Lyman $\alpha$ line and continuum radiative transfer in a clumpy interstellar medium

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ABSTRACT

Aims. Studying the effects of an inhomogeneous interstellar medium (ISM) on the strength and the shape of the Lyman alpha (Ly$\alpha$) line in starburst galaxies.

Methods. Using our 3D Monte Carlo Ly$\alpha$ radiation transfer code, we study the radiative transfer of Ly$\alpha$, UV and optical continuum photons in homogeneous and clumpy shells of neutral hydrogen and dust surrounding a central source. Our simulations predict the Ly$\alpha$ and continuum escape fraction, the Ly$\alpha$ equivalent width EW(Ly$\alpha$), and the Ly$\alpha$ line profile, and their dependence on the geometry of the gas distribution and the main input physical parameters.

Results. The ISM clumpiness is found to have a strong impact on the Ly$\alpha$ line radiative transfer, entailing a strong dependence of the emergent features of the Ly$\alpha$ line (escape fraction, EW(Ly$\alpha$)) on the ISM morphology. Although a clumpy and dusty ISM appears more transparent to radiation (both line and continuum) compared to an equivalent homogeneous ISM of equal dust optical depth, we find that the Ly$\alpha$ photons are, in general, still more attenuated than UV continuum radiation. As a consequence, the observed equivalent width of the Ly$\alpha$ line (EW$_{\text{obs}}$(Ly$\alpha$)) is lower than the intrinsic one (EW$_{\text{int}}$(Ly$\alpha$)) for nearly all clumpy ISM configurations considered. There are, however, special conditions under which Ly$\alpha$ photons escape more easily than the continuum, resulting in an enhanced EW$_{\text{obs}}$(Ly$\alpha$). The requirement for this to happen is that the ISM is almost static (galactic outflows $\leq 200$ km s$^{-1}$), extremely clumpy (with density contrasts $> 10^7$ in HI between clumps and the interclump medium), and very dusty (E(B-V) > 0.30). When these conditions are fulfilled the emergent Ly$\alpha$ line profile generally shows no velocity shift and little asymmetry. Otherwise the Ly$\alpha$ line profile is very similar to that expected for homogeneous media.

Conclusions. Given the asymmetry and velocity shifts generally observed in star-forming galaxies with Ly$\alpha$ emission, we therefore conclude that clumping is unlikely to significantly enhance their relative Ly$\alpha$/UV transmission.

Key words. galaxies: starburst - galaxies: ISM - galaxies: high-redshift - ultraviolet: galaxies - radiative transfer - line: profiles

1. Introduction

Being the intrinsically brightest spectral signature of remote young galaxies (Partridge & Peebles 1967; Schaerer 2003), and possessing a rest wavelength of 1216 Å (making it accessible for optical/near-IR ground-based telescopes for redshifts $z \geq 2$), the Lyman alpha (Ly$\alpha$) line has become the most powerful emission-line probe of the distant young universe. The potential of the Ly$\alpha$ emission line for detection and redshift confirmation of distant galaxies, derivation of star formation rate (SFRs), as well as probe of the ionization state of the intergalactic medium (IGM) (Malhotra & Rhoads 2004; Kashikawa et al. 2006) and the reionisation epoch (Fan et al. 2002; Santos 2004) is enormous, but necessarily relies on a good astrophysical understanding of the processes that regulates the emergent Ly$\alpha$ emission from a galaxy.

The importance of the Ly$\alpha$ line in the cosmological context was first proposed by Partridge & Peebles (1967) who suggested that young high-$z$ galaxies, undergoing their first star-forming event, should be detectable thanks to their strong Ly$\alpha$ emission line. Unfortunately, the first attempts to detect high-redshift galaxies in Ly$\alpha$ gave quite meager results. The observed Ly$\alpha$ fluxes appeared fainter than those predicted and only few Ly$\alpha$ emitters (LAEs) had been detected until the late 1990s (cf. Djorgovski & Thompson 1992, Pritchet 1994). This lack of Ly$\alpha$ emission has nevertheless triggered several studies which have enabled to highlight the high complexity of the resonant Ly$\alpha$ line radiative transfer in starburst galaxies (Meier & Terlevich 1981; Neufeld 1990; Charlot & Fall 1993; Kunth et al. 1998; Tenorio-Tagle et al. 1999; Mas-Hesse et al. 2003; Östlin et al. 2009). While the faint measured Ly$\alpha$ fluxes were originally attributed to the dust attenuation (Pritchet 1994), it has turned out that many physical effects could strongly modify or suppress the Ly$\alpha$ line within galaxies (metallicity, neutral hydrogen kinematics, geometry of the interstellar medium (ISM)). It is only during this last decade, and the development of deep and wide surveys, that many Ly$\alpha$-emitting galaxies have been detected (Hu et al. 1998, 2004; Cowie & Hu 1998; Kudritzki et al. 2000; Rhoads et al. 2000; Taniguchi et al. 2003, 2005; Shimasaku et al. 2006; Gronwall
et al. 2007; Nilsson et al. 2007; Guaita et al. 2010; Ouchi et al. 2003, 2008, 2010).

Because of the factors which contribute to the Lyα radiative transfer, the Lyα line features (line profile, equivalent width EW(Lyα), offset from other emission/absorption lines) encode much information on the properties of individual galaxies: gas kinematics, gas geometry as well as stellar population. For instance, the detection of unusually strong Lyα line in the spectra of high-z galaxies could indicate the presence of population III stars within them (Schaefer 2003), whereas the asymmetry of the line profiles would suggest the presence of strong galactic outflows (Kunth et al. 1998). The derivation of this precious information requires however an accurate interpretation of the Lyα line features, which implies as well a complete understanding of the Lyα radiative transfer in the ISM of galaxies. This is one of the aims of this paper.

Due to the importance of the Lyα line for cosmology, several studies have attempted to understand the physical process governing the escape of Lyα photons from galaxies. Among the parameters which influence the visibility of the Lyα line, dust content, neutral gas kinematics and the geometry of the neutral gas seem to play the most important roles. Dust was originally invoked to explain the absence or the faint Lyα emission from galaxies at large redshift (e.g. Meier & Terlevich 1981). However, Giavalisco et al. (1996) studied a local sample of star-forming galaxies observed with the IUE space telescope and found no clear correlation between Lyα/Hβ or EW(Lyα) and the reddening E(B−V). Other studies have also led to a lack of correlation between the dust attenuation and the strength of the Lyα line, suggesting that other parameters govern the escape of Lyα photons (Kunth et al. 1994; Thuan et al. 1997; Atek et al. 2008). Among them, the role of the neutral gas kinematics was revealed in the 1990s by Kunth et al. (1994) and Lequeux et al. (1995). For 8 local galaxies observed with the Goddard High Resolution Spectrograph (GHRS), Kunth et al. (1998) found that when Lyα line appeared in emission, there was a systematic blueshift of low ionisation states (LIS) metal absorption lines with respect to Lyα, indicative of outflows in the neutral medium. Furthermore, the shape of the Lyα line profiles proved to be asymmetric. Galaxies showing Lyα in absorption showed significantly smaller relative shifts of LIS lines and Lyα. This result clearly shows that the Lyα escape fraction and line shape are strongly affected by the kinematical configuration in the ISM. Phenomenologically it is easy to understand that an outflow in the neutral ISM would promote the escape of Lyα photons and create asymmetric line profiles, since the motion Doppler shifts the line out of resonance and more so for the red side of the line. Finally, several studies of the resonant Lyα transfer have emphasized the importance of the ISM clumpiness on the escape of the Lyα (Neufeld 1991; Giavalisco et al. 1996). In particular, Neufeld (1991) showed that it could be possible to observe an emergent EW(Lyα) higher than the intrinsic one in a dusty and clumpy ISM. As the clumpiness of the ISM is well established in our galaxy (Stutzki & Guesten 1990; Marscher et al. 1993), this parameter must therefore be taken into account in the study of the Lyα radiative transfer.

With the increased number of Lyα radiative transfer codes developed recently (Ahn et al. 2001, 2002; Cantalupo et al. 2005; Verhamme et al. 2006; Pierleoni et al. 2007; Laursen et al. 2009a; Forero-Romero et al. 2011), the transfer of Lyα photons has intensively been investigated in the framework of galaxy simulations. In particular, such simulations allow us to compare the observed Lyα line properties of individual galaxies, both nearby and distant ones (Ahn et al. 2003; Verhamme et al. 2008; Atek et al. 2009). However, although most studies have treated the Lyα radiative transfer in either static or expanding media, the main effects of a multiphase ISM on the Lyα radiative transfer has been the object of few numerical studies (Haiman & Spaans 1999; Richling 2003; Hansen & Oh 2006; Laursen et al. 2012). The aim of this present paper is to carry out a detailed study of both the Lyα and the UV continuum radiative transfer in a large range of dusty, moving, homogeneous and clumpy ISMs. This will allow us to examine in detail the effects of the ISM clumpiness on the features of the Lyα line (Lyα escape fraction, EW(Lyα), Lyα line profiles).

One of the main motivations of our study is also to understand the anomalous strong EW(Lyα) revealed by several observations of LAEs at high-z (Kudritzki et al. 2000; Malhotra & Rhoads 2002; Rhoads et al. 2003; Shimasaku et al. 2006; Kashikawa et al. 2012). While normal stellar population models predict a maximum value of ∼ 240 Å for the intrinsic EW(Lyα) within starburst galaxies (i.e. assuming population I/II stars, Charlot & Fall 1993; Schaefer 2003), it is not rare to observe higher EW(Lyα) from high-redshift sources. Several physical possibilities have already been investigated to explain these high EW(Lyα), such as the presence of either population III stars or Active Galactic Nuclei (AGNs) in the host galaxies. But none of them prove to be consistent with the observations (Dawson et al. 2004; Wang et al. 2004; Gawiser et al. 2006). Another possibility is that the high EW(Lyα) values found are due to the combined effect of IGM absorption (lowering the continuum on the blue side of Lyα at high z) and observational errors biasing the average EW(Lyα) to higher values (Hayes & Östlin 2006). The most popular explanation seems, however, to be the relative boost of Lyα photons result in a clumpy ISM as originally suggested by Neufeld (1991). In this scenario, Lyα and UV continuum photons propagate in a clumpy ISM, where all neutral hydrogen and dust are mixed together in clumps. While Lyα photons would scatter off of the surface of clumps, having their journey confined to the dustless interclump medium, the UV continuum photons would penetrate into the clumps and would suffer greater extinction. Such a scenario would thus produce larger EW(Lyα) than the intrinsic ones, allowing to explain the anomalously high EW(Lyα) observed in some high-z galaxies. Other studies have also invoked a higher transmission of Lyα photons than for the UV continuum, to explain observations of some low redshift Lyα emitters (Scarlata et al. 2009), to understand the overall SED of LAEs at z ~ 4 (Finkelstein et al. 2008, 2009), and to reproduce the Lyα and UV luminosity function of distant galaxies (Dayal et al. 2009; Forero-Romero et al. 2011).

