Lyman-α radiative transfer in Star-forming galaxies

Florent Duval
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Cover image: Composite image of Mrk1486, a nearby star-forming galaxy located at $z \sim 0.0338$ and observed with the Hubble Space Telescope in 2012. Mrk1486 has a disk shape which is seen edge-on on this image. The green channel shows the UV continuum emission from the young and massive stars of the galaxy. The red color shows the continuum-subtracted H$\alpha$ emission, which traces the ionized hydrogen nebulae (as the result of star formation) in which both H$\alpha$ and Ly$\alpha$ photons are produced. Finally, the blue color shows the continuum-subtracted Ly$\alpha$ emission of the galaxy. As most of the Ly$\alpha$-emitting galaxies identified in the Universe, the Ly$\alpha$ emission of Mrk1486 is very extended and emerges into a large Ly$\alpha$-halo that surrounds the galaxy. This is the result of the resonant scattering process experienced by Ly$\alpha$ photons on neutral hydrogen.
Abstract

This thesis focuses on the intrinsically strongest spectral signature of star-forming galaxies: the Lyman alpha recombination line of the hydrogen atom (hereafter Ly$\alpha$). Located at the wavelength of $\lambda_{\text{Ly}\alpha} = 1215.67$ Å in the rest-frame far-ultraviolet spectra of star-forming galaxies, the Ly$\alpha$ line proves to be a vital tracer and a powerful emission-line window to discover and to study the remote young star-forming galaxies of the early Universe.

Although intrinsically very strong, the Ly$\alpha$ line is also a resonant line. As a consequence, the transport of Ly$\alpha$ photons inside the interstellar medium (ISM) of star-forming galaxies is very complex and depends on many ISM quantities (HI mass, dust content, HI gas kinematics and ISM clumpiness). All this process has serious effects on the emergent features of the Ly$\alpha$ line (strength, equivalent width and line profile) that need to be understood for ensuring a proper interpretation of all very promising Ly$\alpha$-oriented studies in astrophysics and cosmology. This is precisely the aim of this thesis to go deeper into our understanding of the complex radiative transport experienced by the Ly$\alpha$ line in star-forming galaxies.

In this work, we carry out both numerical and observational studies of Ly$\alpha$ transport inside the ISM of galaxies.

In Paper I and II, we perform detailed numerical studies that examine the effects of a clumpy ISM on the strength and the shape of the Ly$\alpha$ line. Although poorly studied until now, the effects of a clumpy ISM on Ly$\alpha$ have been routinely invoked to explain the origin of anomalously strong Ly$\alpha$ line observed from high-redshift galaxies. Some analytical studies suggest indeed an higher transmission of Ly$\alpha$ photons over UV continuum ones from clumpy ISMs, resulting in an enhanced Ly$\alpha$ equivalent width EW(Ly$\alpha$). Our results show that although clumpiness facilitates the escape of Ly$\alpha$, it is highly unlikely that any real ISM should result in any enhancement of EW(Ly$\alpha$). Other possible causes are discussed in our papers, leading to the conclusion that the observed high EW(Ly$\alpha$) are more likely produced by cooling radiation or anisotropic escape of Ly$\alpha$ radiation.

Both Paper III and IV are related to the LARS project. This is an ambitious observational program in which 14 nearby star-forming galaxies have been observed with the Hubble Space Telescope (HST) with the aim to investigate how Ly$\alpha$ is transported out of galaxies and what effects each ISM quantity produces on the Ly$\alpha$ line. While Paper III examines the Ly$\alpha$ properties and morphology of individual galaxies, Paper IV presents a detailed study of the surprising Ly$\alpha$ emission line of Mrk1486 (the fifth galaxy of the sample).
To my parents and my brother
This thesis is based on the following publications:


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## Contents

**Abstract**  

**List of Papers**  

1 **Introduction**  
   1.1 This thesis: studying Ly\(\alpha\) radiative transfer in star-forming galaxies  

2 **Galaxy evolution and spectral features**  
   2.1 From the Big Bang to the present-day Universe  
   2.2 Spectral features of distant star-forming galaxies  
      2.2.1 The Ly\(\alpha\) line  
      2.2.2 The H\(\alpha\) and H\(\beta\) lines  
      2.2.3 Forbidden lines of heavy elements  
      2.2.4 The Lyman break at 912 Å  

3 **Exploring the distant Universe through the Lyman-\(\alpha\) line**  
   3.1 Finding distant star-forming galaxies  
      3.1.1 Selection by the Ly\(\alpha\) emission line (LAE galaxies)  
      3.1.2 Selection by the Lyman Break technique (LBG galaxies)  
      3.1.3 Other selection techniques  
   3.2 The Ly\(\alpha\) line in astrophysics and cosmology  
      3.2.1 The star formation rate of galaxies  
      3.2.2 The Ly\(\alpha\) and UV Luminosity functions of galaxy populations  
      3.2.3 Probing the epoch of the cosmic reionization of the Universe  
      3.2.4 Studying the circumgalactic medium of galaxies  
      3.2.5 Identifying the first generation of stars  

4 **Studying Lyman-\(\alpha\) radiative transfer in star-forming galaxies**  
   4.1 Identifying the ISM quantities that enter in the Ly\(\alpha\) transport from observations of nearby star-forming galaxies  
      4.1.1 Dust attenuation  
      4.1.2 HI gas kinematics
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1.3</td>
<td>HI column density</td>
<td>48</td>
</tr>
<tr>
<td>4.1.4</td>
<td>ISM geometry</td>
<td>50</td>
</tr>
<tr>
<td>4.1.5</td>
<td>Summary</td>
<td>51</td>
</tr>
<tr>
<td>4.2</td>
<td>Investigating the Ly$\alpha$ radiative transport in high-redshift star-forming galaxies</td>
<td>52</td>
</tr>
<tr>
<td>4.2.1</td>
<td>Any differences to the Ly$\alpha$ transport inferred in low-redshift galaxies?</td>
<td>52</td>
</tr>
<tr>
<td>4.2.2</td>
<td>The diversity of the Ly$\alpha$ line profiles: probing the ISM properties of high-redshift galaxies</td>
<td>55</td>
</tr>
<tr>
<td>4.3</td>
<td>The LARS sample: going deeper into the study of Ly$\alpha$ radiative transfer in nearby galaxies</td>
<td>57</td>
</tr>
<tr>
<td>4.3.1</td>
<td>The sample</td>
<td>58</td>
</tr>
<tr>
<td>4.3.2</td>
<td>Imaging and spectroscopic observations</td>
<td>58</td>
</tr>
<tr>
<td>4.3.3</td>
<td>Scientific goals</td>
<td>61</td>
</tr>
<tr>
<td>5</td>
<td>The physics of the Lyman-$\alpha$ line</td>
<td>63</td>
</tr>
<tr>
<td>5.1</td>
<td>The Ly$\alpha$ line formation mechanisms and its intrinsic features in starburst galaxies</td>
<td>63</td>
</tr>
<tr>
<td>5.1.1</td>
<td>Ly$\alpha$ line formation mechanisms</td>
<td>63</td>
</tr>
<tr>
<td>5.1.2</td>
<td>The intrinsic Ly$\alpha$ line of star-forming galaxies</td>
<td>64</td>
</tr>
<tr>
<td>5.2</td>
<td>Interaction between Ly$\alpha$ photons and neutral Hydrogen</td>
<td>67</td>
</tr>
<tr>
<td>5.2.1</td>
<td>Absorption process</td>
<td>68</td>
</tr>
<tr>
<td>5.2.2</td>
<td>Re-emission process</td>
<td>72</td>
</tr>
<tr>
<td>5.2.3</td>
<td>The Ly$\alpha$ radiative transfer in HI media</td>
<td>75</td>
</tr>
<tr>
<td>5.3</td>
<td>Interaction between Ly$\alpha$ photons and dust</td>
<td>79</td>
</tr>
<tr>
<td>5.4</td>
<td>Other interactions</td>
<td>81</td>
</tr>
<tr>
<td>5.4.1</td>
<td>Interaction with Deuterium</td>
<td>81</td>
</tr>
<tr>
<td>5.4.2</td>
<td>Collisions</td>
<td>82</td>
</tr>
</tbody>
</table>

**Summary and contribution to the Papers**

**Acknowledgments**

**Publications not included in the Thesis**

**Bibliography**
1. Introduction

The general context to which this thesis belongs is understanding both the formation and the evolution of galaxies, one of the illuminating questions of the modern astrophysics. Since the final decade of the 20th century, and the first observations of the "Hubble Deep Field" with the Hubble Space Telescope (HST), a new era in the exploration of the distant Universe has begun. Nowadays, several thousand of quasars and galaxies at distances corresponding to an epoch when the Universe was 5% of its current age have been identified, allowing astronomers to constrain more accurately their models of galaxy formation and evolution. Among the observational tools at the origin of this great advance for probing the remote young galaxies of the early Universe, the use of the intrinsically strongest spectral signature of these objects: the Lyman alpha recombination line of hydrogen (hereafter Ly$\alpha$).

