ON THE (NON-)ENHANCEMENT OF THE Lyα EQUIVALENT WIDTH BY A MULTIPHASE INTERSTELLAR MEDIUM

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ABSTRACT
It has been suggested that radiative transfer effects may explain the unusually high equivalent widths (EWs) of the Lyα line, observed occasionally from starburst galaxies, especially at high redshifts. If the dust is locked up inside high-density clouds dispersed in an empty intercloud medium, the Lyα photons could scatter off of the surfaces of the clouds, effectively having their journey confined to the dustless medium. The continuum radiation, on the other hand, does not scatter, and would thus be subject to absorption inside the clouds. This scenario is routinely invoked when Lyα EWs higher than what is expected theoretically are observed, although the ideal conditions under which the results are derived usually are not considered. Here we systematically examine the relevant physical parameters in this idealized framework, testing whether any astrophysically realistic scenarios may lead to such an effect. It is found that although clumpiness indeed facilitates the escape of Lyα, it is highly unlikely that any real interstellar media should result in a preferential escape of Lyα over continuum radiation. Other possible causes are discussed, and it is concluded that the observed high EWs are more likely to be caused by cooling radiation from cold accretion and/or anisotropic escape of the Lyα radiation.

Key words: galaxies: ISM – radiative transfer – scattering

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1. INTRODUCTION

Our understanding of the high-redshift universe has expanded tremendously during the last decade, especially due to a single specific emission line, the Lyα line. Tracing in particular galaxies in the process of forming, the shape, intensity, and spatial distribution of this line carry a wealth of information. However, while our theoretical understanding of the physical processes that govern the radiative transfer (RT) of Lyα has also advanced significantly, it is evident that the complexity of density fields, gas kinematics, dust distribution, line formation, impact of the intergalactic medium (IGM), etc., render individually observed lines quite difficult to interpret in detail.

As Lyα emitting galaxies (LAEs) generally are relatively small (Gawiser et al. 2006; Lai et al. 2007; Nilsson et al. 2007), and of low star formation rate (SFR), albeit high Specific SFR (Fynbo et al. 2003; Nilsson et al. 2010), our lack of knowledge is in part due to the difficulties in observing faint galaxies. This obstacle may to some extent be overcome using gravitationally lensed LAEs (e.g., Fosbury et al. 2003; Quider et al. 2009; Christensen et al. 2012a, 2012b), which may boost the observed flux by more than an order of magnitude. Larger surveys of the statistical properties of LAEs, such as their luminosity function (LF; Ouchi et al. 2005, 2008; Shimasaku et al. 2006; Kashikawa et al. 2006; Dawson et al. 2007; Grove et al. 2009) and clustering properties (Gawiser et al. 2007; Gronwall et al. 2007), may overcome some of these complications, although still our ignorance of RT processes easily may result in systematic errors (e.g., Wyithe & Dijkstra 2011). A common technique by which to assess the stellar population of individual galaxies at high redshifts is to measure the equivalent width (EW) W of the Lyα line (e.g., Gronwall et al. 2007; Ouchi et al. 2008; Stark et al. 2010). This quantity is defined as the ratio of the integrated line flux to continuum flux density, $W = \int \Delta \lambda (F(\lambda) - F_0)/F_0$, where the exact limits of the integral are not important as long as the full line is included. For sloped continua, the wavelength dependency of the continuum must also be taken into account. For high EWs, W can be approximated by the relative escape fraction of Lyα and continuum photons. The EW depends on galactic parameters such as the initial mass function (IMF) and the gas metallicity (e.g., Schaerer 2002), and can consequently be used as a probe of these quantities.

In young galaxies, Lyα is produced mainly from recombinations following the ionization of hydrogen surrounding O and B stars. Since these stars are short-lived, a few mega-years after an initial starburst the EW will generally decrease significantly. Stellar population syntheses (e.g., Charlot & Fall 1993; Valls-Gabaud 1993; Schaerer 2003) predict that the EW should initially reach $\sim 240$ Å, eventually declining and settling on roughly 80 Å, where the exact values depend on the assumed IMF and metallicity of the population. Curiously, several observational studies have reported on the detection of much higher EWs (e.g., Hu & McMahon 1996; Kudritzki et al. 2000; Malhotra & Rhoads 2002; Rhoads et al. 2003; Dawson et al. 2004; Hu et al. 2004; Shimasaku et al. 2006; Gronwall et al. 2007; Ouchi et al. 2008; Nilsson et al. 2009; Kashikawa et al. 2011, 2012). While some of these extreme EWs can be attributed to active galactic nucleus (AGN) activity, in many cases this explanation is explicitly excluded. Moreover, such high EWs are not readily explained by simply assuming a more top-heavy IMF. Indeed, the observations pose a serious challenge to our understanding of galaxy formation, stellar evolution, and RT.

In this work, we will distinguish between three related notations. The equivalent width $W_{\text{em}}$ of the intrinsically emitted spectrum is given by the stellar population for instance, a more top-heavy IMF emits a harder spectrum, with relatively more ionizing and hence Lyα photons. When escaping the galaxy, the spectrum has an equivalent width $W_{\text{em}}$; as we shall see below, the interstellar medium (ISM) may possess the ability of transferring an uneven fraction of Lyα versus continuum photons, making $W_{\text{em}}$ larger or smaller than $W_{\text{ext}}$. Finally, as the total number of photons in a line is conserved when traveling
through the universe, whereas the number of continuum photons per wavelength bin is reduced as they are cosmologically redshifted, the observed equivalent width $W_{\text{obs}}$ from a source at redshift $z$ is given by $W_{\text{obs}} = (1 + z) W_{\text{em}}$.

1.1. The Neufeld Scenario

As Ly$\alpha$ photons scatter on neutral hydrogen, their path length before escaping a galaxy will always be longer than that of continuum radiation. Thus, the immediate corollary is that Ly$\alpha$ will be more susceptible to dust absorption than the continuum, implying that $W_{\text{em}} < W_{\text{int}}$. However, Neufeld (1991, hereafter N91) investigated analytically the resonant scattering of Ly$\alpha$ photons through the ISM and found that under special circumstances, the Ly$\alpha$ photon may actually suffer less attenuation than radiation which is not resonantly scattered, e.g., continuum radiation. N91 considered the escape of radiation from the center of a plane-parallel, two-phase structure in which spherical clouds of homogeneously mixed neutral hydrogen and dust lie embedded within a virtually empty intercloud medium (ICM). The number density of clouds is assumed to be small enough that they do not touch, yet sufficiently numerous that they cover most of the sky.

Furthermore, the source of both Ly$\alpha$ and continuum photons is assumed to be point-like and situated in the center of the slab, in the ICM. Under these conditions, N91 showed that Ly$\alpha$ photons, upon entering a cloud, scatter only a few times before returning to the ICM, thereby being exposed arbitrarily little to absorption by dust. Consequently, the journey of the Ly$\alpha$ photons will be confined primarily to the dustless ICM, preserving the total Ly$\alpha$ luminosity. In contrast, the continuum radiation that penetrates the clouds rather than scattering off of their surfaces will be subject to the full attenuation, given by the optical depth from the center and out.

Thus, since the continuum is reduced while the line is more or less preserved, the EW of the escaping radiation can be “boosted” to arbitrarily high values. We define such a boost as

$$b \equiv \frac{W_{\text{em}}}{W_{\text{int}}}.$$  \hspace{1cm} (1)

Of course, the boost does not imply an increased Ly$\alpha$ luminosity, but rather a reduced continuum luminosity.

1.2. Numerical and Observational Support

The mere potential of an EW boost was the conclusion of N91’s studies. Hansen & Oh (2006, hereafter HO06) studied the scenario in more detail, both analytically and numerically. In addition to confirming the boost, they also looked into the effect of galactic outflows of clumpy gas on the line profile, exploring the RT in various geometries.

While HO06 did investigate various extensions of the Neufeld scenario, one of their main conclusions (p. 999) was the same as N91: “If most of the dust resides in a neutral phase which is optically thick to Ly$\alpha$, the Ly$\alpha$ EW can be strongly enhanced.” The results of N91 and HO06 seem a natural explanation of the unusually high observed EWs, and lately such observations have routinely been interpreted within the framework of this scenario, inferring the presence, or absence, of a clumpy, dusty ISM. Thus, Chapman et al. (2005), and lately Bridge et al. (2012), interpret the fact that Ly$\alpha$ radiation is visible from $\sim$50% of a sample of submillimeter galaxies as suggesting the presence of very patchy and inhomogeneous dust distribution. Finkelstein et al. (2007) regard a clumpy ISM as a possible explanation of their high Ly$\alpha$ EWs, and in Finkelstein et al. (2008) propose a parameter $q$ to characterize clumpiness, such that Ly$\alpha$ is attenuated by a factor $e^{-q \tau}$, where $\tau$ is the dust optical depth for non-resonant photons close to the Ly$\alpha$ line. For a given Ly$\alpha$ EW observation they then calculate the clumpiness of the ISM, positing that for $q < 1$ the EW is boosted due to dust clumpiness. This method is further used in Finkelstein et al. (2009a, 2009b, 2011), Yuma et al. (2010), Blanc et al. (2011), Nakajima et al. (2012), and Hashimoto et al. (2013) to infer various degrees of clumpiness in observed LAEs. An equivalent approach was followed in Niino et al. (2009), Kobayashi et al. (2010), and Shimizu et al. (2011). Similarly, Dayal et al. (2008, 2009, 2010, 2011) invoked a clumpy ISM scenario in order to match their simulated LAE LF’s to observed ones. On the other hand, other studies specifically found no reason to invoke a clumpy ISM (e.g., Forero-Romero et al. 2011).