In this paper, we investigate the Neufeld scenario further and examine the physical conditions under which a clumpy ISM could produce a boost of the Lyα line relative to the continuum.

The remainder of this paper is structured as follows. In Section 2 we outline a description of our numerical model, presenting the features of the clumpy media and our assumptions. In Sections 3 and 4 are presented our results.
The Lyα radiative transfer in homogeneous and clumpy media is presented in Section 3, whereas the formation and the features of the emergent Lyα line profiles are described in Section 4. Section 5 is dedicated to the discussion of these results with, in particular, an application of our study to the Neufeld scenario. Finally, our main conclusions are summarised in Section 6.

2. Method

2.1. 3D radiation transfer code

To study the Lyα line and UV–optical continuum radiation transfer in clumpy geometries, we have used the latest version of the 3D Monte Carlo radiative transfer code MCLyα of Verhamme et al. (2006) and Schaerer et al. (2011). To treat the radiation transfer at wavelengths other than Lyα, we here also compute the continuum transfer at other wavelengths assuming scattering and absorption by dust. For the present paper we are interested in three wavelengths, listed in Table 2: the Lyα line (A = 1215.67 Å) and its neighboring UV continuum, and the optical B and V bands.

2.2. 3D geometries, model parameters, and model output

Both for simplicity, and since spherically symmetric outflows with a homogeneous H I shell are able to reproduce a large variety of observed Lyα line profiles in Lyman break galaxies and Lyα emitters (Verhamme et al. 2008; Schaerer & Verhamme 2008; Dessauges-Zavadsky et al. 2010), the same geometry is used to study how a clumpy ISM structure alters the Lyα line and UV continuum. This clumpy geometry is also chosen since it has been shown to reproduce observable continuum properties of starburst galaxies and the Calzetti attenuation law (Gordon et al. 1997; Witt & Gordon 2000; Vijh et al. 2003). Finally, this also allows us to make a detailed study into the continuity of the extensive grid of radiation transfer models by Schaerer et al. (2011).

In practice we adopt the following, simple shell geometries (see figure 1): a static or radially expanding, homogeneous or clumpy shell of H I and dust surrounding the source emitting both Lyα line and continuum photons. Dust and gas (H I) are assumed to be co-spatial in the shell. We assume a point-like central source.

2.2.1. Input parameters

The four physical and the two geometrical input parameters of our models, listed in Table 1, are the following. The radial expansion velocity $v_{\exp}$, the Doppler parameter $b$ of the H I, the mean H I column density $N_{\text{HI}}$, the mean dust absorption optical depth $\tau_a$, the clump volume filling factor FF, and the density contrast $n_{\text{IC}}/n_{\text{C}}$ between the interclump and clumpy medium. Each parcel of the shell (clump or interclump) exhibits the same radial velocity $v_{\exp}$, the Doppler parameter $b = \sqrt{v_{\text{rad}}^2 + v_{\text{turb}}^2}$ reflects the random (thermal +turbulent) motions of the H I. The clumpy (inhomogeneous) medium is defined by the volume filling factor FF of clumps, by their density $n_C$, and by the density contrast $n_{\text{IC}}/n_{\text{C}}$ between clumps and interclumps of lower density $n_{\text{IC}}$. The mean H I column density $N_{\text{HI}}$ is thus related to the (inter)clump density, FF, and the thickness of the shell $L$ by:

$$N_{\text{HI}} = (\text{FF} n_C + (1 - \text{FF}) n_{\text{IC}}) L.$$

Similarly one has

$$
\tau_a = (1 - a) \sigma_d \frac{m_d}{m_H} \frac{M_d}{M_H} N_{\text{HI}},
$$

(2)

where $a$ is the dust albedo, $\sigma_d$ the total dust cross section (scattering + absorption), $m_H$ the proton mass, $m_d$ the dust grain mass, and $(M_d/M_H)$ is the dust-to-gas ratio. In the present paper, the dust optical depth $\tau_a$ — the single parameter used to vary the dust content — is derived assuming a dust grain size of $2 \times 10^{-6}$ cm and a mass $m_d = 3 \times 10^{-17}$ g. The total dust optical depth is defined as

$$
\tau_d = \frac{\tau_a}{(1 - a)},
$$

(3)

and the dust particle density is

$$n_d = n_H \frac{m_H}{m_d} \frac{M_d}{M_H},
$$

(4)

where $n_H$ stands for the clump or interclump density. We adopt the SMC dust properties (albedo $a$ and phase function $g$) listed in Table 2. These properties, together with the clumpy shell geometry also adopted here, have been shown to reproduce observable continuum properties of starburst galaxies (Gordon et al. 1997; Witt & Gordon 2000; Vijh et al. 2003). Although detailed model predictions depend to some extent on the dust properties, the main quantities of interest in this paper – the Lyα and UV continuum escape fractions, and especially their relative values – should not strongly depend on the exact dust properties. We expect that other poorly known properties such as the geometry and velocity field, known to affect sensitively the transfer of Lyα radiation, are more important than the detailed dust properties (Laursen et al. 2009b). For these reasons we have not considered changes of the dust properties, but focus on the effect of geometry and clumpiness in this paper.

To construct clumpy structures with the desired input parameters in practice, we follow a similar approach as Witt & Gordon (2000). We construct a Cartesian grid of $N = 128^3$ cells, within which the shell of thickness $L$ is defined by an inner and outer radius, $R_{\text{min}}$ and $R_{\text{max}}$. Assuming a density $n_C$ for the high density regions (clumps) we then randomly choose a fraction FF of the cells localised in the shell (i.e. cells localised at a radius $R$ such as $R_{\text{min}} \leq R \leq R_{\text{max}}$), which receive a high density $n_C$. The remaining cells in the shell are set to low density $n_{\text{IC}}$. The physical cell size (or equivalently $L$) is then adjusted to reproduce the desired mean radial H I column density $N_{\text{HI}}$, which is computed by drawing random lines of sight through the shell. Finally the dust content is varied by changing the dust-to-gas ratio $(M_d/M_H)$, yielding different values of the mean dust absorption optical depth $\tau_a$.

In Table 3 we summarise the different values that we have explored for the six input parameters describing our models. For the present study we have adopted a filling factor $FF = 0.23$, as explained below (Sect. 2.2.2). The density contrast $n_{\text{IC}}/n_C$ has been varied from 1 (inhomogeneous medium) to 0, reflecting the extreme case of an empty interclump medium. Models have been computed for static shells ($v_{\exp} = 0$) and expansion velocities up to $v_{\exp} = 600$ km s$^{-1}$. Then, a wide range of parameter space has been considered, as listed in Table 3.
Fig. 1. Representation of some 3D homogeneous and clumpy geometries studied in this paper. The star distribution is always localised in the center of the shell, whereas the dust and the H\textsubscript{i} content are distributed around. The dust and H\textsubscript{i} distribution can be "homogeneous" (left), "clumpy" (middle) or "extremely clumpy" (right). In a "clumpy" distribution, the clumps and the interclump medium receive, respectively, a high and a low densities of dust and H\textsubscript{i}. In the case of an "extremely clumpy" distribution, all the dust and the H\textsubscript{i} content are distributed in clumps.

Table 3. Range of values of the six input parameters (column 1-6) describing the homogeneous and clumpy shell models, and derived properties (cols. 7, 8).

| FF  | n\textsubscript{IC}/n\textsubscript{C} | \(v_{\text{exp}}\) [km s\textsuperscript{-1}] | \(b\) [km s\textsuperscript{-1}] | \(N_{\text{HI}}\) [cm\textsuperscript{-2}] | \(\tau_{a}\) | CF | mass spectrum |
|-----|----------------|----------------|----------------|----------------|--------|-----|----------------|
| 0.23| [0, 1]         | 0, 50, 100, 200, 250, 300, 400, 600 | 12.8, 20, 40 | | | | \(\rho(m) \propto m^{-2.04}\) |

Table 1. Six input parameters (top) for and derived parameter (bottom) of the homogeneous and clumpy shell models.

| Parameter | Symbol |
|-----------|--------|
| Radial velocity | \(v_{\text{exp}}\) |
| H\textsubscript{i} velocity dispersion | \(b\) |
| Mean H\textsubscript{i} column density | \(N_{\text{HI}}\) |
| Mean dust absorption optical depth | \(\tau_{a}\) |
| Clump volume filling factor | FF |
| Density contrast | \(n\textsubscript{IC}/n\textsubscript{C}\) |
| Covering factor | CF |

Table 2. Dust parameters (\(a\) and \(g\)) taken from Witt & Gordon (2000) and adopted for Ly\textalpha\ line photons, and continuum photons at UV and optical wavelengths (close to the B and V-band).

| Photons | \(\lambda\) (\textsc{Å}) | \(\tau_{d}/\tau_{V}\) | \(a\) | \(g\) |
|---------|----------------|----------------|-----|-----|
| Ly\textalpha\ | 1215.67 | 0.64 | 0.460 | 0.770 |
| UV | 1235.0 | 0.74 | 0.460 | 0.770 |
| B-band | 4300.0 | 1.38 | 0.495 | 0.633 |
| V-band | 5550.0 | 1.00 | 0.490 | 0.607 |

2.2.2. Characterisation of clumpy structures

Given a choice of the clump volume filling factor FF and the thickness of the shell (i.e. \(R_{\text{max}} - R_{\text{min}}\)), two other interesting quantities describing the inhomogeneous structure can be derived. First, the covering factor CF of the shell corresponding to the fraction of solid angle covered by the clumps as seen from the central source. Models with different covering factors are constructed by varying \(R_{\text{min}}\).

Another interesting quantity is the mass spectrum of the clumps. As clumps we consider, as Witt & Gordon (1996, 2000), all cells directly connected with each other by at least one face. We then determine their mass spectrum, which approximately follows a power law \(\rho(m) \propto m^{-a}\), where \(m\) is the clump mass. Adopting FF = 0.23, we obtain a power law \(\rho(m) \propto m^{-2.04}\) as illustrated in Fig. 2. This mass spectrum is consistent with observations of diffuse interstellar clouds showing a power law with \(a = 2\) (Dickey & Garwood 1989). The value FF=0.23 in our model is then the most appropriate value if we aim to reproduce the interstellar mass spectrum of nearby galaxies. We illustrate in Fig. 2 the mass spectrum obtained with FF= 0.23 (red curve) in a shell geometry defined with \(R_{\text{min}} = 49\) and \(R_{\text{max}} = 64\) cells. The slope of the mass spectrum does not change noticeably decreasing the covering factor CF (i.e. decreasing \(R_{\text{min}}\)).

Let’s mention that some models with other mass spectra (i.e. other filling factors FF) have been studied, such as \(\rho(m) \approx m^{-2.70}\) and \(\rho(m) \approx m^{-3.17}\). However, no notable change is found in any of our results changing only the mass spectrum in clumpy shell structures.