Produced by the most widespread chemical element of the Universe when the electron makes the transition from the first excited state to the ground-state (see figure 1.1), the role played by the Ly$\alpha$ line for galaxy and cosmology research is enormous. Thanks to its convenient rest-frame wavelength of 1215.67 Å (making it accessible for optical and near-infrared ground-based telescopes when observing targets in the far Universe) and its brightness in the spectra of star-forming galaxies, the Ly$\alpha$ line proves to be a vital tracer and a powerful emission-line window to discover and to study the young and primordial star-forming galaxies of the distant Universe. In this way, combined to the advent of the new generation of very large optical telescopes (VLT, SUBARU, KECK) and the development of very sensitive cameras since the 90’s, the use of this bright hydrogen line has allowed both the detection of thousands of galaxies over a large distance range (Hu and Cowie, 1998; Cowie et al., 2010; Deharveng et al., 2008; Ouchi et al., 2010; Shimasaku et al., 2006) and the study of their physical properties from the analysis of the Ly$\alpha$ line’s features. Moreover, the Ly$\alpha$ line is widely used by astronomers for cosmological purposes, such as tracing the large scale structure of the Universe, studying the end of the "Dark age", probing the ionization state of the intergalactic medium (IGM) and the epoch of the cosmic reionization (Kashikawa et al., 2012; Malhotra and Rhoads, 2004; Ouchi et al., 2010).

All the potentials and the versatility of the Ly$\alpha$ line for astrophysical and cosmological studies is undeniably remarkable, but must necessarily rely on a
Figure 1.1: Electronic transitions of the hydrogen atom: when a proton captures an electron, the newly formed hydrogen atom is in an excited state. The electron thus falls down to lower energy orbitals before reaching the first (ground) state of the hydrogen atom (n=1). For each electronic transition, the difference of energy is reemitted in the form of a photon. In particular, the transition between the first excited state (n=2) and the ground-state produces a Lyα photon ($\lambda_{\text{Ly} \alpha} = 1215.67$ Å). In the same way, the transitions between both the second and the third excited states to the first one produce a Hα photon ($\lambda_{\text{H} \alpha} = 6562.8$ Å) and a Hβ photon ($\lambda_{\text{H} \beta} = 4861.1$ Å), respectively.

good astrophysical understanding of all processes that regulate the Lyα line of distant star-forming galaxies. The latter remains however subject to numerous incoherence today, questioning seriously the reliability of all our interpretation based on the Lyα line. Indeed, since the first theoretical predictions of Partridge and Peebles (1967) on the presence of a bright Lyα emission line in the spectra of young and primordial galaxies, several questions have been accumulated from observations of local and remote star-forming objects. In particular, while intrinsically very bright, how can we explain that the spectra of a large fraction of very active star-forming galaxies show no evidence of Lyα emission (or even a pronounced Lyα absorption feature)? What physical quantities control the Lyα line’s properties (strength and line profile) in the interstellar medium (ISM) of galaxies? What do explain the strong discrepancies that exist between the theoretical predictions of the Lyα strength and the
ones observed from star-forming galaxies? It is vital that these problems be understood nowadays, all the more when studying the physical properties of distant galaxies from which the Lyα line may be among the only observables available. Despite several discoveries accumulated during these last twenty years, there is still a long way to go before getting a definite answer to all these questions. This is precisely the aim of this thesis to go further into our understanding of both the complex transport and the changes that the Lyα line experiences within star-forming galaxies.

1.1 This thesis: studying Lyα radiative transfer in star-forming galaxies

The complex physics of the Lyα line is at the origin of these observational complications. More precisely, the Lyα line is distinguished from all other recombination lines of the hydrogen atom. Due to the particular electronic transition that gives rise to Lyα photons (see Fig. 1.1), the Lyα line turns out to be a resonant line. As a consequence, a Lyα photon is very likely to be absorbed by any neutral hydrogen atom located along its trajectory. This absorbing atom is then excited (to the first excited state) and instantly falls down into the ground-state, re-emitting the Lyα photon in a random direction and with a slightly different frequency. This is called a resonant radiation process. In the ISM of a galaxy, particularly rich in neutral hydrogen gas, the result of this resonant scattering is a longer path length which increases the probability that a Lyα photon be destroyed by a dust grain or other chemical species (H2 molecules, deuterium atoms). Moreover, this very complex transport has many consequences on the visibility, the strength and the shape of the emergent Lyα line that need to be understood in order to interpret accurately the Lyα line of distant galaxies. Therefore, the main questions to answer is under what conditions a galaxy may be bright in Lyα, and how to interpret and calibrate the Lyα line to derive accurately any property of the host galaxies.

This thesis is structured as follows. In Chapter 2, we give a general presentation of the distant and primordial star-forming galaxies of the early Universe. More precisely, we first highlight the time period in which both the formation and the evolution of galaxies occur in the history of the Universe. Then, we explain in more details the nature of the most important spectral features of distant star-forming galaxies. In Chapter 3, we focus on the Lyα line of the remote young galaxies, where we give an overview of the enormous potential of the Lyα line for both galaxy and cosmology research. In connection with the articles presented at the end of this thesis, Chapter 4 presents our current knowledge of the Lyα radiative transfer in the ISM of local and distant galax-
ies. Finally, in Chapter 5, we provide a more detailed summary of the physics of the Ly$\alpha$ line. In particular, all elements tackled in this chapter have been included in a Ly$\alpha$ radiative transfer Monte Carlo code MCLya (Verhamme et al., 2006) that has been used throughout each paper presented in this thesis.
2. Galaxy evolution and spectral features

The population of distant star-forming galaxies constitutes a central element of this thesis. Throughout this section, we first highlight the time period in which both the formation and the evolution of galaxies occur in the history of the Universe. That will allow us to specify the exact cosmic time we will focus on throughout this thesis. Second, we explain both the nature and the physical mechanisms at the origin of the most important spectral features of distant star-forming galaxies. In particular, we will focus on the ones astronomers commonly used to detect and to investigate the physical properties of these objects.

2.1 From the Big Bang to the present-day Universe

The history of the Universe shows radically different phases that succeeded one another before reaching the present-day Universe we observe today. These different phases are illustrated in figure 2.1. We describe below each step in more details.

After the Big Bang, the Universe was extremely hot, dense and completely ionized. More precisely, it consisted in a dense plasma of electrons and protons which was effectively opaque to any radiation. As the Universe expanded, the temperature of the plasma decreased and reached about 3000 K when the Universe had aged to 380 000 years. At such a temperature, electrons got captured by protons, leading to the formation of the first Hydrogen (HI) and Helium (He) atoms of the Universe (75% of Hydrogen and 25% of Helium in terms of mass). Most of the newly formed atoms were neutral at the end of this process and the photons started traveling freely through the neutral gas: the Universe became transparent. This phase is known as the **Recombination of the Universe** and is observed at the redshift \( z = 1100 \) today (see figure 2.1).

---

1 All photons scattered continuously on both the free-electrons and the free-protons of the primordial plasma, preventing them from traveling freely through the Universe.
2 Due to the expansion of the Universe, the electromagnetic radiation from a distant source of light is increased in wavelength. The redshift \( z \) measures this spectral shift
Figure 2.1: Evolution of the Universe from the Big Bang (left) to our time (right). Time is represented in the horizontal axis and is increasing to the right. The different phases of the Universe are shown in this diagram: the Recombination of the Universe that occurred 380 000 years after the Big-Bang (at the redshift $z \sim 1100$), the Dark age which had continued until the formation of the first stars and galaxies (at about 400 millions years after the Big Bang, at $z \sim 10$), and the Reionization of the Universe, that occured few million years after the formation of these primordial objects (the reionization of the intergalactic medium probably ended about 800 million years after the Big Bang, at $z \sim 7$).