However, the idealized conditions upon which a boost may be achieved are never taken into account. Accordingly, we believe that a revision of the scenario is timely, and in the present work we aim to investigate the validity of the various premises of this model. We do this by calculating numerically the RT of Ly$\alpha$ and continuum in model galaxies constructed to cover a broad range of plausible as well as implausible systems. In addition to the work of N91 and HO06, the topic of resonant scattering in a multiphase medium has received attention from Haiman & Spaans (1999), Richling et al. (2003), Šurlan et al. (2012), Dijkstra & Kramer (2012), and Duval et al. (2013). Of these, only Duval et al. (2013) concerned themselves with the relative escape fraction of Ly$\alpha$ and continuum, and found tentative evidence for the impractical nature of enhancing the Ly$\alpha$ EW, by investigating the Ly$\alpha$ and continuum RT in an expanding shell of clumps with different values of dust optical depth, expansion velocity, H$\text{I}$ density, and line width. They found that indeed a virtually empty ICM was needed, along with only modest outflow velocities and high $E(B-V)$, for an ISM geometry to result in a boost.

After describing the principles of the applied numerical code in Section 2, we systematically vary all parameters relevant for describing a (model) galaxy in Section 3, one at a time. This gives us a feeling for the impact a given parameter has on the boost. However, as the change of one parameter may very well be either enhanced or counteracted by the change of another, after discussing in Section 4 observational and theoretical constraints on the actual values of the parameters that are likely to be met in real astrophysical situations, we subsequently, in Section 5, undertake a large sample of simulations with random parameters covering these values, constructing a likelihood map of achievable boosts. The results of these calculations are discussed in Section 6, along with a discussion on other possible scenarios that could lead to high Ly$\alpha$ EWs.

2. RADIATIVE TRANSFER SIMULATIONS

N91 regarded each dusty cloud as a scattering particle itself with a certain probability of absorbing a photon. When HO06 developed their numerical model, they followed the same approach. They used a Monte Carlo code, where the path of individual photons was traced as they traveled through the ICM, but whenever a cloud was encountered, the photon would simply be absorbed or scattered at once in some direction away from the cloud. The appropriate probability density functions (PDFs) were calculated on beforehand from fits to a series of RT calculations of photons incident on a cloud surface. This rendered feasible simulations that were otherwise impractical.
In the seven years that have passed since, computational power has increased to a point that “brute force” simulations can in fact be performed rather effortlessly, eliminating the need for several approximations. In the present work, the RT calculations are conducted using the numerical code MoCaLaTA (Laursen et al. 2009a, 2009b). In the following, the basics of the code are outlined.

The galaxy is constructed on a grid of cells, each of which holds a value of the physical parameters important to the RT: the neutral hydrogen density $n_{\text{H}_1}$, the dust density $n_d$, the gas temperature $T$, and the three-dimensional velocity $v_{\text{th,gal}}$ of the gas elements. The original Neufeld scenario concerned itself with radiation escaping from a slab of gas. For numerical reasons, higher resolution can be achieved considering radiation escaping a sphere of multiphase gas, as in HO06. Qualitatively, and even quantitatively except for factors of order unity, the results are equivalent. Thus, a galaxy is modeled as a number $N_{\text{cl}}$ of spherical, non-overlapping clouds with radius $r_{\text{cl}}$, dispersed randomly within a sphere of radius $r_{\text{gal}}$. A cell may be either an ICM cell or a cloud cell. In order to make the clouds spherical, cells on the border between a cloud and the ICM are adaptively dispersed at random in an empty ICM. The temperatures of the clouds and the ICM are the interstellar phases conventionally called the warm neutral medium (WNM) and the hot ionized medium (HIM), respectively. The physical significance of the clouds and the ICM are the interstellar phases conventionally called the warm neutral medium (WNM) and the hot ionized medium (HIM), first identified by Field et al. (1969) and McKee & Ostriker (1977), although in reality $n_{\text{H}_1}v_{\text{cl}}$ is usually somewhat smaller than the chosen $1 \text{ atom cm}^{-3}$. Finally, in the fiducial model, all photons are emitted in the line center, from the ICM in the center of the sphere.

The covering factor $f_c$ is analogous to an optical depth of clouds intercepted by a sightline from the center of the galaxy and out. With a number density $n_{\text{cl}} = N_{\text{cl}}/V_{\text{gal}}$ of clouds, the covering factor of the fiducial model is then $f_c = n_{\text{cl}}V_{\text{gal}}/\sigma_3 = (3/4)N_{\text{cl}}(r_{\text{cl}}/r_{\text{gal}})^3 \approx 2$ (where $\sigma_3$ is the cross section of a cloud). Since an average sightline passing through a cloud traverses a distance $d = V_{\text{gal}}/\sigma_3 = 4r_{\text{cl}}/3$ inside the cloud, the total path traveled inside clouds for an average sightline is $d_{\text{in clouds}}(d) = f_c(d) = N_{\text{cl}}r_{\text{cl}}^3/r_{\text{gal}}^3$.

At the heart of the EW boosting mechanism lies the assumption of the Ly$\alpha$ photons being shielded from the dust by neutral hydrogen while the non-scattered FUV continuum radiation is subject to the “full” dust absorption. Hence, the relevant quantity for dust absorption is the total average absorption optical depth ($\tau_d$) of the dust throughout the galaxy. The dust absorption well as on the actual random realization of cloud positions. In addition to sampling the average spectrum, i.e., the spectrum of photons escaping in all directions, MoCaLaTA calculates the spectra escaping exactly in the six different directions along the Cartesian axes. The more clouds a galaxy comprises, the smaller the spread will be in different directions, and for different realizations. Further, the variation between different directions is much larger than between different realizations. For instance, for a covering factor of $f_c = 0$, the spread of the RT will actually intercept two clouds, while $\sim 10\%$ will intercept no clouds at all (i.e., the covering fraction is $\sim 0.9$ for $f_c \sim 0$), and a non-negligible fraction of the RT will intercept $\geq 5$ clouds (calculated numerically from the average of $10^5$ sightlines from the center and out). These three cases will, respectively, result in a boost close to the $4\pi$ average, no boost at all, and an essentially infinite boost (for a central point source). Thus, the fractional standard deviation $\sigma_3/b$ from different viewing angles is typically of order $50\%$, while for the $4\pi$ average of many realizations of the same model $\sigma_3/b$ is but a few percent.

In the following analysis, the presented values of $b$ represent the $4\pi$ average for a single realization of a given model.

3. Investigating the Criteria for a Boost

In order to systematize which physical conditions are necessary for boosting the EW, we first settle on a fiducial model. In the subsequent sections, several of the implied parameters are then relaxed or varied, individually or in conjunction. When nothing else is stated, the remaining parameters correspond to the fiducial model. Initially, we will not concern ourselves with the realism of the parameters, instead deferring this discussion to Section 4, although we note that several of the chosen values, as well as various derived parameters such as color excess and total galaxy mass, roughly resemble observed typical LAE values.

The fiducial model galaxy is a sphere of radius $r_{\text{gal}} = 5 \text{ kpc}$ consisting of $N_{\text{cl}} = 6500$ of clouds of equal radii $r_{\text{cl}} = 0.1 \text{ kpc}$. The density of neutral hydrogen in the clouds is $n_{\text{H}_1} = 1 \text{ cm}^{-3}$, implying a column density $N_{\text{H}_1,\text{cl}} = 3 \times 10^{20} \text{ cm}^{-2}$ as measured from the center to the surface of a cloud. The clouds are dispersed at random in an empty ICM. The temperatures of the clouds and the ICM are $T_{\text{cl}} = 10^4$ and $T_{\text{ICM}} = 10^6 \text{ K}$, respectively. The physical significance of the clouds and the ICM are the interstellar phases conventionally called the warm neutral medium (WNM) and the hot ionized medium (HIM), first identified by Field et al. (1969) and McKee & Ostriker (1977), although in reality $n_{\text{H}_1}v_{\text{cl}}$ is usually somewhat smaller than the chosen $1 \text{ atom cm}^{-3}$. Finally, in the fiducial model, all photons are emitted in the line center, from the ICM in the center of the sphere.

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optical depth of a single cloud (center-to-face) is \( \tau_{\text{c,cl}} = (1 - A) \tau_{\text{d,cl}} \), where \( \tau_{\text{d,cl}} \) is the total (absorption + scattering) dust optical depth and \( A \) is the dust albedo. Hence, \( (\tau_a) \simeq \tau_{\text{c,cl}} (d_{\text{in clouds}})/r_{\text{cl}} \) (this expression is only approximate, since photons scattering on dust grains may still be subject to absorption by another dust grain before it escapes the galaxy).

Dust grains are built from metals, and the density of dust is thus assumed to scale with metallicity and hydrogen density. Since observationally the optical depth is not readily measured, we will instead refer to the metallicity \( Z \), which is usually more easily probed. Depending on the actual extinction curve used, the constant of proportionality will differ. Furthermore, assuming that the density of dust scales linearly with the metallicity, the dust optical depth can be related to \( Z \) through \( \tau_d = N_\text{H} \sigma_d(\lambda) Z/Z_0 \), where \( \sigma_d \) is the dust cross section per hydrogen nucleus—specific for a given extinction curve—and \( Z_0 \) is the reference metallicity of that extinction curve. For example, for Small Magellanic Cloud (SMC) dust, at the Ly\( \alpha \) wavelength the cross section is \( \sigma_d = 4 \times 10^{-22} \text{ cm}^2 \) with only a small wavelength dependence across the line, and the SMC metallicity is \( Z_0 \simeq 0.25 Z_\odot \).

Having explicated the basics of the model, we now proceed to investigate the impact on the boost of varying the implied parameters.

### 3.1. Cloud Covering Factor

For the Neufeld scenario to be efficient, the sky, as seen from the center of the galaxy, must be sufficiently covered by clouds. N91 asserts that the covering factor \( f_c \) must be larger than unity. In fact, as soon as a single cloud is present, the 4\( \pi r \) average will have \( b > 1 \). Figure 2 shows, for various values of \( n_{\text{H,cl}} \) and \( Z \), how the EW boost changes with \( f_c \). The boosts are seen to follow an approximate log-normal relation, where different combinations of \( n_{\text{H,cl}} \) and \( Z \) with equal dust optical depths lie roughly on the same line. At fixed \( Z \), larger \( \text{H} \) densities result in larger boosts. The Ly\( \alpha \) photons are exposed to the same amount of extinction, but since \( \langle \tau_a \rangle \) is larger, the continuum is reduced more. At fixed \( n_{\text{H,cl}} \), a larger \( Z \) also results in a larger boost due to the higher \( \langle \tau_a \rangle \), but since for each cloud interaction a Ly\( \alpha \) photon experiences a larger probability of being absorbed, combinations with high \( Z \) have smaller boosts than those with high \( n_{\text{H,cl}} \). This is especially true at large values of \( f_c \), where the Ly\( \alpha \) photons interact with many clouds.

