematics at high redshifts must be increasingly influenced by gas that does not participate in ordered rotation in cold disks.

2.3. DLA Metallicity

The metallicity of DLAs can shed light on their expected connection to star formation. The elemental abundances of DLAs are the most accurate measurements in the high-redshift universe of the chemical enrichment of gas by stars. Furthermore, regardless of their exact identity, the mean metallicity of DLAs is the best measure we have of the amount of metal enrichment of neutral gas in the universe at a given epoch. This section will follow the reviews of Pettini (2004, 2006) and Wolfe et al. (2005).

DLAs are generally metal-poor at all redshifts. This points to DLAs as arising in gas that is in its earliest stages of star formation. However, DLAs are not primordial clouds. No DLAs have been found without significant metal absorption. Prochaska et al. (2003) report a “metallicity floor”: though their observations are sensitive to $[M/H] < -4$, none were found with $[M/H] < -3$. Rafelski et al. (2012) show that this metallicity floor continues out to $z \sim 5$. Within the population of DLAs at a particular redshift, there is a wide scatter of metallicities, indicating different rates and stages of star formation within the DLA population.

DLAs can trace the cosmic evolution of metallicity. Wolfe et al. (2005), Neeleman et al. (2013), and Rafelski et al. (2014) report a statistically significant increase in the cosmic metallicity in DLAs with decreasing redshift, in contrast to the earlier conclusions of Pettini (2004). This is in keeping with the expectation that star formation will pollute the neutral gas with metals via supernovae and stellar winds. Rafelski et al. (2014) further report evidence of a rapid increase in DLA metallicity between $z = 5$ and $z = 4.5$.

DLAs can also trace the large-scale distribution of metals. In particular, proximate DLAs (PDLAs), defined to have a velocity offset $<3000$ km s$^{-1}$ relative to their background quasar, are known to have higher metallicities than intervening DLAs, and higher metallicities as the quasar is approached (Ellison et al. 2010, 2011). This suggests PDLAs trace high-mass galaxies in the overdense regions of the universe that host quasars. Indeed, quasars with higher UV luminosities are associated with lower metallicity PDLAs. This is evidence of the direct impact of the quasar on surrounding galaxies, possibly involving the shutting off of star formation.

Ledoux et al. (2006) find evidence of a velocity–metallicity correlation in DLAs, $[X/H] = 1.55 \log(v_{\alpha}) - 4.33$, with $X = $ Zn, S, or Si. This has been confirmed by Neeleman et al. (2013) and Møller et al. (2013), though with shallower slopes: 0.74 and 1.12, respectively. This correlation can be used to constrain the DLA mass–metallicity relationship; see Barnes & Haehnelt (2014), who conclude that metallicity increases with DLA host-halo mass as $[M/H]_{\text{mean}} = 0.7 \log(M_*/10^{11} M_\odot) - 1.8$. There is some evidence, too, that at a fixed halo mass, DLAs with above average velocity width (and thus presumably above average star formation rate) have above average metallicity.

An intriguing clue to the nature of DLA comes from observations of so-called sub-DLAs, with $10^{19} \text{ cm}^{-2} < N_{\text{HI}} < 2 \times 10^{20} \text{ cm}^{-2}$. Imaging searches for DLAs and sub-DLAs galaxies show that DLAs probe smaller sight lines: median impact parameter is 17.4 kpc for the DLA galaxy sample and 33.3 kpc for the sub-DLA sample of Rao et al. (2011). Given the expectation that DLAs probe the densest, innermost, star-forming regions of galaxies, we might expect the sub-DLA population to probe the more pristine, outer regions of galaxies and their surroundings. Somewhat surprisingly, then, sub-DLAs are more metal-rich than DLAs, particularly at low redshift ($z < 1.5$) (Kulkarni et al. 2010). The metallicities of DLAs and sub-DLAs decrease with increasing $N_{\text{HI}}$ (Khare et al. 2007). Given the mass–metallicity relation, this plausibly implies that sub-DLAs are associated with higher-mass systems. One must keep in mind that the properties of DLAs and sub-DLAs vary both with the properties of the host system and the properties of the sight line through said system.

Recently, Cooke et al. (2011a, 2011b) have reported observations of extremely metal-poor DLAs as probes of near-pristine clouds of star formation fuelling gas. The abundance patterns of these systems are consistent with predictions of Population III supernovae, suggesting that these DLAs retain the signature of the earliest episodes of star formation. Intriguingly, some of these systems also show an enhancement of carbon relative to other metals, reminiscent of carbon-enhanced–metal-poor (CEMP) stars—a population of galactic halo stars whose abundances suggest that they were born from gas enriched by the first stars (Beers & Christlieb 2005; Lucatello et al. 2006).

2.4. The Search for DLA Host Galaxies

Searches for the galaxies that are responsible for damped absorption in quasi-stellar object (QSO) spectra have a long history. The most common technique is to search adjacent to quasar sight lines with known absorption systems (Fynbo et al. 1999; Bunker et al. 1999; Kulkarni et al. 2000, 2001; Warren et al. 2001; Christensen et al. 2007). This is a difficult task, as the light of the extremely bright quasar must be accurately subtracted in order to study the light from the galaxy, which is very faint in comparison. Kulkarni et al. (2000) and others caution that a given emission feature could be a point-source function (PSF) artifact rather than a real source. For many years, this search resulted in mostly nondetections (Lowenthal et al. 1995; Bunker et al. 1999; Kulkarni et al. 2000, 2001, 2006; Christensen et al. 2009), searched around 23 high-redshift, high column density Ly$\alpha$ absorbers with NICMOS, finding 41 candidates. Christensen et al. (2007) report that, for $z > 2$, six DLA galaxies have been confirmed through spectroscopic observation of Ly$\alpha$ emission, with other techniques producing a few additional candidates. Christensen et al. added another six Ly$\alpha$ emission candidates to this group. A few DLA counterparts have been discovered by searching in the damped Ly$\alpha$ trough for Ly$\alpha$
emission, beginning with Hunstead et al. (1990), although that particular system failed to be detected by Wolfe et al. (1992) and Lowenthal et al. (1995), only to reappear in Pettini et al. (1997). Further Lyα detections were reported by Fynbo et al. (1999) and Møller et al. (2002, 2004).

Recent success has followed from improved methods. For example, Fumagalli et al. (2010) use higher-redshift absorbers to do the QSO subtraction for lower-redshift systems, detecting one DLA in rest-frame far-ultraviolet (FUV) continuum emission. Fynbo et al. (2010, 2011), noting theoretical predictions and tentative observational evidence of a luminosity-metallicity relation in DLAs, target high-metallicity DLAs and detect two systems in emission. PäuX et al. (2011a, 2011b, 2012) used the Spectrograph for INtegral Field Observations in the Near Infra-red SINFONI integral field spectroscopy to detect faint DLA and LLS galaxies near bright quasars. They detect five galaxies (three DLAs, two LLSs) in Hα emission, four at $z \lesssim 1$, and the other at $z = 2.35$. Noterdaeme et al. (2012a) and Krogager et al. (2013) detect Lyα, (O iii), and Hα emission from DLAs at $z \sim 2.2$. (We will discuss these systems further in § 4.5.) Rahmani et al. (2010) stack the spectra from 341 DLAs observed in the Sloan Digital Sky Survey at $(z) = 2.86$, searching for Lyα emission from the DLA host. They report a nondetection of emission at line center, which ignores the possible effects of Lyα radiative transfer. Rauch & Haehnelt (2011), by relaxing this assumption, report a $2.7\sigma$ detection. DLA host searches at lower redshift have had more success: Rao et al. (2011) use photometric redshifts and colors to detect 27 DLAs (selected as Mg ii absorbers) in emission at $0.1 \leq z \leq 1.0$.

With relatively few DLA host galaxies known at $z \geq 2$, conclusions drawn about DLAs in emission must be tentative. Krogager et al. (2012) use sample of 10 DLAs in emission to argue for two correlations. First, the DLA impact parameter (the distance between the center of the host and the QSO line of sight) decreases with increasing H i column density. This reflects the decrease in column density with distance from the center of the host galaxy, as predicted by simulations (Pontzen et al. 2008; Hummels et al. 2013). Second, DLA metallicity increases with impact parameter, which is interpreted as a corollary of the correlation between DLA cross-section and mass, and between mass and metallicity, though selection biases make comparison with observations difficult.

Rahmati & Schaye (2014) provide a table of 13 confirmed $z \sim 2$–3 DLA-galaxy pairs from the literature. Proper impact parameter varies from $\sim 1$–25 kpc, with a median of 8 kpc. Noting that observations are typically only able to detect galaxies with SFR $\gtrsim 10 M_\odot$ yr$^{-1}$, the observed star formation rates vary from $\sim 3$–70 $M_\odot$ yr$^{-1}$, with a median of $\sim 20 M_\odot$ yr$^{-1}$. Note that the star formation rates (SFRs) are often based on Lyα emission, which is difficult to correct for dust extinction. The associated Lyα luminosities (from eq. [8], § 4.3) range from $3$–800 $\times 10^{42}$ erg s$^{-1}$. The two galaxies with measured stellar masses have $M_* = 2$–12.6 $\times 10^9 M_\odot$. The simulations of Rahmati & Schaye (2014), which incorporate the physics of radiative transfer of the UVB and recombination radiation, show good agreement with these observations, though the problem of small number statistics is exacerbated by a lack of information about nondetections and detection limits (in both luminosity and impact parameter). Such simulations are discussed further in § 2.6.

2.5. DLAs in Gamma-Ray Burst Afterglows

Seeing H i in absorption at cosmological distances requires an extremely bright background source. Quasars are very useful to this end, as we have seen. DLAs can also be seen in the afterglow of gamma-ray bursts (GRBs). Importantly, the absorption seen in GRB-DLAs is intrinsic rather than intervening, that is, the absorbing gas is inside the GRB host galaxy. Thus, GRB-DLAs provide detailed information on the kinematics, chemical abundances, and physical state of the gaseous component of their host galaxy (Fiore 2001; Fynbo et al. 2001; Savaglio et al. 2003; Vreeswijk et al. 2004; Prochaska & Herbert-Fort 2004; Jakobsson et al. 2004, 2006; Fynbo et al. 2006; Prochaska et al. 2006; Watson et al. 2006). Here, we will briefly review the properties of GRB-DLAs, highlighting clues as to their relationship to QSO-DLAs and other high-redshift galaxies.

1. GRB-DLAs have a dramatically different column density distribution than QSO-DLAs, as shown in Figure 4, from Fynbo et al. (2009). While QSO-DLA column density distribution is a monotonically decreasing function of $N_{\text{HI}}$, the GRB-DLA distribution displays a prominent peak at $N_{\text{HI}} = 10^{21.5}$ cm$^{-2}$. Only 1% of QSO-DLAs display such high columns (Pontzen et al. 2010).

2. At $z > 2$, GRB-DLAs display a range of metallicities, from 1/100 solar (Rau et al. 2010) to supersolar (Savaglio et al. 2012). Unlike QSO-DLAs, there is no clear trend of mean metallicity with redshift. Savaglio et al. (2012) has shown that the mean GRB-DLA metallicity for $z = 2$–4.5 is somewhat higher...
2.6. Theoretical Models of DLAs

2.6.1. Early Models of DLAs: From Galaxy Disks to LCDM

In the local universe, most H I atoms are found in the disks of $L_*$-type galaxies. Thus, DLAs have traditionally been considered to be high-redshift galactic disks. This motivated Wolfe (1986) to search for the disks of such galaxies at high redshift by looking for high column density H I in absorption in the spectra of quasars. A variety of models have been proposed, as discussed in this section.

Arons (1972) was the first to suggest that absorption lines in high-redshift QSO spectra could be Lyα absorption from H I in protogalaxies, though in those models the gas is highly ionized and thus not directly relevant to DLAs. York et al. (1986) suggested that some DLAs could be associated with gas-rich dwarf galaxies, which would explain the complexity of the metal line profiles. Schiano et al. (1990) used hydrodynamic simulations of the collapse of a gaseous corona into a “Lyα disk” via radiative cooling to test the idea that DLAs originate in large, massive disks of gas that are the progenitors of present-day galaxies. They concluded that such a scenario is plausible, provided there is sufficient metallicity to allow for rapid cooling. Lu et al. (1996), by considering elemental abundances, found that DLAs are much less metal-enriched than the Galactic disk in its past. They concluded that DLAs are not high-redshift spiral disks in the traditional sense, postulating thick disks or spheroidal components of (dwarf) galaxies as more likely scenarios.

Within the CDM model of cosmic structure formation, Mo & Miralda-Escude (1994) modeled DLAs as gaseous disks within dark-matter haloes. Such models were refined and extended by Kauffmann (1996), who based a disk-formation model on the paradigm of White & Rees (1978): galaxies form by the continuous cooling and accretion of gas within a merging hierarchy of dark-matter haloes. The model also incorporates star formation, with the gas supply regulated by infall from the surrounding halo. Chemical enrichment occurs through the ejection of metals back into the hot IGM by supernovae; this gas then cools back onto the disk. This model predicts, with reasonable success, the redshift dependence of $\Omega_\text{HI}$ as well as $f(N_\text{HI}, X)$. DLAs are predicted to be smaller, more compact, and less luminous than today’s galaxies.

Mo et al. (1998) placed rotationally supported disks within haloes with a Navarro-Frenk-White (NFW) density profile (Navarro et al. 1996), allowing the spin parameter $\lambda$ to vary over a lognormal distribution. These models successfully reproduce $dN/dz$ at $z = 2.5$ by including the contribution of disks with rotation velocities down to 50–100 km s$^{-1}$. An important unknown in this and later models is the smallest halo that can host a DLA. Higher resolution simulations of smaller cosmological volumes by Quinn et al. (1996) indicated that haloes as small as 35 km s$^{-1}$ can host DLAs.

Gardner et al. (1997a) were among the first to study DLAs using numerical simulations of cosmological structure formation. While extending the simulations of Katz et al. (1996a, 1996b), their simulations could not resolve dark-matter haloes below 100 km s$^{-1}$. They used the Press-Schechter formalism to extrapolate the results of their simulation to smaller circular velocities. The results for $dN/dz$ are in good agreement with observations for $z = 2–4$ in an $\Omega_m = 1$ universe. Gardner et al. (1997b), however, applied this method to other cosmological models, showing that in a LCDM universe (with $\sigma_8 = 0.79$), absorbers are underproduced at $2 \leq z \leq 3$ by a factor of 3. Further simulations (Gardner et al. 2001) produced a more adequate fit to the data, though precise predictions were affected by the uncertainty in determining the smallest halo capable of hosting a DLA.

[log($Z/Z_\odot$) = −0.83 ± 0.76] compared to QSO-DLAs [log($Z/Z_\odot$) = −1.39 ± 0.61] (see also Savaglio 2006; Fynbo et al. 2006, 2008; Prochaska et al. 2007). Metal absorption features in GRB-DLAs tend to be, on average, 2.5 times stronger and slightly more ionized that those of QSO-DLAs (de Ugarte Postigo et al. 2012).

3. The velocity width ($v_w$) distribution of GRB-DLAs is consistent with that of QSO-DLAs, with a median of ≈80 km s$^{-1}$ and a high-velocity tail out to 200–300 km s$^{-1}$ (Prochaska et al. 2008), though there are only nine GRBs in the GRB-DLA $v_w$ sample. This suggests that the two populations inhabit parent haloes of comparable mass.

4. There is some evidence that GRB-DLAs are not significantly statistically distinct from the high column density tail of QSO-DLAs. GRB-DLAs seem to smoothly extend the dust properties and metallicity of QSO-DLAs to larger column densities (Fynbo et al. 2009; Guimarães et al. 2012; De Cia et al. 2013).

Given that GRB-DLAs are plausibly selected by their intense star formation, as opposed to the H I cross-sectional selection of QSO-DLAs (Fynbo et al. 2008); Pontzen et al. (2010) modeled GRB sight lines in a cosmological simulation by associating them with young star particles. The result was a successful prediction of the GRB-DLA column density distribution and broad agreement with the range of metallicities. In the simulations, GRB-DLAs occupy dark matter host haloes that are an order of magnitude larger than their QSO counterparts and probe regions typically 4 times closer to the center of their host haloes. This is in agreement with the schematic picture of GRB-DLAs resulting from sight lines that probe the denser, central regions of their host galaxies, as opposed to intervening absorbers where most of the cross-sectional area is in the outskirts of the galaxy (Prochaska et al. 2007). This picture also explains why GRB-DLA metallicities are systematically higher than the QSO-DLA metallicities (Fynbo et al. 2008). By simultaneously probing star formation and ISM gas physics of galaxies, GRB-DLAs provide a much-needed test of galaxy formation simulations.
and long associated cooling times. This mode of accretion is identified by Birnboim & Dekel (2003) and Kereš et al. (2005). In “cold mode” accretion, gas that has never been shock-heated \((T < T_{\text{vir}})\) radiates its potential energy and falls onto the central galaxy along thin filaments. This mode of accretion dominates in low-mass haloes \((M_{\text{halo}} \lesssim 2-3 \times 10^{11} M_\odot)\), and is therefore the main accretion mechanism at high redshift. Both modes can coexist in massive haloes at high redshift, where cold, dense filaments are able to penetrate hot virialized haloes (Dekel & Birnboim 2006; Ocvirk et al. 2008; Dekel et al. 2009; Fumagalli et al. 2014).

The gas in cold streams penetrates deep inside the virial radius (Dekel et al. 2009). The interaction of cold streams with hot halo gas as it settles into a rotating disks has been used to model a population of large, clumpy, rapidly star-forming disk galaxies at high redshift (Dekel et al. 2009; Agertz et al. 2009). The newly accreted gas will fragment to form large \((10^7-10^9 M_\odot)\) star-forming clumps in an extended \(\sim 10\) kpc disc. While the inner parts of the disc have, on average, solar metallicity, the clump-forming region is only \(0.1 Z_\odot\) Brooks et al. (2009) note that star formation in stellar disks of galaxies up to Milky Way mass is primarily fuelled at all times by gas that has accreted cold; such gas can dominate the supply of the stellar disk even in high-mass haloes where most of the gas flowing through the virial radius is hot. The dominant gas supply at all masses is from smoothly accreted gas that has never belonged to another galaxy halo.