The rest-frame spectral energy distribution (SED) of this primordial radiation of the Universe corresponds to the one of a black body heated at about 3000 K (i.e. the temperature of the Universe at the epoch of the Recombination). Nowadays, due to the expansion of the Universe, these "free" photons are mostly detected into the Microwaves field and constitute the so-called "Cosmic Microwave Background" (CMB) radiation. Different space missions have already studied the CMB with a great sensitivity and resolution, such as by the relation: $\lambda/\lambda_0 = 1 + z$, where $\lambda_0$ is the rest-frame wavelength of the radiation and $\lambda$ is the observed one. Moreover, given that the redshift is directly related to the cosmic scale factor $R(t)$ (which represents the relative expansion of the Universe), this parameter can be seen as a tool to estimate both the distance and the time in the Universe. Its value is $z = 0$ in the local Universe, and it increases with the distance of the object.
the COBE, WMAP and PLANCK missions (Bennett et al. 2012, Planck Collaboration et al. 2013). In particular, all these missions revealed very weak temperature fluctuations in different regions of the early Universe. These variations in temperature prove to contain an incredible amount of information on the young Universe. They also correspond to the initial density fluctuations that gave rise to the formation of the structures we observe today (galaxies, galaxy clusters, voids and filaments).

Besides the CMB itself, the Recombination also marked the epoch where the first Ly$\alpha$ emission line of hydrogen was emitted in the history of the Universe. Indeed, the formation of the first hydrogen atoms was accompanied by the emission of all recombination lines of this element through the cascade of the electron to the ground state. Nowadays, the consideration of such a primordial Ly$\alpha$ emission is important to correct any distortion produced by the Hydrogen recombination lines on the CMB. We show in figure 2.2 the total contribution of this early Ly$\alpha$ emission to the CMB, as estimated by Wong et al. (2006). According to these predictions, the intensity of the primordial Ly$\alpha$ emission is relatively weak (i.e. almost 5 order of magnitude less bright than the Cosmic Infrared Background\textsuperscript{1} CIB), making its detection in far-infrared wavelengths extremely challenging.

After the Recombination, the Universe entered in a second phase: the Dark age. During this period, the Universe was only composed of cold and neutral gas whose distribution followed the one of the dark-matter (thus creating the so-called "cosmic-web"). At that time, the Universe remained completely transparent to any radiation and no noticeable source of light was formed (despite the formation of some exotic objects, such as the population III stars; see section 3.2.5). In this way, the Dark-age had lasted for few million years, until the formation of the first stars and galaxies at about 400 million years after the Big Bang (corresponding to the redshift $z \sim 10$).

The first galaxies of the Universe are believed to form by gravitational collapse of neutral hydrogen clouds inside massive dark-matter haloes. Given the very turbulent conditions in which these primordial objects were formed (i.e. experiencing multiple mergers and accreting a large amount of neutral gas over a large cosmic time; White and Rees 1978, Kereš et al. 2005, Brooks et al. 2009, Dekel et al. 2009), the first models of galaxy evolution suggested that the remote young galaxies of the Universe were experiencing intense star-forming events within them (Partridge and Peebles, 1967; Meier, 1976). Nowadays, such a property of primordial galaxies has been confirmed by a large number of observations of these distant objects (Madau et al., 1996). Therefore,

\textsuperscript{1}As the CMB, the Cosmic Infrared Background (CIB) is an infrared radiation coming from all directions in the Universe. Its brightness is mostly due to the bright infrared radiation of both distant star-forming galaxies and quasars.
most of the remote young galaxies were intense star-forming galaxies in which very massive and short lifetime stars (O, B and A type stars) synthesized very quickly the large amount of heavy elements and dust we now observe in the ISM of evolved galaxies in the local Universe.

Besides the production of heavy elements, the high flux of all primordial objects shortward of the Lyman limit (i.e. the Lyman continuum at \( \lambda < 912 \, \text{Å} \)) also contributed to ionize the remaining neutral gas of the intergalactic medium (IGM) of the Universe. This process marked the beginning the Reionization of the Universe (see Fig. 2.1). It built the Universe we observe today, that is composed of evolved galaxies embedded in a warm, tenuous and ionized IGM. The Reionization of the IGM probably ended about 800 millions years after the Big Bang, that is at the redshift \( z \sim 7 \) (Ouchi et al. 2010, Malhotra et al. 2004), but large uncertainties still remain on the exact chronology of this process.

While each phase of the Universe history has been subject of deep observational studies, either the exact chronology or the mechanisms at the origin of these events still remain unclear nowadays. In such a context, the strong Ly\( \alpha \) emission line of the primordial star-forming galaxies appears as a very powerful tool to study the most relevant phases of the evolution of the Universe: the end of the Dark-age, the formation of the first objects, the ionization state of the IGM and the epoch of the reionization of the Universe. Throughout this thesis, we thus focus on a very large period of the evolution of the Universe, that is from the formation of the first galaxies (at \( z \sim 10 \)) to the present-day Universe.

2.2 Spectral features of distant star-forming galaxies

Identifying and studying the physical properties of distant star-forming galaxies is a fundamental key to figure out both the evolution of galaxies and the main phases of the evolution of the Universe. Nevertheless, these different tasks must necessarily rely on a good understanding of the spectral features that characterize these distant objects. The SED of distant star-forming galaxies shows a multitude of bright and pronounced features at different wavelengths. In addition to a very bright UV continuum, which can dominate the SED of these galaxies, numerous emission lines emerge with a large flux over

1 The heavy elements correspond to all chemical elements heavier than hydrogen and helium atoms.

2 The Lyman limit corresponds to the wavelength \( \lambda = 912 \, \text{Å} \). A photon of this wavelength has the minimum energy needed to ionize a hydrogen atom (i.e. \( E \approx 13.6 \, \text{eV} \)).
Figure 2.2: Line intensity of Hydrogen (the sum of Lyα line and two photon emission, see chapter 5) and Helium lines together with different background spectra: the CMB (long dashed line) and the CIB (dot-dashed line). The sum of all the above emission lines of Hydrogen and Helium plus the CMB is also shown in this figure (thin solid). That allows us to visualize the distortion produced by the diverse recombination lines of HI and He to the CMB.

a small wavelength interval (see figure 2.3). This subsection explains both the nature and the origin of the most important spectral features of distant star-forming galaxies. In particular, we will focus on the most commonly used ones to detect and to derive the physical properties of these objects: the Lyα, Hα and Hβ emission lines, the "forbidden" emission lines of heavy elements and the "Lyman break" at 912 Å.

2.2.1 The Lyman α line

The Lyα line is a recombination line of the hydrogen atom, corresponding to the electronic transition between the first excited state and the ground-state of this atom (see Fig. 1.1). Located at the rest-frame wavelength $\lambda_{Ly\alpha}=1215.67$ Å (Far-UV field), the Lyα line is a very strong spectral signature of star-forming galaxies when emitted (Partridge and Peebles [1967], Charlot and Fall [1993], Schuerer [2003]).

As most of the emission lines observed in the SEDs of starburst galaxies, the Lyα line forms essentially through recombination of hydrogen atoms inside the numerous HII regions that surround the most massive and hottest stars
Figure 2.3: Rest-frame composite spectrum of a sample of distant starburst galaxies located in the redshift range \(2 < z < 5\). All spectra were taken from the FORS Deep Field spectroscopic survey (Noll et al., 2004). The main spectral features of distant starburst galaxies are shown in this spectrum: a bright far-ultraviolet radiation, the presence of numerous emission lines (of hydrogen and heavy elements) and the "Lyman break" shortward of 912 Å.

of these galaxies (O and B type stars). These stars emit indeed a large amount of ionizing photons shortward of the Lyman limit which allows them to ionize the surrounding ISM neutral hydrogen gas. Analyzing in detail the recombination process in HII regions (case B of the recombination theory\(^1\); Osterbrock 1989), it turns out that two-third of the Lyman continuum photons produced by stars are converted into the Ly\(\alpha\) line in star-forming galaxies (see chapter 5 for more details). This line thus becomes the intrinsically strongest hydrogen recombination one produced in ionized nebulae.

Given the high intrinsic strength of the Ly\(\alpha\) line in HII regions, numerous analytical and numerical studies have examined details of the intrinsic features of the Ly\(\alpha\) line in star-forming galaxies, such as the Ly\(\alpha\) equivalent width\(^2\).