### 3.2. Cloud Hydrogen Density

To shield the Ly\( \alpha \) photon from the dust, the clouds must be highly optically thick in hydrogen. Since non-absorbed photons are usually reflected after only a handful of scatterings, in principle the clouds could have an optical depth of only a few, although in that case, for realistic metallicities, the dust optical depth would be so low that the continuum passes unhindered through the clouds.

Figure 3 shows how the magnitude of the boost depends on the \( \text{H} \) (column) density of the clouds. Note that for a given series of simulations, the metallicity has been held fixed, meaning that \( \langle \tau_a \rangle \) increases with increasing \( N_{\text{H,cl}} \). Even for solar metallicity, the EW boost is seen to set in only after \( N_{\text{H,cl}} \) surpasses approximately \( 10^{20} \text{ cm}^{-2} \), while, say, 10 times lower metallicity requires 10 times higher \( N_{\text{H,cl}} \). The critical value for a noticeable boost is found where \( N_{\text{H,cl}} \) and \( Z \) conspire to a dust optical depth of order unity.

### 3.3. Dust Contents in the Clouds

The density of dust scales both with metallicity and H\( \text{I} \) density. Increasing the gas density in the clouds will increase the dust density accordingly. This does not change the surface of a cloud from the point of view of a Ly\( \alpha \) photon, but the continuum photons experience a larger total optical depth of dust, and thus the boost increases. For a given H\( \text{I} \) density, increasing the metallicity results in a higher boost. These relations are shown in Figure 4. As expected, larger H\( \text{I} \) densities result in larger boosts, but for sufficiently low metallicities the boost will disappear.
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3.4. Cloud Size Distribution

In the previous simulations the cloud radii were held constant at \( r_{\text{cl}} = 100 \text{ pc} \). As N91 proposed and HO06 confirmed through their numerical model, the covering factor rather than the actual shape and size of the clouds is the important parameter controlling the RT of the Ly\( \alpha \) photons. For the continuum, however, doubling the cloud radius at constant \( f_{\text{c}} \) doubles the dust optical depth, thus increasing the boost. In Figure 5, we investigate the dependency of the boost on cloud sizes, as well as on cloud-size distributions \( P(r_{\text{cl}}) \propto r_{\text{cl}}^{-\beta} \). The dependency on the slope \( \beta \) is seen to be small. In the simulations with varying cloud radii, the slope was held constant at \( \beta = 2 \). This value was chosen to follow HO06.

Both increasing \( r_{\text{cl}} \) or decreasing \( \beta \) at constant \( f_{\text{c}} \) correspond to increasing the \( \langle \tau_{d} \rangle \) and hence \( b \), although it is seen that changes in \( \beta \) affect \( b \) only minutely. On the other hand, changing the cloud sizes but maintaining a constant total \( \text{H} i \) mass implies a constant \( \langle \tau_{d} \rangle \), and hence a constant continuum escape fraction. Consequently, the boost does not change for \( r_{\text{cl}} \gtrsim 100 \text{ pc} \), but at lower \( r_{\text{cl}} \) the number of times that the Ly\( \alpha \) photon interacts with clouds \( (N_{0}) \) becomes so large that the Ly\( \alpha \) escape fraction decreases considerably, reducing the boost.

3.5. Cloud Velocity Dispersion

The very concept of the boost hinges on the fact that neutral gas shields photons close to the line center from the dust. But if a given cloud as a whole has a non-vanishing bulk velocity, the entire spectrum is Doppler-shifted in the reference frame of the cloud, and for sufficiently large velocities, all line photons suddenly are no longer in resonance. In general, \( \text{H} i \) regions may be expected to exhibit such macroscopic motions, described by a cloud velocity dispersion \( \sigma_{V,\text{cl}} \). Figure 6 demonstrates that this is indeed the case; for \( \sigma_{V,\text{cl}} \gtrsim 100 \text{ km s}^{-1} \), the fiducial model is seen to be incapable of boosting the EW. Moreover, whereas in the case of \( \sigma_{V,\text{cl}} = 0 \) a higher covering factor results in a larger boost, introducing random cloud motion reduces the boost even faster; for \( f_{\text{c}} \) twice that of the fiducial model, the boost vanishes already for \( \sigma_{V,\text{cl}} \gtrsim 30 \text{ km s}^{-1} \).

3.6. Cloud Gas Temperature

Increasing the gas temperature\(^3\) \( T_{\text{cl}} \) in the clouds means less atoms with the right velocity for scattering photons exactly at the line center. In return for more atoms available for scattering off center photons. Photons in the wings of the line, however, do not

\(^3\) The parameter “temperature” also covers sub-grid turbulent motion, since this effectively broadens the line profile by a Gaussian.
care about the gas temperature, since the profile here is given by natural broadening. Even so, the difference in the effective cross section of the atoms is not very large. The consequence is that, for increasing $T_d$, the photons penetrate slightly deeper into the cloud, but not enough to affect the boost, as seen in Figure 7. The only difference is that the line profile of the escaping radiation is somewhat broadened.

3.7. Galactic Outflows and Infall

Gas elements also move in large-scale, collective motions, seen, e.g., in galactic outflows (Johnson & Axford 1971; Rupke et al. 2002; Shapley et al. 2003; Veilleux et al. 2005). For the same reason as in Section 3.5, such motions should act so as to diminish the boost, as was also realized by HO06. This stands in contrast to what is expected (Kunth et al. 1998; Dijkstra & Wyithe 2010) for a more homogeneous shell of gas being expelled from the galaxy, surrounding a central source and covering the full sky. In that case, the Ly$\alpha$ photons that would otherwise have to scatter their way through the shell, being very vulnerable to dust absorption, may be shifted away from the line center and escape through the shell with minimal absorption.

Figure 8 shows how the EW boost depends on the expansion velocity $V_{\text{out}}$. The wind speed is a function of distance $r$ from the center and is modeled assuming that the gas elements receive an acceleration $a \propto r^{-\alpha}$ (Steidel et al. 2010; Dijkstra & Kramer 2012). The speed thus increases from 0 at $r = 0$ to the terminal velocity $V_{\text{out}}$ at $r = r_{\text{gal}}$. Note, however, that the exact wind profile is not a major determinant of the resulting boost.

The curves in Figure 8 resemble those in Figure 6, although they are somewhat more shallow. The reason is that a photon bouncing off of a cloud in a galactic wind will, in general, upon its next encounter with a cloud, meet a cloud with roughly the same velocity. In the case of random motions, the relative velocity of the next cloud may be very high, increasing the probability of the photon being absorbed.

For reasons of symmetry, in terms of $b$ the same results are obtained if the velocities are inverted, as would be the case for galactic gas accretion (e.g., Dijkstra et al. 2006b). The spectra, however, would be reflected about the line center.

3.8. ICM Hydrogen Density

Thus far, we have assumed an ICM completely void of both dust and neutral gas. Due to the high temperature of the ICM, the hydrogen is expected to be quite highly ionized. Similarly, due to the high temperature, as well as the stronger ionizing UV radiation field, dust may be expected to be partly depleted. However, even a single scattering in the ICM may be fatal to a Ly$\alpha$ photon: precisely because of the high temperature, a scattering event in the ICM is likely to occur on a high-velocity atom moving more or less perpendicular to the path of the photon such that the velocity relative to the trajectory of the photon is small. Unless the photon is scattered close to (or opposite to) the same direction, it will be highly Doppler-shifted, such that the next time it encounters a cloud, it will penetrate deeply into the dusty medium with a higher probability of being absorbed. This effect is investigated further in Section 3.10.

For our fiducial model’s radius of $r_{\text{gal}} = 5$ kpc, an optical depth of order unity in the ICM for a line center photon is reached for an H$\alpha$ density $n_{\text{H}i} \sim 10^{-8}$ cm$^{-3}$. Due to the resonance nature of the scattering, somewhat higher densities are allowed as soon as the photon has diffused a few Doppler widths from the line center. This effect is visible in Figure 9 where the boost is shown as a function of ICM H$\alpha$ density for different cloud densities and metallicities.

3.9. ICM Dust Density

The neglect of dust in the ICM may be justified by the fact that dust grains will tend to get destroyed in hot and ionized media. Nevertheless, dust does exist in H$\alpha$ regions, albeit generally at lower densities. For an increasing covering factor the photons’ paths through the ICM are increased as they walk randomly through the galaxy. The mean free path between each cloud interaction is $1/f_c$, while the average number of cloud interactions is $N_0 = f_c^2 + (4/5)f_c$ (see Appendix A.4). Thus, the average path length for a photon out of our fiducial model of $r_{\text{gal}} = 5$ kpc is $(d_{\text{path}}) \simeq 14$ kpc. For a density of 0.01 cm$^{-3}$, $Z = Z_\odot$ and no dust destruction, the total optical depth of dust actually reaches $(\tau_{\text{ICM}}) \sim 0.2$. For larger densities $r_{\text{gal}}$ and $f_c$, $(\tau_{\text{ICM}})$ could exceed unity, while if part of the dust is destroyed, it may be neglected altogether.
Figure 9. EW boost $b$ as a function of H$_i$ density $n_{H,i}$ in the ICM. Results are shown in red, green, and blue for cloud number densities $n_{H,cl} = 0.1$, 1, and 10 cm$^{-3}$, respectively, in combination with cloud metallicities $Z = 0.1 Z_\odot$ (dashed) and 1 $Z_\odot$ (solid).

(A color version of this figure is available in the online journal.)