Inflowing gas is only half the story, however. Galactic winds, powered by some combination of stellar winds, supernovae, cosmic ray heating and AGN, are ubiquitous in both the local and distant universe (see Veilleux et al. [2005] for a comprehensive review). As Steidel et al. (2010) notes, virtually every \(z > 2\) galaxy bright enough to be observed spectroscopically is driving out material at velocities of at least several hundred kilometers per second. Such winds are the primary mechanism by which star formation feeds back upon itself and energy and metals are circulated within galaxies and their environment. This feedback is widely believed to explain why stellar mass fails to follow halo mass in a \(\Lambda\)CDM cosmology, especially at low masses \((M_{\text{halo}} \lesssim 10^{11} M_\odot\); see Silk & Mamon 2012). Hydrodynamical simulations that fail to model feedback inevitably form galaxies with too many baryons.

2 While the conclusions of Kereš et al. (2005) have been reproduced in higher resolution smoothed-particle hydrodynamics (SPH) simulations (Brooks et al. 2009; Kereš et al. 2009) and adaptive mesh refinement (AMR) simulations (Ocvirk et al. 2008; Agertz et al. 2009; Dekel et al. 2009), they have recently been challenged by the moving mesh simulations of the AREPO code (Nelson et al. 2013). While there is still a low vs. high-mass dichotomy for cold vs. hot accretion, AREPO concludes that more massive haloes \(M_{\text{halo}} \gtrsim 10^{11} M_\odot\) have a much smaller cold fraction than is seen in SPH simulations. This is due to both an order-of-magnitude higher hot accretion rate, and a factor of 2 lower cold accretion rate. For cold streams, the AREPO flows are disrupted in massive haloes at \(0.25-0.5 \ r_{\text{vir}}\). Nelson et al. (2013) attribute the difference to numerical blobs of cold gas in SPH simulations. The situation, and the implications for the observable properties of gas accretion, remains unclear.
Simulations of galactic winds, particularly those in a cosmological context, must rely on unresolved subgrid physics to approximate the combined effect of stellar and supernovae feedback. A range of prescriptions are available (e.g., Springel & Hernquist 2003; Oppenheimer & Davé 2006, 2008; Governato et al. 2007; Hopkins et al. 2011, 2012; Barai et al. 2013); all are poorly constrained by observations and “first principles” simulations. The simulations of Shen et al. (2013) show inflowing and outflowing gas coexisting in the CGM: about one third of all the gas within the virial radius is outflowing. This outflowing gas is enriched with the products of star formation, so that at the virial radius, inflowing gas has metallicity 0.05 $Z_{\odot}$, while the mean metallicity of outflowing gas is 0.56 $Z_{\odot}$. Outflows tend to be bipolar, taking the path of least resistance perpendicular to the plane of the disk, in agreement with observations at both low (Lynds & Sandage 1963; Bland & Tully 1988; Ohyama et al. 2002, e.g., M82) and high (Bordoloi et al. 2011, 2014; Bouché et al. 2012) redshift.

The launching of a large-scale galactic wind is not guaranteed, as the energy input may only pressurize the ISM (Kereš et al. 2009). Oppenheimer et al. (2010) find that the mean recycling time decreases with halo mass, meaning that recycled wind material is an important mode of accretion (distinct from cold and hot modes) in high-mass haloes. In particular, in their favored momentum-driven wind model, gas accreted via the fountain mode, fuels over 50% of the global star formation density at $z \lesssim 1.7$.

### 2.6.3. DLAs in Cosmological Simulations

Returning to DLAs within cosmological simulations, Nagamine et al. (2004) used SPH simulations in the context of the $\Lambda$CDM model. Their simulations included the effects of radiative cooling, the ultraviolet background (UVB), star formation, supernovae feedback, and, in particular, considered the effect of galactic winds using a simple phenomenological model that involves giving gas particles a “kick” in a random direction to drive them out of dense star-forming regions. They used the Press-Schechter formalism to extend their results beyond the resolution limit of their simulations. The result was a reasonable agreement with $\Omega_{\text{HI}}(z)$ so long as “strong” winds were invoked; otherwise, there was too much gas left in the DLAs. Their prediction for $dN/dz(z)$ was also reasonably successful. Finally, $f(N_{\text{HI}}, X)$ is slightly underpredicted, with strong winds necessary to prevent overprediction at high $N$. Nagamine et al. (2007) refined the previous models with a more careful consideration of winds, concluding that DLAs are hosted by small ($M_{\text{halo}} < 10^{12} h^{-1} M_\odot$), faint galaxies.

Further cosmological simulations have been able to model the DLA population without using analytic extensions based on the Press-Schechter formalism. The first to accomplish this was Razoumov et al. (2006), who used AMR cosmological simulations to address both the neutral gas cross-section and the gas kinematics. Their results show that $f(N_{\text{HI}}, X)$ is overpredicted for $N_{\text{HI}} > 10^{21} \text{ cm}^{-2}$, which may be due to the effects of grid resolution or the absence of a model for the formation of $H_2$, which will affect the highest density systems. The velocity width distribution is dramatically underpredicted at high $v_{\text{gas}}$, even when star formation is taken into account (Razoumov et al. 2008). Another surprising conclusion of these simulations was the abundance of DLAs that are not associated with any halo—intergalactic DLAs were found in tidal tails and quasifilamentary structures.

Pontzen et al. (2008) analyzed DLAs in the galaxy formation simulations of Governato et al. (2007, 2008) and Brooks et al. (2007). These simulations produce impressively realistic disk galaxies at $z = 0$. It is thus a major success that the simulations, with no further tweaking of free parameters, are able also to match $f(N_{\text{HI}}, X)$ at $z = 3$, apart from a slight overprediction at high $N_{\text{HI}}$. Good agreement is also found with the distribution of metallicities in DLAs, something previous simulations were unable to do. However, as before, DLA velocity width data is not reproduced, with too few high-$v_{\text{gas}}$ systems. Tescari et al. (2009) followed a familiar pattern—success with $f(N_{\text{HI}})$ but too few large $v_{\text{gas}}$ systems, possibly due to inadequate mixing of wind-phase metals.

Hong et al. (2010) mimicked metal diffusion by tying metals directly to H i, and had somewhat more success in producing large $v_{\text{gas}}$ systems. Cen (2012) used an adaptive mesh-refinement code to study DLAs in two small cosmological volumes (for resolution reasons), one centred on a $1.8 \sigma$ overdensity and one on a $1 \sigma$ underdensity. These simulations bracket the observed column density and velocity width distributions. The OverWhelmingly Large Simulations (OWLS) project has been used to study QSO absorption systems, often in conjunction with postprocessing to account for $H_2$ formation and ionizing radiation. The simulations have studied the observed $z = 3$ abundance of $Ly\alpha$ forest, Lyman limit, and DLA absorption systems probed by quasar sight lines over 10 orders of magnitude in column density (Altay et al. 2011), the lack of evolution in $f(N_{\text{HI}}, X)$ below $z = 3$ (Yajima et al. 2012a), and the effect of subgrid feedback prescriptions (Altay et al. 2013) and ionizing radiation from the UV background and local stellar sources (Rahmati et al. 2013) on the DLA population. There is some tension between Rahmati et al. (2013), who conclude that their predictions are highly sensitive to assumptions about the ISM, especially for $N_{\text{HI}} > 10^{21} \text{ cm}^{-2}$, and Yajima et al. (2012a), who conclude that ionizing radiation from stars makes little difference to DLAs, as it is absorbed in very dense, compact clouds that contribute little to the DLA cross-section.

Berry et al. (2014) studied DLAs using semianalytical models of galaxy formation. They found that they needed to “extend” their gas disks by giving them more than their share of the halo angular momentum in order to reproduce the observed properties of DLAs at $z < 3$, while all models failed at $z > 3$.

An important constraint on models of DLAs comes from the use of cross-correlation to study host halo masses. For example,
Gawiser et al. (2001); Adelberger et al. (2003); Bouché & Lowenthal (2004); Cooke et al. (2006a, 2006b) measured the cross-correlation of DLAs with Lyman break galaxies (LBGs). These observations, together with the modeling of Lee et al. (2011), suggest that DLAs inhabit smaller haloes than LBGs, with average halo masses of $10^{11} M_\odot$ compared to $10^{11.5} - 12 M_\odot$ for LBGs.

More recently, however, Font-Ribera et al. (2012) calculated the cross-correlation of DLAs in the BOSS survey with the Ly$\alpha$ forest, concluding that the derived DLA bias indicated a significantly larger typical halo mass of $\sim 10^{12} M_\odot$. This conclusion was supported by Barnes & Haehnelt (2014). They used a simple analytical model of DLAs, which reproduces the column density and velocity width distribution of DLAs, to argue that the observed DLA bias presents a significant challenge to existing DLA models and galaxy formation simulations more generally, plausibly indicating that photoionization and stellar feedback are more efficient in ionizing and/or ejecting HI from haloes than is accounted for in current subgrid models.

The physical picture of DLAs that emerges from these simulations can be summarized as follows.

1. DLAs arise in the ISM and CGM of low-mass, gas-rich galaxies. Most absorbers with $N_{\text{HI}} > 10^{17}$ cm$^{-2}$ at $z = 3$ reside inside galaxy haloes, and either have been ejected from the ISM or will become part of the ISM by $z = 2$ (van de Voort et al. 2012). For DLAs, ISM absorption is most likely for systems with $N_{\text{HI}} > 10^{22}$ cm$^{-2}$, with a significant fraction of DLAs not arising from the gaseous disks of spiral galaxies but rather from filaments, streams, and clumps (Fumagalli et al. 2011). An example is shown in Figure 5. DLAs typically probe galaxies on approximately kiloparsec scales, or the inner $\sim 10\%$ of the virial radius (Rahmati & Schaye 2014).

2. DLAs arise in dark-matter haloes in the mass range $10^{10} - 10^{12} M_\odot$, which have very low stellar masses $< 10^9 M_\odot$ (Rahmati & Schaye 2014). DLAs host haloes are generally smaller than the host haloes of LBGs. In this mass range, gas accretion is predicted to be via cold streams (Birnboim & Dekel 2003; Kereš et al. 2005), that is, gas which enters dark-matter haloes without being shock-heated above $\sim 10^4$ K. Van de Voort et al. (2012) show that most of the gas in LLSs and DLAs has never been shock-heated, though the smooth component of cold streams is highly ionized (Fumagalli et al. 2011). LLSs and DLAs at high redshift thus plausibly include the elusive cold streams of cosmological simulations.

3. DLA kinematics, derived from associated metal line absorbers, remain a significant hurdle for simulations. To reproduce the high-$\nu_g$ systems, significant “nongravitational” sources of motion are required, that is, velocity components beyond that of a purely virialized halo of gas. Plausible sources include the motion of satellite haloes inside a larger parent halo and supernovae-driven galactic winds.

4. The relatively low metallicity and low internal star formation rates of DLA gas are explained by the fact that, at high redshift, they arise in gas that is on the outskirts of or outside of the ISM of small galaxies.

The typical limitations of cosmological hydrodynamical simulations—resolution, box size, subgrid physics—all apply here. In particular, the importance of stellar and supernovae feedback to the properties of the ISM and CGM, and hence DLAs, makes theoretical predictions dependent on the details of processes that no simulation can yet resolve. The ability of Ly$\alpha$ absorption to probe ISM and CGM gas at high redshift makes it one of the most important tests of galaxy formation simulations.

3. MG II ABSORPTION TRACING H I

The Mg II λ2796, 2803 doublet probes a large range of neutral hydrogen column densities $10^{16} \lesssim N(\text{HI}) \lesssim 10^{22}$ cm$^{-2}$ (Churchill et al. 2000a; Rigby et al. 2002), having typical temperatures of 30,000–40,000 K and average total hydrogen densities of $\sim 0.1$ atoms cm$^{-3}$ (Churchill et al. 2001; Ding et al. 2005). Such conditions yield a large range of Mg II rest-frame equivalent widths, $0.02 \lesssim W_\lambda(\lambda 2796) \lesssim 10$ Å, that are detectable in the spectra of background quasars and galaxies probing intervening foreground objects. It has been convincingly demonstrated that Mg II absorption is produced within gaseous haloes surrounding galaxies and is not produced within the diffuse intergalactic medium (see review by Churchill et al. [2005]).
A significant quantity of H i is probed by Mg II absorption, comparable to roughly 15% of the gas residing in DLAs and 5% of the total hydrogen in stars (Kacprzak & Churchill 2011; Ménard & Fukugita 2012). Roughly 20% (50%) of all Mg II absorption systems with $0.6 \leq W_r(\lambda 2796) \leq 1.7$ Å [$W_r(\lambda 2796) > 1.7$ Å] are associated with DLAs. Furthermore, Ménard & Chelouche (2009) demonstrated a direct relation between the Mg II rest equivalent width and the H i column density such that the geometric mean column density is $N(\text{HI}) = A W_r(\lambda 2796)^\beta$, where $A = (3.06 \pm 0.55) \times 10^{19}$ cm$^{-2}$ Å$^{-\beta}$ and $\beta = 1.73 \pm 0.26$ and is valid for $0.5 \leq W_r(\lambda 2796) \leq 3$ Å and $0.5 \leq z \leq 1.4$.

### 3.1. Mg II Absorption Statistics

Current surveys place the number of known Mg II absorbers at around $\sim 41,000$ systems spanning a redshift range of $0.1 < z < 2.3$ (e.g., Sargent et al. 1988; Steidel & Sargent 1992; Churchill et al. 1999; Narayanan et al. 2007; Barton & Cooke 2009; Chen et al. 2010a; Quider et al. 2011; Werk et al. 2012; Zhu & Ménard 2013; Seyffert et al. 2013) and $\sim 100$ Mg II systems spanning a redshift range of $1.9 < z < 6.3$ (Matejek & Simcoe 2012). The distribution of Mg II rest-frame equivalent widths consists of two distinct populations: Strong systems, $W_r(\lambda 2796) > 0.3$ Å, are well described by an exponential distribution (Nestor et al. 2005; Zhu & Ménard 2013; Seyffert et al. 2013), while weaker systems follow a power-law distribution (Churchill et al. 1999; Narayanan et al. 2007). These two distinct populations can be simultaneously described with a Schechter function (Kacprzak et al. 2011b).

The incidence rate $dN/dz$ of absorption systems (number per unit redshift and rest equivalent width) provides detailed information on their cross-section and number density as a function of redshift. Seyffert et al. (2013) found that the physical cross-section of Mg II absorbers increases by a factor of 3 between $0.4 < z < 2.3$ for $W_r(\lambda 2796) \geq 0.8$ Å. Over the redshift range $0.4 < z < 5.5$, the rate of incidence of weaker absorbers [$0.6 < W_r(\lambda 2796) < 1.0$ Å] is roughly constant, which suggests that these absorbers are established early and are being constantly replenished as a function of time (Zhu & Ménard 2013; Matejek & Simcoe 2012). Meanwhile, the incidence rate for stronger absorbers ($W_r(\lambda 2796) > 1.0$ Å) increases toward $z \sim 2$ and then decreases toward $z \sim 5$, similar to the cosmic star formation history (e.g., Bouwens et al. 2011a). The strikingly similar shapes of these two quantities points to a direct connection between strong absorbers and star formation (Zhu & Ménard 2013; Matejek & Simcoe 2012).

### 3.2. Association with Galaxies

The pioneering work of Bergeron (1988) and Bergeron & Boissé (1991) identified the first galaxies in close proximity to a quasar sight line and at the same redshift as absorbing gas traced by Mg II absorption. Of the $\sim 41,000$ known Mg II absorbers, there are $\sim 300$ galaxies that are spectroscopically confirmed to reside at same redshift as the absorber (e.g., Nielsen et al. 2013; Werk et al. 2012). These galaxies span a redshift range of $z = 0.1$ (Barton & Cooke 2009; Kacprzak et al. 2011a) to $z = 2$ (Bouché et al. 2012; Lundgren et al. 2012). The small galaxy sample sizes reflect only the difficulty of obtaining large amounts of telescope time required to complete these spectroscopic surveys around quasars. In addition, stacking techniques have been used to probe 1000’s of galaxy haloes (Zibetti et al. 2007; Bordoloi et al. 2011; Ménard et al. 2011).

Absorption by Mg II around galaxies extends to projected galactocentric distances ($D$) of $\sim 200$ kpc. Host halo size scales with galaxy luminosity and halo mass with some dependence on galaxy color (Steidel 1995; Zibetti et al. 2007; Kacprzak et al. 2008; Chen et al. 2010a; Nielsen et al. 2013; Churchill et al. 2013). Using clever stacking and cross-correlation techniques between Mg II absorption systems and massive red galaxies, Zhu et al. (2014) and Pérez-Ráfols et al. (2014) detect absorption out to 20 Mpc around galaxies with $M_B = 10^{13.5} M_\odot$. These extended Mg II profiles appear to change slope on scales of $\sim 1$ Mpc, which is the expected transition from being dominated by the dark-matter halo to where it is dominated by halo-halo correlations (Zhu et al. 2014).

Within these Mg II haloes, the average gas covering fraction is estimated to be $50$–$90\%$ for galaxies at $z \sim 0.6$ (Tripp & Bowen 2005; Chen & Tinker 2008; Kacprzak et al. 2008; Chen et al. 2010a; Nielsen et al. 2013; Churchill et al. 2012b), possibly decreasing to 25% at $z \sim 0.1$ (Barton & Cooke 2009). The gas covering fraction has a radial and azimuthal dependence that increases toward the host galaxy center and also along its major and minor axes (Nielsen et al. 2013; Kacprzak et al. 2012). Furthermore, from halo abundance matching (see Trujillo-Gomez et al. 2011), we know that the covering fraction within a given $D$ is constant with halo mass, $M_h$, over the range $10.4 \leq \log M_h \leq 13.3$ (Churchill et al. 2013a).