\(^1\)The case B of the recombination theory assumes that the newly formed Ly\(\alpha\) photons are always re-absorbed by the neutral hydrogen atoms of the HII region. It is the optically thick case, the most likely configuration in a HII region.

\(^2\)The equivalent width of a line measures the ratio of the integrated luminosity of
Figure 2.4: Predicted temporal evolution of the Lyα equivalent width EW(Lyα) of the nebular emission for instantaneous burst (solid lines) and constant star formation (dashed lines). It is assumed here that all ionizing photons emitted by the stellar population (i.e. at wavelength $\lambda < 912$ Å) contribute to ionize hydrogen atoms in the HII region. The dash-dotted lines show the total EW(Lyα) (nebular + stellar) for constant star formation. Three different metallicities are shown in this figure: $Z = 0.02$ (solar metallicity, black), 0.004 (red) and 0.0004 (blue). A Salpeter IMF is assumed in these models. Although not explicitly indicated in this figure, the Lyα line always appears in emission in all cases (i.e. EW(Lyα) > 0 Å) except for an instantaneous burst where EW(Lyα) may become negative after $\sim$ 50 Myrs (due to the stellar Lyα absorption component of the B-type stars). Source: Schaerer and Verhamme (2008)

EW(Lyα), the Lyα luminosity and the time scale of the Lyα emission. During the 1960s, the first calculation of Partridge and Peebles (1967) highlighted the possible strong luminosity of the Lyα line in the SEDs of primordial star-forming galaxies. Although based on simplified assumptions (such as assuming that each recombination of hydrogen atoms leads to the emission of a photon in the Lyman series, or reproducing the radiation of O and B type stars by a simple black-body emission), their model predicted that $\sim$ 7 % of the total line over the monochromatic luminosity of the continuum: $EW = L_{\text{line}}/L_{\text{continuum}}$. $L_{\text{line}}$ can be expressed in erg.s$^{-1}$ and $L_{\text{continuum}}$ in erg.s$^{-1}$.Å$^{-1}$. The equivalent width of a line is thus expressed in Angstrom unit. It is positive for emission lines and is negative for absorption ones.
tal bolometric luminosity of star-forming galaxies might be contained into the intrinsic Ly$\alpha$ line. Nowadays more complex numerical studies that include more realistic synthetic stellar atmosphere and evolution models have been carried out over the last two decades (Charlot and Fall, 1993; Schaerer, 2003). All these recent numerical simulations still predict a very strong intrinsic Ly$\alpha$ emission line in star-forming galaxies, as shown in figure 2.4 (Schaerer and Verhamme, 2008). For different stellar metallicities $Z$ and star formation histories for the host galaxy, the intrinsic Ly$\alpha$ equivalent width EW(Ly$\alpha$) is predicted to be as high as 240 Å (for normal stellar metallicities; i.e. population I stars) or 360 Å (for very metal-poor stars; i.e. population II stars) before declining due to both the decrease of the Lyman continuum flux and the aging of the stellar population. Therefore, the Ly$\alpha$ line appears as a strong probe of the stellar formation activity in galaxies, which explains its importance for detecting and studying high-redshift star-forming galaxies.

However, although intrinsically very bright, the Ly$\alpha$ line’s strength is also its weakness as neutral hydrogen is very likely to absorb it. As mentioned above, Ly$\alpha$ photons undergo a complex resonant radiation process in the ISM of starburst galaxies, which has strong consequences on the observed features of the Ly$\alpha$ line (luminosity, EW(Ly$\alpha$), line profile). Such a complex radiative transport of the Ly$\alpha$ line has to be taken into account to derive correctly its intrinsic features and study more accurately the physical properties of distant star-forming galaxies (age of the starburst, star formation rate, dust attenuation, etc.).

2.2.2 The H$\alpha$ and H$\beta$ lines

Both the H$\alpha$ and the H$\beta$ lines are recombination lines of the hydrogen atom. They correspond respectively to the electronic transition between the second and the third excited state to the first one of this atom (see Fig. 1.1). Their rest-frame wavelength is $\lambda_{H\alpha} = 6562.8$ Å and $\lambda_{H\beta} = 4861.1$ Å, respectively.

Although intrinsically weaker than the Ly$\alpha$ line$^2$, both the H$\alpha$ and the H$\beta$ lines have the advantage of not being resonant transitions. The resonant scattering from the first excited state of the hydrogen atom is indeed negligible in the ISM of galaxies. Therefore, both the H$\alpha$ and the H$\beta$ lines are only af-

$^1$The stellar metallicity ($Z$) measures the mass proportion of "heavy elements" (elements heavier than hydrogen or helium) in stars. Usually, the metallicity of stars are compared with the solar value ($Z_\odot$).

$^2$According to the recombination process in HII regions (case B of the recombination theory; Osterbrock 1989), the Ly$\alpha$ flux is higher than both the H$\alpha$ and the H$\beta$ flux in such ionizing hydrogen nebulae. The expected intrinsic flux ratio are around: Ly$\alpha$/H$\alpha$ $\sim$ 8.7 and Ly$\alpha$/H$\beta$ $\sim$ 27.
fected by dust attenuation, allowing them to escape from star-forming galaxies more easily than the Lyα line. As a consequence, when observed, both Hα and Hβ lines constitute a good alternative to the Lyα line in order to detect distant star-forming galaxies (Hayes et al., 2010) and to derive precisely their physical properties.

2.2.3 Forbidden lines of heavy elements

While the recombination process leads to the formation of strong hydrogen recombination lines in HII regions, collisional excitations are at the origin of the formation of strong "forbidden" lines of heavy elements in ionized nebula. Among the forbidden lines that appear in the UV, optical and NIR fields of the SED of star-forming galaxies, we can easily distinguish the following ones (see Fig. 2.3): O[III]λλ4959,5007; O[II]λλ3726,3729; N[II]λλ6546,6583; Ne[III]λλ3869,3968 and S[II]λλ6731,6716 Å. Furthermore, besides the "forbidden" lines, a multitude of "semi-forbidden" and "permitted" lines of heavy elements also appear in the SED of star-forming galaxies. Nonetheless, most of them are relatively faint and can only be observed under long exposure spectroscopic observations (i.e. such as the "semi-forbidden" and "permitted" lines of OII, CII, CIII, CIV).

Besides using the brightest forbidden optical lines for detecting starburst galaxies at various redshifts (Maschietto et al., 2008; Tadaki et al., 2012), astronomers pay a special attention to these lines for studying the physical conditions in ionized nebulae. In particular, comparing observations to different nebular models, the analysis of some forbidden lines allows to derive the chemical composition of the ionized nebulae, the electron temperature, the electron density, as well as the nature of the excitation source in the host galaxy (Starburst or Active Galactic Nucleus; Baldwin et al. 1981, Veilleux et al. 1987, Stasinska et al. 2006).

2.2.4 The Lyman break at 912 Å

Besides the strong emission lines that compose the SED of distant star-forming galaxies, the observed far-UV continuum exhibits a strong break at the Lyman edge (i.e. at about 912 Å). As shown in figure 2.5 the spectral flux can drop almost to zero shortward of this limit. This step down, commonly named "Lyman-break", is due to the strong absorption of the Lyman continuum photons by the neutral hydrogen atoms located either in the stellar atmosphere, the ISM of the galaxy or the IGM.

Depending on the physical properties of the host galaxy, the Lyman-break might be more or less pronounced in the observed SED. At a first estimation,
the amplitude of the Lyman break depends mostly on both the UV luminosity and the neutral hydrogen mass of the galaxy. The total mass of a distant star-forming galaxy thus becomes an important parameter in the detection of the Lyman break. Indeed, low mass high-z galaxies tend to have very faint UV luminosity and low HI mass which prevents any observer from detecting both the UV continuum and the Lyman-break of these objects. However, large and massive star-forming galaxies (as shown in Fig. 2.5) are very likely to exhibit both high HI mass and intense star formation activities within them. Such intense star-forming activities must lead to a very bright UV continuum emission which renders the Lyman-break particularly easy to detect.