Figure 10. EW boost $b$ as a function of dust density in the intercloud medium, parameterized through the amount of metals in the form of dust, $(Z/Z_\odot) \times (\xi_{d,ICM}/\xi_{d,0})$, where the last term is the dust-to-metal ratio in terms of the values typically found in the predominantly neutral environments from where the dust extinction curve is taken (here the SMC). Results are shown for galaxies of $r_{gal} = 5$ (green) and 10 kpc (red), in combination with total (neutral + ionized) hydrogen density $n_{H,ICM} = 10^{-3}$ (dashed) and $n_{H,ICM} = 10^{-2}$ cm$^{-3}$ (solid).

(A color version of this figure is available in the online journal.)

Figure 11. EW boost as a function of temperature $T_{ICM}$ in the ICM, for neutral hydrogen densities $n_{H,i} = 10^{-3}$ (dotted), $n_{H,i} = 10^{-6}$ (dashed), and $n_{H,i} = 10^{-4}$ cm$^{-3}$ (solid).

As mentioned in Section 3.8, although scatterings in the ICM evidently are rare, a single such event may easily result in the subsequent absorption of a photon. Figure 11 explores this effect, but it is seen that only for rather high values of $n_{H,i}$ does the boost decrease significantly. For low densities, scatterings are so rare that even though some photons are absorbed, it does not affect the net result much. For very high temperatures, the boost increases again since the number of atoms available with the right velocity to scatter a photon becomes too small.

3.10. ICM Gas Temperature

Although star formation tends to be centrally located (e.g., Fruchter et al. 2006), obviously the photons are not emitted from a point source in reality. However, as long as the initial emission direction is isotropically distributed, photons emitted in the outskirts of the galaxy may be emitted both in an outward direction, being subject to a lower covering factor and thus a smaller boost, or toward the center, resulting in a higher covering factor and higher boost. As the number of cloud interactions scale nonlinearly with $f_c$, however, an extended emission profile does result in a slightly lower boost, although the effect is miniscule, as seen in Figure 12.

While the extended emission relaxes the notion of a central point source, all photons were still emitted from the ICM, as in the case of the central source in all previous sections. However, as the Ly$\alpha$ radiation is assumed to originate from gas surrounding young stars, which form from gas clouds that have recently cooled sufficiently to initiate star formation, it is probably more realistic to have at least a fraction of the photons originating from within the clouds. In Figure 13, we investigate how the EW boost changes for an increasing correlation of the photon sources with the clouds. As expected, taking this effect into account diminishes the boost, as the path out of a cloud is longer for a Ly$\alpha$ photon than for a continuum photon.
3.12. Intrinsic Line Profile

In the fiducial model, all Lyα photons are emitted exactly in the line center, i.e., as a delta function. In reality, the intrinsic line will have a finite width, which is a convolution between the natural, Lorentzian line profile and the thermal, Gaussian distribution of the atom velocities. Moreover, macroscopic motion of the gas parcels emitting the photon will cause an effective broadening of the line. As the temperature of the emitting gas is of the order 10⁴ K, corresponding to a line width of ~10 km s⁻¹, macroscopic motion may dominate over thermal (see Section 4.1). From non-resonant lines such as Hα, we know that the intrinsic line width may easily reach tens of km s⁻¹, i.e., several Doppler widths. As photons born this far from the line center are not efficiently shielded from the dust, they are more prone to dust absorption.

The effect of a broadened emission line profile is shown in Figure 14.

4. TOWARD A REALISTIC MODEL

Whereas the fiducial model in the previous section was not chosen to be particularly realistic, but rather to roughly resemble the original Neufeld scenario, we now proceed to investigate what values of the physical parameters we in fact expect to meet in real LAEs. In building a “realistic” model, it should be kept in mind that several of the input parameters are mutually dependent. For instance, under the assumption of approximate pressure equilibrium, the temperatures and densities are related as \( n_{\text{tot, cl}} T_{\text{cl}} \sim n_{\text{tot, ICM}} T_{\text{ICM}} \), where the subscripts “tot” refer to the total number density of all particles. The H\(_\text{i}\) densities are then given by the ionization fractions which, in turn, depend on not only temperature but also the chemical composition, i.e., on metallicity. Note, however, that due to very different cooling timescales of the WNM and HIM, the different phases of the ISM need not be in thermal equilibrium. Furthermore, the dependencies of some of the parameters may actually serve to counteract a boost. For instance, a larger galaxy in general entails a larger \( f_c \), which may increase \( b \), but since the larger mass also typically implies a larger \( \sigma_V \), \( b \) is quickly reduced again. Similarly, although an increased metallicity tends to increase \( b \), metals also donate free electrons, which aids in increasing the neutral fraction of hydrogen in the ICM, thus decreasing \( \alpha \).

The approach taken here is to identify for each parameter the minimum and the maximum values conceivably encountered in LAEs, as well as more typical ranges. Subsequently, a series of RT simulations are run with the physical parameters taking random values in the chosen ranges, and finally regions of high and low likelihood are identified in the parameter space, exploring whether any of these models lead to a significant boost.

LAEs span a wide range of physical characteristics, and in many aspects it does not make sense to speak about a “typical LAE.” It is often stated that LAEs are quite young, fairly small, relatively highly star-forming galaxies of rather low metallicity and dust content. However, one must bear in mind that many of these aspects are a consequence of the selection criterion picking out objects at high redshifts, i.e., at early epochs. In the following sections, values and ranges of the relevant parameters argued to be more or less representative of LAEs are summarized from the literature. An overview of the values is found in Table 1.

4.1. Cloud Hydrogen Density and Temperature

Gas does not cool equally well at all temperatures. Rather the cooling function exhibits several plateaus at which the gas temperature tends to settle. This is part of the reason for the different phases of the ISM; for gas which is in rough pressure equilibrium, the densities of the phases are set by their temperature, and thus, although variations do exist, they are not expected to span many orders of magnitude within a given phase. In the WNM, to which the clouds in the model correspond, characteristic hydrogen densities are 0.2–0.5 (e.g., Carilli et al. 1998; Ferrière 2001; Gloeckler & Geiss 2004)—typically probed by H\(_\text{i}\) 21 cm emission—with a neutral fraction close to unity. At low (high) pressure, \( n_{\text{H}, \text{II}} \) may reach values of ~0.02 (3) cm⁻³ (Wolfire et al. 2003). If densities rise much above ~1 particle cm⁻³, cooling becomes so efficient that the gas will tend to contract further to a cold neutral medium (CNM) and molecular clouds, thus quickly decreasing \( f_c \). The temperature of the WNM is of the order 10⁴ K, ranging from 8000 K to 12,000. Since small-scale turbulence effectively broadens the line in the same way as thermal motion, this process can be taken into account using a higher temperature. Turbulence is usually of the order of (a few times) the speed of sound (e.g., Gaensler et al. 2011) which, in turn, is the same order as the thermal motion. The effect can thus be simulated by letting \( T = 2–3 \times 10^4 \) K. Note also that much of the WNM may be in a thermally unstable phase (Heiles & Troland 2003), reaching temperatures below 5000 K.

4.2. ICM Hydrogen Density and Temperature

Surrounding the neutral gas is the HIM, heated and ionized to a large degree by supernova shock waves sweeping through the ISM. Expanding due to the larger pressure, and thus diluting, the cooling timescales are so long that temperatures of \( 5 \times 10^5–5 \times 10^6 \) K and higher are easily maintained (Brinks et al. 2000; Tüllmann et al. 2006, 2008). Densities in the range \( 10^{-3}–10^{-2} \) are typical here (Dopita & Sutherland 2003; Ferrière 2001), but since the fraction of neutral hydrogen at these temperatures is of the order \( n_{\text{H}, \text{ICM}} \sim 10^{-8}–10^{-5} \) (House 1964;
Figure 13. EW boost $b$ as a function of probability $P_d$ for a photon to be emitted from inside a cloud. An emission PDF with a scale length of $H = 1$ kpc has been adopted. For $P_d = 0$, the model reduces to the fiducial model, except for the somewhat extended emission which has only a modest influence on $b$ (cf. Figure 12). For $P_d = 1$, all photons are emitted from the interior of clouds. Results are shown for all combinations of $f_c \sim 2, 4, n_{H_\text{I,cl}}/\text{cm}^{-3} = 1, 10$, and $Z/Z_\odot = 0.1, 1$.

Sutherland & Dopita (1993), scattering in the ICM is very rare. These properties are usually probed through X-ray emission (e.g., Tüllmann et al. 2006) or absorption lines of highly ionized metals (e.g., Park et al. 2009). Note that the shock waves push the phases out of equilibrium and may in fact dominate the state of the ISM (de Avillez & Breitschwerdt 2005). Since small residual clumps of neutral gas may increase the effective average neutral fraction in the ICM, we will investigate densities up to $n_{H_\text{I,ICM}} = 10^{-6} \text{ cm}^{-3}$.

4.3. Covering Factor

A typical covering factor is difficult to establish, but a hint is provided by spectra of sources lying behind intervening galaxies. For instance, Noterdaeme et al. (2012) fit low-ionization absorption lines such as Sii—originating from cool clouds—in a quasar spectrum, the line of sight toward which passes through a DLA lying at $z = 2.2$, with 5–8 components. The impact parameter of the sightline with respect to the central emission of the DLA galaxy counterpart is pretty small ($\lesssim 1$ kpc), and thus in this case the covering factor is roughly $f_c \approx 2.5$–4. At a somewhat larger impact parameter of a DLA, $\sim 6$ kpc, J.-K. Kroager et al. (in preparation) fit the absorption lines in the spectrum of a background quasar with five components.

In the Milky Way (MW), the number of neutral clouds per kiloparsec in the plane is roughly 4–8 (Knude 1979, 1981; Franco 2012). Although this implies a high covering factor along a sightline in the plane, perpendicular hereto the covering factor is only of order unity. Since the disk has formed from a collapsed sphere, one may expect a smaller number of clouds per kiloparsec for a spherical system. For instance, the scale height of the MW’s WNM is approximately $h = 300$ pc and its radius is $R_{\text{MW}} \sim 15$ kpc (Binney & Merrifield 1998); distributing the clouds over a sphere of the same radius reduces the number density of clouds by a factor of $\sim R_{\text{MW}} / h = 50$.