It has been firmly established that rest-frame equivalent width is anticorrelated with $D$ at the $8\sigma$ level (Lanzetta & Bowen 1990; Steidel 1995; Churchill et al. 2000b; Kacprzak et al. 2008; Chen et al. 2010a; Rao et al. 2011; Nielsen et al. 2013; Kacprzak et al. 2013). The anticorrelation can be represented by a single log-linear relation $\log[W_r(\lambda 2796)] = (-0.015 \pm 0.002) \times D + (0.27 \pm 0.11)$ that is found to be valid for Mg II absorption around galaxies within 0 kpc $< D < 200$ kpc (Nielsen et al. 2013; Kacprzak et al. 2013). This anticorrelation could be interpreted as a radially decreasing gas density profile surrounding galaxies, although the complex velocity structure of the absorption systems, which is independent of $D$, suggests that the absorption arises from a variety of ongoing dynamical events within the galaxy and halo (Churchill et al. 1996). Recent work has shown that host galaxy virial mass determines the extent and strength of the Mg II absorption: the mean equivalent width increases with virial mass at fixed $D$, and decreases with $D$ for fixed virial mass with the majority of the absorption produced...
within 0.3 viral radii (Churchill et al. 2013). On average, it appears that the Mg II equivalent width is not dependent on, or is weakly correlated with, galaxy halo mass (Bouché et al. 2006; Gauthier et al. 2009; Lundgren et al. 2009; Churchill et al. 2013; Gauthier et al. 2014).

### 3.3. Theory

Semianalytical models and isolated galaxy simulations (e.g., Mo & Miralda-Escude 1996; Burkert & Lin 2000; Lin & Murray 2000; Maller & Bullock 2004; Chen & Tinker 2008; Kaufmann et al. 2008; Tinker & Chen 2008) have been invoked to study isolated galaxy haloes. In these models, Mg II absorption typically arises from condensed, infalling, pressure-confined gas clouds within the cooling radius of the hot halo. These models reproduce the general statistical properties of the absorber population. However, they lack the dynamic influences of cosmic structures and local environments.

Currently, one of the limitations of cosmological simulations is that local sources of ionizing radiation are not properly accounted for, although some attempts have been made (Goerdt et al. 2012). Ionizing radiation can have a significant effect on high column density absorbers with $N$(HI) $> 10^{17}$ cm$^{-2}$ where Mg II absorption is typically found (Rahmati et al. 2013). Nonetheless, there have been some attempts to study Mg II absorption in simulations. Using simulated quasar absorption-line sight lines through cosmological simulations, Kacprzak et al. (2010a) demonstrated that Mg II absorption arises in filaments and tidal streams with the gas infalling with velocities in the range of the rotation velocity of the simulated galaxy. This is consistent with simulations of Stewart et al. (2011), who showed that these cold-flows produce a circumgalactic corotating gaseous disk that is infalling toward the galaxy. In absorption these structures are expected to produce $\sim$100 km s$^{-1}$ velocity offsets relative to the host galaxy in the same direction of galaxy rotation, which is consistent with observations (Steidel et al. 2002; Kacprzak et al. 2010a). The accreting gas spends only 1–2 dynamical times in this disk before accreting onto the host galaxy (Stewart et al. 2013).

Simulations have yet to consistently reproduce the observed Mg II covering fractions (Ford et al. [2013], though some recent simulations are very close), which are typically underestimated by a factor of 2 or more. However, Stewart et al. (2011) showed that the Mg II covering fraction drops dramatically for galaxies with a halo mass above $M_h > 10^{12}$ $M_\odot$, where cold-mode accretion is predicted to be quenched when the halo is massive enough to support a stable shock near the virial radius (e.g., Dekel & Birnboim 2006; Dekel et al. 2009; Keres et al. 2009; van de Voort et al. 2011). This phenomena may have been directly observed for one galaxy (Churchill et al. 2012b), however, Churchill et al. (2013a) has shown statistically that the covering fraction does not precipitously drop for $M_h > 10^{12}$ $M_\odot$, which is in direct conflict with theoretical expectations of a mass-dependent truncation of cold-mode accretion.

### 3.4. Sources of Mg II Absorption

The goal of absorption-line studies is to determine the exact source of the absorption so we can study specific phenomena/physics in detail. However, we have yet to determine an efficient method of conclusively determining the origin of individual systems. In general, there are five likely sources of Mg II absorption: (1) ISM, (2) high-velocity clouds (HVCs), (3) tidal debris, (4) galactic outflows, and (5) filamentary accretion.

**ISM.**—A significant fraction of cool gas is located within the ISM of galaxies. Mg II absorption is always detected along quasar sight lines that probe the ISM of our Milky Way (e.g., Savage et al. 2000; Bowen et al. 1995). The majority of absorption seen in galaxy spectra arises from the ISM; only a small fraction of the absorbing gas appears to be outflowing/infalling (see Martin et al. [2012], and references therein). It is increasingly difficult to find extremely low impact parameter systems as the quasar either outshines faint foreground galaxies or becomes more obscured by large low-redshift foreground galaxies. However, several studies report Mg II absorption systems detected within $\sim$5 kpc of local (Bowen et al. 1996) and low-redshift galaxies (Kacprzak et al. 2013) that have a similar $W_r(\lambda 2796)$ distribution to that of the Milky Way.

**HVCs.**—HVCs are expected to contribute to the covering fraction of Mg II absorbers because they are sources of Mg II absorption around local galaxies (e.g., Savage et al. 2000; Herenz et al. 2013). This contribution is difficult to compute because we can only currently measure it for the local galaxy population. It has been estimated that roughly 30%–50% of known strong Mg II absorbers arise from HVCs (Richter 2012; Herenz et al. 2013). This suggests that the majority of absorbers have an alternative origin.

**Tidal Debris.**—Low-redshift H I surveys show that galaxies having undergone a minor merger/interaction typically exhibit a perturbed/warped H I disk that is more extended than those of isolated galaxies (e.g., Fraternali et al. 2002; Chynoweth et al. 2008; Sancisi et al. 2008). It is common to detect Mg II absorption near galaxy groups. In most cases, the absorbing gas tends to have lower metallicity than the nearby host galaxies, and the absorption-line kinematics tend to be more complex. In addition, stellar tidal features are commonly seen for galaxy group members All of the above suggests that the gas has a tidal origin within the intragroup medium (York et al. 1986; Kacprzak et al. 2007, 2010b; Rubin et al. 2010; Meiring et al. 2011; Battisti et al. 2012; Gauthier 2013). Chen et al. (2010a) demonstrates that group galaxies do not follow the well-known anticorrelation between $W_r(\lambda 2796)$ and $D$, but exhibit a more random distribution of $W_r(\lambda 2796)$ as a function of $D$ (also see Yoon & Putman 2013). These results suggest that galaxy environment plays a role in the metal distribution within galaxy haloes.

The extreme role of environment is further evident in galaxy clusters where H I disks are truncated (e.g., Chung et al. 2009) and the CGM covering fraction is significantly reduced (Yoon &
Galactic Outflows.—High equivalent width Mg II absorption has been observed to directly trace 100–1000 km s\(^{-1}\) galactic-scale outflows originating from their host galaxies (Tremonti et al. 2007; Weiner et al. 2009; Martin & Bouché 2009; Rubin et al. 2010; Chelouche & Bowen 2010; Coil et al. 2011; Lundgren et al. 2012; Martin et al. 2012; Rubin et al. 2014; Bordoloi et al. 2014). These outflows can extend out to ∼50 kpc and are orientated along the galaxy minor axis (Bordoloi et al. 2011; Bouché et al. 2012; Gauthier & Chen 2012; Kacprzak et al. 2012; Bordoloi et al. 2014; Kacprzak et al. 2014), having opening angles of ∼100° (Kacprzak et al. 2012; Bordoloi et al. 2014; Martin et al. 2012). The outflows observed in disk galaxies produce Mg II equivalent widths and velocities that are higher for the face-on systems compared to the edge-on ones, which is consistent with a primarily bipolar outflow geometry (Bordoloi et al. 2014). Furthermore, the outflowing absorbing gas velocities originating from the host galaxies appear to correlate with the host galaxy SFRs and B-band magnitude/mass (Weiner et al. 2009; Rubin et al. 2010; Martin et al. 2012; Kornei et al. 2012; Bordoloi et al. 2014). Similarly, correlations between host galaxy colors and SFRs with Mg II equivalent widths detected along quasar sight lines probing their halos also indirectly suggest that absorption is produced in outflows (Zibetti et al. 2007; Noterdaeme et al. 2010; Nestor et al. 2011).

Additional evidence of outflows is provided by a handful of absorption systems with measured metallicities near solar that exist near galaxies (Noterdaeme et al. 2012a; Krogager et al. 2013; Péroux et al. 2013; Crighton et al. 2014; Kacprzak et al. 2014). It is expected that these high-metallicity systems are outflowing from their host galaxies. This is supported by the fact that some of these quasar sight lines tend to probe galaxies along their projected minor axis, which is where outflows are expected to exist (Péroux et al. 2013; Kacprzak et al. 2014). Further evidence supporting outflows comes from combined kinematic, geometric, and metallicity arguments showing that the velocities of gas outflowing directly from a galaxy at z = 0.2 can reproduce the observed transverse absorption velocities found at 58 kpc along the galaxy’s projected minor axis (Kacprzak et al. 2014).

Filamentary Accretion.—Mg II absorption has been observed infalling (Martin et al. 2012) onto highly inclined galaxies with velocities of ∼200 km s\(^{-1}\) (Rubin et al. 2012). This is consistent with Kacprzak et al. (2011b) who showed that Wr(λ2796) is correlated with galaxy inclination, implying a significant fraction of absorption systems are coplanar and likely accreting toward the galaxy. The bimodal azimuthal angle distribution of quasar sight lines with detected Mg II absorption around host galaxies, shown in Figure 6, also suggests that infall occurs along the projected galaxy major axis (Bouché et al. 2012; Kacprzak et al. 2012).

The corotating and infalling accretion seen in the simulations of Stewart et al. (2011) is consistent with observations of Steidel et al. (2002) and Kacprzak et al. (2010a) that show Mg II absorption residing fully to one side of the galaxy systemic velocity and aligned with expected galaxy rotation direction—mimicking the rotation curve out into the halo.

Additional key evidence is provided by a handful of systems with measured absorption-line metallicities ranging between |M/H| < −1.8 to −1 that exist near galaxies that have nearly solar metallicities (Zonak et al. 2004; Chen et al. 2005; Tripp et al. 2005; Cooksey et al. 2008; Kacprzak et al. 2010b; Ribaudo et al. 2011; Thom et al. 2011; Bouché et al. 2013; Crighton et al. 2013). It is expected that these low-metallicity systems are accreting onto their host galaxies and possibly trace cold-mode accretion.

3.5. Future Progress

A large body of evidence suggests that the majority of Mg II absorption traces both outflows from star-forming galaxies and accretion onto host galaxies. While it is clear both processes are occurring, it remains difficult to disentangle which absorption systems may be uniquely associated with either process.

Two measurements may aid in identifying which absorption systems are associated with either outflows or accretion: galaxy orientation with respect to the quasar sight line and the absorption-line metallicity. The Mg II spatial distribution relative to the host galaxy provides a promising test since outflows are expected to extend along the host galaxy minor axis (e.g., Strickland et al. 2004), while accretion should progress along
filaments toward the galaxy major axis (e.g., Stewart et al. 2011). In Figure 6, Kacprzak et al. (2012) shows that Mg II absorption is primarily concentrated around the projected major and minor axes of host galaxies. Galaxies with no measurable absorption have a random distribution of quasar line-of-sight position angles. Furthermore, star-forming galaxies drive the bimodal distribution, while red galaxies show some signs of gas accretion along the projected major axis (Kacprzak et al. 2012). This is consistent with previous works and recent models (Bordoloi et al. 2011; Bouché et al. 2012; Bordoloi et al. 2014).

In addition, since outflows are expected to be metal-enriched and accreting material metal-poor, comparing the absorption-line and host galaxy metallicity provides another suitable test for discriminating outflows from accretion (e.g., Bouché et al. 2013; Crighton et al. 2014, and references therein). Recent work by Lehner et al. (2013) shows that the metallicity distribution of Lyman limit systems, $16.2 \leq N(\text{HI}) \leq 19$, is bimodal with metal-poor and metal-rich populations that peak at 2.5% and 40% of solar metallicity (Fig. 7). Thus, similar to the galaxy orientation bimodality, it is suggestive of two dominant sources of the majority of absorption-line systems: the metal-rich population likely traces winds, recycled outflows, and tidally stripped gas while the metal-poor population is consistent with cold accretion.

Measuring the metallicity and relative orientations, combined with relative kinematics, yields the most promising selection criteria in isolating individual sources producing Mg II absorption (see Kacprzak et al. 2014). Future H I surveys, such as WALLABY (targeting 600,000 galaxies at $z = 0–0.25$) and DINGO (targeting 100,000 galaxies at $z = 0–0.40$), using the Australian Square Kilometer Array Pathfinder (ASKAP) will provide complementary data that will aid in our understanding of galaxy evolution and feedback processes.

4. Lyα IN EMISSION

4.1. Physics of Lyα Emission

Partridge & Peebles (1967) predicted that Lyα emission would be an excellent tracer of young galaxies. Unlike absorption-lines studies, which give one-dimensional information, Lyα emission can trace gas in three dimensions (two spatial and one wavelength). While it was three decades before observational searches for Lyα emitters were successful, the detection of Lyα emission is now an important window into the high-redshift universe.

The physics of Lyα emission is neatly summarized by the mechanisms by which a hydrogen atom is excited into the $2^2P$ state.

**Recombination.**—When an electron and a proton combine to make neutral hydrogen, the electron may pass through the $2^2P$ state on its way to the ground state:

$$e^- + H^+ \rightarrow H(2^2P) + \text{photon(s)} \rightarrow H(1^2S) + \text{Lyα}.$$  

For atoms at $T = 10^4$ K, with only a weak dependence on temperature, $\sim 42\%$ of recombinations will pass through the $2^2P$ state on their way to the ground state and produce a Lyα photon, $\sim 38\%$ will go directly to the ground state and produce an ionizing photon, and $\sim 20\%$ go to the $2^2S$ state, producing two continuum photons in a forbidden transition to the ground state (Gould & Weinberg 1996). If the surrounding medium is optically thick to ionizing radiation, then ionizing photons will be reprocessed, while Lyα photons are simply scattered. In this case, known as “case B,” Lyα photons are emitted at $\sim 68\%$ of the rate at which ionizing radiation is absorbed.

Thus, the photoionization of neutral hydrogen will produce Lyα radiation. The H I could surround the photoionizing source, producing nebular emission. In star-forming galaxies, for example, massive O and B stars (and Population III stars) produce copious ionizing radiation (Bromm et al. 2001; Schaerer 2003; Raiter et al. 2010), which immediately encounters H I in the surrounding ISM from which the stars formed. Upon recombination, Lyα photons are emitted. Because the Lyα line is narrow and strong, it should (in theory) provide a signature of primeval, high-redshift galaxies.

For the same reason, ionizing radiation from quasars should light up the surrounding gas in Lyα. Haiman & Rees (2001) studied the effect of a quasar turning on within an assembling protogalaxy and found that it would boost Lyα emission in a

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3 Resonant absorption of a higher Lyman-series photon (Lyβ+) will also result in a cascade back to the ground state, possibly resulting in Lyα emission. The Lyβ+ photon itself will result from recombination or excitation, and so can be included in the respective case.
spatially extended region dubbed “Lyα fuzz.” While observations show that the fraction of LAEs associated with AGN is a few percent (Gawiser et al. 2006; Ouchi et al. 2008) the brightest, most spatially extended emitters (“blobs”) could be driven by an obscured quasar (Overzier et al. 2013).

An H I cloud can also be illuminated by an external source of ionizing photons, such as the UV background or a nearby quasar. Observations of these fluorescent Lyα emitters (FLEs) hold great potential—they illuminate gas outside of galaxies, where most of the baryons are at high redshift. Further, for clouds that are optically thick to ionizing radiation, the surface brightness of the fluorescent emission is set by the strength of the ionizing background (Gould & Weinberg 1996; Cantalupo et al. 2007).

Excitation.—An H I atom can be placed in the 2P state via collisional excitation. Most collisions at the relevant temperatures place the H I atom in an n = 2 state: ~25% go to the 2S state and ~75% go to the 2P state. Approximately 10% of the energy is lost to bremsstrahlung, meaning that ~68% of the thermal energy that is radiated away by collisional excitation is in the form of Lyα photons (Gould & Weinberg 1996). However, the Lyα collisional emissivity is a strong function of temperature. For example, for gas in collisional ionization equilibrium (e.g., self-shielded), the emissivity drops by ~5 × 10^3 between its peak at 1.8 × 10^4 K and 1 × 10^4 K (Thoul & Weinberg 1995).

There is thus an important connection between Lyα emission and cooling radiation, long recognized as a crucial ingredient in galaxy formation (Binney 1977; Silk 1977; White & Rees 1978), Birnboim & Dekel (2003) and Kereš et al. (2005) found that gas accretes onto galaxies in two modes: a hot mode, where particles are heated to Tvir ~ 10^6 K before cooling via bremsstrahlung and accreting onto the galaxy quasi-spherically; and a cold mode, where particles that have never been heated above ~10^5 K are accreted along filaments, and cool primarily by Lyα line emission. Thus, gas that is cooling within dark-matter halos is expected to radiate a substantial fraction of its gravitational energy via collisionally excited Lyα emission (Haiman et al. 2000; Fardal et al. 2001).

We will examine these mechanisms and emitters in more detail in later sections. Next, we will survey the history and current status of observations of Lyα emission from the high-redshift universe.

4.2. Physics of Lyα Scattering

Lyα photons are strongly scattered by HI, and so an understanding of radiative transfer (RT) effects is crucial to interpreting Lyα observations. With quasar absorption spectra frequently revealing H I regions with column densities NHI of order 10^{16}-10^{22} cm^{-2} (§ 2), extremely large optical depths of τ_0 = 10^3-10^9 are likely to be encountered by emitted Lyα photons (see Eq. [1]). This is particularly true when ionizing radiation is the source of Lyα photons. At temperatures of ~10^4 K, the optical depth of H I in Lyα is about 10^4 times larger than the optical depth at the Lyman limit (Osterbrock 1989, p. 77). A Lyman limit photon that enters an H I region will be absorbed at a depth of τLL ~ 1. When recombination produces a Lyα photon, this photon will find itself at an optical depth of τ Lyα ~ 10^4.