A second pronounced step can also be observed shortward of the Ly$\alpha$ line of the host galaxy (i.e. at the rest-frame wavelength $\lambda < 1215.67$ Å). This attenuation is visible in figure 2.5 where the UV continuum flux shortward of the Ly$\alpha$ line appears weaker than the one seen redward of the line. This second attenuation is simply due to the foreground neutral hydrogen clouds of the IGM. Those IGM clouds, located at any redshift $z$ between the galaxy’s redshift ($z_{gal}$) and $z = 0$, are very likely to absorb a significant flux of the UV continuum (emitted by the galaxy) at the Ly$\alpha$ wavelength in their own referential. As a consequence, each successive Ly$\alpha$ absorption reduces the spectral

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**Figure 2.5:** Composite rest-frame spectrum of deep $z \sim 3$ star-forming galaxy spectra (Shapley et al., 2006). This figure represents the average Far-UV spectrum of those galaxies between the Lyman continuum at $\lambda = 800$ Å and $\lambda = 1500$ Å. An important break of the UV continuum flux can be easily observed shortward of 912 Å and 1216 Å.
flux shortward of the Ly$\alpha$ line of the galaxy. Let’s remark that the density of IGM clouds tends to increase with redshift (Kim et al. 1997, 2001). Therefore, the amplitude of this second break increases with the redshift of the host galaxy. In particular, for the farthest galaxies located at a redshift $z$ corresponding to an epoch earlier than the reionization, the observed UV continuum flux shortward of the Ly$\alpha$ line is expected to completely drop to zero. This is the so-called "Gunn-Peterson" effect (Gunn and Peterson 1965).
3. Exploring the distant Universe through the Lyman-α line

Nowadays, the Lyα line has become the most powerful emission-line probe of the high-redshift Universe. In this chapter, we give an overview of the enormous potential of the Lyα line for both galaxy and cosmology research. First of all, we discuss the different observational techniques which are commonly used to detect high-redshift star-forming galaxies, focusing in particular on the central role played by the Lyα line. Then, we explain how the Lyα line of those galaxies can be used for astrophysical and cosmological purposes, when inferring the star-formation rate (SFR) of distant galaxies, probing the ionization state of the IGM or identifying the exact epoch of the cosmic reionization.

3.1 Finding distant star-forming galaxies

3.1.1 Selection by the Lyα emission line (LAE galaxies)

As Partridge and Peebles (1967) first suggested, the Lyα line presents many advantages for the detection of high-redshift starburst galaxies. First of all, the Lyα line constitutes a very strong intrinsic spectral signature of star-forming galaxies with an intrinsic equivalent width up to 240 - 360 Å for normal stellar populations (i.e. population I/II stars; Charlot & Fall 1993; Schaerer 2003). Furthermore, thanks to its rest-frame wavelength of 1216 Å, the Lyα line is shifted into the optical and near-infrared (Near-IR) wavelengths for galaxies further away than z = 2.1, making ground based observations possible. For several decades, astronomers have thus taken advantage of this strong emission line to identify star-forming galaxies at different redshifts.

The technique that uses the Lyα emission line to detect high-redshift starburst galaxies is called the Narrow-band technique. Figure 3.1 presents a good illustration of this method, showing the detection of a galaxy at redshift z = 6.96 thanks to its strong Lyα emission line (Iye et al. 2006). The idea of this technique consists in making several images of the same field of sky: the first one through a narrow-band filter centered at a wavelength \( \lambda_{NF} \) where the Lyα line should be redshifted (i.e. the filter NB973 in Fig. 3.1), and the other ones...
Figure 3.1: This figure shows the detection of a Lyα-emitting galaxy at $z = 6.96$ using the narrow-band technique (Iye et al., 2006). The upper panel shows a clear flux excess through the narrow-band filter NB973, compared to the one of the neighbouring broad-band filters ($B$, $V$, $R$, $i'$ and $z'$ broad-band filters). The flux excess is due to the fact that the Lyα line of the galaxy is seen through the filter NB973. The middle panel shows a zoom in the observed SED of the galaxy (red line). The Lyα emission line of the galaxy appears at 9680 Å, which confirms the detection of a high-$z$ star-forming galaxy at $z = 6.96$. The bottom panel just shows the different sky emission lines that are observed in the same wavelength range.

through different broad-band filters which cover the neighbouring UV continuum of the Lyα line (i.e. the filters $B$, $V$, $R$, $i'$ and $z'$ in Fig. 3.1). Measuring the flux excess in narrow-band compared to the continuum broad-bands, a source showing a high flux excess in the narrow-band filter is interpreted as a distant galaxy whose strong Lyα emission line is seen through the narrow-band filter. Such interpretation needs nevertheless more analysis before confirming the detection of a distant galaxy. It is through a subsequent analysis of the SED of this object that we can confirm the presence of a Lyα line through the narrow-band filter (see figure 3.1 middle panel). In practice, astronomers agree on the same threshold to select a galaxy candidate on the basis of the flux excess observed in narrow-band. This threshold corresponds to the flux excess
produced by a Lyα line showing a rest-frame equivalent width EW(Lyα) > 20 Å. Therefore, all galaxies detected with the Narrow-band technique show a rest-frame EW(Lyα) > 20 Å and are commonly called Lyα emitters (LAEs).

Since the late 1990s, the detection of LAEs has become quite common with more than three thousand spectroscopically confirmed LAEs until now. These have been detected over a wide redshift range 0.02 < z < 7.62 (Hu and Cowie, 1998; Cowie and Hu, 1998; Kunth et al., 1998, 2003; Rhoads et al., 2000; Hu et al., 2010; Ouchi et al., 2010; Taniguchi et al., 2003; Shimasaku et al., 2006; Gronwall et al., 2007; Nilsson et al., 2007; Kashikawa et al., 2011; Hu et al., 2004; Iye et al., 2006; Hibon et al., 2011; Schenker et al., 2014), although the farthest ones have been mostly detected at some specific redshifts. Indeed, the strong emission lines of the sky at the Near-IR wavelengths, such as the OH lines, complicate the detection of the Lyα line when redshifted to such wavelengths (i.e. for z > 5.7). Therefore, astronomers use different narrow-band filters placed between the OH lines of the sky to detect LAEs, but such a strategy strongly reduces the redshift ranges that are accessible to ground-based telescopes.¹

Although the Lyα emission line is nowadays an efficient tool to identify distant star-forming galaxies, almost three decades had passed between the first prediction of the existence of bright LAEs at high-redshift and the first detection of such galaxies. Indeed, all surveys using the narrow-band technique or a spectroscopic approach between 2 < z < 6 had not given any LAE until the late 1990s (e.g. Djorgovski & Thompson 1992; Pritchet 1994). At that time, the lack of detection put into question all theoretical predictions on the presence of a strong Lyα line in the SED of high-redshift star-forming galaxies. Nevertheless, thanks to the development of both very large telescopes (KECK in 1996, VLT in 1998 and Subaru in 1999) and very sensitive CCD cameras, the first detection of LAEs occurred in 1998 when Dey et al. (1998) and Hu and Cowie (1998) found respectively one LAE at z = 5.34 and a small sample of 15 spectroscopically confirmed LAEs at z = 3.4 and 4.5. It is thus during this last decade that we have detected all LAEs known to date (at redshifts 2 < z < 7.62 using ground-based telescopes, and at z < 2 using UV space telescopes; Kunth et al. 1998, 2003, Deharveng et al. 2008, Cowie et al. 2010).

In parallel to the detection of LAEs, astronomers take an active interest in studying the physical properties of these galaxies with the aim of constraining the models of galaxy evolution. The physical properties of LAEs are now derived precisely thanks to deep observations of these objects (Boone et al., 2007; Gawiser et al., 2007; Finkelstein et al., 2007; Tapken et al., 2007). Overall, LAEs are intrinsically small and very compact (with an effective radius

¹The contamination of the sky emission lines renders the following redshifts more easily accessible for ground-based observations: z = 4.5, 4.8, 5.7, 6.5, 7.7 and z > 8
R \sim 0.6 \pm 0.1 \text{ kpc at } z \sim 6; \text{ Dow-Hygelund et al. 2007). They exhibit a low stellar mass (between } \sim 10^8 \text{ and } \sim 10^9 M_\odot \text{ at } z \sim 3, \text{ or between } \sim 10^6 \text{ and } \sim 10^{10} M_\odot \text{ at } z \sim 5; \text{ Gawiser et al. 2007, Lai et al. 2007, 2008, Pirzkal et al. 2007), they are composed of young stellar populations (< 90 Myrs et } z \sim 3 \text{) and they exhibit low dust attenuations (Gawiser et al., 2007; Lai et al., 2008) (see table 3.1). Due to the low mass of these galaxies, LAEs have moderate star formation rates (SFR) of about } 10 M_\odot \text{ yrs}^{-1} \text{ between } z \sim 3 \text{ and } z \sim 6 \text{ (Gawiser et al., 2007; Lai et al., 2008; Nilsson et al., 2007). The observed Ly} \alpha \text{ equivalent width of LAEs is able to reach > } 200 \text{ Å (Malhotra and Rhoads, 2004; Shimasaku et al., 2006), especially from the youngest and the most compact ones (Finkelstein, 2010).}

### 3.1.2 Selection by the Lyman Break technique (LBG galaxies)

As explained in section 2.2.4, the observed far-UV continuum of high-redshift star-forming galaxies exhibits a strong discontinuity at the Lyman limit, at about 912 Å (rest-frame wavelength). This spectral feature, also called "Lyman-break", is caused by the absorption of all photons shortward of 912 Å by neutral hydrogen atoms located either within the galaxy itself or along the line of sight in the IGM.