2.2.3. Input spectra

In the region close to Ly\textalpha\ we assume that the spectrum consists of a flat UV continuum (i.e. constant in number of photons per frequency interval) plus the Ly\textalpha\ line, characterised by a Gaussian with an equivalent width \(E_{\text{W,int}(\text{Ly}\alpha)}\) and Full Width at Half Maximum \(F_{\text{WHM}_{\text{int}(\text{Ly}\alpha)}\). All pho-
can be computed \textit{a posteriori} from our simulations for arbitrary input spectra (line + continuum), as described in Verhamme et al. (2006), $f_{\text{esc}}(\lambda_{\alpha})$ is slightly dependent on the FWHM of the input line profile, but independent on the value of $EW_{\text{int}}(\lambda_{\alpha})$.

The UV continuum escape fraction $f_{\text{esc}}(\text{UV})$ is computed redward of the Ly$\alpha$ line. Assuming the Calzetti et al. (2000) attenuation law we can compute the corresponding colour excess as

\begin{equation}
E(B - V)_{\text{Calzetti}} = -2.5 \frac{k(1235)}{\text{ergs} \cdot \text{cm}^{-2} \cdot \text{s}^{-1} \cdot \text{str}^{-1}} \log (f_{\text{esc}}(\text{UV})),
\end{equation}

with $k(1235) = 11.4$ according to the Calzetti law.

From the escape fraction of radiation at the optical wavelengths listed in Table 2 we can also determine the true colour excess

\begin{equation}
E(B - V)_{\text{real}} = -2.5 \log \left( \frac{f_{\text{esc}}(\lambda_{\alpha})}{f_{\text{esc}}(\text{UV})} \right),
\end{equation}

where $EW_{\text{int}}(\lambda_{\alpha})$ is the intrinsic Ly$\alpha$ equivalent width.

2.2.5. Validation

To test the radiation transfer, we have compared our results to Witt & Gordon (2000), whose dust parameters are adopted in our calculations. We have constructed a clumpy shell model using the same discretisation and input parameters. The derived mass spectrum is in good agreement with these authors. The resulting continuum escape fractions, shown in Fig. 3, and other results are found in excellent agreement with Witt & Gordon (2000), which validates our code.

3. The Ly$\alpha$ and UV continuum radiation transfer in homogeneous and clumpy media

In this section we study the radiative transfer of Ly$\alpha$ and the UV continuum photons in homogeneous and clumpy shell geometries.

3.1. The UV continuum escape fraction

In Figs. 4 and 9, we examine the evolution of the UV escape fraction $f_{\text{esc}}(\text{UV})$ in homogeneous and clumpy media. As shown in both figures, $f_{\text{esc}}(\text{UV})$ depends on three main parameters:

1) the dust content ($\tau_{\text{dust}}$)
2) the clumpiness of the dust distribution, assumed to trace the HI distribution ($n_{\text{HI}}/n_{\text{C}}$)
3) the covering factor (CF)
The other parameters describing our shell geometries, the outflows ($v_{\text{exp}}$), the H\textsc{i} column density ($N_{\text{HI}}$) and the temperature of the matter ($b$) do not show any effect on the UV escape fraction, as expected.

Figure 4 illustrates the effects produced by both the dust content (i.e. $n_{\text{IC}}$) and the clumpiness of the dust distribution (i.e. $n_{\text{IC}}/n_{C}$) on $f_{\text{esc}}$(UV). We adopt here three media with the following conditions: FF = 0.23, CF = 0.997 and $n_{\text{IC}}/n_{C}$ = 1.0. 0.01, 0. Qualitatively, we can summarize the effects produced by both $n_{\text{IC}}$ and $n_{\text{IC}}/n_{C}$ on $f_{\text{esc}}$(UV) in the following way:

- $\tau_{\text{d}}$: in homogeneous and clumpy media, an increase in the dust optical depth $\tau_{\text{d}}$ always produces a decrease in the UV escape fraction.

- $n_{\text{IC}}/n_{C}$: a decrease in $n_{\text{IC}}/n_{C}$ from 1 to 0 (i.e. from a homogeneous to an extremely clumpy dust distribution) always increases the UV escape fraction. A clumpy dust distribution produces indeed higher UV escape fractions compared with an equivalent homogeneous distribution of equal dust content (i.e. equal $\tau_{\text{d}}$).

Clumpy media are thus more transparent to UV continuum radiation, as previously shown by Boisse (1990); Hobson & Scheuer (1993); Witt & Gordon (1996, 2000). The facts that the dust content concentrates in clumps and that the interclump medium becomes more optically thin, allow UV photons to escape any clumpy media in two different ways (Witt & Gordon 1996): first, like in homogeneous dusty media, UV photons have to scatter against few dust grains before escaping clumpy media (dust localized in clumps or in between clumps). But, in clumpy media, UV photons take advantage of the weak opacity of the inter-clump medium, which allows them to escape more easily clumpy media than any homogeneous dusty geometry. Second, continuum photons can also directly escape clumpy media if several free spaces appear between clumps. However, that can be only possible in extremely clumpy media ($n_{\text{IC}}/n_{C}$ ≈ 0). In this case, continuum photons are not affected by the weak dust content localized between clumps and can directly escape clumpy media getting through holes which appear between clumps.

The covering factor CF is thus an important parameter controlling the UV escape fraction in clumpy media. Figure 9 shows this dependence in the particular case of extremely clumpy shell geometries ($n_{\text{IC}}/n_{C}$ = 0). As expected, the UV escape fraction $f_{\text{esc}}$(UV) decreases when the covering factor increases to unity (i.e. all lines-of-sight are covered by one or more clumps from the photon source when CF = 1).

Furthermore, in the particular case of extremely clumpy shell geometries ($n_{\text{IC}}/n_{C}$ = 0), we can also notice that the covering factor CF provides a general lower limit for $f_{\text{esc}}$(UV). As shown in Figs. 4 and 9, the UV escape fraction always converges on an asymptote $f_{\text{esc}}$(UV) = 1 − CF, corresponding to the direct escape fraction.

Besides this qualitative approach concerning the dependence of $f_{\text{esc}}$(UV) to $n_{\text{IC}}$, $n_{\text{IC}}/n_{C}$ and CF, Fig. 4 illustrates other quantitative results: in homogeneous geometries the UV escape fraction decreases very rapidly with the dust optical depth $\tau_{\text{d}}$. If we define $f_{\text{esc}}$(UV) = $e^{-\tau_{\text{eff}}}$, the effective optical depth $\tau_{\text{eff}}$ is equal to $\tau_{\text{d}}$ in the absence of scattering. With scattering the effective absorption increases, and one has $\tau_{\text{eff}} > \tau_{\text{d}}$. In clumpy media the situation is different as photons can escape more easily, hence $\tau_{\text{eff}} < \tau_{\text{d}}$.

The escape fraction of the optical continuum photons evolves in the same way as for the UV photons in homogeneous and clumpy media. Combining the escape fraction of both the B and the V-band in the same media as those
studied in Fig. 4, we illustrate in Fig. 17 the evolution of the derived colour excess E(B-V). This figure can be used to translate the dust optical depth $\tau_\alpha$ of Fig. 4 in terms of colour excess E(B-V).

3.2. The Lyα radiative transfer in homogeneous and clumpy media: two regimes appear

Besides the three main parameters which control the radiative transfer of the UV continuum photons (i.e. $\tau_\alpha$, $n_{IC}/n_C$ and CF), three other parameters also determine the radiative transfer of the resonant scattered Lyα photons, namely $v_{exp}$, $N_{HI}$ and $b$. We now discuss the influence of these parameters on the UV continuum and on Lyα. For simplicity we here assume a constant value of $b$ in all cells (clump or interclump). Overall we find that we can identify two regimes where the Lyα propagation is quantitatively different, which we now explain. The separation between the regimes will be discussed after that (Sect. 3.3).

3.2.1. The “low contrast” regime: homogeneous and weakly clumpy media

Propagation of Lyα photons in the “low contrast” regime

We show in Fig. 5 the typical way Lyα photons propagate in the “low contrast” regime. We deduce this propagation from our numerical simulations, studying the number and the location of each interaction between the Lyα photons and the HI atoms in clumpy media. In this regime, we notice that the Lyα radiative transfer is characterised by a (pseudo-)random walk in the medium, both in and in between clumps.

\[ f_{\text{esc}}(\text{Lyα}) = \begin{cases} \text{Lyα escape fraction} & \text{if } \tau_\alpha > \tau_\text{crit} \\ \text{UV} & \text{if } \tau_\alpha \leq \tau_\text{crit} \end{cases} \]

Figure 6 shows the dependence of $f_{\text{esc}}(\text{Lyα})$ on the dust content ($\tau_\alpha$) of the medium, for different values of clumpiness ($n_{IC}/n_C$). The “low contrast” regime includes all curves of this figure, except the particular case $n_{IC}/n_C = 0.00$ which belongs to the “high contrast” regime. Note that the quantity $\tau_\alpha$ can be related to the colour excess through Fig. 4.

Qualitatively, we see that $f_{\text{esc}}(\text{Lyα})$ always decreases with increasing $\tau_\alpha$, as expected. The same is true for increasing $n_{IC}/n_C$. However, we see that for a given value of $\tau_\alpha$, increasing $n_{IC}/n_C$ results in a faster decrease of $f_{\text{esc}}(\text{Lyα})$ than $f_{\text{esc}}(\text{UV})$, the reason being the highly increased path length of Lyα photons due to resonant scattering. Thus, in the “low contrast” regime Lyα radiation is more vulnerable to dust than UV continuum radiation.

A change of the covering factor CF has also a noticeable effect on $f_{\text{esc}}(\text{Lyα})$ in the “low contrast” regime (CF measuring the proportion of holes which appear between clumps). As the clumps cover an increasing fraction of the sky, it becomes indeed increasingly difficult for the photons to escape, and when CF $\approx 1$, $f_{\text{esc}}(\text{Lyα})$ drops drastically.

Finally, the effect of a change of $v_{exp}$ and $N_{HI}$ on $f_{\text{esc}}(\text{Lyα})$ is shown in Fig. 7. We notice that $f_{\text{esc}}(\text{Lyα})$ always increases with increasing $v_{exp}$ as well as with $N_{HI}$ decreasing. Since the effect of the expansion velocity is to shift the Lyα photons away from the line center, they undergo progressively fewer scattering as $v_{exp}$ increases. In fact, for an intrinsic Lyα line width of $FWHM_{int}(\text{Lyα})$ (this value is 100 km s$^{-1}$ in Fig. 7), a galactic outflow showing a velocity $v_{exp} \gtrsim 2 \times FWHM_{int}(\text{Lyα})$ is enough to allow Lyα photons escape as easily as UV continuum photons. As expected, an increase in $N_{HI}$ always leads to a decrease in...
Fig. 7. Evolution of the Lyα escape fraction $f_{\text{esc}}(\text{Ly}a)$ as a function of dust optical depth $\tau_{\text{UV}}$ for various values of expansion velocity $v_{\text{exp}}$ and mean neutral hydrogen column density $N_{\text{HI}}$. The clumpy medium studied here is built with: FF = 0.23, CF = 0.997 ($H_{\text{min}} = 49$ and $H_{\text{max}} = 64$ cells), $n_{\text{ic}}/n_{\text{c}} = 0.01$ and $b = 40$ km s$^{-1}$. The expansion velocities $v_{\text{exp}}$ and Hi column densities that we adopt are: $v_{\text{exp}} = 0, 100$ and 250 km s$^{-1}$ and $N_{\text{HI}} = 10^{19}$ cm$^{-2}$ and $2 \times 10^{20}$ cm$^{-2}$. It is seen that $f_{\text{esc}}(\text{Ly}a)$ increases with increasing $v_{\text{exp}}$, as well as with decreasing $N_{\text{HI}}$.