Radiative transfer calculations are necessary for any theoretical prediction of the spectra and spatial distribution of Lyα emission. Lyα photons will typically undergo many scatterings before escaping an H I region. The properties of the emergent radiation depend sensitively on the spatial distribution, kinematics, temperature, and dust content of the gas.

We will begin by examining a simple scenario for which an analytic solution is available. Harrington (1973) and Neufeld (1990) derived an analytic expression for the spectrum J(x, τ_0) of radiation emerging from an optically thick (√τ_0 > 10^3/α) uniform, static slab of neutral hydrogen, where line-center photons are injected at the center of the slab, atomic recoil is neglected, τ_0 is the center-to-edge optical depth at line center, x is the frequency of Lyα radiation relative to line center and in units of the thermal Doppler frequency width, and a is the ratio of the Lorentz to (twice) the Doppler width. The analog of this solution for a uniform sphere is shown in Figure 8.

The key to understanding this spectrum is that the photon executes a random walk in both frequency and physical space. When a photon is in the Doppler core, its mean free path is very short, so there is very little spatial diffusion. Most scatterings are with atoms that have the same velocity along the direction of motion as the atom that emitted the photon. Occasionally, however, the photon will collide with a very fast moving atom from the tail of the Maxwell-Boltzmann distribution, with large velocities perpendicular to the photon’s direction. When this
photon is reemitted, it will be far from line-center. The photon is now traveling through a slab that is comparatively optically thin. What happens next depends on the optical depth of the slab ($\tau_0$).

In the case of moderate optical depth ($\alpha \tau_0 \lesssim 10^3$), a single “catastrophic” scattering into the wings is enough to render the slab optically thin to the photon. A rough estimate of the frequency of the escaping photons ($x_e$) is given by,

$$\tau \approx \tau_0 e^{-\Delta x} \approx 1 \Rightarrow x_e \approx \pm \sqrt{\ln \tau_0}.$$ (6)

This case is discussed in Osterbrock (1962). Adams (1972) introduced the term “single longest flight” to describe this scenario.

For extremely optically thick media ($\sqrt{\alpha \tau_0} \lesssim 10^3$), however, the optical depth in the damping wings is enough to prevent the photon from escaping from the medium in a single long flight. Instead, the photon will execute a random walk in physical space with a relatively long mean free path. Osterbrock (1962) showed that during this “walk in the wings,” there will also be a random walk in frequency space: the rms Doppler shift of each scatter is $x \sim 1$, with a mean shift per scatter of $1/|x|$, biased to return the photon to line center. Thus, after a large number of scatterings, the photon will return to the Doppler core and once again experience very little spatial diffusion. The cycle of an initial scatter to the wings followed by the random walk back to the core (in frequency space) is termed an “excursion” (Adams 1972).

It is at this point that Adams (1972) points out a mistake in Osterbrock (1962), the resolution of which is quite illuminating. Osterbrock (1962) assumes that, in extremely optically thick media, the distance traveled in any particular excursion will be small compared to the size of the region. Thus, each excursion can be considered to be a single step in an ordinary random walk. However, Adams (1972) points out that we can test this assumption by asking which is more likely to happen first: the photon uses a large number of small excursions to random-walk out of the medium, or the photon uses one large excursion to escape? Adams (1972) showed that it is the second option—photons will escape the medium on their “single longest excursion.”

We can again give a rough estimate of the escape frequency of the photons. If a photon is scattered to frequency $x$ in the wings, and each scattering sends the frequency on average $1/|x|$ back to the core, then each excursion will contain $N \sim x^2$ scatterings. Between each scattering, the photon will travel a physical distance $\Delta s$ defined by $\sigma_n n_{HI} \Delta s \sim 1$. If this distance was traveled at line center, it would correspond to an optical depth of $\Delta \tau_0 = \sigma_0 n_{HI} \Delta s = \sigma_0 / \sigma_x$. Now, $\sigma_0 / \sigma_x \approx 1 / H(a, x) \sim x^2 / a$, where we have (reasonably) assumed that we are in the damping wings of the Voigt function $H$. Thus, between each scattering, the photon will travel a line-center optical depth of $\Delta \tau_0 \sim x^2 / a$. Further, after $N$ scatterings, the photon will have traveled an rms line-center optical depth of $\tau_{0\text{ms}}^\text{rms} \sim \sqrt{N} \Delta \tau_0 = |x|^3$ (see, e.g., Rybicki & Lightman 1979, p. 35).

The photon will escape when, in the course of an excursion, it can diffuse a distance comparable with the size of the medium, i.e., $\tau_{0\text{ms}}^\text{rms} \sim \tau_0$. Putting the above equations together, we find that the critical escape frequency is $x_e \sim (\alpha \tau_0)^{1/3}$. This agrees very well with the analytic solutions of Harrington (1973) and Neufeld (1990) for a static slab, which has its peak at $x_p = \pm 0.06(\alpha \tau_0)^{1/3}$. The static sphere solution of Dijkstra et al. (2006a) has its peak at $x_p = \pm 0.92(\alpha \tau_0)^{1/3}$. This means that if we modeled a DLA as a static sphere of HI at temperature $T$ with maximum edge-to-edge column density $N_{HI}$, a Ly$\alpha$ photon emitted at the center of the system will emerge with a characteristic frequency (expressed as a velocity) of:

$$v_p = 165.7 \, \text{km s}^{-1} \left(\frac{T}{10^4 \, \text{K}}\right)^{1/6} \left(\frac{N_{HI}}{2 \times 10^{20} \, \text{cm}^{-2}}\right)^{1/3},$$ (7)
even though the gas itself is static.

Given the complexity expected of the distribution and kinematics of H I in the real universe, Monte Carlo simulations are the method of choice for Ly$\alpha$ radiative transfer models. In full generality, a radiative transfer problem is specified by the number density of H I ($n_{HI}$), the Ly$\alpha$ emissivity ($\epsilon$, in photons s$^{-1}$ cm$^{-3}$), the bulk velocity $v_b$, the temperature $T$, and the dust number density ($n_d$) and scattering/absorption properties, all as a function of position. The Monte Carlo algorithm involves creating a photon and propagating it in a random direction for a certain distance (that depends on the optical depth), at which point the photon will interact with an atom. After the interaction, the photon will have a new frequency and a new direction chosen from an appropriate distribution. We repeat until the photon escapes the system. Mock observations of the system are built up from the escaping photons. The algorithm is discussed in detail in Barnes (2009). A plethora of Ly$\alpha$ radiation transfer codes, based on the Monte Carlo technique, have been published (Ahn et al. 2001; Zheng & Miralda-Escudé 2002; Cantalupo et al. 2005; Verhamme et al. 2006; Dijkstra et al. 2006a; Hansen & Oh 2006; Tasitsiomi 2006; Laursen & Sommer-Larsen 2007; Barnes et al. 2011; Tajima et al. 2012b). Different geometrical and kinematic configurations can be tested with these models. We will consider specific applications of such simulations in the following sections.

4.3. Ly$\alpha$ Emitters (LAEs)

Search for Ly$\alpha$ emitters.—For many years, attempts to detect the population of high-redshift Ly$\alpha$ emitters (LAE) proved mostly unsuccessful (e.g., Koo & Kron 1980; Meier & Terlevich 1981; Djorgovski & Thompson 1992; de Propris et al. 1993; Pritchet 1994; Thompson et al. 1995), with the discovery of only a handful of candidates (Wolfle et al. 1992; Møller & Warren 1993; Macchetto et al. 1993). This was in strong...
disagreement with the predictions of Partridge & Peebles (1967), who predicted emission lines as intense as a few $10^{45}$ erg s$^{-1}$ (corresponding to fluxes of a few $10^{-14}$ erg s$^{-1}$ cm$^{-2}$ at $z = 3$), which should have been seen by the aforementioned surveys. For example, Thompson et al. (1995) conducted both a shallow/wide survey ($F_{1216} \gtrsim 10^{46}$ erg s$^{-1}$ cm$^{-2}$ over $\approx 10^3$ Mpc$^3$) and a deeper/smaller one ($F_{1216} \gtrsim 10^{44}$ erg s$^{-1}$ cm$^{-2}$ over $\approx 10^3$ Mpc$^3$) using narrowband (NB) imaging at $\approx 3$–5 that led to no detections.

Telescopes remained blind to the long-sought distant Ly$\alpha$ galaxy population until the late 1990s, and the advent of high-sensitivity and larger collecting-area instruments. Hu et al. (1998) detected 10 LAE candidates with the 10 m Keck II telescope in a deeper survey at $z = 3.4$, spanning only $46$ arcmin$^2$ over $\delta z = 0.07$. Their sensitivity ($L_{1216} \gtrsim 10^{42}$ erg s$^{-1}$) enabled them to find a more common, faint, LAE population. Rhoads et al. (2000) found ~150 bright LAEs ($L_{1216} \gtrsim 10^{42}$ erg s$^{-1}$) at $z = 4.5$ as part of the Large Area Lyman Alpha survey (Rhoads et al. 2000; Malhotra & Rhoads 2002). Their observations took advantage of the 8192$^2$ pixel CCD Mosaic camera at the 4 m Mayall telescope of Kitt Peak National Observatory to cover 0.72 deg$^2$ in the redshift range 4.37 $\lesssim z \lesssim 4.57$, corresponding to a volume of almost $10^6$ Mpc$^3$. The large surveyed volume allowed them to probe rarer, brighter LAEs.

Many ideas have been suggested to explain the previous failures to uncover high-redshift LAEs, e.g., short Ly$\alpha$ emission duty cycle (Charlot & Fall 1993), stellar absorption (Valls-Gabaud 1993), or line suppression due to metals and dust (Meier & Terlevich 1981; Hartmann et al. 1988; Charlot & Fall 1993). In addition, the models of Partridge & Peebles (1967) were based on the monolithic collapse paradigm of galaxy formation, which overpredicts the Ly$\alpha$ luminosities of galaxies in the early universe.

Haiman & Spaans (1999), using a hierarchical galaxy formation formalism and a simple model of dust extinction, showed that the properties of the population observed by Hu et al. (1998) could be roughly recovered. Moreover, the escape of Ly$\alpha$ photons from galaxies is very sensitive to resonant scattering in H i gas (e.g., Hummer 1962; Auer 1968; Harrington 1973; Ahn et al. 2001). Indeed, even for low dust content the observed fluxes can be considerably reduced because of dust grain absorption along the increased path of resonantly scattered Ly$\alpha$ photons (Hummer & Kunasz 1980; Neufeld 1990; Charlot & Fall 1991). An extreme example of the impact of Ly$\alpha$ resonant scattering is the strong Ly$\alpha$ absorption profile observed in metal/dust-poor low-redshift galaxies (Kunth et al. 1994; Ostlin et al. 2009). Similar processes are thought to alter Ly$\alpha$ spectra of high-redshift galaxies, and therefore the visibility of LAEs (see § 4.2).

Ly$\alpha$ radiative transfer is strongly affected by interstellar gas kinematics, geometry and ionization state (Kunth et al. 1998; Tenorio-Tagle et al. 1999; Shapley et al. 2003; Mas-Hesse et al. 2003; Verhamme et al. 2006; Laursen et al. 2009; Yajima et al. 2012b), dust distribution (Neufeld 1991; Hansen & Oh 2006), intergalactic attenuation (Madau 1995; Dijkstra et al. 2007a), making the interpretation of Ly$\alpha$ observations difficult. We will next discuss such observations of LAEs, returning to theory in § 4.4.

**Observational methods.**—Ly$\alpha$ photons emitted at high redshift ($2 \lesssim z \lesssim 7$) can be detected from the ground in the optical and near-infrared. However, only certain spectral ranges are free from confusion due to night skyline emission. This translates into a series of redshift windows at which LAEs can be observed from Earth.

At low redshift ($z \lesssim 2$), the Ly$\alpha$ line is seen in the ultraviolet, and one needs to utilize space instrumentation. Observations in the local universe are even more restricted due to (i) the strong geocoronal emission which blinds nearby Ly$\alpha$ emission lines, and (ii) the damped H i absorption produced by the Galactic center, which suppresses many lines of sight. Nevertheless, low-redshift LAEs have been studied by space-based telescopes, e.g., with the HST (Hubble Space Telescope; Kunth et al. 1998; Ostlin et al. 2009), IUE (International Ultraviolet Observatory; Meier & Terlevich 1981; Terlevich et al. 1993) and GALEX (Galaxy Evolution Explorer; Deharveng et al. 2008; Cowie et al. 2010). Observations of nearby LAEs probe galaxies on small scales, providing detailed Ly$\alpha$ and multwavelength mapping of the interstellar and circumgalactic media (e.g., Hayes et al. 2013). Although samples are still rather small, the analysis of well-resolved objects can serve as a useful benchmark for interpreting high-redshift data (Mas-Hesse et al. 2009).

At high redshift, thousands of galaxies have been found via the Ly$\alpha$ emission line; Table 1 presents a compilation of Ly$\alpha$ surveys. The most popular imaging technique to detect LAEs requires a set of broad- and narrowband (NB) filters to detect the emission line at the redshifted Ly$\alpha$ wavelength (e.g., Ouchi et al. 2008), and references in Table 1). Figure 9 shows examples of the various filters used with the Subaru/SuprimeCam to detect LAEs at $z = 3.1, 3.7, 4.5, 4.9, 5.7, \text{ and } 6.6$. Color-magnitude selections are usually applied to the NB detections to ensure the reliability of the LAE candidates and remove contaminants from the sample, such as lower-redshift Hα, O ii or O iii emitters. These criteria can introduce a bias if they preferentially select LAEs with large equivalent widths, or if they eliminate objects without a signature of IGM attenuation (Laursen et al. 2011), ionizing emission from the galaxy itself is expected to photoionize the surrounding H i gas.

Alternatively, Ly$\alpha$ emission lines can be identified spectroscopically in blind surveys, or as part of a follow-up of NB candidates. Spectroscopic observations have been carried out by several teams in the last years, e.g., Rauch et al. (2008) with VLT/FORS2, Kashikawa et al. (2011) with Subaru/FOCAS (Faint Object Camera and Spectrograph) and Keck II/DEIMOS (DEep Imaging Multi-Object Spectrograph), and Cassata et al. 2014 PASP, 126:969–1009
\begin{table}
\centering
\begin{tabular}{|l|c|c|c|c|c|c|c|}
\hline
Reference & Redshift & $N_{\text{obj}}$ & EW$_{\text{rest}}$ (Å) & $L_{\text{Ly}\alpha}$ ($10^{42}$ erg s$^{-1}$) & Ident. technique & Instrument & Area (arcmin$^2$) \\
\hline
Barger et al. (2012) & 0.67–1.16 & 28 & 20 & 3 & grism & GALEX & 2286 \\
Blanc et al. (2011) & 1.9–3.8 & 98 & 20 & 4 ($z \approx 3$) & IFS & VIRUS & 169 \\
Guaita et al. (2010) & 2.07 ± 0.02 & 250 & 20 & 0.64 & NB & MOSAIC & 998 \\
Cassata et al. (2011) (Deep) & 2.6–6.6 & 42 & – & $\approx 0.4$ ($z \approx 3$) & MOS & VIMOS & 2230 \\
Cassata et al. (2011) (Ultra-Deep) & 2.4 & 188 & – & $\approx 0.1$ ($z \approx 3$) & MOS & VIMOS & 576 \\
Hayes et al. (2010) & 2.2 ± 0.05 & 38 & 20 & 0.3 & NB & FORS1 & 56 \\
Nilsson et al. (2009) & 2.26 ± 0.05 & 170 & 20 & 2.3 & NB & WFI & 1190 \\
van Breukelen et al. (2005) & 2.3 & 14 & – & $\approx 1.1$ ($z \approx 3$) & S-S & FORS2 & 0.252 \\
Rauch et al. (2008) & 2.67–3.75 & 27 & – & $\approx 0.1$ ($z \approx 3$) & S-S & FORS2 & 169 \\
Grove et al. (2009) & 2.8–3.2 & 83(59) & 25 & $\approx 0.4$ & NB-MOS & FORS1 & 133 \\
Yamada et al. (2005) & 3–5 & 198 & 20 & 3 ($z \approx 4$) & IB & S-Cam & 944 \\
Hayashino et al. (2004) & 3.09 ± 0.03 & 283 & 37 & 4.1 & NB & S-Cam & 770 \\
Ciardullo et al. (2012) & 3.1 ± 0.04 & 141 & 20 & 2.1 & NB & MOSAIC II & 1000 \\
Gronwall et al. (2005) & 3.11 ± 0.02 & 162 & 20 & 1.2 & NB & MOSAIC II & 993 \\
Kudritzki et al. (2000) & 3.13 ± 0.01 & 9 & – & 1.8 & S-S & FORS & 50 \\
Ouchi et al. (2008) & 3.13 ± 0.03 & 356(41) & 64 & 1 & S-Cam & FOCAS-VIMOS & 3538 \\
Cowie & Hu (1998) & 3.44 ± 0.03 & 10 & 17 & 2 & NB & LRIS & 46 \\
Ouchi et al. (2008) & 3.69 ± 0.03 & 101(26) & 44 & 4 & NB & S-Cam & 3474 \\
Malhotra & Rhoads (2002) & 3.71 ± 0.12 & 6 & 53 & 5 & IB & S-Cam & 132 \\
Fujita et al. (2003) & 4.47 ± 0.10 & 194(110) & 14 & 5 & NB & MOSAIC & 1116 \\
Shimasaku et al. (2006) & 5.7 ± 0.05 & 89(28) & 17 & 2.2 & NB & S-Cam & 725 \\
Rhoads & Malhotra (2001) & 5.73 ± 0.06 & 18 & 14 & 5 & NB & MOSAIC & 1116 \\
Dressler et al. (2011) & 5.75 ± 0.05 & 122 & – & 1 & MNS & IMACS & 110 \\
Hu et al. (2010) & 6.54 ± 0.08 & 27 & – & 6.7 & NB & S-Cam & 4168 \\
Kashikawa et al. (2006) & 6.56 ± 0.05 & 75(17) & 17 & 4.8 & NB & S-Cam & 320 \\
Hu et al. (2010) & 6.56 ± 0.05 & 207(24) & 14 & 2.5 & NB & S-Cam & 3722 \\
Ouchi et al. (2008) & 5.7 ± 0.05 & 401(17) & 27 & 3 & NB & S-Cam & 4168 \\
Shibuya et al. (2012) & 7.26 ± 0.08 & 4(1) & 0 & 10 & NB & S-Cam & 1718 \\
Hibon et al. (2010) & 7 ± 0.04 & 7 & – & 9 & NB & S-Cam & 2340 \\
Tilvi et al. (2010) & 7.7 ± 0.005 & 4 & – & 5 & NB & NEWFIRM & 784 \\
Krug et al. (2012) & 7.7 ± 0.01 & 4 & – & 5 & NB & NEWFIRM & 760 \\
\hline
\end{tabular}
\caption{(Nonexhaustive) Compilation of Surveys of LAEs}
\end{table}

Notes.—Columns.—Col. (1): Redshift; Col. (2): Number of LAE detections (Number of candidates confirmed with spectroscopy); Col. (3): Ly$\alpha$ rest-frame equivalent width threshold (Å); Col. (4): Ly$\alpha$ luminosity threshold in units of $10^{42}$ erg s$^{-1}$ (we assume $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$); Col. (5): Observational technique to identify Ly$\alpha$ sources; Col. (6): Instrument used for detection (Instrument used for follow-up observation); Col. (7): Field size (arcmin$^2$).