The Lyman-break is shifted into the optical wavelengths for redshifts } z > 3. \text{ Therefore, the use of ground-based optical telescopes makes the detection of distant galaxies on the basis of this break possible. The Lyman Break technique is the name given to this method. We give a good illustration of this technique in Figure 3.2 where we show the detection of a } z \sim 3 \text{ galaxy thanks to this spectral feature. In practice, this technique consists in observing the same field of sky through different broad-band filters (U, G and R bands in Fig. 3.2). Then, comparing the images each other, we can identify the objects which appear through successive filters (G and R bands in Fig. 3.2) and disappear through others because of the Lyman-break (U band in Fig. 3.2). The SED of each object is thereafter analyzed in order to confirm the detection of a distant star-forming galaxy on the basis of its strong Lyman break. The Ly} \alpha \text{ line (either in absorption or in emission) is also identified in the SED to derive the exact redshift of the galaxy.}

All galaxies detected with the Lyman-Break technique are commonly called Lyman break galaxies (LBGs). It is a very effective technique from which few thousands LBGs have been identified until now. This method is currently used to detect star-forming galaxies up to } z \sim 9-12 \text{ (Oesch et al., 2013) and has been used to identify a large number of galaxies at } 1 \leq z \leq 8 \text{ (Steidel et al., 1996, 1999, 2003; Cooke et al., 2005, 2006; Bouwens et al., 2007, 2013; Madau et al., 1996; Cristiani et al., 2000; Shapley et al., 2003; Ouchi et al., 2004a,b).}
Figure 3.2: The Lyman Break method. The upper panel shows the UV modelled SED of a star-forming galaxy located at \(z \sim 3\) (black line). At this redshift, an observer sees the Lyman-break at \(\lambda \sim 3700\,\text{Å}\) (red dashed line). Three different broad-band filters are chosen to detect a galaxy at such a redshift: the U, G and R broad-band filters, respectively centered at 3650 Å, 5100 Å and 6580 Å. The result of the Lyman Break technique is shown in the bottom panel (Burgarella et al., 2006): a \(z \sim 3\) starburst galaxy (in the circle) is detected through the G and R bands, but not in the U one because of the Lyman break. Source: www.astro.ku.dk/jfynbo/pics/.

Verma et al., 2007; Ly et al., 2009, 2011; Bielby et al., 2012).

Regarding their physical properties, many differences appear with regard to the ones of LAEs (see table 3.1). Besides the high star formation rates of LBGs (between \(10 - 100\, M_\odot\,\text{yr}^{-1}\) at \(z \sim 3\); Giavalisco et al. 2002), these galaxies tend to be older (\(< 300\,\text{Myrs at } z \sim 3\); Shapley et al. 2001), more massive (with \(\sim 10^8 < M < 10^{11}\, M_\odot\) between \(z \sim 1\) and \(z \sim 4\); Shapley et al. 2001, Verma et al. 2007, Gawiser et al. 2006, Elsner et al. 2008) and dustier than LAEs (Gawiser et al., 2007, 2006; Pentericci et al., 2007, Korner et al., 2010). Furthermore, in the light of their high mass, LBGs tend to be spatially more extended than LAEs (with a mean effective radius \(R \sim 1.8\) kpc at \(z \sim 3\), or \(R \sim 0.8 \pm 0.6\) kpc at \(z \sim 6\); Akiwama et al. 2008, Bouwens et al. 2006). The two observational selection techniques used to detect LBGs and LAEs may explain the differences observed between the physical properties of these two populations of galaxies. Indeed, due to a spectroscopic magnitude limit of \(R \leq 25.5\)
for detecting LBGs at $z \sim 3$ (Shapley et al., 2003), the Lyman Break technique tends to favor the detection of bright and massive (and possibly dustier) high-$z$ galaxies than the ones identified with the Narrow-band method.

Concerning the Ly$\alpha$ spectral feature of LBGs, a surprising diversity of strengths is observed. While the Ly$\alpha$ line is the intrinsically strongest hydrogen emission line produced in star-forming galaxies, $\sim 25\%$ of LBGs at $z \sim 3$ emit a strong Ly$\alpha$ emission line that would satisfy the Narrow-band excess criterion commonly used to identify LAEs (i.e. $\text{EW}(\text{Ly}\alpha) > 20$ Å). The rest of LBGs show either a weak Ly$\alpha$ emission line or a strong Ly$\alpha$ absorption line (Shapley et al., 2003). What could explain this strong Ly$\alpha$ absorption in LBGs? No clear answer have been reached so far. Nevertheless, it is important to notice that LBGs showing a Ly$\alpha$ line in absorption tend to be more massive, dustier and older than the ones showing a Ly$\alpha$ line in emission (Shapley et al., 2003; Pentericci et al., 2007). This highlights the complexity of the Ly$\alpha$ radiative transfer inside the ISM of star-forming galaxies, as discussed in chapters 4 and 5.

3.1.3 Other selection techniques

Although the techniques discussed above have let to the largest fraction of high-redshift galaxies identified until now, other methods of detection exist and lead to the identification of new galaxy populations.

- Selection by other emission lines (H$\alpha$, H$\beta$, O[II] and O[III] emitters)

Besides the Ly$\alpha$ line, a multitude of strong optical emission lines can be used by astronomers to identify galaxy candidates at high-redshifts. In this way, several surveys have already detected a multitude of distant star-forming galaxies at $z < 4.5$ (spectroscopically confirmed) on the basis of their bright H$\alpha$, H$\beta$, O[III]$\lambda\lambda 4959,5007$ or O[II]$\lambda\lambda 3726,3729$ emission lines (Thompson et al., 1996; Pahre and Djorgovski, 1995; Teplitz et al., 1998, 1999; Drozdovsky et al., 2005; Hayes et al., 2010). Especially at low redshifts (i.e. $z < 4$), the use of these optical emission lines is particularly efficient and appears as a good alternative to the Ly$\alpha$ line for finding distant star-forming galaxies. Indeed, let’s mention that recent surveys have showed that about 90% of $z \sim 2.2$ star-forming galaxies do not emit sufficiently bright Ly$\alpha$ emission to be detected by standard selection criteria (i.e. $\text{EW}(\text{Ly}\alpha) > 20$ Å; Hayes et al. 2010). Therefore, all low-redshift surveys based on the optical emission lines give larger galaxy samples than the ones obtained with the Ly$\alpha$ line.

Nevertheless, although very bright relative to their neighbouring continuum, the use of these optical emission lines has certain limitations. On the
Figure 3.3: This figure illustrates the SED of both nearby (upper panel) and distant (lower panel) quasars. When we compare both SEDs each other, we can see the presence of a multitude of absorption lines in the observed spectra of distant quasars. These different absorption lines are due to the presence of neutral hydrogen clouds located along the line-of-sight of the quasar in the IGM. source: http://www.astr.ua.edu/keel/agn/forest.html

one hand, the shift of the optical lines into the Near-IR wavelengths (at $z > 0.06$ for H$\alpha$ and $z > 0.41$ for O[III]λλ4959,5007) requires a high instrumental sensitivity to be detected. On the other hand, the high atmospheric opacity of the sky in infrared prevents any detection above $z \sim 4.5$ with ground-based telescopes (redshift limit for the H$\beta$ line; K-band limit). The use of the future generation of space telescopes, such as the James Webb Space Telescope (JWST), will render the exploration of further galaxies on the basis of these strong optical emission lines possible. Before that, the Ly$\alpha$ line remains one of our few windows to discover and to study galaxies located at very high-redshift (i.e. $z > 4.5$).