The Lyα equivalent width $\text{EW}(\text{Ly}a)$:

Combining the definition of the Lyα equivalent width (Eq. 8) and Eq. 9, we always have:

$$\text{EW}_{\text{obs}}(\text{Ly}a) \leq \text{EW}_{\text{int}}(\text{Ly}a)$$

In the “low contrast” regime, the observed Lyα equivalent width $\text{EW}_{\text{obs}}(\text{Ly}a)$ is thus always lower or equal to the intrinsic one $\text{EW}_{\text{int}}(\text{Ly}a)$. In other words the Lyα equivalent width is not “boosted” by clumping in this regime.

3.2.2. The “high contrast” regime: extremely clumpy shell geometries

The “high contrast” regime of the Lyα radiative transfer is defined by clumpy media showing a very low ratio $n_{\text{IC}}/n_{\text{C}}$, i.e. a high density contrast at least $n_{\text{IC}}/n_{\text{C}} \leq 1.5 \times 10^{-4}$ for the input parameters considered throughout this study (see Sect. 3.3). To describe the main effects and peculiarities of this regime we here restrict ourselves to the most extreme case with $n_{\text{IC}}/n_{\text{C}} = 0$.

Propagation of Lyα photons in the “high contrast” regime:

The way Lyα photons propagate now differs qualitatively from the radiative transfer in the “low contrast” regime. The details of the way we deduce the propagation of Lyα photons in the “high contrast” regime is given in Sect. 4, where we study the Lyα line shape. We sketch in Fig. 8 the propagation of Lyα photons in the “high contrast” regime. The Hi content distributed between clumps is now weak enough that scattering between clumps can be neglected, and for a fraction of the Lyα photons, the radiative transfer is characterised by rebounces on the clumps, as originally suggested by Neufeld (1991). The remaining Lyα photons propagate in the same way as UV photons, that is penetrating the clumps, being exposed to the dust, or escape the medium freely (if CF < 1).

Lyα escape fraction $f_{\text{esc}}(\text{Ly}a)$:

Figure 6 shows the evolution of $f_{\text{esc}}(\text{Ly}a)$ as a function of the dust content (i.e. $\tau_{\text{UV}}$) in the “high contrast” regime ($n_{\text{IC}}/n_{\text{C}} = 0$). Again, note that the quantity $\tau_{\text{UV}}$ can be related to the colour excess through Fig. 17. From Fig. 6 it is evident that $f_{\text{esc}}(\text{Ly}a)$ always decreases as $\tau_{\text{UV}}$ increases. However, the decrease is slower than that of $f_{\text{esc}}(\text{UV})$, allowing the curve of $f_{\text{esc}}(\text{Ly}a)$ to cross that of $f_{\text{esc}}(\text{UV})$ at a certain optical depth $\tau_{\text{c}}$ ($\tau_{\text{c}} \approx 3.8$ in Fig. 6). This is not possible in the “low contrast” regime, and it is this quantitative difference that defines the threshold between the low and the high contrast regime.

Figure 9 illustrates the effect of a change of the covering factor CF on $f_{\text{esc}}(\text{Ly}a)$ in the “high contrast” regime. Again, we see that both $f_{\text{esc}}(\text{Ly}a)$ and $f_{\text{esc}}(\text{UV})$ always decreases with increasing CF. However, whereas $f_{\text{esc}}(\text{UV})$ approaches asymptotically the value 1–CF (corresponding to all clumps being fully opaque to the UV so that escape is possible only through direct escape), $f_{\text{esc}}(\text{Ly}a)$ maintains
a higher value. Furthermore, we can notice from the Fig. 9 that the value of the critical optical depth $\tau_c$ (where $f_{\text{esc}}(\text{Ly}\alpha)$ crosses $f_{\text{esc}}(\text{UV})$) strongly decreases as CF decreases.


The effect of a change of $v_{\text{exp}}$ and $N_{\text{HI}}$ on $f_{\text{esc}}(\text{Ly}\alpha)$ is shown in Fig. 10. We can see that these effects are different and more complex than those of the “low contrast” regime. More precisely, two different domains appear in the “high contrast” regime (see Fig. 9).

- $f_{\text{esc}}(\text{Ly}\alpha)$ results in a decrease in $v_{\text{exp}}$ and an increase of $N_{\text{HI}}$. We adopt as well the following expansion velocities $v_{\text{exp}}$ and HI column densities $N_{\text{HI}}$: $v_{\text{exp}} = 0, 100$ and $250$ km s$^{-1}$ and $N_{\text{HI}} = 10^{19}$ cm$^{-2}$ and $2 \times 10^{20}$ cm$^{-2}$. We indicate the critical dust optical depth $\tau_c$ where the curve of $f_{\text{esc}}(\text{Ly}\alpha)$ for $v_{\text{exp}} = 0$ km s$^{-1}$ cross the curve of $f_{\text{esc}}(\text{UV})$.

- $f_{\text{esc}}(\text{Ly}\alpha)$ strongly decreases as CF decreases.

Finally, in the “low contrast” regime, we can notice that a velocity $v_{\text{exp}} \gtrsim 2 \timesFHMI(\text{Ly}\alpha)$ is enough to prevent any scattering on the clumps. In this case, Ly$\alpha$ photons escape the medium in the same way than UV photons.

**Ly$\alpha$ equivalent width $\text{EW}(\text{Ly}\alpha)$:**

Qualitatively, Figs. 6, 9, and 10 reveal that in the “high contrast” regime $f_{\text{esc}}(\text{Ly}\alpha)$ can be both higher or lower than $f_{\text{esc}}(\text{UV})$, depending on the actual value of $\tau_a$. From the definition of $\tau_c$ (i.e. the value of $\tau_a$ where the curves of $f_{\text{esc}}(\text{Ly}\alpha)$ and $f_{\text{esc}}(\text{UV})$ cross each other), we have

\begin{equation}
\text{f}_{\text{esc}}(\text{Ly}\alpha) \leq \text{f}_{\text{esc}}(\text{UV}) \text{ if } \tau_a \leq \tau_c, \tag{11}
\end{equation}

and

\begin{equation}
\text{f}_{\text{esc}}(\text{Ly}\alpha) \geq \text{f}_{\text{esc}}(\text{UV}) \text{ if } \tau_a \geq \tau_c, \tag{12}
\end{equation}


\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig9}
\caption{Ly$\alpha$ (blue lines) and UV (red lines) escape fraction as a function the dust optical depth $\tau_a$ for different values of covering factor CF in the “high contrast” regime ($n_{IC}/n_C = 0.00$). In this figure, all media have for common parameters: FF = 0.23, $n_{IC}/n_C = 0.00$, $N_{\text{HI}} = 10^{19}$ cm$^{-2}$ $v_{\text{exp}} = 0$ km s$^{-1}$ and $b = 40$ km s$^{-1}$. The values $\tau_{e1}$, $\tau_{e2}$ and $\tau_{e3}$, corresponding to the values of $\tau_a$ where the Ly$\alpha$ and UV escape fractions of CF1, CF2 and CF3 cross, are marked. While $f_{\text{esc}}(\text{UV})$ always converges towards the limit $f_{\text{esc}}(\text{UV}) = 1$ - CF in extremely clumpy media, $f_{\text{esc}}(\text{Ly}\alpha)$ shows higher values.
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig10}
\caption{Ly$\alpha$ (blue lines) and UV (red line) escape fractions as a function of the dust optical depth $\tau_a$ in the “high contrast” regime, for various values of expansion velocity $v_{\text{exp}}$ and hydrogen column density $N_{\text{HI}}$. The extreme clumpy media have in common: FF = 0.23, CF = 0.997 ($R_{\text{min}} = 49$ and $R_{\text{max}} = 64$ cells), $n_{IC}/n_C = 0.00$ and $b = 40$ km s$^{-1}$. We adopt as well the following expansion velocities $v_{\text{exp}}$ and HI column densities $N_{\text{HI}}$: $v_{\text{exp}} = 0, 100$ and $250$ km s$^{-1}$ and $N_{\text{HI}} = 10^{19}$ cm$^{-2}$ and $2 \times 10^{20}$ cm$^{-2}$. We indicate the critical dust optical depth $\tau_c$ where the curve of $f_{\text{esc}}(\text{Ly}\alpha)$ for $v_{\text{exp}} = 0$ km s$^{-1}$ cross the curve of $f_{\text{esc}}(\text{UV})$.}
\end{figure}
where we note that $\tau_c$ is mainly a function of CF.

Combining the definition of the Lyα equivalent width (Eq. 8) with both Eqs. 11 and 12, we obtain:

$$EW_{\text{obs}}(\text{Ly} \alpha) \leq EW_{\text{int}}(\text{Ly} \alpha) \text{ for } \tau_a \leq \tau_c,$$

and

$$EW_{\text{obs}}(\text{Ly} \alpha) \geq EW_{\text{int}}(\text{Ly} \alpha) \text{ for } \tau_a \geq \tau_c,$$

The fact that $f_{\text{esc}}(\text{Ly} \alpha)$ can exceed $f_{\text{esc}}(\text{UV})$ thus allows for an enhancement (“boost”) of the equivalent width of the Lyα line. However, as summarized in Sect. 5.2, such an enhancement can only occur under strict physical conditions, concerning the kinematics (i.e. an expansion velocity $v_{\exp} \leq 2 \times FWHM_{\text{int}}(\text{Ly} \alpha)$), the clumpiness and the dust content of the clumpy ISM.

3.3. The critical ratio $n_{IC}/n_C$ separating the two regimes of the Lyα radiative transfer

We can quantify the distinction between the two regimes of the Lyα radiative transfer by the low to high density ratio $n_{IC}/n_C$. Figure 11 illustrates this limit $n_{IC}/n_C$ as a function of the average HI column density $N_{\text{HI}}$ in our clumpy media. This limit is defined in the following way. Above the curves shown in Fig. 11, it is impossible to obtain $f_{\text{esc}}(\text{Ly} \alpha) > f_{\text{esc}}(\text{UV})$ in models with physical parameters listed in Table 3. Such media belong to the “low contrast” regime. Conversely, the area localized below the curves corresponds to the “high contrast” regime where it is possible to observe the inequality $f_{\text{esc}}(\text{Ly} \alpha) > f_{\text{esc}}(\text{UV})$.