Acronyms.—NB: Narrowband imaging; IB: Intermediate-band imaging; S-S: Slit Spectroscopy; IFS: Integral Field Spectroscopy; MOS: Multiobject Spectroscopy; S-Cam: Suprime-Cam; MNS: Multislit Narrowband Spectroscopy.

Some flux/EW limits and survey areas/depths given in this table are only approximate values; the reader should refer to the original articles for full details on the surveys. Similarly, the number of LAEs that we quote, $N_{\text{obj}}$, can either correspond to the total number of detections, or to the number of objects used to compute the luminosity functions.

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All methods to identify LAEs must face the problem of false positives, interlopers that can be confused with Lyα-emitting galaxies. In addition to low-redshift emission line objects (galaxies or AGN), AGN located at the same redshift as the targeted galaxies can contaminate LAE samples at the level of a few percent (Ouchi et al. 2008).

In addition to Lyα-selected surveys, Lyα emission is also often seen in Lyman break galaxies (hereafter, LBG; Steidel & Hamilton 1993; Steidel et al. 1999), which are selected via their (1) intense UV magnitude and (2) the discontinuity caused by photoelectric absorption ($\lambda < 912 \text{ Å}$) in the interstellar medium and line blanketing by the intervening Lyα forest ($912 > \lambda > 1216 \text{ Å}$). The Lyman break technique (or dropout technique) efficiently selects high-redshift, star-forming galaxies using a set of broadband UV and optical filters (Steidel et al. 2003; Gabasch et al. 2004; Bouwens et al. 2007; McLure et al. 2009; Bouwens et al. 2011b, and references therein).

**Statistical properties of Lyα emitters.**—LAEs observed in current surveys span a range of Lyα luminosities from $\sim 10^{42} \text{ erg s}^{-1}$ to a few times $10^{45} \text{ erg s}^{-1}$ (e.g., Shimasaku et al. 2006; Gronwall et al. 2007; Ouchi et al. 2008). The typical Lyα luminosity reached by wide-field surveys probes star formation rates (SFR) greater than $\sim 1 M_\odot \text{ yr}^{-1}$, according to

$$L_{\text{Ly}α} = 1.1 \times 10^{42} \left( \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \right) \text{ ergs}^{-1}. \quad (8)$$

This equation is derived from the SFR-Hα relation for constant star formation rate (Kennicutt 1983, 1998) and the Lyα-Hα emissivity ratio under case B recombination (Brocklehurst 1971; Osterbrock & Ferland 2006). The following assumptions are made to compute the coefficient in equation (8): (i) Salpeter initial mass function (IMF), (ii) solar metallicity, and (iii) ionization-bound nebula (no ionizing photon can escape the medium). The conversion factor can vary significantly if we modify these assumptions, especially for very low metallicities or extreme IMF cutoff (Schaerer 2003; Raiter et al. 2010).

The Lyα luminosity function (LF) at various redshifts has been used to characterize the evolution of LAEs as a population. It does not seem to evolve significantly from $z = 6$ to 3 as the characteristic number density ($\Phi^\ast \sim 10^{-5} \text{ Mpc}^{-3}$) and luminosity of LAEs ($L^\ast \sim \alpha \text{ few} 10^{42} \text{ erg s}^{-1}$) appear to remain almost unchanged over this redshift range (Hu et al. 1998; Ouchi et al. 2008; Cassata et al. 2011).\footnote{Although the Lyα LFs reported by Ouchi et al. (2008), Gronwall et al. (2007), and Cassata et al. (2011) at $z \sim 3$ are in good agreement, these surveys have applied very different LAE selection criteria. Ouchi et al. (2008) select only strong line emitters (EW > 64 Å), whereas Gronwall et al. (2007) use EW > 20 Å. The spectroscopic survey of Cassata et al. (2011) does not apply any EW selection. A large fraction of the LAEs reported by Gronwall et al. (2007) and Cassata et al. (2011) have EW < 64 Å, which might have been missed by Ouchi et al. (2008). The apparent agreement between $z = 3$ LFs may be affected by observational uncertainties and cosmic variance.}

$^5$ It is worth noticing that, unlike the Lyα LF, the UV LF of...
LBGs evolves significantly (as expected in a hierarchical growth scenario), its characteristic luminosity being about 10 times larger at $z = 3$ than at $z = 6$ (Gabasch et al. 2004; Bouwens et al. 2007; McLure et al. 2009; Bouwens et al. 2011a).

The nonevolution of the Ly$\alpha$ LF is a subject of debate. Hu et al. (2010) find a significantly lower abundance of LAEs at $z = 5.7$ than Ouchi et al. (2008) and Shimasaku et al. (2006). The former argue that the photometric sample of Ouchi et al. (2008) at the same redshift might contain a large fraction of contaminants, leading them to strongly overestimate the $z = 5.7$ LF. However, the recent spectroscopic follow-up of the Shimasaku et al. (2006) sample at the same redshift by Kashikawa et al. (2011) seems to favor a low contamination rate and a value of $\Phi^*$ consistent with Ouchi et al. (2008), though slightly smaller. Additional and more homogeneous datasets with spectroscopic confirmations will refine constraints on the Ly$\alpha$ LFs.

A differing evolution of the Ly$\alpha$ and UV LFs would imply a variation with redshift of the mechanisms that power the Ly$\alpha$ emission, or more probably the ability of Ly$\alpha$ photons to escape galaxies. Hayes et al. (2011) have quantified this evolution in terms of the “sampled-average volumetric” Ly$\alpha$ escape fraction, defined as the ratio of observed to intrinsic Ly$\alpha$ luminosity density. Figure 10 (from Hayes et al. 2011) illustrates the rise of this volumetric escape fraction from $z \approx 0 - 6$. They find an evolution of the escape fraction that scales like $(1 + z)^{2.6}$ over this redshift range (red curve). Although it is not shown on this figure, we note that the $f_{esc}(\text{Ly}\alpha)$ value derived by Wold et al. (2014) at $z = 1$ is fully consistent with this relation.

Dijkstra & Jeeason-Daniel (2013) derive an effective Ly$\alpha$ escape fraction from SFR and Ly$\alpha$ luminosity functions, instead of luminosity densities (see also Blanc et al. 2011). Their results are in good agreement with those of Hayes et al. (2011), except at $z = 0.35$. Indeed, the value quoted by Hayes et al. (2011) at this redshift may be underestimated, because $f_{esc}(\text{Ly}\alpha)$ is computed by comparing the Ly$\alpha$ luminosity density (as observed above a given detection threshold) to the total SFR density.

Regarding the faint-end slope of the Ly$\alpha$ LF, and its evolution with redshift, low-luminosity sources have been found in very deep surveys down to a few $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ (Rauch et al. 2008; Cassata et al. 2011; Dressler et al. 2011). The data seem to favor steeper slopes (and especially a steepening toward higher redshift). However, the number of detections at such low fluxes is limited; larger samples are required to draw robust conclusions.

A valuable observable to tackle questions of Ly$\alpha$ emission and radiative transfer is the Ly$\alpha$ equivalent width (EW), which measures the intensity of the line with respect to the adjacent continuum. Most LAEs have (rest frame) Ly$\alpha$ EW between 0 and 100 Å; the tail of the distribution extends to 250 Å (Shimasaku et al. 2006; Gronwall et al. 2007; Ouchi et al. 2008; Cassata et al. 2011). Higher EW values have been claimed (e.g., Malhotra & Rhoads 2002; Dawson et al. 2007; Adams et al. 2011), and recently Kashikawa et al. (2012) reported a $z = 6.5$ LAE with EW $= 436_{-149}^{+422}$ Å. Such large EW are surprising because they exceed the standard limit of 240 Å set by theoretical models of stellar-powered Ly$\alpha$ emission (Charlot & Fall 1993). Assuming that these extreme EW are real Ly$\alpha$ sources, they might hint at a top-heavy IMF, very low-metallicity stars (Schaerer 2003), or radiative transfer effects in neutral hydrogen (see § 4.4; and also Neufeld [1991]). They could also imply that Ly$\alpha$ emission is not powered by star formation alone. Indeed, such measurements are often lower limits with no obvious continuum detection, so other processes like cooling radiation or fluorescence may contribute significantly to the Ly$\alpha$ emission.

In recent years, several groups have studied the link between LAEs and LBGs. Shapley et al. (2003) find that half of $z = 3$ LBGs have detectable Ly$\alpha$ emission, and only 25% display a Ly$\alpha$ equivalent width larger than 20 Å. As part of a spectroscopic survey of faint LBGs, Stark et al. (2011) have characterized the fraction of Ly$\alpha$-emitting galaxies within UV continuum-selected dropout galaxies between $z = 3$ and 7. They find that the fraction of strong emitters (EW $> 50$ Å) increases toward fainter UV luminosities. As shown in Figure 11 (black points and error bars), the LAE fraction increases from $\approx 10\%$ at $M_{UV} = -21$ to about 50% for galaxies as faint as $M_{UV} = -19$ at $3 < z < 6.2$. This result echoes the observed trend between UV magnitude and Ly$\alpha$ EW: UV bright galaxies have lower Ly$\alpha$ EW, while fainter ones seem to be stronger Ly$\alpha$ emitters on average (Ando et al. 2006; Ouchi et al. 2008). Further, the fraction of Ly$\alpha$-emitting galaxies at fixed UV luminosity is found to increase from $z \approx 3$ to 6 (Stark et al. 2010, 2011; Curtis-Lake et al. 2012). The rise is even more significant when considering weaker Ly$\alpha$ line emitters (EW $> 25$ Å; Ono et al. 2012).
Untangling the relationship between the LAE and LBG populations is complicated by their respective selection criteria. Gawiser et al. (2006) points out that up to 80% of narrowband-selected LAEs have the right colors to be detected by typical LBG surveys at z = 3, but only 10% are bright enough in the UV continuum (assuming a detection limit of $R_{AB} \leq 25.5$).

Indeed, narrowband surveys of LAEs preferentially pick up low-continuum galaxies. Nevertheless, the fraction of LAEs among samples of dropout galaxies increases as fainter LBG surveys are carried out (e.g., Stark et al. 2010). Ly$\alpha$ emission from high-redshift sources, and its variation with respect to the physical properties of galaxies, remains to be fully understood.

Physical properties of Ly$\alpha$ emitters.—The H$\i$ gas distribution of LAEs can be constrained by comparing the spatial extent of Ly$\alpha$ and UV emission. Bond et al. (2011) and Gronwall et al. (2011) conducted HST imaging on a subsample of $z = 3$ LAEs previously Ly$\alpha$-selected by Gronwall et al. (2007). They find that the Ly$\alpha$ emission of these objects is typically compact (<1.5 kpc), and almost coincides with the far-UV (<1 kpc) that traces the young stars. This contrasts with similar observations at lower redshift, which suggest that Ly$\alpha$ is more extended than the UV continuum and H$\alpha$ emission by factors of 2–3 (Hayes et al. 2013). This could indicate an evolution of the morphology of LAEs with redshift, or at least a change in the neutral gas distribution surrounding those galaxies (Ostlin et al. 2009; Nilsson et al. 2009; Bond et al. 2012). Deeper observations by Steidel et al. (2011) show a diffuse halo of Ly$\alpha$ emission extending well beyond the galaxy; these observations will be discussed further in § 4.5.

Physical properties of LAEs have been studied with multiband photometry and stacking. These analyses reveal that these objects have moderate star formation rates ($1–10 M_\odot$ yr$^{-1}$) and low stellar masses ($10^8–10^9 M_\odot$) (Gawiser et al. 2006; Finkelstein et al. 2007; Ono et al. 2010a; Vargas et al. 2014), such that LAEs are thought to be the building blocks of local $L^*$ galaxies (Gawiser et al. 2007). LAEs are also believed to host young stellar populations on average ($\approx 100$ Myr) and have low dust content, as suggested by their blue colors (Ouchi et al. 2008; Ono et al. 2010a). These characteristics are also typical of local galaxies with Ly$\alpha$ in emission (Hayes et al. 2014). Note that higher stellar masses, older ages, and significant dust extinction have also been reported by Finkelstein et al. (2009), Pentericci et al. (2009), and Ono et al. (2010b), which may highlight an inherent spread in the population of LAEs. Further uncertainties arise from spectral energy distribution (SED) fitting techniques and their assorted assumptions: star formation history, IMF, dust model, nebular emission, etc. (Finkelstein et al. 2009; Schaerer & de Barros 2009).

Compared to LAEs, LBGs are on average larger (a few kiloparsecs), more massive ($10^{10–11} M_\odot$), highly star-forming ($10–1000 M_\odot$ yr$^{-1}$), old ($\approx 1$ Gyr), and dusty ($E(B–V) \approx 0.3$) (Adelberger & Steidel 2000; Papovich et al. 2001; Shapley et al. 2001; Giavalisco 2002). The rest-frame UV sizes of LAEs and LBGs are similar at $z \approx 3$, and thereafter LBGs grow as $H(z)^{-1}$ while LAEs remain remarkably constant (Malhotra et al. 2012). Shapley et al. (2001) divided their sample of $z = 3$ LBGs into two categories, according to the age of the stellar populations. They find that the old sample ($\approx 1$ Gyr) contains stronger Ly$\alpha$ emitters than the young galaxy sample (<35 Myr). While the two samples show rather similar stellar masses, older galaxies are more dusty and less star forming. Shapley et al. (2001) propose an evolutionary sequence for LBGs: young, starbursting galaxies quickly produce dust, extinguishing their Ly$\alpha$ emission; later, when dust content has decreased (possibly ejected by Type II supernovae), Ly$\alpha$ is seen in emission. While supported by the work of Kornei et al. (2010) and GALEX observations of Oteo et al. (2012) at $z \approx 0.3$, this picture contrasts with other observations reporting that Ly$\alpha$ emission is preferentially found in younger galaxies (Gawiser et al. 2006; Pentericci et al. 2007; Finkelstein et al. 2007; Pirzkal et al. 2007; Cowie et al. 2011) and with the older idea that Ly$\alpha$ emission is related to an early phase of galaxy formation (Hu & McMahon 1996; Dijkstra & Wyithe 2007).

As an added complication, it has been shown that the relation between Ly$\alpha$ emission and color excess $E(B–V)$ is scattered. While Ly$\alpha$ emission is often found to anticorrelate with dust extinction (Shapley et al. 2003), young and dusty objects can also appear as Ly$\alpha$ emitters (Finkelstein et al. 2009; Pentericci et al. 2009; Yuma et al. 2010).

While Ly$\alpha$ emission is an excellent tool for detecting high-redshift galaxies, questions remain about the nature of LAEs and their link with LBGs. The observed scatter in the relations between Ly$\alpha$ emission and the physical properties of galaxies calls for a better understanding of the processes governing the production and the radiative transfer of Ly$\alpha$ photons. Theoretical models are therefore crucial to decyphering the Ly$\alpha$ signature of high-redshift galaxies.
4.4. Lyα Emission in Theory: Models of LAE Galaxies

The scattering of Lyα photons through neutral hydrogen in galaxies implies that models must take into account, and thus can potentially constrain, the kinematics, structure, and composition of the ISM of high-redshift galaxies.

Importance of ISM kinematics.—A striking feature of Lyα-emitting galaxies is the shape of their line profiles (see Fig. 12). Most show a broad, asymmetric red line; other spectral shapes are observed (P Cygni, double peaked, damped, etc.; Shapley et al. 2003; Mas-Hesse et al. 2003; Tapken et al. 2004; Dawson et al. 2004; Tapken et al. 2007). Though IGM absorption might be partly responsible for the attenuation of the blue side of the Lyα line, similar line shapes are observed in the local universe (e.g., Kunth et al. 1998; Heckman et al. 2011). The diversity of Lyα profiles is largely due to radiative transfer effects in the ISM of galaxies.

Ahn et al. (2000, 2001, 2002) and Zheng & Miralda-Escudé (2002) were amongst the first to use Monte Carlo radiative transfer codes to predict Lyα spectra from simple models of protogalaxies. Dijkstra et al. (2006a, 2006b) studied Lyα transfer through collapsing clouds, representing the gas accretion experienced by primordial galaxies (see also Zheng & Miralda-Escudé 2002). They find a boost of the blue peak and a suppression of the red part of the Lyα profile, at odds with what is usually observed.

Signatures of neutral gas outflows are detected ubiquitously at all redshifts in galaxies, with velocities ranging from a few tens to hundreds of kilometers per second (e.g., Pettini et al. 2001; Martin 2005; Weiner et al. 2009). Shapley et al. (2003) used more than 800 spectra of LBGs to construct a high-signal-to-noise composite spectrum. They find kinematic offsets between Lyα emission and low-ionization interstellar (LIS) absorption lines. The absorption lines associated with outflowing gas are blueshifted compared with the systemic redshift of the galaxies, such that \(\Delta v_{\text{LIS}} \approx -150 \text{ km s}^{-1}\). In contrast, Lyα emission appears to be redshifted, with a typical offset of \(\Delta v_{\text{LIS}} \approx +360 \text{ km s}^{-1}\). Comparable results have been reported in both LBGs and LAEs (Steidel et al. 2010; McLinden et al. 2011; Finkelstein et al. 2011b; Kulal et al. 2012; Berry et al. 2012).