4.4. Cloud Metallicity and Dust Density

Generally lying at high redshifts where metals have had less time to build up, LAEs tend to have lower metallicities, and hence dust densities, than local galaxies. Measured values of $Z$ range from metallicities as low as $\sim 10^{-2} Z_\odot$ to values similar to local values, and in some cases even supersolar metallicities have been found at high redshifts (e.g., Savaglio et al. 2012; Acquaviva et al. 2012). In a survey of $\sim 10^5$ LAEs at $z = 2.2$, Nakajima et al. (2012) found a lower limit for the average metallicity of an LAE of $Z = 0.09 Z_\odot$. Even low-redshift LAEs tend to have modest metallicities ($Z \lesssim 0.1$–1; Giavalisco et al. 1996; Östlin et al. 2009).

Correspondingly, measured color excesses tend to be modest. For example, at $z \sim 3$ Gronwall et al. (2007) and Pirzkal et al. (2007) found $E(B-V)$’s lying approximately in the range 0.01 to 0.1. Verhamme et al. (2008) found similar values by fitting Lyα line profiles using the Lyα RT code MCLYa (Verhamme et al. 2006). At $z = 2.2$, Hayes et al. (2010) found values spanning all the way from 0 to $\sim 0.3$. For comparison, our fiducial model has $E(B-V) = 0.05$.

In our model we assume that the dust-to-metal ratio $\xi_{\text{cl,d}}$ in the clouds is equal to that of our reference extinction curve such that $\tau_d$ scales linearly with $Z$. Observations of $\xi_{\text{cl,d}}$ at high redshifts are sparse, but tend to be similar (e.g., Pettini 2003; Savaglio et al. 2003) or slightly lower. Various analytical and numerical calculations predict a metallicity-dependent evolution of the dust-to-metal ratio, such that $\xi_{\text{cl,d}}$ reaches present-day values only after timescales of 10–100 Myr (Gall et al. 2011) or even several gigayears (Inoue 2003; see also Matsson 2011). Moreover, measurements in the local but very low metallicity galaxy I Zw 18 indicate that $\xi_{\text{cl,d}}$ is lower in such galaxies (Herrera-Camus et al. 2012). Since we have used the extinction law of the SMC, which is also a low-metallicity galaxy with a rather young stellar population, we expect that its extinction will not be substantially different from that of high-redshift galaxies.

4.5. Cloud Velocity Dispersion

From the virial theorem, the components of a galaxy of mass $M$ and radius $r$ will have characteristic velocities of the order $c^2 = \sqrt{GM/r}$, where the factor $C$ depends on the geometry and the actual mass distribution, as well as on whether the system is rotation- or dispersion-dominated (Binney & Tremaine 2008). For dispersion-dominated galaxies, $M$ refers to the total, dynamical mass of the system, and $C \approx 6.7$ for various galactic mass distributions (Forster Schreiber et al. 2009). For rotation-dominated galaxies, the appropriate mass is the mass enclosed within $r$, and $C \approx 2.25$, again averaged over various galactic mass distribution models (Épimnet et al. 2009).

Measured values of the H I velocity dispersion, or of the stellar velocity dispersion which arguably reflects the velocity field of the gaseous components, range from $\sim 10$–30 km s$^{-1}$ for dwarf galaxies (e.g., Peterson & Caldwell 1993; van Zee et al. 1998) to several hundred km s$^{-1}$ for large ellipticals (e.g., McElroy 1995). Note that observationally what is measured is the dispersion along a line of sight or an average of many lines of sight and hence corresponds to the dispersion in one dimension. If there is no preferred direction of motion, the three-dimensional velocity dispersion, which is what is referred to in Section 3.5, is a factor of $\sqrt{3}$ times higher.

Our fiducial model has a total H I mass of $6.7 \times 10^8 M_\odot$. For small galaxies, the ratio of H I to the total, dynamical mass
is roughly 0.1 (Skillman et al. 1987; van Zee et al. 1997, 1998). Thus, the velocity dispersion should be approximately 50 km s⁻¹.

At high redshift, most galaxies may not yet have had time to form a disk, and may thus be expected to be dispersion-dominated. For galaxies that eventually settle into a disk, the velocity dispersion tends to decrease (e.g., Thomas et al. 2012). For instance, for intermediate- to late-type spirals, Bershady et al. (2011) found that the central vertical velocity dispersion tends to decrease (e.g., Thomas et al. 2012).

### 4.6. Galactic Outflow Velocity

Although not ubiquitous, galactic winds seem to be rather common in high-redshift galaxies. The outflows are produced by the kinetic and/or thermal feedback of massive stars and supernovae on the ISM. Radiation pressure and heating engender expanding bubbles of primarily ionized gas that sweeps up interstellar material, eventually escaping the galaxy (or possibly re-entering the system after having reached several virial radii; Heckman 2002). Outflows are usually detected through low-ionization absorption lines such as MgII and FeII which appear blueshifted with respect to the systemic velocity. Typical values are of the order 100 km s⁻¹ (e.g., Pettini et al. 2001; Rubin et al. 2011), but range all the way from 0 up to ~1–2000 km s⁻¹ (e.g., Shapley et al. 2003).

Various models for galactic outflows have been put forward: Orsi et al. (2012) equate $V_{\text{out}}$ with the circular velocity, which is of the same order as $\sigma_V$, discussed in the previous section. Bertone et al. (2005) and Garel et al. (2012) apply a weak dependency on SFR, with $V_{\text{out}} \propto SFR^{0.2} \times 10^{10}$, where the SFR is given in units of $M_\odot$ yr⁻¹, and the constant of proportionality is $\sim 300–1000$ km s⁻¹.

In the context of LAEs, the effect of an outflow is to diminish the blue peak of the otherwise symmetric, double-peaked line profile. This is noticeable already ~10 km s⁻¹, and by ~100 km s⁻¹, the blue peak may be erased altogether (e.g., Dijkstra et al. 2006a). Most high-redshift LAE profile observations have resulted in the well-known, asymmetric red peak only. However, using sufficiently high resolution, $R \gtrsim 1–2000$, it seems that a significant fraction (20%–50%) of LAEs actually show at least signatures of a blue peak, indicating only modest outflow velocities (Venemans et al. 2005; Tapken et al. 2007; Kulaur et al. 2012; Yamada et al. 2012).

This hypothesis is in qualitative agreement with the recent findings of Hashimoto et al. (2013), who interpret the smaller offset of LAE Lyα lines with respect to the systemic velocity, compared with those of Lyman break galaxies (LBGs), as being due to smaller outflow velocities. Note, however, that the line offset to a large degree depends on the column density, which, due to the generally much higher gas mass of LBGs, naturally will be larger.

For the reasons given above, and since a large outflow velocity was found to quickly destroy the boost anyway, we will restrict ourselves to investigating rather small values of $V_{\text{out}}$, from 0 to 100 km s⁻¹.

### 4.7. Emission Sites

Since evidently the extent of the photon-emitting region is not of major importance (see Section 3.11), for simplicity we will confine our grid of models to one value only, viz., $H_{\text{em}} = 1$ kpc. This value is roughly equal to the UV half-light radius of LAEs at redshifts $2 \lesssim z \lesssim 6$ (see Figure 2 of Malhotra et al. 2012).

The typical environment from which photons are emitted is more crucial. Originating in the H I/Hi boundaries surrounding...
massive stars, the concept of emitting the Ly$\alpha$ photons from the ICM is rather dubious. Massive stars are predominantly born in giant molecular clouds (GMCs; e.g., Garay & Lizano 1999). Since such stars are short-lived, with lifetimes of but a few megayears, they are not expected to travel very far from the dense clouds from which they were born. This favors a high value of $P_{\perp}$, a probability of being emitted from a cloud rather than from the ICM. On the other hand, the intense UV radiation carves out a Strömgren sphere, which reaches a size of the order of 10(s) pc in a few megayears (Hosokawa & Inutsuka 2006; Gendelev & Krumholz 2012). If they are matter-bounded rather than radiation-bounded, the Ly$\alpha$ photons start to stream freely out into the surrounding lower-density medium.

Although Israel (1978) found that most massive stars are located in the outskirts of GMCs (in the MW), Waller et al. (1987) argue that they tend to be more centrally located, but that ∼50% of the H$\text{ii}$ regions used to probe O and B stars in reality are just parcels of ionized gas that was once in molecular form near the surface of their host cloud. On the other hand, Gendelev & Krumholz (2012) reason that internal turbulence in the GMCs creates filamentary structure so that any star has a high probability of being born near the surface.

Regardless of the massive stars being born deep in the GMCs, or being born closer to the edge so that blisters allow a high escape fraction of ionizing and hence Ly$\alpha$ photons, the GMCs themselves are usually embedded in the WNM. The density of the WNM being several orders of magnitude lower than the GMCs, a Strömgren sphere that breaks out of a GMC may be able to grow faster, facilitating escape into the ICM.

Massive stars also exist in exposed clusters, such as in the Pleiades. Although the stars necessarily are born in dense clouds, some stellar groups manage to ionize and blow away the neutral gas. Observations of this at high redshifts are difficult, but in the nearest 2 kpc of the Sun, Lada & Lada (2003) estimate the (lower limit) birthrate of embedded clusters to be 2–4 Myr$^{-1}$ kpc$^{-2}$, which is more than an order of magnitude higher than that of open clusters (0.25–0.45 Myr$^{-1}$ kpc$^{-2}$; Elmegreen & Clemens 1985; Battinelli & Capuzzo-Dolcetta 1991).

In a study of 45 GMCs in M33, Imara et al. (2011) found 29 to be spatially and kinematically coincident with a local peak in atomic gas, 13 to be kinematically coincident but located near the edge or on a filament between two peaks, and the remaining three not to be associated with any high-density atomic gas. In the region NGC 602/N90 in the SMC, Goulieermis et al. (2012) found an “unusually large fraction” of 60% of the main-sequence stars to be clustered, while the rest are diffusely distributed in the intercluster area.

Additionally, in the MW 10%–20% of all O stars are found in ultracompact H$\text{ii}$ regions, still embedded in their natal molecular cloud (Churchwell 1990).