- Damped Ly$\alpha$ systems (DLAs)

Besides the strong spectral absorption feature blueward of 912 Å, the intergalactic HI clouds produce another type of absorption in the observed SEDs of distant quasars: the Ly$\alpha$-forest. Figure 3.3 presents a good illustration of this phenomenon, where we compare the observed SEDs of both nearby and distant quasars. As seen in this figure, the Ly$\alpha$-forest corresponds to a multitude
of absorption lines shortward of the Lyα emission line of the host galaxy. Each cloud of neutral hydrogen located along the line of sight absorbs a significant flux in the SED of the background quasar. This absorption occurs at the Lyα wavelength in the referential of the HI cloud (λ_{Lyα} = 1215.67 Å). Taking into account the redshift z_{HI} of the HI absorbing cloud, the absorption line is seen at the wavelength λ_{abs} = λ_{Lyα}(1 + z_{HI}) in the observed SED of the quasar. Both the strength and the width of the absorption lines (in the Lyα-forest) give us precious information on the hydrogen column density \(N_{HI}\) of the intergalactic HI clouds.

The analysis of the Lyα-forest allows astronomers to identify another class of distant galaxies, commonly called Damped Lyα absorbers (DLAs). If the hydrogen column density of the HI absorbing system exceeds \(2 \times 10^{20} \text{ cm}^{-2}\), the Lyα absorption line that appears in the Lyα-forest is particularly saturated and characterized by pronounced damping wings in the observed SED of a distant quasar (see figure 3.4). We classify such an object as a DLA.

Nowadays, DLAs in quasars spectra are assumed to result from the absorption of radiation by the ISM of foreground galaxies (Djorgovski et al. 1996, Petitjean 1998). However, the high flux of the background quasars makes the detection of the DLA host galaxies very challenging (Wolfe et al., 2005). Therefore, only a few DLA host galaxies have been identified by optical observations so far. We can mention the DLA host galaxies identified by Moller et al. (2004) and Rauch et al. (2008) on the basis of their weak Lyα emission line, as well as a bright DLA host galaxy that corresponds to a luminous LBG (DLA 2206-19A; Moller et al. 2002). These observations tend to confirm the nature of DLAs, classified as a class of distant galaxies particularly rich in neutral hydrogen.

Due to the very few detection of DLA host galaxies, the exact properties of these objects have not been well established yet. Big efforts are made nowadays to understand the similarities between this potential class of galaxies and the UV/Lyα-selected ones (LBGs and LAEs). The most accurate results derived until now from studies of DLAs is their chemical composition. While DLAs show weak evidence of dust attenuation, the mean metallicity of these galaxies is systematically lower than the ones derived for other galaxies at the same redshift (especially between the redshifts \(z=0.5\) and \(z=3.0\), with a metallicity going from \(10^{-3} Z_{\odot}\) to \(\sim Z_{\odot}\); Pettini 2004, Wolfe et al. 2005). In the local Universe, some DLAs show similarities with LAEs, especially in terms of star formation rate and continuum emission properties (Rauch et al. 2008). Nevertheless, no conclusion can be formulated for the moment on the exact

\(^1\)The hydrogen column density \(N_{HI}\) corresponds to the number of hydrogen atoms located along the line-of-sight. It is expressed in terms of number of hydrogen atoms per square centimeters (\(\text{cm}^{-2}\)).
properties of this population of galaxies.

- **Selection in far-infrared and submillimeter wavelengths (SMGs, LIRGs and ULIRGs)**

For several decades, astronomers have also probed high-redshift star-forming galaxies from observations in far-infrared and submillimeter wavelengths. Such attempts have allowed to identify new populations of very powerful star-forming galaxies.

While some starburst galaxies show no evidence of dust extinction (such as a large fraction of LAEs), there exist high-redshift galaxies in which dust attenuation fully obscures both the UV and optical radiation. All this absorbed energy is re-emitted thereafter by dust in far-infrared wavelengths, at about 60 - 100 \( \mu \text{m} \) (rest-frame wavelengths). In this way, depending on the redshift of the host galaxies, an observer will observe this very bright far-infrared radiation into the submillimeter (submm) or millimeter (mm) field. Therefore, the detection of distant starburst galaxies in far-infrared and submillimeter wavelengths consists in detecting the very bright dust emission signature of these objects.

All galaxies detected on the basis of their thermal dust emission are com-
monly called *Submillimeters Galaxies* (SMGs), *Luminous Infrared Galaxies* (LIRGs) or *Ultra Luminous Infrared Galaxies* (ULIRGs). This classification is just based on both the wavelengths range at which the galaxy is detected\(^1\) and the far-infrared luminosity of the object\(^2\).

Since the advent of very sensitive detectors, such as SCUBA (Holland et al., 1999, Arger et al., 1998, Eales et al., 1999) and LABOCA (Kreysa et al., 2003), a very large number of SMGs have been identified so far (Scott et al., 2002; Webb et al., 2003; Borys et al., 2003; Geach et al., 2005; Hodge et al., 2013). In terms of physical properties, it is interesting to notice the differences that exist between these dust-obscured star-forming galaxies and the UV/Ly\(\alpha\)-selected ones, such as LAEs and LBGs (see table 3.1). SMGs tend to be the most massive and powerful star-forming galaxies at high-redshift (with a prodigious SFR of about \(\sim 1000 \ M_\odot \, \text{yr}^{-1}\), as derived from the rest-frame far-infrared luminosity of SMGs; e.g. Chapman et al. 2005). Furthermore, they are more luminous and dustier than LAEs and LBGs. However, the exact nature of SMGs remains still unclear. In particular, in contrast of both LAEs and LBGs populations, SMGs seem often to show evidence for an AGN contribution in their spectrum (the AGN fraction of \(z \sim 2.3\) SMGs yields to \(\sim 17\%\); Wang et al. 2013). Nevertheless, the presence of polycyclic aromatic hydrocarbon (PAH) features in the far-infrared spectra of high-z SMGs suggests also that starburst activity contributes significantly to the Far-infrared luminosity of these galaxies (Lutz et al. 2005).

Despite these main differences, few similarities exist between submillimeter galaxies and UV/Ly\(\alpha\)-selected ones. First, although very dusty, a large fraction of SMGs still exhibit a relatively bright UV and optical radiation in their SEDs. Therefore, 80\% of SMGs at \(z \approx 2\) could be found using the Lyman Break technique (Reddy et al. 2005). Second, SMGs prove to be particularly bright in Ly\(\alpha\). Using the SCUBA galaxies sample at \(z = 1.7\), about 80\% of SMGs emit a strong Ly\(\alpha\) emission line that would satisfy the Narrow-band technique criterion used to select LAEs (i.e. \(\text{EW(Ly}\alpha) > 20 \ \AA\); Chapman et al. 2005, Nilsson & Moller 2009). Therefore, there exists a clear overlap between SMGs, LBGs and LAEs.

The strong Ly\(\alpha\) emission lines observed in the SEDs of SMGs is surprising in view of the strong dust attenuation UV and Ly\(\alpha\) photons must experience.

---

\(^1\)While galaxies detected in submillimeter or millimeter wavelengths are normally referred to as "submm galaxies" or SMGs, the ones detected with far-infrared camera are classified as "Luminous infrared galaxies" (LIRGs) or "Ultra luminous infrared galaxies" (ULIRGs).

\(^2\)The far-infrared luminosity criterium consists in distinguishing LIRGs from ULIRGs. While ULIRGs correspond to galaxies that exhibit a far-infrared luminosity above \(10^{12} \ L_\odot\), LIRGs correspond to galaxies showing a lower luminosity.
in these galaxies. This highlights again the complexity of the Lyα radiative transfer in the ISM of star-forming galaxies, which is the question at hand in this thesis. Other physical properties of the ISM of SMGs seem to help Lyα photons to escape easily from these dusty objects.

3.2 The Lyα line in astrophysics and cosmology

Besides the interest of using the Lyα line in detecting and confirming the redshift of distant starburst galaxies, the potential of the Lyα line in cosmology research is also enormous. In this section we give an overview of the versatility of the Lyα line for astrophysical and cosmological purposes. In particular, we will focus on the most important information that is possible to derive by analyzing the features of the Lyα emission line of distant star-forming galaxies.