All points shown in Fig. 11 have been obtained studying a clumpy medium defined with: FF = 0.23, CF = 0.997, $v_{\exp} = 0 \text{ km s}^{-1}$, $\tau_a = 25$ and $b = 40 \text{ km s}^{-1}$. All media built with different parameters show a critical ratio $n_{IC}/n_C$ (at the limit between the low and the high contrast regimes) lower than that shown in Fig. 11. Each curves shown in this figure corresponds to three different physical conditions applied in our clumpy media. The star dots are obtained assuming an unique turbulent velocity $b = 40 \text{ km s}^{-1}$ in and in between clumps, and an inter-clump medium composed by both HI atoms and dust grains. The circle dots are obtained assuming the same turbulent velocity ($b$) but a dust-free interclump medium. Finally, the squares are obtained applying two different temperatures in clumps and in between clumps ($b = 40 \text{ km s}^{-1}$ in clumps and $T = 10^6K$ between clumps) and assuming an interclump medium only composed by HI atoms. This case is discussed in Sect. 3.4.

From the single temperature case (star and circle dots) we can already mention four main results concerning the border separating the two regimes of the Lyα radiative transfer:

The critical ratio $n_{IC}/n_C$ separating both regimes is very low: studying a large range of HI column density $N_{\text{HI}} [10^{17}, 10^{22}] \text{ cm}^{-2}$, we notice that the limit separating both regimes is reached for very weak ratios $n_{IC}/n_C$ ($1.5 \times 10^{-4}$, $1.3 \times 10^{-6}$). That suggests that the “high contrast” regime can only be found in galaxies showing the most extremely clumpy ISMs (composed only by cold clouds of neutral hydrogen gas embedded in an extremely ionized interclump medium). The critical ratio has to decrease with increasing $N_{\text{HI}}$ to maintain a sufficiently low column density between the clumps.

The interclump medium can be optically thick for Lyα photons on the border separating the two regimes: In Fig. 12 we show the limit of Fig. 11, but translated in terms of HI column density between clumps $N_{\text{HI,IC}} = (1 - FF) \times n_{IC}L$. While the interclump medium is optically thick for Lyα photons at line center above $N_{\text{HI,IC}} = 6 \times 10^{13} \text{ cm}^{-2}$ (assuming $b = 40 \text{ km s}^{-1}$ between clumps)$^1$, we can clearly see that the “high contrast” regime can extend to somewhat higher interclump column densities, into the optically thick regime. Nevertheless, this is only possible if the temperatures in and in between clumps are the same (star and circle dots). If the temperatures in and in between the clumps differ (square dots), the interclump medium has to be optically thin in order to observe the “high contrast” regime (see Sect. 3.4).

The limit $n_{IC}/n_C$ separating both regimes is not affected by the presence of dust between clumps: The critical ratio $n_{IC}/n_C$ represented by both the star and the circle dots on Fig. 11 are the same. Thus, the presence of dust between clumps has no effect on the limit separating both regimes of the Lyα radiative transfer.

$^1$ The optical depth at line center is $\tau_0 = 3.31 \times 10^{-14}T_4^{-1/2}N_{\text{HI}} = 3.31 \times 10^{-14}(12.85\text{km s}^{-1}/b)N_{\text{HI}}$, e.g. Verhamme et al. (2006).
3.4. The effects of an inhomogeneous temperature on the Lyα radiative transfer

If we want to render the physics of our clumpy media more realistic, we must assume different temperatures inside and between the clumps. There is ample evidence for such a multi-phase ISM. For example, for the stability of the clumps a pressure equilibrium should intervene between the two phases of our clumpy media, implying a higher temperature in the interclump medium. Also, it is well known that different regions coexist in the real ISM of any galaxies (McKee & Ostriker 1977). In particular, we can distinguish the warm neutral atomic medium (WNM, where HI atoms are present in the atomic form) to the hot ionized medium (HIM, where HI atoms are in great majority ionized). To explore in a simplified manner these effects we have made calculations assuming a temperature of $T = 10^4$ K in the interclump medium (as those measured in the HIM), but a lower temperature in all clumps ($b = 40$ km s$^{-1}$), by analogy to the WNM. We then examine the effects on the Lyα radiative transfer and on the ratio $n_{IC}/n_C$ separating the two regimes identified above.

Quantitatively, the Lyα radiative transfer properties behave in a similar fashion for different interclump temperatures. However, as shown in Fig. 11, the ratio $n_{IC}/n_C$ separating both regimes is found to be lower than for the case of constant temperature. In other words, the “high contrast” regime is more limited when the temperature in the interclumps medium is higher than those in clumps. The reason for this is the following: on one hand the optical depth in the interclump medium decreases (with $T^{-1/2}$), simulating thus a medium with even lower density, i.e. a higher contrast. On the other hand, the temperature increase leads to a larger frequency redistribution of the scattered Lyα photons, which eases their escape due to higher frequency shifts. This effect dominates over the former, rendering thus the clumps more transparent to Lyα radiation, where they are strongly absorbed by the dust. This explains why even higher density contrasts are needed to achieve significant Lyα “rebounce” on the clumps, if the interclump medium is hotter than the clumps.

In terms of interclump column densities the limit between the regimes is shown in Fig. 12. In contrast to the case of uniform “cold” temperatures, the limit is now found at quite low column densities of the interclump medium, corresponding to an optically thin regime. Indeed, such low column densities are needed if one wants to avoid significant scattering of Lyα with the corresponding high frequency shifts in a hot interclump medium.

4. Lyα line profiles formation in homogeneous and clumpy shells

In this section we give an overview of the different emergent Lyα line profiles produced in the expanding homogeneous and clumpy shell geometries of our model.

4.1. Lyα line profiles from dust free homogeneous and clumpy shell geometries

First we shall consider the case of a dust free ISM and examine how the Lyα profiles are modified by a clumpy ISM structure. The line profiles shown in this section are obtained assuming an intrinsic Lyα line characterized by $EW_{int}(\text{Lyα}) = 80$ Å and $FWHM_{int} = 100$ km s$^{-1}$.

We know that in dust free cases the total Lyα flux is preserved, and since the continuum is not attenuated (due to the absence of absorption), the Lyα equivalent width is thus preserved, in other words the observed EW is identical to the intrinsic one. This holds obviously both for homogeneous and clumpy structures. The only effect of clumps is to modify the exact frequency redistribution of photons, i.e. the shape of the emergent Lyα line profile. However, as we will see, the changes to the line profile are only relatively small, when the covering factor of the clumps is large.

We first examine the Lyα line profiles for dust free homogeneous and clumpy structures with low density contrasts (i.e. clumpy structures showing an optically thick interclump medium for Lyα photons). In Fig. 13 we study such structures built with the following parameters: $N_{HI} = 2 \times 10^{20}$ cm$^{-2}$, $b = 40$ km s$^{-1}$ and $v_{exp} = 0, 100, 300, 400$ km s$^{-1}$. It clearly appears that the Lyα line profiles emerging from dust free weakly clumpy shell geometries do not show any noticeable difference compared to homogeneous structures with the same/ corresponding properties.

In homogeneous and weakly clumpy media, the mechanisms of formation of the line profiles, as well as their dependence on the parameters $v_{exp}$, $N_{HI}$ and $b$, are identical to those explained in detail in Verhamme et al. (2006) for homogeneous shell structures. In other words, in the dust free case, weakly clumpy media do not significantly differ from the homogeneous ones in terms of line profiles.

Turning now to clumpy media with large density contrasts (i.e. clumpy structures showing an optically thin interclump medium for Lyα photons) we find again very similar line profiles as in the homogeneous case, as also shown in Fig. 13. Compared with the line profiles observed from static weakly clumpy and homogeneous media we now see a central peak at line center ($v_{los} \approx 0$ km/s). The for-
the width and the intensity of each peak are noticed. For high density contrast cases (low density contrast), let us first examine the homogeneous contrast, and the bottom line the clumpy medium with a homogeneous case, the middle the low density contrast. Fig. 13 shows the homogeneous case, the middle the low density contrast, and the bottom line the clumpy medium with a high density contrast.

We now examine the main effects produced by dust on the Lyα line profiles. These photons can then propagate in two different ways in the interclump medium: either by escaping through the holes which appear between clumps, or scattering off of the surface of clumps. Both features preserve the intrinsic frequency of the Lyα photons, which allows to form the central peak seen at center of the Lyα line (v_{\text{obs}}=0). The covering factor governs mostly the importance of the central emission, as shown in Fig. 14 for a static shell. As expected, the central emission increases with decreasing the covering factor.

Besides the predicted Lyα line profiles in dust-free clumpy shell geometries behave in the same way as already shown for homogeneous shells by Verhamme et al. (2006), with the main parameters determining the Lyα profile being the expansion velocity v_{\text{exp}}, the mean HI column density N_{\text{HI}}, and the Doppler parameter b.

4.2. Lyα line profiles from dusty homogeneous and clumpy shell geometries

We now examine the main effects produced by dust on the Lyα line profiles emerging from clumpy shell geometries. In Fig. 15 we illustrate the evolution of the line profiles predicted for static homogeneous and clumpy shell geometries as a function of the dust optical depth τ_{\text{dust}}. The top line shows the homogeneous case, the middle the low density contrast, and the bottom line the clumpy medium with a high density contrast. Let us first examine the homogeneous and low density contrast cases (n_{\text{IC}}/n_{\text{C}} = 1.00 and 0.01 respectively). Increasing τ_{\text{dust}} from 0 to 1, the Lyα line still appears in emission in both cases. But, a clear decrease in both the width and the intensity of each peak are noticed. For τ_{\text{dust}} = 3, more than 99.8% and 98% of the Lyα photons are absorbed by the dust, respectively in the homogeneous and the clumpy media. Therefore, an absorption profile emerges from the homogeneous medium, while faint emission line is predicted from the weakly clumpy medium. Higher dust optical depths τ_{\text{dust}} are needed to obtain absorption line profiles from weakly clumpy media, typically τ_{\text{dust}} \gtrsim 35 in the case of n_{\text{IC}}/n_{\text{C}} = 0.01.

For extremely clumpy shell geometries (n_{\text{IC}}/n_{\text{C}} = 0.00, Fig. 15), the evolution of the Lyα line profile is different. Increasing τ_{\text{dust}} from 0 to 1, we notice a clear decrease of the width of both lateral peaks, as well as an increase of the relative intensity of the central peak. The photons composing the central peak indeed interact very weakly with the dust.
which explains why this peak becomes the dominant one in the line profile as $\tau_\alpha$ increases. When $\tau_\alpha$ is further increased from 1 to 3, both lateral peaks are destroyed by dust. The central peak thus becomes the only peak composing the line profile above $\tau_\alpha \gtrsim 3$. It is interesting to note that we cannot obtain absorption line profiles in extremely clumpy media ($n_{HC}/n_C = 0.00$). Indeed, as the Ly$\alpha$ photons composing the central peak interact very weakly with dust, they are always able to escape the medium for any dust optical depth $\tau_\alpha$, giving thus rise to an emission line. Comparing the relative escape of the Ly$\alpha$ and UV continuum photons, we note that the only case in Fig. 15 where the Ly$\alpha$ equivalent width is (slightly) enhanced is found in the bottom right panel. Indeed, in this case $\tau_\alpha$ is close to critical dust optical depth $\tau_\alpha \approx 3$ for this example of extremely clumpy medium, where we expect such an enhancement (cf. Sect. 5.2.2).