From these considerations, we consider $P_{\perp}$ = 0.1 to be a lower value, 0.2–0.5 to be a more or less realistic value, and 0.9 to be the highest value.

### 4.8. ICM Dust Density

Since the various ways of destroying dust tend to correlate with processes that also ionize gas (collision, sputtering, sublimation, and evaporation), the dust-to-metal ratio $\xi_d$, and hence the dust-to-gas ratio, in ionized gas may be expected to be lower than in neutral regions. However, most extinction curves are obtained from sightlines crossing several phases of the ISM, although typically only the correlation of the extinction with the neutral hydrogen is probed. Hence, the variation of $\xi_d$ with $z_{HI}$ is not well constrained. Whereas $\xi_d$ in neutral gas seems to be more or less universal over different phases, metallicities, and redshifts, the observations that do exist generally indicate a lower $\xi_d$ in regions of ionized gas, albeit with large variations. On the basis of a discussion of various such regions, Laursen et al. (2009b) argue (Section 2.1.1) that $\xi_d$ in these regions ranges between a factor of $10^{-4}$ lower than in the neutral phases to values similar to these, but with typical values of $10^{-2}$ times lower. This is an average over several different types of H$\text{ii}$ regions, in particular also the very dust-depleted IGM; in the HIM $\xi_d = 10^{-1}$ may be more representative. A similar discussion was given recently by Paladini et al. (2012, Section 5), where it is also noted that the mere radiation pressure may be able to clear large volumes of dust.

### 4.9. Emission Line Width

The intrinsic Ly$\alpha$ line width is given by a convolution of the natural, thermal, and turbulent broadening. As discussed in Section 4.1, turbulence may dominate over thermal motions. Since scattering changes the line shape in a highly non-trivial way, Ly$\alpha$ line shape observations do not reveal the intrinsic shape. Instead the width of non-resonant lines such as H$\alpha$, which are produced in the same locations as Ly$\alpha$, arguably can be used as a probe. Since the emitting regions also exhibit larger-scale motions, however, when observing the line integrated over the full galaxy it will usually be much broader.

When galaxies are well resolved, the internal motion of clouds is more easily disentangled. In nearby galaxies, Yang et al. (1994) found H$\alpha$ line widths (in terms of standard deviations) of 20–30 km s$^{-1}$. At higher redshifts, using CO lines where large-scale motions have been removed, Swinbank et al. (2011) determine the internal velocity dispersion of the components of a starburst galaxy at $z = 2.3$ to be 45–85 km s$^{-1}$.

### 4.10. Cloud-size Distribution

As mentioned previously, the covering factor rather than the actual shapes and sizes of the clouds is the crucial factor in determining the boost. However, for $P_{\perp} > 0$, the size of the clouds becomes important, as smaller clouds imply an easier escape from the first cloud. On the other hand, at a given covering factor a larger cloud size implies more attenuation of the continuum. In Section 3.4, we used $\beta = 2$ when keeping $r_{\perp}$ constant in order to follow HO06. Measured slopes tend to be shallower, $\beta \sim 1.6$ (Dickey & Garwood 1989; Williams & McKee 1997). Obviously, in reality the WNM does not consist of spherical clouds, so in order for the conclusions not to depend too much on the chosen cloud sizes, we will study a broad range of cloud sizes and distributions. Approximately half of the simulations will be run with a fixed cloud size, both $r_{\perp} = 30$ pc and $r_{\perp} = 100$ pc, while the other half is run with $r_{\perp} = 20–200$ pc and $\beta = 1–2.5$. This cloud size range is roughly consistent with that of the LMC (Kim et al. 2003). Smaller cloud sizes probably require further cooling, while larger clouds will get torn apart by large-scale motion, at least in rotation-dominated objects (Newton 1980).

### 5. RESULTS

Having settled upon more or less realistic ranges of the parameters important for the RT, summarized in Table 1, a large number ($2 \times 10^4$) of simulations is carried out in the multidimensional parameter space $\mathcal{P}$ spanned by the parameters.

Additional $2 \times 10^4$ models were run in the “usual” range (enclosing the “typical” range) in order to more finely occupy
this region of $\mathcal{P}$. Note that even for the $2 \times 10^4$ models in the full range, the density of points in $\mathcal{P}$ does not represent which values are most typical; first, several of the parameters are too uncertain to say anything meaningful about their probability distribution, and second, even if this was possible, it would imply an infeasible high number of simulations in order to also sample the low-probability regions of $\mathcal{P}$. Whereas in all previous simulations $10^5$ photons were used to ensure convergence, in order to be able to adequately sample $\mathcal{P}$, we use only $10^3$ photons per model. In most simulations, the resulting boost is accurate to within roughly 10% (determined from 100 random resimulations which were run to convergence); in simulations where the continuum escape fraction is very low, usually implying a large boost, this tends to overestimate the boost. One hundred of such simulations were resimulated to convergence; of these, 5 were found to have underestimated $b$ by 20%–30%, while the rest had overestimated $b$ by $\sim0$–300%. However, as will be evident below, all of these models correspond to physically extremely unlikely models.

The results of the simulations are displayed in Figure 15 where the boosts of all models are shown as a function of the total average column density ($N_{\text{HI}}$) of neutral hydrogen, colored according to their metallicity. The gray-shaded contours indicate regions of likelihood, based on the parameter value ranges listed in Columns 2 and 3 of Table 1. “Typical LAE” models all lie within the dark gray area, while “unusual” models lie within the light gray area.

The remaining models all have rather unrealistic values. We have marked with black circles the ones for which nevertheless at least one of the following inequalities is true: $n_{\text{HI},cl} \lesssim 1.5$ cm$^{-3}$, $Z \lesssim 1.25$, $\sigma_{V,cl} \gtrsim 10$, or $P_{\text{cl}} \gtrsim 0.10$; these models are regarded as “extreme, but possibly conceivable,” while the remaining are regarded as “extreme and probably inconceivable.”

6. DISCUSSION

By far, the majority of the models reveal a boost of $\lesssim 1$. Furthermore, the ones that exhibit $b > 1$ tend to have supersolar metallicity, very high cloud HI densities ($\sim 5 \times 10^4$ typical values), very low velocity fields (both $v_{\text{out}}$ and $\sigma_{V,cl}$ are $<10$ km s$^{-1}$), virtually empty intercloud media, and a high fraction ($>80\%$) of photons born in the ICM.

Of the models labeled “extreme, but possibly conceivable” (indicated in Figure 15 by the black circles), 12 have resulted in a boost of $b > 1.5$. For reference, the high EWs in Finkelman et al. (2009b) and Kashikawa et al. (2011, 2012) required boosts of $>1.5$, 1.4–2.5, and $3.6^{+3.5}_{-1.2}$, respectively (assuming $W_{\text{em}} = 240$ Å). Taking a closer look at these model reveals that they all lie close to the (admittedly somewhat arbitrary) threshold between “conceivable” and “inconceivable.” Moreover, although outflow velocity was not considered as a defining threshold, all except one have $v_{\text{out}} \sim 1$ km s$^{-1}$. One model has $v_{\text{out}} = 17$ km s$^{-1}$, but has slightly supersolar metallicity ($Z = 1.1 Z_\odot$), low velocity dispersion ($\sigma_{V,cl} = 14$ km s$^{-1}$), low emission cloud-correlation ($P_{\text{cl}} = 0.15$), a narrow intrinsic emission line ($\sigma_{\text{em}} = 15$ km s$^{-1}$), and high cloud densities ($n_{\text{HI},cl} \gtrsim 1.5$ cm$^{-3}$) but virtually empty ICM ($n_{\text{HI,ICM}} \simeq 10^{-10}$ cm$^{-3}$).

The 12 models were all resimulated with $10^3$ photons. These resimulations reduced the value of the boost somewhat in all but one case (where it increased by a few percent). Furthermore, inspecting the emerging spectra (Figure 16) shows that all models exhibit very narrow emission lines. In order for the Neufeld scenario to work, the Ly$\alpha$ photons by definition are not allowed to scatter much, lest they would diffuse too much in frequency, eventually being so far from the line center that they would be able to penetrate the clouds. The resimulated lines have, on average, a FWHM of $110$ km s$^{-1}$, and the broadest line has a width of only $150$ km s$^{-1}$. This is much narrower than observed Ly$\alpha$ lines, which typically are many hundreds of km s$^{-1}$ broad, and rarely below $250$–300 km s$^{-1}$ (e.g., Rhoads et al. 2003; Fynbo et al. 2003; Hu et al. 2004; Shimasaku et al. 2006). As a further consideration, in spite of the vanishing outflow velocities, almost all of the spectra lack the prominent double-peak feature of Ly$\alpha$ radiation escaping a static medium. Also, at high redshifts such a narrow line would be very vulnerable to scattering in the circumgalactic medium (see, e.g., Laursen et al. 2011; Jeeson-Daniel et al. 2012). Note that we have not included any rotation in these simulations, which could in principle broaden the lines. However, since again observed lines are much broader than expected rotational velocities, they cannot be rotationally dominated.

Additionally, if a given “too high”-EW LAE is supposed to be caused by a multiphase medium preferentially absorbing the continuum, rather than some effect increasing the Ly$\alpha$ flux, then that LAE should also exhibit a certain reddening of the continuum. In general, however, the opposite seems to be the case: in a large sample of COSMOS LBGs and LAEs, Mallery et al. (2012) found a clear anti-correlation between the ratio of SFRs calculated from the Ly$\alpha$ and from SED fitting, respectively, and $E(B-V)$. Similar results were found by Shapley et al. (2003) and Pentericci et al. (2009). On the scale of individual galaxies, Atek et al. (2008) found in at least four out of six nearby galaxies that the regions of high EW correlate with the regions of low $E(B-V)$. Most of the high-EW regions are diffuse Ly$\alpha$ emission, which is probably Ly$\alpha$ photons produced in the star-forming regions being scattered toward the observer.

6.1. Alternative Scenarios

Based on the results presented above, it seems that the Neufeld scenario will allow for an increased Ly$\alpha$ EW under very special circumstances only, and thus serves as a very unlikely explanation for the observed high Ly$\alpha$ EWs. The reports of high EWs nevertheless exist and warrant an explanation. In the following we hence discuss miscellaneous alternatives.