Doppler shifts induced by winds ease the escape of Lyα, since the photons are scattered away from the Lyα line center (Kunth et al. 1998; Tenorio-Tagle et al. 1999; Mas-Hesse et al. 2003). However, an anticorrelation between Lyα EW and kinematic offset (\(\Delta v_{\text{LIS}} - \Delta v_{\text{LIS}}\)) is reported (Shapley et al. 2003; Hashimoto et al. 2013): stronger Lyα emission is found in cases where the velocity shift is smaller. Although these results are still debated (Verhamme et al. 2008; Berry et al. 2012), it may indicate that the enhancement of dust extinction due to resonant scattering in H I remains the main driver of Lyα escape from galaxies. Alternatively, Ferrara & Ricotti (2006) interpret this trend as the time evolution of a galactic wind: after the starburst, the outflow slows down and the covering factor is reduced, which favors the escape of Lyα photons.

Radiative transfer through an expanding shell is also invoked to explain the line profiles of Lyα-emitting galaxies (Ahn et al. 2003; Verhamme et al. 2006, 2008). In this model (Fig. 13), an isotropic Lyα source is located at the center of a thin, homogeneous, and spherical shell of H I gas mixed with dust. The expanding shell mimics the gas outflow generated by strong stellar winds and supernovae during starburst events, associated with...
photionization and subsequent Lyα emission (Weaver et al. 1977; Chevalier & Clegg 1985; Ferrara & Ricotti 2006; Nath & Silk 2009). Using different values of the shell parameters (expansion velocity $V_{\text{exp}}$, H I column density, dust opacity, and thermal/turbulent velocity of the gas within the shell), Verhamme et al. (2008) are able to reproduce the wide variety of observed Lyα profiles (see also Schaefer & Verhamme 2008; Lidman et al. 2012). As an example, we show in Figure 12 three Lyα profiles of LBGs at $z = 3$ from Tapken et al. (2007) that are successfully fitted by the shell model of Verhamme et al. (2008). Typical red asymmetric profiles arise from photons backscattered from the receding side of the shell (red arrow, Fig. 13), while photons directly emitted toward the observer will be preferentially destroyed by dust due to a smaller Doppler shift (blue arrow, Fig. 13).

Shell models provide a simple and physically motivated interpretation of Lyα spectra, but they remain very idealized. In particular, the emitted spectra do not depend on the spatial extent of the H I entrained in the wind. The observations of Steidel et al. (2010, 2011) indicate clumpy outflows and the presence of scattering gas well outside the ISM of LAEs. More realistic models of the impact of a galactic wind on the circumgalactic medium of high-redshift galaxies are required, and are discussed in § 4.5.

Importance of ISM structure and composition.—Hansen & Oh (2006) simulated the transfer of Lyα photons through clumpy media. Since the analytic model of Neufeld (1991), it has been argued that a multiphase ISM could explain the abnormally high observed Lyα EW, as previously discussed in § 4.3. Of particular importance is the distribution of dust, as interactions with dust can destroy Lyα photons. Neufeld (1991) models an ISM in which dust is locked in dense H I clouds that are embedded in a diffuse, dust-free, intercloud medium (ICM). Lyα and UV-continuum photons are generated at the center of a plane-parallel slab in the diffuse phase. While (nonresonant) continuum radiation passes through the clouds and is attenuated by dust, Lyα photons are scattered off the surface of the clouds as a result of their high probability of interaction with hydrogen. The resulting Lyα boost is called the “Neufeld effect,” which Finkelstein et al. (2011a) quantify with the parameter $q$:

$$q = \tau_{\text{Ly} \alpha}/\tau_{\text{cont}},$$

where $\tau_{\text{Ly} \alpha}$ is the dust opacity of Lyα photons, and $\tau_{\text{cont}}$ is the dust opacity of UV-continuum photons. In the simplest case, one expects $q \ll 1$ for a clumpy ISM, and $q \gg 1$ for a homogeneous ISM. Note, however, the simulations of Laursen et al. (2013), discussed below.

Finkelstein et al. (2011a) measured $q$ using the ratio of emission line fluxes for a sample of 12 GALEX LAEs at $z \sim 0.3$. They find that most of the sample lies at $q \sim 1 - 3$, indicating that the ISM neither enhances nor seriously attenuates Lyα. Even for those LAEs with $q < 1$, they note an important caveat, first discussed by Scarborough et al. (2009): if the dust is clumpy, then the observed line ratios do not follow the simple exp$\{-\tau_{\text{cont}}\}$ law. Further, Blanc et al. (2011) showed from the HETDEX pilot survey that the Lyα escape fraction, estimated from Lyα and (dust-corrected) UV luminosities, anti-correlates with dust extinction, as shown in Figure 14 (see also Atek et al. 2014). The black circles correspond to the $z = 2-4$ sources observed by Blanc et al. (2011). The dearth of $q \ll 1$ objects indicates that the Neufeld effect is not a common process in LAEs. In spite of some dispersion, the cloud of points is well fitted by a $q = 1$ model (black solid line, Fig. 14), which suggests that Lyα and continuum photons suffer a very similar dust extinction. The green triangles indicate the objects found by Atek et al. (2009) at $z = 0.3$, which agree fairly well with the data of Blanc et al. (2011). The red solid line is the relation reported by Kornei et al. (2010) for LBGs at $z = 3$. It lies slightly below the $q = 1$ relation measured for LAEs at the same redshift and is consistent with the idea that LAEs are a high-$f_{\text{esc}}$ subset of the LBG population.

The simulations of Hansen & Oh (2006) suggest that the Neufeld effect will be strong if most of dust grains reside in optically thick H I clouds. Recently, Laursen et al. (2013) and Duval et al. (2014) revisited this issue, finding that a significant boost requires a relatively rare confluence of conditions: high metallicity, little outflow, very high cloud density, very low

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7 It should be remembered that while H I scattering does not destroy Lyα photons, it can scatter them below the surface brightness limit of observations, so that Lyα photons disappear in the noise, so to speak.
density of H I in the ICM, and Lyα and UV photons that originate from regions deprived of neutral gas. They conclude that an EW boost is unlikely to occur in real galaxies, with $q \ll 1$ no guarantee of a homogeneous ISM. The preferential escape of Lyα compared with UV continuum is also not seen in the Lyα RT hydrodynamic simulations of Yajima et al. (2012b) and Verhamme et al. (2012).

Although many numerical Lyα RT experiments have been published, only a few have focused on transfer through interstellar media in state-of-the-art hydrodynamic simulations. As they include a range of relevant physics, like gas cooling, star formation, feedback, metal enrichment or dust formation, such studies are essential to gaining insight into the complex mechanisms altering the Lyα line. We emphasize that the “Lyα escape fraction,” as calculated by simulators, usually refers to the ratio of emitted to escaping Lyα photons at Lyα emitters (LAE) at $z = 2 - 4$ and 0.3, respectively. The escape of Lyα photons is anticorrelated with dust extinction, despite a strong dispersion. The black lines show the expected correlation for different clumpiness parameters $q$. The $q = 1$ model, for which Lyα and continuum photons suffer a similar dust extinction, describes well the median distribution of the data. It suggests that the impact of Lyα resonant scattering is partly suppressed, certainly due to geometry or kinematic effects. At given $E(B - V)$, Lyman break galaxies display lower $f_{\alpha}$ than LAEs on average (red solid line; Kornei et al. 2010). Reproduced by permission of the AAS. See the electronic edition of the PASP for a color version of this figure.

FIG. 14.—Observed relation between the Lyα escape fraction and the color excess $E(B - V)$ (Blanc et al. 2011). The black circles and the green triangles are the measurements of Blanc et al. (2011) and Atek et al. (2009) for Lyα emitters (LAE) at $z = 2 - 4$ and 0.3, respectively. The escape of Lyα photons is anticorrelated with dust extinction, despite a strong dispersion. The black lines show the expected correlation for different clumpiness parameters $q$. The $q = 1$ model, for which Lyα and continuum photons suffer a similar dust extinction, describes well the median distribution of the data. It suggests that the impact of Lyα resonant scattering is partly suppressed, certainly due to geometry or kinematic effects. At given $E(B - V)$, Lyman break galaxies display lower $f_{\alpha}$ than LAEs on average (red solid line; Kornei et al. 2010). Reproduced by permission of the AAS. See the electronic edition of the PASP for a color version of this figure.

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Laursen et al. (2009) analyzed the transfer of Lyα photons in $z \approx 3$ galaxies extracted from a cosmological $N$-body/hydrodynamical simulation. Although their sample contains only nine galaxies, there is a clear trend between Lyα escape fraction and the mass of the host halo. The quantity $f_{\alpha}$ is of order unity for galaxies in $10^9 - 10^{10} M_\odot$ haloes, but only a few percent for $10^{11} - 10^{12} M_\odot$. There are two complementary reasons for this trend. First, galaxies in smaller haloes form fewer stars, hence limiting the production of metals/dust. Second, the shallower gravitational potential wells of low-mass galaxies makes supernovae feedback more efficient at disturbing the ISM, which could help Lyα photons escape from galaxies in smaller haloes.

Unlike most of the other models which assume density/temperature cuts to determine the state of the gas (ionized vs. neutral), the simulations of Yajima et al. (2014) include the transfer of ionizing radiation. It allows them to compute (1) the recombination of hydrogen that powers the Lyα emission and (2) the ionization state of the ISM. However, the resolution of the zoom-in region investigated by these authors (250 h$^{-1}$ comoving pc) is not sufficient to accurately model the ISM on small scales. They find that the median $f_{\alpha}$ is almost constant ($\approx 25\%$) between $z = 0$ and 3, and increases toward higher redshifts to reach a value of about 90% at $z = 10$, mainly due to galaxies being increasingly metal- and dust-poor at high redshift. They interpret the trend at low redshift as a mutual cancellation of the effects of increased metallicity and dust, and decrease ISM gas fraction. At all redshifts, the values of $f_{\alpha}$ are nonetheless very scattered around the median. Yajima et al. (2014) find only weak correlations between Lyα escape fraction and the galaxy properties. The quantity $f_{\alpha}$ anticorrelates with host halo mass, galaxy mass, and dust mass, but the dispersion in these relations is again quite significant. A clearer trend is that metal-enriched galaxies have lower $f_{\alpha}$, in good agreement with the observations of Atek et al. (2009), Kornei et al. (2010), and Blanc et al. (2011), discussed above.

Verhamme et al. (2012) showed that the small-scale structure of the ISM has a strong effect on the escape of Lyα photons. They performed Lyα radiative transfer within two simulations of idealized dwarf galaxies at different resolution ($\sim 20$ and 150 pc, respectively), run with the adaptive-mesh refinement code RAMSES (Teyssier 2002). Gas density maps of the two simulations are shown in Figure 15. In the higher-resolution galaxy, the ISM can cool down to 100 K via metal cooling and fragment into smaller clumps in the disk. The Lyα escape fraction $f_{\alpha}$ is as low as 5% in this case, whereas it goes up to 50% for the lower-resolution (with smoother gas distribution) galaxy. Verhamme et al. (2012) also report that the Lyα line profile, escape fraction, and equivalent width vary with respect to the angle at which the galaxy is viewed; especially the latter is higher in the face-on direction. As pointed out by previous studies (Charlot & Fall 1993; Laursen et al. 2009; Zheng et al. 2010; Barnes et al. 2011), orientation effects may introduce a bias in LAE observations where a Lyα EW detection threshold is set.
4.5. Ly\(\alpha\) Emission and the CGM

The extremely large cross-section for Ly\(\alpha\) scattering off H\(\text{I}\) makes Ly\(\alpha\) spectra sensitive to gas outside of galaxies. In a hierarchical cosmology, the environment of a galaxy plays a crucial role in its formation. The CGM, introduced in $\S$ 2.6.2, potentially includes infalling cold streams, hot and shocked infalling gas, satellite galaxies, feedback from AGN, and outflowing galactic winds and recycling galactic fountains of hot wind fluid and entrained cool star formation enriched gas.

What light does Ly\(\alpha\) emission throw on the CGM? Ly\(\alpha\) emission is an ideal tracer of the CGM, being copiously produced by star-forming galaxies and strongly scattered by H\(\text{I}\). Further, Ly\(\alpha\) is the strongest emission line from cooling gas in the universe. Fardal et al. (2001) estimate that Ly\(\alpha\) emission accounts for 57\% of cooling radiation, with just 2% coming from bremsstrahlung.

Note, however, that they assume primordial composition gas. More recent calculations by Bertone et al. (2013), which take into account ~2000 emission lines from 11 elements, show that while Ly\(\alpha\) carries about 50\% of the energy in H and He lines, it carries 13\% of the total energy emitted by diffuse gas ($n_H < 0.1 \text{ cm}^{-3}$) at $z = 2$. Most of the diffuse emission comes from dense ($n_H \sim 10^{-3}$–$10^{-7}$ cm$^{-3}$), cool ($\sim 10^3$–$10^4$ K), metal-rich (0.1–1 solar) gas, 80\% in emission lines and 20\% in the continuum (see Fig. 14 of Bertone et al. [2013]).

Spatially resolved Ly\(\alpha\) spectra are sensitive to the distribution, kinematics, and dust content of CGM gas. As discussed in § 4.4, the vast majority of Ly\(\alpha\)-emitting galaxies at high redshift have spectral lines shifted to the red by hundreds of kilometers per second, in agreement with models of Ly\(\alpha\) radiative transfer through an expanding galactic wind (Verhamme et al. 2006). Spectra alone, however, cannot constrain the spatial extent of the gas and so cannot say whether the gas simply puffs up the ISM or is blasted right out of the halo. We require ultradeep, spatially resolved observations.

Rauch et al. (2008) performed an ultradeep spectroscopic search for low surface brightness Ly\(\alpha\) emitters at redshift $z \approx 3$. A 92 hr exposure with the ESO VLT FORS2 instrument yielded a sample of 27 faint line emitters with fluxes of a few times $10^{-18}$ erg s$^{-1}$ cm$^{-2}$. Based on their large number density, the sample is likely dominated by Ly\(\alpha\) emitters, rather than low-redshift interlopers. A number of lines of evidence lead Rauch et al. (2008) to claim that these emitters are the host galaxies of DLAs:

1. Both must host extended, optically thick neutral hydrogen.
2. The incidence rate ($dN/dz$) for the emitters and for DLAs is consistent. The combination of the large sizes and high space density of the emitters mean that they can account for the high incidence rate of DLAs.
3. Both populations have a low star formation rate, which would explain the low success rate for direct searches for the counterparts of DLAs, and the low observed metallicity of DLAs.
4. Both populations have low dust content, assuming that a high dust content would extinguish the line.
5. If the large sizes of the emitters are due to radiative transfer effects (which seems likely in light of the strict upper limits on extended star formation in DLAs derived by Wolfe & Chen [2006]), then the emitters must contain significant amounts of neutral hydrogen. The majority of H\(\text{I}\) at these redshifts resides in DLAs.

Barnes & Haehnelt (2009, 2010) used an analytic model of neutral hydrogen in dark-matter haloes and radiative transfer simulations to simultaneously reproduce the observed...
properties of DLAs and the faint Lyα emitters of Rauch et al. (2008). These emitters are hosted by $10^{9.5} - 10^{12}$ $M_\odot$ haloes, with little contribution from haloes with virial velocities $\lesssim 50 - 70$ km s$^{-1}$. Their observed sizes are due to centrally concentrated star formation at a few tenths of solar mass per year, producing Lyα photons that scatter through the surrounding $H\,\alpha$ and are observable (at the flux limit of Rauch et al. [2008]) to $\sim 30 - 50$ kpc.

Steidel et al. (2011) used a sample of 92 continuum-selected galaxies at $\langle z \rangle = 2.65$ to study very faint Lyα emission surrounding LBGs. The CGM of LBGs had previously been studied in absorption: Steidel et al. (2010) studied the CGM at $z > 2$ within $\sim 125$ kpc of Lyman break galaxies using a sample of 512 close galaxy pairs. These galaxies predominantly show Lyα emission (when present) that is strongly redshifted ($\Delta v_{Ly\alpha} \approx +445$ km s$^{-1}$), while the strong interstellar absorption lines are strongly blueshifted ($\Delta v_{IS} \approx -160$ km s$^{-1}$), consistent with the presence of a galactic wind ($\S$ 4.4). Absorption from $H\,\alpha$ and metals is observed in the CGM, with absorber equivalent width declining with impact parameter. A very rapid decline in equivalent width is observed at large distances, beginning at 70–90 kpc for all transitions except Lyα, which remains strong out to 250 kpc. Similarly, Rudie et al. (2012) observe that $H\,\alpha$ absorbers within $\sim 100$ kpc of galaxies at $z \sim 2.5$ have $10^3$ times higher median $N_{H\alpha}$ than random IGM absorbers; even at 1000 kpc, $H\,\alpha$ absorbers have a median $N_{H\alpha}$ twice as high as the IGM.

In emission, Steidel et al. (2011) stacked UV continuum and Lyα line images to reach a surface brightness threshold of $\sim 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (Fig. 16). While the UV continuum drops with an exponential scale length of 3–4 kpc (proper) and is undetectable beyond 24 kpc, Lyα emission is $\sim 5$–10 times more extended, with a scale length of 20–30 kpc. Lyα remains detectable out to $\sim 80$ kpc, comparable to the virial radius of the galaxies. Such signal is missed by NB observations and slit spectroscopy of individual objects, so that the Lyα flux of LAEs is underestimated. They argue that this emission arises from resonantly scattered Lyα photons in the CGM.

Other groups have also attempted to study the CGM through Lyα stacking. Matsuda et al. (2012) stacked 2128 Lyα emitters and 24 protocluster LBGs at $z = 3.1$, observed with a narrowband filter on Subaru Suprime-Cam. They too found extended Lyα haloes down to surface brightness limits of $\sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$, with a trend for larger scale lengths for LAEs in higher-density (megaparsec) environments. Feldmeier et al. (2013), however, sound a warning: *surface photometry at very low flux levels is treacherous*, sensitive to large-scale flat-fielding and point-spread function issues that may not have been taken into account in previous works. They observe smaller (5–8 kpc) scale Lyα haloes at $z = 3.1$ and no evidence for haloes at $z = 2.1$, down to $6 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. Jiang et al. (2013) find no conclusive evidence of Lyα haloes around $z = 5.7$ or 6.5 in a stack of 40 LAEs, reaching $1.2 \times 10^{-19}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. Thus, LAEs seem to have significantly fainter Lyα haloes than Steidel’s LBGs. This is consistent with the order-of-magnitude smaller star formation rates and lower-mass host haloes of LAEs, implying a lower-density environment (a la Matsuda).