We now turn to a case with outflows in Fig. 16. In this figure, we adopt otherwise identical parameters to those shown in Fig. 15. Increasing $\tau_\alpha$ in any media (homogeneous or clumpy), we first notice a quick decrease of the intensity of both the dominant red peak (those shifted at $v_{\text{obs}} = 2 \times v_{\text{exp}}$) and the small blue bump. This is due to higher number of scatterings these photons undergo, which increases their destruction probability, as already discussed by Verhamme et al. (2006). For the highest dust content ($\tau_\alpha = 3$), the Ly$\alpha$ line escaping homogeneous and clumpy media exhibits an asymmetric profile, but whose the dominant peak is found at line center ($v_{\text{obs}} = 0$). Finally, like in the static case, we notice that the intensity of the line increases as the clumpiness of the medium increases. In none of the cases shown here we find a ”boost” of the Ly$\alpha$ equivalent width, since the velocity is too large.

5. Discussion

5.1. Effects of a clumpy ISM on the radiation attenuation

Given the evolution of the Ly$\alpha$ and continuum escape fraction in homogeneous and clumpy systems (Sect. 3), it is clear that a clumpy medium always produces higher Ly$\alpha$ and continuum escape fraction compared with an equivalent homogeneous medium of equal dust and hydrogen mass. This main result was demonstrated by several previous studies focused on the transfer of the continuum radiation in clumpy media (Boisse 1990; Hobson & Scheuer 1993; Witt & Gordon 1996, 2000; Varosi & Dwek 1999), but also from other studies focused on the Ly$\alpha$ line (Neufeld 1991; Hansen & Oh 2006).

The attenuation of the radiation in a galaxy is thus strongly dependent on both the dust content and the dust distribution around the radiation sources. For illustration, we show in Fig. 17 the dependence of the colour excess $E(B-V)$ on both the dust content ($\tau_\alpha$) and the clumpiness of the dust distribution in the shell geometries studied throughout this paper. In this figure we compare two different definitions of the colour excess: $E(B-V)_{\text{real}}$, which corresponds to the exact colour excess because estimated from the original definition of the colour excess (from the V and B bands), and $E(B-V)_{\text{Calzetti}}$, which is estimated from both the Calzetti attenuation law (Calzetti et al. 2000) and the UV escape fraction (see Eqs. 6 and 7). In practice, the Calzetti attenuation law is usually used to estimate the dust attenuation in starburst galaxies. It is then $E(B-V)_{\text{Calzetti}}$, which would be measured by an observer. The Fig. 17 allows then us to see in which extend the colour excess $E(B-V)_{\text{Calzetti}}$ from the Calzetti law, deviates from the real colour excess $E(B-V)_{\text{real}}$ as a function of $\tau_\alpha$ and the clumpiness of the dust distribution.

In a general way, we can notice that the clumpiness of the dust distribution strongly affects both the colour excess $E(B-V)_{\text{real}}$ and $E(B-V)_{\text{Calzetti}}$ (Witt & Gordon 2000). The colour excess decreases as the dust distribution is clumpy and as the dust optical depth decreases in media. Comparing now both definitions of $E(B-V)_{\text{Calzetti}}$ and $E(B-V)_{\text{real}}$, we can notice that $E(B-V)_{\text{Calzetti}}$ does not reproduce very well the real evolution of the colour excess $E(B-V)_{\text{real}}$. This deviation between both definitions is explained by a clear evolution of the attenuation law (which measures, at each wavelength, the reduction in the stellar flux from a dusty ISM) as the dust distribution and the dust content change in media. As mentioned in Witt & Gordon (2000), this divergence shows that the use of the same and unique attenuation law in the analysis of a large sample of galaxies (which show different dust geometries and dust content) can become a source of error in the dust attenuation correction for individual galaxies.

5.2. High Ly$\alpha$ EWs and the Neufeld model

5.2.1. Physical conditions needed in the ISM

According to our study of the Ly$\alpha$ transfer in clumpy media, there exists a regime in which the Neufeld scenario works. This regime corresponds to the “high contrast” regime, as explained in detail in Sect. 3.2.2. It is only found in the most extremely clumpy shell geometries of our model, that is composed by clouds of H$\alpha$ and dust embedded in an interclump medium close to be optically thin for Ly$\alpha$ photons. However, even in this configuration, the Neufeld model only works when the following five main conditions concerning the clumpiness, the kinematic, the dust content and the spatial distribution of the clumps around the stars are fulfilled:
The galaxy outflow has to be relatively slow: Assuming an intrinsic Lyα line width $FWHM_{int}(Lyα)$, a galactic outflow with an expansion velocity $v_{exp} \gtrsim 2 \times FWHM_{int}(Lyα)$ km s$^{-1}$ is needed to be able to enhance EW(Lyα) under the Neufeld scenario. In starburst galaxies, the width of the intrinsic Lyα line is lower than 100 km s$^{-1}$ (Teplitz et al. 2000; Baker et al. 2004; Erb et al. 2003; McLinden et al. 2011), which implies an expansion velocity $v_{exp}$ lower than 200 km s$^{-1}$ in the ISM. We illustrate this limit in Fig. 18. This figure shows the evolution of the ratio $f_{esc}(Lyα)/f_{esc}(UV)$ as a function of the dust content (measured here in terms of colours excess $E(B-V)_{ocalzetti}$) in an extremely clumpy shell geometries. We here adopt $b = 12.8$ km s$^{-1}$, $N_{HI} = 10^{19}$ and $2 \times 10^{20}$ cm$^{-2}$ and $V_{exp} = 0, 100, 200$ km s$^{-1}$, typical of values obtained in the analysis of high-z Lyα line profiles (Verhamme et al. 2008). Finally, let us mention that the curves shown in this figure illustrate the highest enhancements of EW(Lyα) we can obtain adopting such physical conditions in a clumpy medium; they reach up to a factor 3–4. Adopting $FWHM(Lyα)_{int} = 100$ km s$^{-1}$ in Fig. 18 we can notice that no significant enhancement of EW(Lyα) is obtained for $v_{exp} \gtrsim 200$ km s$^{-1}$. Above such expansion velocity, all Lyα photons are Doppler shifted out of resonance, preventing them to scatter off of the surface of clumps and to escape clumpy ISMs more easily than UV continuum photons.

The galaxy outflow has to be relatively uniform (constant velocity): Lyα photons can scatter on the surface of clumps (Fig. 8) under the condition that each clumps move weakly each other. Should the opposite occur (that is assuming a random component $v_{random}$ in the velocity of each clumps) a strong Doppler shift can occur between clumps which prevents Lyα photons to scatter against clumps anymore. Finally, such effect strongly decreases the Lyα escape fraction $f_{esc}(Lyα)$ in a clumpy ISM. In Fig. 19, we illustrate how the enhancements of EW(Lyα) shown in Fig. 18 are affected by a nonuniform outflow. In this figure, we assume a radial and random velocity $v_{clump}$ for each clump, such that $v_{clump} = v_{exp} + v_{random}$, where $v_{random} = v_{max}$ with $r \in [-1,1]$ a random number. We notice a clear decrease of the ratio $f_{esc}(Lyα)/f_{esc}(UV)$ as $v_{random}$ increases.

The H I content between clumps must be extremely small: The Neufeld model was originally developed assuming an interclump region sufficiently poor in H I atoms, such that it is completely transparent to Lyα photons. In our simulations, we have identified the allowed H I content in the interclump medium to allow the Neufeld scenario to work. There is indeed a certain H I limit above which Lyα photons cannot freely propagate between clumps, preventing them to escape the medium more easily than UV photons. In all physical conditions, our simulations confirm that the Neufeld model only works if the interclump medium stays optically thin for Lyα photons, that is if the radial H I column density of the interclump medium ($N_{H I,IC}$) is lower than 3 × $10^{14}$ cm$^{-2}$ (with a temperature of $T = 10^6$ K between clumps). For instance, focussing on the clumpy shell geometries studied in Fig. 18, we notice that no enhancement of EW(Lyα) is obtained if the radial H I column density between clumps exceeds $1.5 \times 10^{14}$ cm$^{-2}$ (for the curve $N_{HI} = 10^{19}$ cm$^{-2}$) and $2.3 \times 10^{14}$ cm$^{-2}$ (for the curve $N_{HI} = 2 \times 10^{20}$ cm$^{-2}$). In terms of ratio $n_{IC}/n_{C}$, such limits correspond to a density ratio of $6.90 \times 10^{-9}$ (for the curves $N_{HI} = 10^{19}$ cm$^{-2}$).
cm$^{-2}$) and $3.45 	imes 10^{-7}$ (for the curve $N_{HI} = 2 \times 10^{20}$ cm$^{-2}$). In reality, lower densities ratios can be observed in a real ISM, if the cold clouds of neutral H (T = 10$^4$ K, $n_{HI} = 0.3$ cm$^{-3}$) are embedded in a very hot and ionized interclumps medium ($T = 10^6$ K, $n_{HI} \approx 5 \times 10^{-3}$ cm$^{-3}$ and $x_{HI} < 10^{-5.5}$). In other words, an efficient "boost" of Lyα with respect to the continuum would require such extreme ISM conditions.

A high dust content has to be embedded in clumps: As explained in Sect 3.2.2 and shown Fig. 18, no enhancement of EW(Lyα) is found below a certain critical dust content (noted $\tau_c$ in Fig. 6). A high dust content is indeed needed in the ISM in order to absorb more efficiently UV continuum photons than Lyα photons, which thus produces an enhancement of EW(Lyα). As shown in Fig. 18, a colour excess higher than $E(B-V)_{calc,cen} = 0.32$ (i.e. $\tau_c \approx 5$) would be needed in order to enhance EW(Lyα) by a factor higher than 3. This dust content limit mainly depends on the covering factor CF of the ISM, where it decreases as CF decreases.

The distribution of the clumps around the stars: The spatial distribution of the clumps around the stars plays an important role in the enhancement of EW(Lyα). A covering factor CF close to unity is needed in order to get a enhancement of EW(Lyα) as high as those shown in Fig. 18. The enhancement of EW(Lyα) is indeed maximized when CF = 1, but it strongly decreases as CF decreases around the stars. A low covering Factor CF does not allow to block effectively UV continuum photons than Lyα photons, thereby decreasing the enhancement of EW(Lyα). In particular, under the physical conditions adopted in Fig. 18, we notice that the enhancement of EW(Lyα) stays lower than 1.38 for CF $\leq$ 0.68.

Let’s mention that, in both figures 18 and 19, the total Lyα flux is taken into account to derive the EW(Lyα) enhancement. However, an observer could measure a lower EW(Lyα) in practice if Lyα is scattered into an extended low surface brightness region, as recently observed around distant starburst galaxies (Steidel et al. 2011) or in nearby galaxies (Östlin et al. 2009).