6.1.1. Measuring Errors and Misinterpretations

First, it must be remembered that the mere report of an enhanced EW does not necessarily imply an enhanced EW. For faint continua, determining the EW is associated with considerable error, and most of the proclaimed high EWs have huge error bars. For instance, Henry et al. (2010) found six sources with $W_{\text{em}} > 240$ Å, but caution that the uncertainties in such high EWs typically exceed 100 Å.

Another source of confusion is insufficient knowledge about the impact of the IGM on the Ly$\alpha$ line, mainly a problem for photometrically determined EWs. At high redshifts, neutral hydrogen in the IGM scatters a significant fraction of the photons in the Ly$\alpha$ line, mainly a problem when the continuum and the line itself and is sometimes accounted for as “emission, which is probably Ly$\alpha$ photons produced in the star-forming regions being scattered toward the observer.”
Figure 15. “Likelihood map” of the boosts obtained for models with realistic and sub-realistic parameter values. The boost is shown, arbitrarily, as a function of average neutral hydrogen column density $\langle N_{\text{HI}} \rangle$ as measured from the center to the surface of a galaxy. Each point represents a galaxy, the physical parameters of which are a realization of random values in the ranges discussed in Sections 4.1–4.10 and summarized in Table 1. The metallicity of a galaxy is depicted by the color of the associated point. Models of “typical” and “unusual” parameters all lie within the dark and light gray regions, respectively. The rest of the models have rather unrealistic parameters, but the ones that have either $n_{\text{HI,cl}} \leq 1.5 \, \text{cm}^{-3}$, $Z \leq 1.25$, $\sigma_{V,cl} \geq 10 \, \text{km s}^{-1}$, or $P_{cl} \geq 0.10$ are marked by black circles.

even if the correlation of the state of the IGM with the sources is taken into account, large fluctuations in the neutral fraction of hydrogen exists, which may also be a possible source of error (e.g., Laursen et al. 2011; Jeeson-Daniel et al. 2012). Negligence of the impact of intervening H\textsc{i} clouds, in combination with effects of continuum slope, dust reddening, and measurement errors, may in extreme cases give rise to an interpreted “boost” of $>2$ for photometric EWs (Hayes et al. 2006).

6.1.2. Stellar Population

The theoretical upper limit for the Ly$\alpha$ EW of 240 Å assumes a Salpeter (1955) IMF at solar metallicity. For decreasing metallicities, the main sequence of a stellar population is
shifted to the blue, resulting in a slower decline of the ionizing photon production, and thus a higher Lyα shift to the blue, resulting in a slower decline of the ionizing UV radiation (Schaerer 2003). Nevertheless, even for $Z \sim 0.02 Z_\odot$, the EW of a starburst is “only” 350 Å, i.e., corresponds to an interpreted boost of $\sim 1.5$.

For even lower values of $Z$ very high values of $W_{\text{int}}$ may be reached. An extreme case of a low-metallicity population would be one consisting of Population III stars (e.g., Tumlinson et al. 2003; Zackrisson et al. 2011). While still not observationally confirmed, stars born from (close to) metal-free gas are expected to be able to reach very high masses. Being particularly luminous in the Lyman continuum, such a population of stars will be able to emit a remarkable fraction of their photons in Lyα. Whereas a “normal” population emits 6%–7% of its bolometric luminosity in Lyα, 10%–40% can be reached for sufficiently low metallicities, with a resulting $W_{\text{int}}$ of several thousands of Angstrom (Bromm et al. 2001; Schaerer 2002; Raiter et al. 2010). However, at metallicities this low, no dust should yet have formed, and thus no reddening should be observed. Moreover, with such a high metallicity, the EW of the Hβ line at 1640 Å is expected to be noticeable. In some of the high Lyα-EW cases, this was specifically looked for but not detected (Dawson et al. 2004).

Shifting one or both of the IMF mass limits toward higher masses or applying a shallower slope implies a relatively larger fraction of high-mass stars with a harder ionizing UV spectrum and thus a larger $W_{\text{int}}$. For instance, increasing the upper mass limit from 100 to 500 $M_\odot$ (corresponding to a rise in average mass from 3.1 to 3.4 $M_\odot$ only) for a $Z = 5 \times 10^{-4} Z_\odot$ population, strengthens $W_{\text{int}}$ from $\sim 400$ Å to $\sim 700$ Å, while further increasing the lower mass limit from 1 to 500 $M_\odot$ (corresponding to a rise in $(M)$ to 112 $M_\odot$) strengthens $W_{\text{int}}$ to $\sim 900$ Å (see Figure 7 of Schaerer 2003).

In all cases, the above values assume an instantaneous burst of stars; with the early O and B stars dying fast, the EWs of these extreme populations quickly decline, reaching more modest values after only a few megayear, and would thus have to be observed in a special period of their lives. For continuous star formation, high EWs can be found at any point in time, although the values will always be lower than the initial EWs of the instantaneous bursts. For $Z = 5 \times 10^{-4} Z_\odot$, $W_{\text{int}}$ increases from $\sim 180$ Å to $\sim 240$ ($\sim 500$ Å for a mass range 1–500 ($50$–$500$) $M_\odot$). This can be compared to $W_{\text{int}} \sim 100$ Å or less for $Z \gtrsim 0.02 Z_\odot$.

### 6.1.3. Delayed Escape of Lyα

In principle, for a short-lived starburst the Lyα photons—having their path length out of the galaxy increased—could be observed after the continuum has already faded, resulting in a higher EW. This was investigated for a homogeneous sphere of dust-free gas by Roy et al. (2010) and Xu et al. (2011) who found that, depending on the column densities, the Lyα radiation may be appreciably delayed. When clumpiness is introduced, we find that the escape time decreases significantly. For instance, if all the gas in the fiducial model is distributed homogeneously, the Lyα photons escape with a typical delay of $t_{\text{esc}} \sim 100$ kyr if there is no dust. In contrast, with the clumpy structure, $t_{\text{esc}} \sim 20$ kyr (not considering the photons that escape directly without interacting with any clouds). When dust is added, $t_{\text{esc}}$ is reduced further, since the photons that have the longest escape time are the ones that are most prone to absorption.

For larger $r_{\text{gal}}$, $t_{\text{esc}}$ increases. However, even among the models with $r_{\text{gal}} = 10$ kpc, few have $t_{\text{esc}} > 100$ kyr. Compared to the typical lifetime of the O and B stars of several megayears, a stellar continuum should still be visible as the Lyα radiation reaches its maximum.

Solving simultaneously the RT for Lyα and ionizing UV radiation in a spherically symmetric model galaxy, Yajima & Li (2012) found that most of the Lyα photons could remain trapped until the galaxy has been fully ionized, at which point the “old” and the “new” Lyα photons are released together, resulting in Lyα EWs of up to $\sim 1000$ Å. It is unclear, however, how applicable these results are to more realistically simulated galaxies, where low-density regions are ionized more rapidly, allowing the Lyα photons to leak in those directions.

In a cosmologically simulated galaxy of approximate radius 25 kpc, Laursen & Sommer-Larsen (2007) found a typical path length of the Lyα photons of $\sim 40$ kpc, i.e., a delay with respect to the continuum of $\sim 50$ kyr. This simulation, however, did not include ionizing UV RT.

### 6.1.4. AGN Activity

If a galaxy contains an AGN, the Lyα EW may be much higher than the 240 Å. The line widths of these objects are so broad, however, that such objects can usually be excluded, as in, e.g., Rhoads et al. (2003) and Dawson et al. (2004). Even type II AGNs, i.e., objects where the broad-line region is not visible, typically have larger line widths than the observed high-EW objects. Furthermore, if the majority of the high-EW systems were due to AGN activity, that would be inconsistent with the X-ray emission (e.g., Wang et al. 2004; Gawiser et al. 2006).

### 6.1.5. Viewing Angle

All the models studied in this work are spherically symmetric. For a flattened system, photons escape more easily face-on than edge-on. But since Lyα photons scatter and thus wander around in the galaxy, their probability of escaping from the face before reaching the edge is increased, and thus a higher EW will be observed face-on. Without information about the system’s morphology, this can be interpreted as an EW boost. That this is

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**Figure 16.** Average spectrum (solid line) and 1σ region (gray-shaded area) of the marginally realistic models giving a boost larger than $\delta = 1.5$. With an average (maximum) FWHM of 110 (150) km s$^{-1}$, these lines are much narrower than typical observed high-EW LAs.
For relatively massive galaxies, Goerdt et al. (2010) found at \(z = 2.5\) that cold gas accreting can give rise to significant Ly\(\alpha\) emission of up to a few times \(10^{-17}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) on scales of 10–100 kpc, which is comparable to typical line strengths. Such gravitational cooling gives rise to not only Ly\(\alpha\) radiation but also a continuum, although it is much fainter relative to the stellar continuum. Dijkstra (2009) calculated analytically the EW of the cooling radiation from a collapsing halo and found that, depending on where the continuum is measured, the intrinsic EW of the cooling radiation is \(\gtrsim 950\) Å. Numerically, a few studies have addressed this issue and find that in general the fraction of the Ly\(\alpha\) radiation that stems from gravitational cooling increases with \(z\), from \(\sim 10\%\) at \(z = 3.6\) (Laursen & Sommer-Larsen 2007), to \(\sim 16\%–18\%\) at \(z = 5.7–6.5\) (Dayal et al. 2010), to \(\sim 50\%–60\%\) at \(z = 7–8\) (Jensen et al. 2013). Similarly, Yajima et al. (2012a) found that cooling radiation becomes comparable to recombination Ly\(\alpha\) for \(z > 6\). Obviously, large deviations from these values exist, both numerically and in reality, as in the case of Ly\(\alpha\) blobs where in some cases no stellar continuum is seen at all; a viable explanation for these objects is cold accretion (Nilsson et al. 2006; Dijkstra & Loeb 2009).