The scattering of Lyα photons in the CGM was investigated by Barnes et al. (2011), who modeled the scattering of Lyα photons emitted by a central source through the ISM and CGM of galaxies drawn from an SPH cosmological simulation. The simulations reveal a Lyα halo extending to scales comparable to the virial radius, with an extent that depends on the wind prescription used in the simulation. The more efficient feedback implementations result in reduced column densities at the center and, therefore, reduced diffusion in frequency space and narrower spectral profiles. The simulated spectra display a more prominent blue peak than most observed LAEs, which may be due to the chosen galaxies being smaller and having lower star formation rates than typical LBGs. This conclusion is consistent with the observations of multiply peaked Lyα emission by Kuljes et al. (2012), who note that such systems have systematically slower outflows (as measured by absorption lines). The Lyα-emitting halo around star-forming galaxies is predicted to extend well beyond the CGM, though at very low surface brightness (Zheng et al. 2011; Jeong-Daniel et al. 2012).

Because a first principle calculation of the distribution and kinematics of cold gas in galactic outflows is currently not feasible, Dijkstra & Kramer (2012) studied a phenomenological model of a galactic wind, wherein large numbers ($\sim 10^2$–$10^3$) of cold, dense, dusty spherical clumps of $H\,\alpha$ are outflowing isotropically in pressure equilibrium with a hot component. Following the simple model of Steidel et al. (2011), they consider a wind that accelerates ($a \propto r^{-\alpha}$, $\alpha > 1$) to $\sim 800$ km s$^{-1}$ at large distances ($\sim 100$ kpc). The full parameter space of the model is explored using a Monte Carlo Markov Chain (MCMC) simulation, constraining the parameters using absorption line data. A suite of constrained models is used in a radiative transfer calculation to predict the Lyα emission. The emitters are too faint and too centrally concentrated to match observations because the clumps at large distances are too few and too fast to significantly scatter escaping Lyα photons. Models in which gravity decelerates the clumps beyond $\sim 10$ kpc and in which the outflow is bipolar are more successful in reproducing both the absorption and emission line data.

Notsera et al. (2012a) observed Lyα, [O II] and Hα emission from a DLA, inferring a large SFR ($\sim 25$ $M_\odot$ yr$^{-1}$) from a low-mass galaxy ($M_{halo} \sim 10^{10}$ $M_\odot$). The Lyα emission is double peaked and spatially extended, which would suggest the static Neufeld solution (see $\S$ 4.2 and Fig. 8), except that the blue and red peaks arise from spatially distinct regions, separated by a few kiloparsec and on opposite sides of the star-forming region. They successfully reproduce the observed properties of the system with a model in which two ionized jets expel gas through a spherical distribution of cold, neutral
infalling clouds. Similarly, Christensen et al. (2012) and Krogager et al. (2013) are able to reproduce observed Ly$\alpha$ emission spectrum using a model of a dusty, clumpy outflow at $\sim 100 \text{ km s}^{-1}$. These models use the MoCaLaTA code of Laursen et al. (2009) and show the need for data other than the Ly$\alpha$ spectrum to constrain the RT calculation.

In light of the faintness of the CGM, Cantalupo et al. (2005) investigated the illumination of extragalactic H I by a nearby quasar. This provides a method of observing otherwise undetectable gas in the CGM and in small, dark galaxies. The observations of Cantalupo et al. (2012), using VLT/FORS to perform a deep narrowband survey for Ly$\alpha$ emission within approximately megaparsec of a hyperluminous QSO at $z=2.4$, reveal a population of emitters whose equivalent width distribution, luminosity function, and the average luminosity versus projected distance are consistent with detailed radiative-transfer simulations of quasar fluorescence. Their large EW ($>800 \text{ Å}$) rule out internal star formation as the source of Ly$\alpha$. Some of the emitters resemble extended filaments, compatible with the expectations for circumgalactic cold flows, though this interpretation is not unique. Very recently, Cantalupo et al. (2014) reported observations of a filamentary, 460 kpc Ly$\alpha$ emission region that includes a radio-quiet quasar but extends well beyond the virial radius. This object is plausibly the cosmic web, lit up by the quasar, a conclusion supported by cosmological hydrodynamical simulations combined with Ly$\alpha$ and ionization radiative transfer.

Hennawi & Prochaska (2013) simultaneously analyzed absorption and emission from H I in the CGM of quasars using close projected quasar pairs. While extended Ly$\alpha$ fuzz is detected on 50 kpc scales in $\sim 30\%$ of the sample (possibly up to $50\%–70\%$ when the effects of the single slit are accounted for), it is significantly less emission than would be naively expected given the covering fraction of optically thick HI absorbers and the ionizing flux from the quasar. This is argued to be evidence of anisotropic quasar emission.

Ly$\alpha$ blobs (LABs).—There is another class of Ly$\alpha$ emitter at high redshift, which is extended ($\sim 10–150 \text{ kpc}$), extremely luminous ($L_{\text{Ly}\alpha} \sim 10^{43}–10^{44} \text{ erg s}^{-1}$) and rare, with a number density of $\sim 10^{-5.8} \text{ comov. Mpc}^{-3}$ (Dijkstra & Loeb 2009), as compared to $\sim 10^{-2.7} \text{ comov. Mpc}^{-3}$ for the population of Ly$\alpha$ emitters in van Breukelen et al. (2005). These are the imaginatively named Ly$\alpha$ Blobs (LABs) (Fynbo et al. 1999; Keel et al. 1999; Steidel et al. 2000; Francis et al. 2001; Palunas et al. 2004; Matsuda et al. 2004; Chapman et al. 2004; Bower et al. 2004; Villar Martín et al. 2005; Dey et al. 2005; Matsuda et al. 2006; Nilsson et al. 2006; Prescott et al. 2009, 2013; Francis et al. 2013). Their physical nature remains mysterious, and it is not clear where they stand in relation to the astrophysical sources of Ly$\alpha$ outlined above. Intriguingly, Keel et al. (2009) find a dearth of LABs at low redshift ($z=0.8$). Three mechanisms are suggested as the energy source for LABs. They are not mutually exclusive.
1. **Internal photoionizing sources.**—LABs are the Lyα fuzz predicted by Haiman & Rees (2001), or the Lyα corona predicted by Furlanetto et al. (2005). LABs contain internal sources of ionizing radiation in the form of an AGN or star-forming galaxy, possibly obscured. The cosmological simulations of Cen & Zheng (2013) suggest that starbursts are responsible for the majority of Lyα from LABs. This is the scenario suggested, for example, by the multiwavelength studies of Chapman et al. (2004), Geach et al. (2007, 2009), and Overzier et al. (2013). The polarization of Lyα emission from LAB1 is evidence of scattering, suggesting a central source of Lyα photons (Hayes et al. 2011). However, the 1.1 mm imaging survey of Tamura et al. (2013) places strict a upper limit on ultraluminous obscured star formation, indicating that most LABs are not powered by intense, dusty star formation. The population of dusty Lyα emitters discovered by Bridge et al. (2012), 50% of which are extended (≥25 kpc), show warm far-IR colors consistent with being in a short-lived AGN feedback phase. LABs have also been discovered around high-redshift quasars (Smith et al. 2009; North et al. 2012).

2. **Cooling radiation.**—LABs consist of gas that is radiating away its gravitational potential energy as it cools into massive galaxies. Dijkstra et al. (2006a, 2006b) and Dijkstra & Loeb (2009) considered simple analytic models of this scenario, showing that the Lyα line widths and number densities of LABs can be reproduced by cold accretion if ~20% of the gravitational potential energy of the gas is converted to radiation. More detailed hydrodynamical simulations of the connection between LABs and cold flows have been performed by Faucher-Giguère et al. (2010), Goerdt et al. (2010) and Rosdahl & Blaizot (2012). These simulations do not agree on whether cooling radiation alone can power LABs—the sensitivity of collisional ionization and the cooling rate to the temperature, density, and metallicity of the gas make such calculations worryingly dependent on resolution, subgrid physics, self-shielding and ionizing radiative transfer, heating–cooling balance, and other bugbears of numerical simulation. The simulations of Goerdt et al. (2010) support the analytic findings of Dijkstra & Loeb (2009), that haloes of mass ~10^{12}–10^{13} M⊙ at z ~ 3 can reproduce the extent, luminosity, and irregular morphologies of LABs, with most of the Lyα emission coming from 50–100 kpc cold streams. This scenario is argued for observationally by Nilsson et al. (2006), Smith & Jarvis (2007), and Smith et al. (2008), usually on the basis of a nondetection of associated AGN or star formation. (But if the accretion rate is so high, why doesn’t it fuel an AGN and/or form stars?)

3. **Galactic superwinds.**—A starburst powers a barrage of supernovae, which sweep cooling, dense, radiating shells of H i into the IGM (Taniguchi & Shioya 2000; Mori et al. 2004). This scenario is favored observationally by Ohyama et al. (2003) and Saito et al. (2008) on the basis of broad wing emission components on the red side and a sharp cutoff on the blue side of the Lyα line as predicted by wind models (§ 4.4). Observations of associated, spatially extended narrow Lyα absorption lines in the spectra of active galaxies (e.g., Humphrey et al. 2013), which suggest the presence of an H i bubble outside the Lyα nebula, are consistent with a starburst-driven superbubble. However, Yang et al. (2011) and McLinden et al. (2013) report that the velocity offset of Lyα with respect to [O III] is consistent with zero, suggesting that outflows are not the primary driver of Lyα escape.

Higher resolution observations have not particularly clarified the situation. Weijmans et al. (2010) observed LAB1 and showed that Lyα is emitted from five distinct clumps: two are associated with LBGs, one with a heavily obscured submillimeter galaxy, and two do not appear to be associated with a galaxy. The complex morphology is shown in Figure 17. Detailed observations of LABd05 by Prescott et al. (2012) reveal a blob containing 17 small galaxies, none of which are at the peak of the Lyα emission, with a smooth, nonfilamentary morphology and a similarly extended UV surface brightness profile. Francis et al. (2013) presented integral field spectroscopy of an LAB at z = 2.38, noting a chaotic velocity structure, two associated compact red massive galaxies, evidence of a superwind, an infalling filament of cold gas that resonantly scatters Lyα photons, and bow shocks and tidally stripped gas in outer subhaloes.

Fainter LABs are similarly complex. Rauch et al. (2011, 2014, 2013) report long-slit spectroscopic observations of extended, ultrafaint Lyα emitters discovered by Bridge et al. (2012), 50% of which are extended (~37 kpc proper) “blue fan” with evidence of substructure. This is interpreted as evidence of an infalling, filamentary cloud of H i that is illuminated by stellar ionizing radiation. The large inferred ionizing escape fraction, together with HST evidence of a stellar tidal tail, hint that the filament may be tidal debris from an interaction that has aided the escape of the ionizing continuum. The second system also suggests the influence of galaxy interactions. The system is extended, asymmetric with spatially irregular stellar components and shows evidence for a very young starburst and possibly a Lyα-emitting filamentary structure. The tadpole shape and blue, partly turbulent tails of the filaments seen in the third system are interpreted as evidence of ram pressure stripping as dwarf galaxies leave behind contrails of gas and stars as they fall into a more massive halo.

Taken together, these systems suggest that galaxy interactions play an important role in the production and escape of Lyα photons in protogalaxies. Such a link has been suggested previously by Cooke et al. (2010), who discovered that all LBG pairs in their sample that are separated by ≤15 kpc (projected) exhibit Lyα in emission, in stark contrast to 50% of the LBG population as a whole. Similarly, Jiang et al. (2013) find a large fraction (~50%) of z = 5.7–6.5 LAEs show signs of merging/interaction, as do the handful of z = 2.4 double-peaked Lyα emitters of Chonis et al. (2013). This suggests a scenario in which galaxy interactions, as well as providing fuel for star formation (Tilvi et al. 2011), sufficiently disrupt and ionize the ISM to give Lyα photons an easy escape.
Shimizu & Umemura (2010) presented a model in which galaxies cannot only appear as LAEs when a burst of star formation occurs (i.e., a Ly$\alpha$ bright phase; see also Dijkstra & Wyithe [2007]; Nagamine et al. [2007]), but also when a young satellite galaxy is accreted onto a more massive object. The simulations of Yajima et al. (2013) suggest that a merger can cause a burst in both star formation and cooling radiation, which can result in a LAB. LABs (and their radio-loud counterparts—see below) are often associated with overdense environments (Keel et al. 1999; Steidel et al. 2000; Palunas et al. 2004; Matsuda et al. 2004, 2009), which may suggest a link to galaxy interactions, and/or gas accretion.

Extended Ly$\alpha$ emission is also associated with high-redshift radio galaxies. Selecting sources by their radio emission generally finds the most massive high-redshift objects, either galaxies or AGN. Giant Ly$\alpha$ haloes (or nebulae) have been discovered around many radio galaxies, and their properties have been studied by Reuland et al. (2003); Villar-Martín et al. (2005); van Breugel et al. (2006); Villar-Martín et al. (2007); Geach et al. (2007); Villar-Martín et al. (2007); Villar-Martín (2007); Miley & De Breuck (2008); Courbin et al. (2008); Zirm et al. (2009). These objects resemble LABs, except that they are radio loud, have a higher surface brightness (by a factor of $\sim$5) and contain large, multicomponent galaxies (van Breugel et al. 2006). Reuland et al. (2003) have suggested the following evolutionary sequence: LABs represent the very first stage in the formation of a large galaxy (or a set of smaller galaxies that later merge) and evolve into radio-loud Ly$\alpha$ haloes when galaxy merging triggers an AGN.

4.6. Ly$\alpha$ Emission in Cosmological Context

To understand the properties and evolution of the LAE population as a whole, it is essential to investigate Ly$\alpha$-emitting galaxies in their cosmological context. Observations of Ly$\alpha$ emitters are sensitive to the large-scale structure of the universe, and in particular to the ionization state of the IGM.

**LAEs in semianalytic models.**—As large samples of LAEs became available in the early 2000s, semianalytic models of galaxy formation attempted to model the statistical properties of LAEs. These models incorporate the hierarchical evolution of dark-matter haloes analytically (Press & Schechter 1974; Sheth & Tormen 2002) or with $N$-body simulations (e.g., Springel et al. 2005). Galaxies are formed within dark-matter haloes according to semianalytic recipes or SPH simulations. Predictions of observed Ly$\alpha$ emission must incorporate the Ly$\alpha$ escape fraction ($f_{\text{esc}}$). This has been modeled with simple phenomenological
prescriptions (e.g., Kobayashi et al. 2007) and more sophisticated calculations based on numerical Ly$\alpha$ radiative transfer (e.g., Garel et al. 2012).

The simplest approach assumes that a constant fraction of Ly$\alpha$ photons escape from each galaxy, with the value of $f_{\text{esc}}$ adjusted to fit Ly$\alpha$ LF (e.g., Le Delliou et al. 2005, 2006; Dayal et al. 2008, 2009; Nagamine et al. 2010). The typical reported value of $f_{\text{esc}} = 10\%$ is strongly model dependent because the intrinsic Ly$\alpha$ LF depends on the underlying dark-matter simulation and its cosmology, the baryonic prescriptions used to model galaxy formation, and the IMF. For example, the best-fit $f_{\text{esc}}$ value varies from 0.02 to 0.20 when changing from a top-heavy IMF to a more standard Kennicutt IMF (Le Delliou et al. 2006).

Alternatively, “duty cycle” models have been investigated (Samui et al. 2009; Nagamine et al. 2010). In these scenarios, only a fraction of galaxies are turned on as Ly$\alpha$ emitters at a given time. In the model of Nagamine et al. (2010), based on a cosmological SPH simulation, a duty cycle of 7% (20%) is necessary to reproduce both the UV LFs of LBGs and Ly$\alpha$ LFs of LAEs at $z = 3$ ($z = 6$).

These simple models quantify how the intrinsic Ly$\alpha$ LFs from models have to be modified to reproduce the data, either in terms of Ly$\alpha$ luminosity (constant fraction scenario) or LAE density (duty cycle scenario). It remains to be seen whether more physical models support either picture.

An obvious method to deal with the dust extinction of the Ly$\alpha$ line is to treat it the same way as UV continuum, neglecting resonant scattering. Various models have been tried using simple screen- and slablike distributions of dust (Haiman & Spaans 1999; Mao et al. 2007; Kobayashi et al. 2007; Shimizu et al. 2011). Additional parameters are often included to improve the agreement with the UV and Ly$\alpha$ data. In Kobayashi et al. (2007), a phenomenological implementation is developed for the Ly$\alpha$ escape fraction, varying the visibility of an LAE depending on whether the starburst galaxy is in a preoutflow, outflow, or postoutflow phase. The model reasonably reproduces the UV LFs of LBGs and Ly$\alpha$ LFs of LAEs between $z \approx 3–6$.

To assess the impact of the Neufeld effect discussed in § 4.4, clumpy dust distributions have been investigated in the context of cosmological simulations (Dayal et al. 2008; Kobayashi et al. 2010; Shimizu et al. 2011; Dayal et al. 2011). The ISM clumpiness is usually described by the $q$ (free) parameter, defined in equation (9). This is equivalent to tuning independently the Ly$\alpha$ and continuum dust extinction. In addition to UV and Ly$\alpha$ LFs, a very clumpy model (e.g., Kobayashi et al. [2010], assume $q = 0.15$) can reproduce other observed quantities, such as the Ly$\alpha$ EW distribution and the anticorrelation between UV magnitudes and Ly$\alpha$ EWs.