Concerning the required dust extinction and the high density contrast of neutral hydrogen (i.e. $n_{HI}/n_C < 10^{-7}$), these conditions seem more characteristic of molecular clouds embedded in a very hot and ionized medium. The Neufeld model could therefore only work in such a galactic environment. It is nevertheless interesting to notice that these necessary conditions to get an enhancement of EW(Lyα) in a clumpy ISM are in perfect agreement with those originally predicted by Neufeld (1991). In his original paper, Neufeld proposed indeed three suitable conditions for an enhancement of EW(Lyα) in a clumpy ISM: the interclump medium (ICM) must exhibit a very low density with a negligible small absorption and scattering coefficients to Lyα photons, the clumpy ISM must show a large covering factor (CF) and a sufficiently small volume filling factor that the ICM can "percolate" (i.e. every part of the interclump medium must be connected to every other part), and the probability for Lyα photons of being reflected by the clumps must be higher than the probability to be absorbed. In particular, this last probability should increase when $v_{exp}$ decreases and $N_{HI}$ increases, which is well consistent with our results. In addition to the criteria proposed by Neufeld (1991), our work highlights the extreme sensitivity of the Neufeld scenario to the kinematic of the clumps (i.e. the large scale outflows and the velocity dispersion of the clumps), and its strong dependence on the dust content. Given the ubiquitous evidence for outflows from most star-forming galaxies and the widespread presence of dust, it is essential to take these effects into account. Furthermore, beyond the work of Neufeld (1991), our detailed radiation transfer models including the Lyα line but also transfer of continuum photons at other wavelengths, also allow us to predict consistently the resulting attenuation (reddening) and the detailed Lyα line profile, which can directly be compared to observations.

5.3. Studying the ISM through the Lyα line profile

Although the Lyα line profiles emerging both from homogenous and clumpy ISMs are quite similar (Fig. 13), we have identified two main effects produced by the ISM clumpiness on the Lyα line profiles. First, we have seen that an extremely clumpy ISM favours the formation of a peak at the line center of the line profile ($v_{obs}=0$ km s$^{-1}$). Second, since Lyα escape is facilitated in a clumpy medium, the effect of the dust on the Lyα line profile is less efficient than in homogeneous media (Figs. 15 and 16). This can lead to intense Lyα emission emerging from a very dusty clumpy ISM, whereas an absorption line profiles would emerge from a homogeneous medium with the same dust content.

This second effect of the ISM clumpiness on the Lyα line profiles can be a source of uncertainties if we aim to derive some informations on the ISM of distant starburst galaxies (kinematics $v_{exp}$, HI column density $N_{HI}$, dust content $\tau_c$) from Lyα line fitting (Verhamme et al. 2008; Schaerer & Verhamme 2008). Indeed, depending on the homogeneity/clumpiness of the ISM, different derived parameters of the ISM can be obtained studying the same sample of galaxies. Among the ISM parameters it is possible to derive from
the fit of both the Lyα line and the UV continuum (ν_{exp}, N_{HI}, π) to the dust optical depth (π), the dust content. In summary, assuming an isotropic scattering and dust grains distributed within an empty interclump medium.

The fitting formula is a function of two parameters (Eq. 59 by dust grains (g = 0) in optically thick spherical clumps, and the Lyα equivalent width correlates with reddening (e.g. Shapley et al. 2003), facts naturally explained by radiation transfer models with a homogenous ISM (Verhamme et al. 2008; Schaerer & Verhamme 2008). These findings also argue against a very clumpy, high-contrast ISM, at least for the majority of LBGs.

5.4. Comparison with Hansen & Oh (2006)

We now compare our results with the recent numerical study of Lyα transfer in multiphase and dusty media from Hansen & Oh (2006) (hereafter HO06). The clumpy media studied in HO06 are only extremely clumpy, that is composed of very optically thick spherical clumps (HI + dust) distributed within an empty interclump medium. From such clumpy media, HO06 deduce analytical formulae fitting the behavior of both the continuum and the Lyα escape fractions as a function of gas geometry, motion and dust content. In summary, assuming an isotropic scattering by dust grains (g = 0) in optically thick spherical clumps, the fitting formula is a function of two parameters (Eq. 59 in HO06):

\[ f_{esc}(\nu) = \frac{1}{\cosh(2\epsilon_c(\nu)N_0)} \]  

where \( N_0 \) (a geometrical parameter) corresponds to the average number of clumps encountered by photons before escaping the medium in the absence of absorption, and where \( \epsilon_c(\nu) \) (a dust parameter) corresponds to the probability of a photon of frequency \( \nu \) to be absorbed rather than reflected by a clump. In the clumpy shell geometries of our model, both parameters can be derived in the following way. Firstly we notice that \( N_0 \) tends to evolve as \( N_0 \approx 1.1f\epsilon^2 + 1.42fc \), where \( f_{c} \) corresponds to the mean number of clumps intersected along a random line of sight. The parameter \( \epsilon_c(\nu) \) can simply be estimated using the formula derived in HO06 (eq. 27 of their paper):

\[ \epsilon_c(\nu) = \frac{2\sqrt{\epsilon(\nu)}}{(1 + \sqrt{\epsilon(\nu)})} \]  

with \( \epsilon(\nu) \) as the absorption probability per interaction (HI or dust) at frequency \( \nu \). In particular, \( \epsilon(\nu) \) is thus given by \( \epsilon(\nu) = 1 - a \) for the UV continuum photons, with \( a \) the dust albedo.

We compare in Fig. 20 the equation 15 (full lines) to the UV continuum escape fraction derived from the clumpy shell geometries of our model (grey dots). In this figure, two clumpy shell geometries are studied. The first structure, built with \( FF = 0.10, CF = 0.38 \) and \( n_{HC}/n_{C} = 0 \), shows \( N_0 = 1.0 \) (top line). The second structure, assuming \( FF = 0.15, CF = 0.70 \) and \( n_{HC}/n_{C} = 0 \), shows \( N_0 = 4.28 \) (bottom line). In Fig. 20, we just change the values of \( \epsilon_c(\nu) \) changing the albedo \( a \) of the dust grains, as shown in Eq. 16. Although a certain difference appears as \( \epsilon_c \) tends towards 1, the continuum escape fraction deduced from our numerical simulations are rather well fitted by the analytical formula of HO06 (Eq. 15). In particular, the UV escape fraction follows well the same dependance on \( N_0 \) and \( \epsilon_c \) as predicted by Eq. 15 for the low absorption regime (\( \epsilon_c < 0.4 \)). The difference observed close to \( \epsilon_c = 1 \) is also observed in HO06 and is explained by a geometrical effect. As suggested by these authors, a better fit can be obtained in this regime rescaling the term \( \epsilon_c(\nu)N_0 \) (Eq. 15) as \( k\epsilon_c(\nu)N_0 \), where \( k \) is a unity fitting parameter.

Although our numerical simulations reproduce reasonably well all the results and fitting formula of HO06, our conclusions diverge from theirs concerning the Neufeld model. As an application of their numerical study, HO06 give a quantitative estimation of the EW(Lyα) enhancements produced by different clumpy and dusty ISMs (Fig. 18 of their paper). We reproduce in Fig. 21 (left panel) the results of HO06. These results are based on the following assumptions concerning the clumpy media: 1) the clumps are extremely opaque to Lyα photons, but 2) each
clump is not opaque to dust extinction (i.e. the total dust optical depth for a single clump, taking into account the effect of scattering plus absorption, is \( \tau_d < 1 \))\(^2\), rendering each clump optically thin for UV continuum photons. Given these assumptions, HO06 adopt a constant value of \( f_{esc}(L_\alpha) \) (which is derived by an analytical method based on Eq. 15), whereas the UV continuum escape fraction is assumed to behave like in homogeneous media. In a homogeneous medium composed of dust grains with an albedo \( \epsilon_d = 0.5 \), the UV escape fraction is approximately given by the following equation:

\[
 f_{esc}(UV) = \frac{1}{\cosh(\sqrt{4\epsilon_d(\tau_a^2 + \tau_d)})} \tag{17}
\]

On the right panel of the Fig. 21 we show the results obtained studying the same media than HO06 (i.e. six clumpy media constructed with three different values of \( N_0 = 1, 4 \) and 10), but using our own numerical approach. In particular, we derive each curve of the right panel studying the real evolution of \( f_{esc}(UV) \) and \( f_{esc}(L_\alpha) \) with full Monte Carlo simulations. We can clearly see that we cannot reproduce, neither quantitatively nor qualitatively, the curves of HO06. This strong difference is explained by both assumptions made by HO06 on \( f_{esc}(UV) \) (i.e. Eq. 17) and \( f_{esc}(L_\alpha) \) (i.e. a constant value under any dust optical depth \( \tau_a \)), which cannot be rigorously met in any clumpy media constructed with low values of \( N_0 \), as studied in Fig. 21. We compare in Fig. 22 the UV and Ly\( \alpha \) escape fractions deduced from our simulations to the assumptions made in HO06. Firstly, while HO06 use the Eq. 17 to deduce the evolution of \( f_{esc}(UV) \) as a function of \( \tau_a \) (i.e. \( f_{esc}(UV) \) is therefore assumed to behave like in homogeneous media, which is only correct if the clumpy media are composed of enough optically thin clumps distributed in a way they can intersect all line of sights around the stars), this assumption clearly underestimate the correct values of \( f_{esc}(UV) \) in the clumpy media studied in Fig. 21. This discrepancy is explained by the fact that those clumpy media are composed of very few clumps which cannot intersect all line of sights around the photon sources\(^3\). Furthermore, this small number of clumps prevent them from staying optically thin to dust extinction in the range of \( \tau_a [0 : 2] \). As a consequence, a large fraction of UV continuum photons can directly escape the clumpy media through several free spaces which appear between clumps, preventing \( f_{esc}(UV) \) from behaving like in homogeneous media (i.e. Eq. 17). Secondly, the constant values of \( f_{esc}(L_\alpha) \) assumed by HO06 from their Eq. 15 tend to overestimate those obtained from our simulations. This second discrepancy is mainly explained by the fact that \( f_{esc}(L_\alpha) \) always increases as the dust optical depth \( \tau_a \) decreases in any clumpy media.

In conclusion, the assumptions of HO06 clearly underestimate the correct values of \( f_{esc}(UV) \) and overestimate those of \( f_{esc}(L_\alpha) \). This explains why the enhancements of EW(Ly\( \alpha \)) obtained in HO06 (left panel in Fig. 21) are much higher than those deduced from our simulations (right panel). Furthermore, the right panel shows the inversion of the curves (in terms of \( N_0 \)) as \( \tau_a \) increases. The highest enhancement of EW(Ly\( \alpha \)) are indeed produced by clumpy media showing \( N_0 \leq 10 \) have always a covering factor CF \( < 0.90 \).

\(^2\) Nevertheless, the total dust optical depth across the entire clumpy medium can be greater than unity if many clumps are intersected along the radius of the medium.

\(^3\) All clumpy media showing \( N_0 \leq 10 \) have always a covering factor CF \( < 0.90 \).
media containing the highest number of clumps around stars.