Note, however, that these values are quite model-dependent and should be treated with caution, as the simulations do not perform the full RT of ionizing radiation coupled with the hydrodynamics. Note also that gravitational collapse is not the only means of heating the accreting gas; it may also be photoheated, as considered by Rosdahl & Blaizot (2012), who nevertheless do not consider nebular Ly\(\alpha\). In spite of the uncertainties associated with the magnitude of the cooling radiation being large, they do hint at an increasing fraction of cooling-to-nebular Ly\(\alpha\) radiation with redshift, as may be expected. Observationally, however, there is still only tentative evidence for cooling radiation (Rauch et al. 2011; Ribaudo et al. 2011).

While the photons of stellar origin, both Ly\(\alpha\) and continuum, tend to be born in regions of comparatively high densities of both dust and neutral gas, thus being more prone to dust absorption, the cooling photons may escape more or less freely. Thus, cooling radiation could dominate even at quite low redshifts, although the actual fraction is difficult to assess observationally as long as the escape fraction of stellarly produced photons is still associated with such large uncertainties.

6.1.7. Star Formation Stochasticity

When calculating the resulting EW from a distribution of stellar masses, an infinite number of stars are usually assumed. Using the numerical code SLUG (Fumagalli et al. 2011; da Silva et al. 2012), Forero-Romero & Dijkstra (2013) found that for low-SFR galaxies, stochasticity alone results in a distribution of EWs from \(W_\alpha/4\) to \(3W_\alpha\), where \(W_\alpha\) is the mean EW. However, as noted by the authors since this effect is minimal for SFRs \(\gtrsim 1 M_\odot\) yr\(^{-1}\), which are hardly visible at high redshifts, it cannot serve as an explanation for most of the observed high-EW galaxies.

6.1.8. Inhomogeneous Escape

For resolved galaxies, regions with no star formation may scatter Ly\(\alpha\) from distant regions toward the observer, such that these particular regions exhibit extreme EWs (Hayes et al. 2007). Integrated over the source, however, Ly\(\alpha\)-overluminous regions cancel out with underluminous regions (modulo other effects affecting the RT).
7. SUMMARY AND CONCLUSION

We have carried out a comprehensive set of Lyα and FUV continuum RT calculations, systematically varying the significant physical parameters, first separately and then in unison. The aim was to investigate whether a multiphase ISM is capable of preferentially absorbing the continuum so as to enhance the observed Lyα EW. The motivations for this study are the numerous observations of LAEs exhibiting EWs larger than what is theoretically expected, together with the previously proposed explanation of such a “boost” being a consequence of a clumpy ISM (Neufeld 1991; Hansen & Oh 2006). In the suggested model, a galaxy consists of a number of clouds, physically corresponding to the ISM phase called the “WNM,” dispersed in a low-density medium corresponding to the phase called the “HIM.”

We find that, while indeed it is possible to construct a model galaxy with the said ability, the physical properties needed are extremely unlikely to be found in a real galaxy. In order for a galaxy to enhance its intrinsic Lyα EW, a number of criteria must be met.

1. The metallicity must be high (\(\gtrsim\)solar).
2. The density of the WNM must be very high (\(\gtrsim5\) times typical values).
3. The density of the HIM and its ionization fraction must be very low, so that the total density of neutral hydrogen in this phase does not exceed \(~10^{-7}\) cm\(^{-3}\).
4. The bulk (\(\gtrsim80\%-90\%\)) of the Lyα and FUV photons must originate from regions where the stars have blown away the neutral gas from which they were born.
5. The galaxy must have virtually no outflows (\(V_{\text{out}} \lesssim 10\) km s\(^{-1}\)).
6. The velocity dispersion of the gas clouds must be very low (\(\lesssim10\) km s\(^{-1}\)).

In particular, the latter two points are important; the whole point of the proposed multiphase model is that the paths of the Lyα photons are confined to a dust- and gasless medium, never penetrating the dusty clouds but instead scattering off of their surfaces. This mechanism works because of the resonant nature of Lyα scattering. However, as soon as the clouds have a small velocity, especially random motions, the Lyα photons can be extended so as to include the continuum. For a given EW this is readily accomplished by first determining whether an emitted photon is a line rather than a continuum photon, with a probability \(P(\text{line}) \propto W_{\text{int}}/\Delta\), and then determining the exact wavelength of the photon depending on the intrinsic line profile or the slope of the continuum (in this study taken to be flat in \(\nu\)). For a broad wavelength region around Lyα, numerically there is no difference in the RT of the two kinds of photons.

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APPENDIX

EXTENDING AND TESTING MoCaLaTA

A.1. Implementing Continuum Radiation

The original version of MoCaLaTA included only the RT of Lyα, i.e., the initial frequency probability distribution of photons followed a Voigt profile with the Gaussian core given by the temperature/turbulence of the gas. To calculate EWs, the wavelength range \(\Delta\) transferred through the medium must be extended so as to include the continuum. For a given EW this is readily accomplished by first determining whether an emitted photon is a line rather than a continuum photon, with a probability \(P(\text{line}) \propto W_{\text{int}}/\Delta\), and then determining the exact wavelength of the photon depending on the intrinsic line profile or the slope of the continuum (in this study taken to be flat in \(\nu\)). For a broad wavelength region around Lyα, numerically there is no difference in the RT of the two kinds of photons.

A.2. Building the Grid

In order to construct spherical clouds, we make use of adaptive mesh refinement (AMR), where cells may be refined into eight subcells. As the clouds themselves are uniform, high resolution is only needed at their surfaces, not their interior. To build the AMR grid, we use the following approach.

Given a number \(N_{\text{cl}}\) of clouds and a distribution of sizes specified by a minimum and maximum radius \(r_{\text{min}}\) and \(r_{\text{max}}\), as well as a size distribution power-law index \(\beta\), cloud centers are placed randomly in a sphere of radius \(r_{\text{gal}}\), such that no clouds overlap. The clouds’ surfaces are then marked by a number of auxiliary particles, typically \(~10^3\). Subsequently, the grid is smaller than that of the WNM (e.g., Ferrière 2001), the covering factor of these phases is smaller. Moreover, they will typically be embedded inside the WNM, affecting only those photons that were already trapped in the clouds. In addition to the points mentioned above, it must also be remembered that the intrinsic Lyα EW of a galaxy exhibiting a high observed EW must be high, i.e., the stellar population must be very young (\(~\text{a few Myr}\)) otherwise an even higher boost would be needed to bring the EW above the theoretical limit.

In conclusion, we consider the Neufeld model to be an extremely unlikely reason for the observed high EWs. We have discussed a number of other possible explanations (Section 6.1) of which the most probable, in our opinion, is an excess of Lyα radiation from cold accretion (which may contribute \(~0.1–1\) times the stellar Lyα, depending on redshift, and may escape much more easily), and/or anisotropic escape of Lyα (the Lyα flux may vary in different directions by a factor ~1–10, depending on irregularity of the galaxy and aperture of the detector).

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constructed starting from a mother grid of base resolution $2^3$, recursively refining any cell that contains more than one particle. Finally, each cell is labeled either a “cloud” cell or an “ICM” cell, depending on the distance to the nearest cloud center, and the physical parameters then assigned accordingly. Note that all cells belonging to a given cloud share the same bulk velocity, such that there are no velocity gradients inside a cloud.

The auxiliary particles can be positioned in different ways so as to constitute the cloud surface; the most straightforward way is to place them at a random position at a distance $r_{cl}$ from the center of the cloud. However, it turns out that in general some particles end up so close to each other that in order to refine the cells sufficiently hundreds of refinement levels may be needed. Distributing the particles evenly on the surface ensures that roughly the same level of refinement is needed everywhere. Various algorithms exist for this geometrical exercise (see, e.g., Saff & Kuijlaars 1997).

A.3. Altering the Acceleration Scheme

To speed up calculations, MoCaLaTA makes use of various acceleration schemes. The most efficient is the core-skipping scheme: since scatterings of photons near the line center are usually associated with negligible spatial movement, while it typically takes of the order $10^5$ scatterings to “escape” the core, these scatterings can be skipped by drawing the random velocity of the scattering atom from a centrally truncated Gaussian, favoring fast moving atoms that can give the photon a large Doppler shift. In MoCaLaTA, the critical wavelength defining when the acceleration scheme can be invoked is dependent on the product $a \tau_0$, such that for higher H\textsubscript{i} column densities and lower temperatures, a larger critical value can be used, allowing for a larger speed up. The value of $a \tau_0$ is specific to a given cell, and is calculated from the center of the cell to the face.

Since the code has previously been used for galaxies extracted from cosmological simulations, cells are usually surrounded by other cells of similar physical conditions, i.e., there are no large gradients. In the present idealized simulations, however, where densities may go from zero to some extreme value over the course of a single cell step, this poses a problem for photons close to the line center scattering on the surface of a cloud.

In reality, the photon typically escapes after a handful of scatterings, changing its frequency only of the order 1.5 Doppler widths. With the acceleration scheme, the first scattering pushes the photon artificially far out in the wing, rendering the optical depth of hydrogen significantly reduced, such that the photon is able to penetrate the cloud (or the next cloud) too much, with a corresponding higher probability of being absorbed by dust.

We solve this issue by calculating $a \tau_0$ not from the cell center, but from the current position of the photon to the face of the cell. Unfortunately, the consequence is a quite less efficient acceleration.

A.4. Testing the Code

In the original Neufeld scenario, that is, with no velocity fields etc., the physical parameters most important to the RT are $N_0$ and $\epsilon_i$, i.e., the average number of clouds with which a Ly\textalpha photon emitted from the center of a spherical conglomeration of clouds interacts, and the probability per cloud interaction that a photon (Ly\textalpha or continuum) is absorbed. No analytical solution exists for these quantities, but HO06 found that they could be well fitted by $N_0 = f_c \frac{\tau^2}{2} + (4/5) f_c$ (in the absence of absorption) and $\epsilon_i \simeq 3 \epsilon_i^{5/9} / (1 + 2 \epsilon_i^{2/3})$, where $\epsilon_i$ is the probability of absorption per (gas or dust) interaction for an incident photon lying at $\xi$ Doppler widths from the line center. The results are shown in Figure 18.

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