Dayal et al. (2011) coupled cosmological SPH simulations and ionizing RT calculations to predict the ionization state of the intergalactic medium on large scales. They use a phenomenological recipe for ISM dust extinction and an analytic model for Ly$\alpha$ IGM opacity along the line of sight. They conclude that the IGM transmission alone cannot explain the Ly$\alpha$ and UV LFs at $z = 5–7$ and that the ISM extinction, described by a clumpy dust distribution, is required to simultaneously match UV and Ly$\alpha$ data. There is tension between the success of clumpy ISM models, which assume the enhancement of the escape of Ly$\alpha$ radiation over that of UV continuum, and the current interpretation of observations, and with detailed numerical RT simulations, as we have seen in § 4.4.

The models discussed above all use phenomenological prescriptions to describe $f_{\text{esc}}$; they do not model the resonant scattering of Ly$\alpha$ photons in the ISM. Only recently have simulations have incorporated Ly$\alpha$ RT calculations into galaxy formation models in a cosmological context.

Forero-Romero et al. (2012) computed the Ly$\alpha$ escape fraction of galaxies by postprocessing the MareNostrum SPH simulation, approximating the ISM as a dusty slab of gas with the Ly$\alpha$ sources being homogeneously distributed. Following Charlot & Fall (2000), the dust distribution is described using two components: a homogeneous ISM and dense birth clouds of young stars. Resonant scattering of Ly$\alpha$ photons is taken into account only for the homogeneous phase, using an analytical fit to numerical RT calculations for a slab configuration. The H$\ I$ opacity of birth clouds is assumed to be low, and so their dust extinction of Ly$\alpha$ photons is taken as for the UV continuum. Their model provides a reasonable match with Ly$\alpha$ and UV LF at $z = 5–6$, although the faint end is strongly overpredicted. They find that $f_{\text{esc}}$ decreases toward more massive host haloes, echoing the results of Laursen et al. (2009). In an extension of this model, Forero-Romero et al. (2012) argue that the average lower $f_{\text{esc}}$ of galaxies in massive haloes is an important factor in explaining the small fraction of LAEs found in samples of LBGs.

A similar conclusion is drawn in the work of Garel et al. (2012), though their physical hypotheses are quite different. Noting that galactic winds are ubiquitous in high-redshift galaxies (Steidel et al. 2010), Garel et al. (2012) consider Ly$\alpha$ emission that is powered by star formation and scattered within a neutral outflow represented by a spherical shell. They couple the semianalytic model of galaxy formation GALICS (Galaxies In Cosmological Simulations; Hatton et al. 2003) with a library of numerical Ly$\alpha$ RT experiments (Schaerer et al. 2011), based on the expanding shell model of Verhamme et al. (2006). In their model, higher velocity, denser and more dusty shells are found in more massive, star-forming galaxies. Their Ly$\alpha$ LFs and UV LFs of LAEs and LBGs are in good agreement.

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$^8$Dayal et al. (2011) computes the IGM attenuation of a Gaussian Ly$\alpha$ spectrum, unprocessed by ISM scattering. Internal radiative transfer effects are expected to alter the line emerging from the galaxy. In particular, outflows are expected to redshift the Ly$\alpha$ line, reducing the effect of IGM attenuation (Dijkstra & Wyithe 2010).

$^9$http://astro.ft.uam.es/marenostrum/.
with high-redshift observations. In particular, the model predicts a large abundance of faint-line emitters (10^{11–12} erg s^{-1}); low-SFR galaxies are mostly dust free and so have a Lyα escape fraction of the order of unity. However, f_{\text{esc}} is strongly dispersed (from zero to one) for massive/star-forming galaxies as a result of a trade-off between larger shell velocities and H i/dust opacities.

Shell models are useful for interpreting Lyα line profiles (§ 4.4) and statistical properties of LAEs (luminosity functions, mean stellar masses, overlap with LBGs, etc.; Garel et al. [2012]; see also Orsi et al. [2012]). Nonetheless, they assume a physical picture of galactic outflows that is quite idealized, and more realistic models are needed.

**LAE-LBG connection.**—Cosmological models of both LAEs and LBGs can illuminate the apparent tension between their physical properties (as discussed in § 4.3). Although it is reported that LBGs tend to be more evolved than LAEs, with higher stellar mass and dust content, the simulations of Dayal & Ferrara (2012) suggest that z \approx 6 LAEs and LBGs have similar physical properties. They find that LAEs are a subset of the LBG population; different observed properties result only from different selection criteria.

Using their numerical Lyα radiative transfer models, Verhamme et al. (2008) argue that the link between LBGs and LAEs is mainly governed by RT effects due to variations in H i and dust opacities. They suggest that galaxy mass is the driver of variation of gas and dust content. This would explain the small fraction of LBGs with Lyα in emission (Shapley et al. 2003; Stark et al. 2011): LBGs are highly star-forming, massive galaxies, in which the Lyα emission can be strongly suppressed (see also Garel et al. 2012). Environment must also play a role—using \sim 57,000 z \sim 3 LBGs in the Canada–France–Hawaii Telescope Legacy Survey (CFHTLS) Deep Field, Cooke et al. (2013) showed from their auto- and cross-correlation functions that LBGs with Lyα in emission versus absorption live in very different environments, e.g., parent haloes of 10^{11} M_\odot versus 10^{13} M_\odot.

While the UV LF of LBGs decreases from z = 3 to z = 6 (Bouwens et al. 2007), the UV LF of LAEs appears to increase over this redshift range and is a reasonable match for LBGs at z = 6 (Ouchi et al. 2008). This trend can be interpreted as LAEs being a subpopulation of LBGs, where the LBG fraction increases toward higher redshift. The dropout technique preferentially detects bright UV-continuum galaxies; hence a significant fraction of low-continuum objects (i.e., LAEs with high equivalent width) are missed by LBG surveys at z = 6 (10%–46%; Dow-Hygelund et al. 2007). Therefore, LAEs and LBGs do not necessarily arise from the same population. The apparent overlap of the LAE/LBG UV LF at z = 6 may be accidental (Dijkstra & Wyithe 2007).

**Lyα and the IGM.**—Though this review is focused on galaxy properties, the interaction of Lyα radiation with the intergalactic medium (IGM) can greatly affect the observed properties of Lyα emitters. Gunn & Peterson (1965) first predicted that the presence of H i in the IGM would absorb radiation blueward of rest-frame Lyα as the expansion of the universe redshifts this light into resonance. Following the recombinination of the primordial plasma, the universe was neutral until the formation of sources able to reionize the IGM. In spite of intense research, the nature of these sources is still unknown, and the epoch of reionization (EoR) is only partially constrained. Observations of the cosmic microwave background suggest that the EoR began around z = 11 (Larson et al. 2011). Based on the analysis of the spectra of high-redshift quasars (Fan et al. 2006), the universe must have been almost completely reionized at z \gtrsim 6.

The Lyα emission line from high-redshift galaxies is a useful tool for probing the variation in the ionization state of the IGM. One expects that, as the fog of neutral hydrogen clears during reionization, a population of hitherto obscured Lyα-emitting galaxies will burst into view. An increase in Lyα attenuation could trace a sudden change in the neutral fraction of the IGM (x_{\text{HI}}), providing a diagnostic of the epoch of reionization (Miralda-Escude 1998; Haiman & Spaans 1999; Rhoads & Malhotra 2001). Several authors have suggested that a rapid evolution of the Lyα luminosity function at high redshift would reflect a change in the IGM neutral fraction (Malhotra & Rhoads 2004; Santos 2004; Haiman & Cen 2005; Mao et al. 2007), especially if there were no corresponding evolution of the UV LF of LAEs. While Hu et al. (2010) find that L_{\text{Lyα}} remains unchanged between z = 5.7 and 6.6, Ouchi et al. (2010) and Kashikawa et al. (2011) measure a decline of about 30%, along with little evolution of the UV LF (see also Kashikawa et al. 2006). This small increase in the Lyα attenuation translates into a neutral fraction x_{\text{HI}} \lesssim 20%, according to Ouchi et al. (2010), which would imply that the universe is still highly ionized at z = 6.6. On the other hand, Dijkstra et al. (2007b) have shown that the observed drop of the Lyα LF between z = 5.7 and 6.6 is expected from the IGM evolution due to cosmic expansion, even if the universe remains fully ionized (see also Laursen et al. 2011).

The spectral line profile can also constrain reionization. Hu et al. (2010) and Kashikawa et al. (2011) find very similar shapes of Lyα composite spectra at z = 5.7 and 6.5. Nevertheless, they note that the peak of the rest-frame Lyα equivalent width distribution shifts toward lower values from z = 5.7 to 6.5, perhaps due to an increase of the IGM contribution to the damping of the Lyα line. The interpretation of this effect is not straightforward given that infalling and outflowing gas in the vicinity of the galaxy can also strongly affect the Lyα profile. For instance, Dijkstra & Wyithe (2010) demonstrate that radiative transfer through galactic winds can increase the visibility of the Lyα line even for a highly neutral IGM.

Few Lyα surveys at z \gtrsim 7 have been conducted, and the number of detections is still small. Nonetheless, small statistics or even nondetections can constrain the change of the LF. Observations tentatively indicate an evolution of the Lyα-emitting
galaxy population $z = 6 - 7$ (Shibuya et al. 2012; Clément et al. 2012; Caruana et al. 2014), which can be accounted for using models positing a rapid increase of $x_{\rm HI}$ (Mao et al. 2007; Kobayashi et al. 2010; Dijkstra et al. 2011; Jensen et al. 2013). On the other hand, Tilvi et al. (2010), Hibon et al. (2012), and Krug et al. (2012) find no conclusive evidence for a variation of $L^*$ up to $z = 7 - 8$, based on photometric samples. Future spectroscopic follow-up observations will certainly provide more accurate estimates.

The evolution of the fraction of Ly$\alpha$ emitters $\chi_{\rm Lya}$ among samples of Lyman break galaxies provides another useful probe of the ionization state of the IGM. As discussed in § 4.3, Stark et al. (2010) measure an increase of $\chi_{\rm Lya}$ from $z = 3$ to $z = 6$. Interestingly, the trend starts to reverse at $z > 6$. Pentericci et al. (2011), Ono et al. (2012), and Schenker et al. (2012) report that $\chi_{\rm Lya}$ drops from $z = 6$ to $z = 7$, as shown in Figure 18. Furthermore, the drop of the fraction of LAEs is more significant among the fainter UV-selected galaxies. These galaxies are less clustered than brighter ones and located in low-density environments (e.g., Giavalisco & Dickinson 2001; Adelberger et al. 2005), which may indicate that reionization occurred later in low-density regions, privileging an inside-out model. Indeed, galaxies in more clustered regions can blow larger ionized bubbles during the EoR, which should boost the Ly$\alpha$ transmission (McQuinn et al. 2007; Iliev et al. 2008; Mesinger & Furlanetto 2008; Dayal et al. 2009). A strong signal in the two-point correlation of LAEs in the EoR is predicted by McQuinn et al. (2007).

Whether or not reionization is over by $z \sim 6$ is not yet clear (e.g., Mesinger 2010; McGreer et al. 2011; Raskutti et al. 2012), and there is no conclusive evidence that Ly$\alpha$ observations at $z = 6 - 7$ are the signature of a sharp transition of the IGM neutral fraction. Other reasons can explain the Ly$\alpha$ attenuation around $z = 6 - 7$, such as the intrinsic evolution of the galaxies (Dayal et al. 2008; Dijkstra et al. 2007b; Samui et al. 2009), a change in kinematics and covering factor affecting the escape of Ly$\alpha$ photons from galaxies (Dijkstra et al. 2011), observational uncertainties (Pentericci et al. 2011), or the increase of the number density of optically thick absorption systems (Bolton & Haehnelt 2013).

Ly$\alpha$ radiative transfer through the IGM has been studied by a number of authors. Laursen et al. (2011) traced Ly$\alpha$ photons from emitters between $z = 2.5$ and 6.5 through a cosmological simulation of the IGM. Figure 19 shows the average transmission of wavelengths around Ly$\alpha$ as a function of the redshift of the emitter. We see that, even at fairly low redshifts, the IGM is able to erase a substantial fraction of the blue side of the intrinsic spectrum. At higher redshifts, even the red side of the line can be affected. Note also that this is the average transmission: individual sight lines can vary substantially. For example, at $z = 3.5$ the transmission on the blue side ($\Delta v < -200$ km s$^{-1}$) varies between 0.2 and 0.95.

Laursen et al. (2011) note that, in some cases, a single, red Ly$\alpha$ peak seen in high-redshift galaxies could be the result of an intrinsic double-peaked spectrum with the blue side erased by the IGM. While this effect is not sufficient to explain the predominance of red peaks in LAEs, it does demonstrate the importance of the IGM in interpreting Ly$\alpha$ spectra. Conversely, Dijkstra & Wyithe (2010) and Dijkstra et al. (2011) have emphasized that the intrinsic Ly$\alpha$ spectra affects IGM transmission. The presence of a galactic wind in a prereionization galaxy will shift most of the Ly$\alpha$ photons to the red side before they encounter the IGM. Even a mild wind ($\sim 25$ km s$^{-1}$) increases ISM transmission relative to predictions that assume that Ly$\alpha$ emission peaks at line center (e.g., Iliev et al. 2008).

Zheng et al. (2011) have emphasized the importance of large-scale structure for LAE visibility—lower $\text{H} \text{I}$ densities and larger velocity gradients aid Ly$\alpha$ escape, meaning that, for example, LAEs are more visible for sight lines that look along a filament than across one (see also Wyithe & Dijkstra 2011; Greig et al. 2013; Behrens & Niemeyer 2013). Such studies are crucial to controlling the systematics of massive observational programs underway to measure cosmological parameters using LAEs as tracers of the cosmic web, such as the Hobby-Eberly Telescope Dark Energy Experiment (HETDEX; Hill et al. 2008), whose aim is to measure the spectroscopic redshifts of 800,000 LAEs between $1.9 < z < 3.5$.

Ly$\alpha$ may provide a way of directly observing the IGM, and thereby mapping the cosmic web. Hogan & Weymann (1987) predicted that the UV ionizing background falling on clouds of $\text{H} \text{I}$ in the IGM would produce detectable Ly$\alpha$ fluorescence. This emission would allow us to study the size and morphology of these clouds, as well as the strength of the UV background.
The calculations of Hogan & Weymann (1987) were refined by Gould & Weinberg (1996), who correctly predicted that detecting FLEs would be difficult even with a 10 m telescopes. The more sophisticated modeling of Cantalupo et al. (2005) have reduced expectations of observing FLEs further still, by showing that simplifications such as a static, plane slab geometry overpredict the visibility of FLEs. Similarly, the cosmological simulations of Kollmeier et al. (2010) predict that, in the absence of a strong ionizing continuum source, the highest fluorescent surface brightnesses at \( z = 3 \) are \( \sim 2 \times 10^{-19} \) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\), which would require \( \gtrsim 1000 \) hr to detect. Cantalupo et al. (2007) report that despite the observational efforts of themselves and others in finding a handful of plausible candidates, there is still some doubt about whether UVB-powered FLEs have actually been detected. As noted above, the observations of Cantalupo et al. (2014) of the Ly\( \alpha \)-emitting environment of a quasar may represent out best hope of seeing the IGM in emission.

A more comprehensive review of the ability of Ly\( \alpha \)-emitting galaxies to probe cosmic reionization can be found in Dijkstra (2014).

5. SUMMARY AND FUTURE

We have reviewed what observations and theoretical models of Ly\( \alpha \) emission, and Ly\( \alpha \) and Mg II absorption have told us about the interstellar, circumgalactic, and intergalactic medium of galaxies. Individually, each tracer provides direct insight into the state and physics of the gas in and around galaxies. Much more can be understood by combining these different spectral probes. We saw in § 4.5 that modeling of the Ly\( \alpha \) emission and absorption of DLAs dramatically improves constraints on galaxy properties. The low-ion absorption lines of DLAs constrain kinematics, metallicity and, via galaxy formation models, DLA halo mass distribution and even galactic feedback (§ 2). The samples of Mg II absorbers (and their associated galaxies) in the redshift range that can be probed by Ly\( \alpha \) from the ground could shed light on the accretion and feedback physics that shapes star-forming galaxies. Observations of the dust, stellar, and star formation properties of Ly\( \alpha \) galaxies must continue to inform models of Ly\( \alpha \) emission.

Our understanding of Ly\( \alpha \) emission remains largely untouched by 21 cm observations. The 21 cm transition is an ideal complement to Ly\( \alpha \): it is emitted by the same atoms, with a different dependence on temperature, is often optically thin (at least in the warm-neutral medium), and provides a wealth of kinematic and spatial information. The 21 cm observations would greatly assist theoretical models of Ly\( \alpha \) emitters, providing a constraint on the extent, structure, and kinematics of H I that is independent of the sources of Ly\( \alpha \) photons. At the moment, resolution and brightness limits have confined 21 cm observations to the local universe, while the UV wavelength of Ly\( \alpha \) keeps ground-based observations to \( z \gtrsim 2 \). Future radio telescopes, space-based Ly\( \alpha \) observations, and Mg II observations at intermediate redshifts will continue to close the gap.

The increasing number of detections of LAEs at high redshift in recent times has significantly improved our understanding of the physical nature of these galaxies and put tighter constraints on theoretical models (see § 4). Nonetheless, larger samples (especially with spectroscopic confirmation) and multiwavelength observations will help greatly to refine existing models. Thanks to MUSE, KCWI, HETDEX, and more, samples of LAEs will soon become orders of magnitude larger, deeper, and more detailed. Space-based observation of local Ly\( \alpha \) emitters will also provide important tests of our understanding of the relevant physics. In particular, ISM models and galactic outflows in Ly\( \alpha \)
radiative transfer calculations could be better informed by local observations, allowing models to replace their current simple approximations. From a theoretical viewpoint, high-resolution hydrodynamic simulations with Ly\(\alpha\) radiative transfer and large cosmological volumes are necessary to provide further insights into the complex mechanisms governing Ly\(\alpha\) emission in galaxies and reproduce the wide variety of properties seen in the LAE population.

For DLAs and Mg\(\text{II}\) absorbers, future southern hemisphere surveys, similar to SDSS, will provide a factor of 2 or so more systems, from which we can learn about the details of gas physics around galaxies. Further advancements in simulations are required to interpret the data. The full range of gas cloud sizes for absorbers—from a few parsec to a few kiloparsec—has not yet been resolved in cosmological simulations. Higher-resolution simulations and the inclusion of important physical processes such as AGN feedback and self-shielding will shed light on gas within and around galaxies.

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