Drawing the parallel with our study of the Neufeld scenario in Sect. 5.2, we can notice that most of the models showing an enhancement of EW(Ly\(\alpha\)) in Fig. 21 (right panel) respect quite well each conditions under which the Neufeld scenario works in a clumpy ISM: 1) the interclump medium is optically thin for Ly\(\alpha\) photons (\(n_{IC}/n_C = 0\)), 2) the expansion velocities \(v_{\text{exp}}\) is slow and uniform and 3) the enhancements of EW(Ly\(\alpha\)) occur above a certain dust optical depth \(\tau_d\) equal to (0, 0, 0.3) in each clumpy media (\(N_0 = 1, 4, 10\)). Furthermore, as expected when an enhancement of EW(Ly\(\alpha\)) occurs in a clumpy ISM, the Ly\(\alpha\) line profiles emerging each clumpy geometries studied in Fig. 21 are symmetric and peaked at the line center, as expected.

5.5. Recent models of Ly\(\alpha\) transfer in clumpy large-scale outflows

Recently Dijkstra & Kramer (2012) have presented radiative transfer calculations of Ly\(\alpha\) photons propagating through clumpy, dusty, large scale outflows using phenomenologically motivated models constrained by absorption line measurement from Steidel et al. (2011). The calculations of Dijkstra & Kramer mostly focus on the Ly\(\alpha\) surface brightness distribution. However, since their calculations do not follow the behavior of the UV continuum, it is not possible to infer any information on the presence or absence of an efficient “Neufeld effect”. Furthermore the Ly\(\alpha\) line profiles predicted by their models are not presented. It is therefore not possible to compare our results with the calculations of Dijkstra & Kramer (2012), and to confront their model to the most direct and sensitive observable, the Ly\(\alpha\) line profile itself.

6. Summary and conclusions

To examine and understand the effects of clumpy ISM structures on the Ly\(\alpha\) line and UV observations of star-forming galaxies we have carried out detailed radiation transfer calculations using our 3D Ly\(\alpha\) Monte Carlo code MCLya (Verhamme et al. 2006; Schaerer et al. 2011). Indeed, clumping can in principle significantly alter the transfer of Ly\(\alpha\) in galaxies, as shown early by Neufeld (1991), and has often been invoked to explain strong Ly\(\alpha\) emission or a higher transmission for Ly\(\alpha\) photons than for the UV continuum (e.g. Kudritzki et al. 2000, Malhotra & Rhoads 2002, Rhoads et al. 2003, Shimazakura et al. 2006). However, only few detailed numerical studies of these effects has so far been undertaken (Haiman & Spaans 1999; Richling 2003; Hansen & Oh 2006; Laursen et al. 2012), albeit with some simplifying assumptions in most of these works. Furthermore we wish to identify in which conditions clumping affects the line transfer and how much, and how this is reflected in the emergent Ly\(\alpha\) line profiles.

Our radiation transfer calculations allow us to study simultaneously the dependence of both the Ly\(\alpha\) and the continuum escape fractions, the Ly\(\alpha\) equivalent width EW(Ly\(\alpha\)), and the Ly\(\alpha\) line profiles on the HI content, the dust content, kinematics, gas geometry, and clumping properties. Since spherically symmetric outflows with a homogeneous HI shell are able to reproduce a large variety of observed Ly\(\alpha\) line profiles in Lyman break galaxies and Ly\(\alpha\) emitters (Verhamme et al. 2008; Schaerer & Verhamme 2008; Dessauges-Zavadsky et al. 2010), the same geometry is used to study how a clumpy ISM structure alters the Ly\(\alpha\) line and UV continuum. This clumpy geometry is also chosen since it has been shown to reproduce observable continuum properties of starburst galaxies and the Calzetti attenuation law (Gordon et al. 1997; Witt & Gordon 2000; Vijh et al. 2003).

Our main results can be summarized as follows:

- A clumpy and dusty medium is always more transparent to Ly\(\alpha\), UV and optical continuum photons compared to an equivalent homogeneous medium of equal dust content, as already known from earlier studies (Boisse 1990; Hobson & Scheuer 1993; Witt & Gordon 1996, 2000). A clumpy medium thus allows to decrease the global effect of the dust absorption on any radiation.
- The UV and optical continuum escape fraction depend on three parameters in homogeneous and clumpy shell geometries: the dust content, the “clumpiness” of the dust distribution (described by the density contrast \(n_{IC}/n_C\)), and the covering factor CF (defined here as the fraction of solid angle of the central photons source
covered by the clumps). In a general way, the continuum escape fraction decreases as the clumpiness of the dust distribution decreases (i.e. \( n_{\text{IC}}/n_C \) increases), and as both the dust content and the covering factor increase.

- Three additional parameters, i.e. in total six, control the Ly\( \alpha \) line transfer: the dust content, the density contrast \( n_{\text{IC}}/n_C \), the covering factor, as well as the \( \text{HI} \) column density, the velocity field and the gas temperature. The Ly\( \alpha \) escape fraction always increases with increasing the clumpiness (i.e. \( n_{\text{IC}}/n_C \) decreases), and with decreasing dust content and covering factor. However, the \( \text{HI} \) column density and the kinematics of the gas do not affect the Ly\( \alpha \) escape in the same way for homogeneous or clumpy media. That creates two different regimes for the Ly\( \alpha \) radiative transfer in clumpy media.

- The first regime (called “low contrast” regime in this paper) comprises homogeneous and weakly clumpy shell geometries, corresponding to an interclump density above \( n_{\text{IC}}/n_C \gtrsim 1.5 \times 10^{-4} \) for the physical conditions adopted in our model (such that the interclump medium is also optically thick for Ly\( \alpha \)). In this regime, the Ly\( \alpha \) escape fraction increases with increasing expansion velocity \( v_{\exp} \) and with decreasing \( \text{HI} \) column density \( N_{\text{HI}} \), as for a homogenous ISM. The Ly\( \alpha \) escape fraction is then always less or equal to the UV escape fraction, which implies that the emergent Ly\( \alpha \) equivalent width \( EW_{\text{obs}}(\text{Ly}\alpha) \) is lower than the intrinsic one \( EW_{\text{int}}(\text{Ly}\alpha) \).

- The second regime (called “high contrast” regime) is found in the most extremely clumpy shell geometries of our model (\( n_{\text{IC}}/n_C \lesssim 1.5 \times 10^{-4} \) for the physical conditions adopted in our model). This corresponds to a clumpy medium composed of very dense clumps embedded in an interclump region which is optically thin for Ly\( \alpha \) photons. Two main differences appear compared to the other regime. First, as was originally suggested by Neufeld (1991), it is possible to observe a Ly\( \alpha \) escape fraction which is higher than for the UV continuum. In particular, this is possible above a certain “critical” dust optical depth \( \tau_c \). Second, whereas for \( \tau_c \leq \tau_i \), the Ly\( \alpha \) escape fraction behaves as in the “low contrast” regime, the opposite behavior is found for high enough dust content (\( \tau_c > \tau_i \)), where \( f_{\text{esc}}(\text{Ly}\alpha) \) increases with decreasing \( v_{\exp} \) and increasing \( N_{\text{HI}} \).

- Overall we have identified two main effects of the ISM clumpiness on the shape of the Ly\( \alpha \) line profiles. First, extremely clumpy ISM favours the formation of a peak at the center of the line profile (\( v_{\text{obs}}=0 \)). Second, the intensity of the Ly\( \alpha \) line increases as the clumpiness of the medium increases, as expected.

- Schematically, the following Ly\( \alpha \) line profile morphologies are predicted from homogeneous and clumpy shell geometries: “double-peak” profiles with identical/similar peaks symmetric around the source redshift (for static media), asymmetric redshifted profiles (from expanding media), and absorption line profiles (from very dusty, homogeneous or weakly clumpy media). These types have already been identified in homogeneous models (Verhamme et al. 2006). In very clumpy, static and dusty shells, a new category is found: “three peaks” profiles similar to the double-peak profiles with an additional third component at line center.

As an application of our study, we have examined the conditions under which the Neufeld model (Neufeld 1991) can work in a clumpy ISM, i.e. when an enhancement of the observed \( EW_{\text{obs}}(\text{Ly}\alpha) \) can be obtained. We find that the following five conditions must be simultaneously fulfilled for the “Neufeld” effect to be effective:

- The \( \text{HI} \) content must be very low between clumps, typically the \( \text{HI} \) column density in the interclump region must be \( \lesssim 3 \times 10^{14} \text{ cm}^{-2} \) to remain optically thin for Ly\( \alpha \) photons. Otherwise, Ly\( \alpha \) photons scatter strongly against \( \text{HI} \) atoms localized between clumps and cannot escape the clumpy medium more easily than UV photons.

- The galactic outflow has to be slow with outflow velocities of the order of \( v_{\exp} \lesssim 2 \times HW M_{\text{int}}(\text{Ly}\alpha) \) \text{ km s}^{-1}. Otherwise Ly\( \alpha \) photons are too redshifted from the clumps and cannot scatter anymore on the surface of clumps, as suggested in the Neufeld model.

- The galactic outflow has to be as uniform and constant as possible in velocity for efficient interactions of Ly\( \alpha \) photons with dust.

- A high dust content must be embedded in clumps to absorb as much as possible the UV continuum, which increases the Ly\( \alpha \) equivalent width. For the physical conditions and clumpy shell geometries adopted here, we find that an enhancement of \( EW(\text{Ly}\alpha) \) by a factor 3–4 can only occur for a colour excess \( E(B-V) \gtrsim 0.3 \).

- A large covering factor is needed in order to get a noticeable enhancement of \( EW(\text{Ly}\alpha) \).

The above conditions are in agreement with the general findings of Neufeld (1991). However, our results differ from those of Hansen & Oh (2006), who make some simplifying assumptions, which are not consistent with more rigorous radiation transfer calculations. In our study, the Neufeld model does not work as easily as suggested in Hansen & Oh (2006).

Given our results it seems quite unlikely/difficult to find conditions in a clumpy, spherically symmetric ISM, where Ly\( \alpha \) photons can escape more easily than the nearby UV continuum, i.e. where the phenomenon suggested by Neufeld (1991) can be at play. Furthermore, when these conditions are fulfilled we generally find that the emergent Ly\( \alpha \) line profile shows emission at line center and little asymmetry. Such profiles do, however, not represent the profiles typically observed in high-redshift galaxies, which are known to be redshifted in the galaxy rest-fame and asymmetric. Other arguments against the Neufeld effect being effective may be if the sites of Ly\( \alpha \) emission are relatively close to or within cold, dusty environments such as molecular clouds, which could absorb more efficiently Ly\( \alpha \) photons than the UV continuum (Laursen et al. 2012; Verhamme et al. 2012).

The simulations from this paper and the success of homogeneous, spherically expanding models in reproducing the large variety of observed Ly\( \alpha \) line profiles and velocity shifts between photospheric, low ionization absorption, and the Ly\( \alpha \) line (Verhamme et al. 2008; Schaerer & Verhamme 2008) seem to indicate that effects to due inhomogeneities in the ISM and deviations from spherical geometry are not dominant. Why simple geometries work so well may appear somewhat puzzling, and certainly remains worth understanding more in depth. More detailed observations and
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