3.2.1 The star formation rate of galaxies

The star formation rate (SFR) is one of the most important tools for our understanding of the evolution of galaxies. The analysis of the SFRs of starburst galaxies at different redshifts gives precious information on both the phases of intense star formation in the past of the Universe and its evolution over cosmic time (Madau et al., 1996; Bouwens et al., 2007, 2008).

The SFR (expressed in solar mass units, $M_{\odot}$ yr$^{-1}$) corresponds to the stellar mass produced per year in a galaxy. Nowadays, different techniques are used to estimate the SFRs of nearby and distant galaxies, each technique being developed for different wavelength ranges across the SEDs of galaxies: far-UV radiation, far-IR radiation (Kennicutt Jr., 1998), radio emission (Condon, 1992) or even X-rays radiation (Ranalli et al., 2003). For high-redshift galaxies ($z > 2$), the most commonly used technique to derive the SFRs consists in using their rest-frame far-UV continuum luminosity between 1500 Å and 2800 Å (Steidel et al., 1999; Giavalisco et al., 2004; Bouwens et al., 2006, 2007, 2008). Firstly, the far-UV continuum radiation of distant galaxies has the advantage to be redshifted into the optical field for galaxies further away than $z \approx 2$, making ground-based optical observations possible. Secondly, the far-UV radiation can be seen as an "instantaneous" tracer of the current star formation rate of galaxies, because produced almost entirely by the newly formed and shortlived massive stellar populations ($M > 5M_{\odot}$; $t < 100$ Myr). According to the calibration of Kennicutt (1998), where it is assumed a Salpeter initial mass function (IMF; Salpeter 1955) and a constant star formation over a period of $> 10^8$ years, the SFR of a star-forming galaxy is proportional to its intrinsic far-UV luminosity ($L_\nu$). It is given with good approximation by the relation:
Table 3.1: Summary of the main physical properties of different populations of high-redshift starburst galaxies. From this table, some similarities and differences can be noticed between each galaxy population. In this table, we emphasize on the Ly$\alpha$ emission observed from each type of galaxies, mainly because it constitutes a useful tool to be able to unify all these population of galaxies. Overall, all values indicated in this table result from surveys carried out at $z \sim 3$.

<table>
<thead>
<tr>
<th>Properties</th>
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<th>DLA</th>
<th>LAE</th>
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<td>strong</td>
<td>absorption</td>
<td>80%</td>
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<td>$\sim 10^{40}$ erg s$^{-1}$</td>
<td>$\sim 10^{42}$ erg s$^{-1}$</td>
<td>$\sim 10^{41}$ erg s$^{-1}$</td>
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<tr>
<td>SFR (z = 3)</td>
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<td>0-1 M$_{\odot}$ yr$^{-1}$</td>
<td>1-10 M$_{\odot}$ yr$^{-1}$</td>
<td>10$^2$-10$^3$ M$_{\odot}$ yr$^{-1}$</td>
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<td>age</td>
<td>&gt; 300 Myr</td>
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<td>mass</td>
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<tr>
<td>nature of Starburst</td>
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<td>obscured spectrum</td>
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The Ly$\alpha$ emission

Values indicated in this table result from surveys carried out at $z \sim 3$. From each type of galaxies, mainly because it constitutes a useful tool to be able to unify all these population of galaxies. Overall, all similarities and differences can be noticed between each galaxy population. In this table, we emphasize on the Ly$\alpha$ emission observed from each type of galaxies. From this table, some
Besides using the rest-frame far-UV luminosity, both the H\(\alpha\) and Ly\(\alpha\) recombination lines of the hydrogen atom constitute a good alternative to measure the SFRs of distant star-forming galaxies (Ajiki et al., 2003; Taniguchi et al., 2005; Tapken et al., 2007). As explained in section 2.2, the hydrogen lines of a starburst galaxy reemit a large fraction of the stellar luminosity shortward of the Lyman limit (i.e. at \(\lambda < 912 \text{ Å}\)). They provide therefore a direct and sensitive probe of the young massive stellar populations of the host galaxies (O and B-type stars). However, while only the H\(\alpha\) line of low-redshift galaxies is accessible for ground-based telescopes (this line is redshifted to wavelengths which cannot be observed easily from the ground beyond \(z \sim 2.6;\) K-band limit), the Ly\(\alpha\) line has the advantage to be detected in the optical field for \(z < 6.5\). The Ly\(\alpha\) line thus appears particularly useful for deriving the SFRs of very high-redshift galaxies, where the UV continuum radiation of these galaxies can be too weak to be measured. Following again the calibration of Kennicutt (1998) and the same assumptions, astronomers usually derive the SFRs of star-forming galaxies from the H\(\alpha\) and the Ly\(\alpha\) luminosities (\(L(H\alpha)\) and \(L(Ly\alpha)\)) using the following relations:

\[
SFR_{H\alpha}(M_\odot \text{yr}^{-1}) = 7.9 \times 10^{-42} L(H\alpha) \text{ ergs s}^{-1} Hz^{-1} \quad (3.2)
\]

\[
SFR_{Ly\alpha}(M_\odot \text{yr}^{-1}) = 9.1 \times 10^{-43} L(Ly\alpha) \text{ ergs s}^{-1} Hz^{-1} \quad (3.3)
\]

The equation 3.3 is just derived from the equation 3.2 assuming an intrinsic flux ratio Ly\(\alpha\)/H\(\alpha\) = 8.7 in star-forming galaxies (case B of the recombination theory, Osterbrock et al. 1989). In both equations 3.2 and 3.3, both the H\(\alpha\) and the Ly\(\alpha\) luminosities correspond to the intrinsic ones. This gives an idea of the reliability of each method to derive the SFR of individual galaxies. On the one hand, the H\(\alpha\) line provides an accurate and reliable estimate of the SFRs (as a simple correction for dust extinction allows to derive the correct intrinsic H\(\alpha\) luminosity). On the other hand, the complexity of the physics of the Ly\(\alpha\) line makes the use of this line less reliable and tends to underestimate the correct SFR of galaxies. (Tapken et al., 2007). Indeed, the very complex transport experienced by Ly\(\alpha\) photons inside the ISM of star-forming galaxies makes the Ly\(\alpha\) line suffering greater extinction than non-resonant photons, which implies that a simple dust correction is not enough to go back to the intrinsic Ly\(\alpha\) luminosity. This problem renders the interpretation of the Ly\(\alpha\) line extremely uncertain and prevent us from deriving precisely the SFRs of galaxies from this line.

In a cosmological point of view, each indicator mentioned above enable to measure the SFRs at different redshifts, allowing astronomers to study the evo-
Figure 3.5: This figure illustrates the evolution of the SFR density (or SFRD, expressed in $M_\odot \text{ yr}^{-1} \text{ Mpc}^3$) of the Universe including only LBGs and SMGs galaxies with UV luminosities brighter than $0.3L^*_{z=3}$ (upper panel) and brighter than $0.04L^*_{z=3}$ (bottom panel) ($L^*_{z=3} \approx 5.42 \times 10^{28} \text{ erg s}^{-1} \text{ Hz}^{-1}$; Bouwens et al. 2007). The SFR density is shown both with and without a correction for dust extinction (the upper dots are corrected for dust attenuation, which is not the case for the other ones). The orange and blue areas show respectively the approximate uncertainties. In particular, we can clearly notice that the SFR density reached a maximum in the past, at about $z \approx 2-3$. 

The solution of the star formation over cosmic time. The figure [3.5] presents a good illustration of the evolution of the star formation rate with redshift (Bouwens et al., 2007). This figure, commonly called "Madau diagram" (Madau et al., 1996), represents the star formation rate density (SFRD) (i.e. the star formation rate measured per unit comoving volume, usually expressed in $M_\odot \text{ yr}^{-1} \text{ Mpc}^3$) as a function of the redshift $z$. Both LBGs and SMGs galaxies are taken into account in this diagram. While the derived SFRD is estimated with the best dust correction (orange field) and without any dust correction (blue field), we can notice the divergence of the indicators at high-redshifts, due to the fact that some effects are more or less corrected according to the studies (incompleteness for low luminosity galaxies, ...). Nevertheless, we can clearly notice that the SFR density reached a maximum at about $z \approx 2-3$ (that is about $\sim 10$ or
Figure 3.6: Left panel: UV Luminosity functions of LAEs located at redshift $z \sim 3$ (upper panel), $\sim 4$ (middle panel) and $\sim 6$ (lower panel) (Ouchi et al., 2008). While no evolution is found between redshift 3 and 4, the UV LF of LAEs increases between $z \sim 4$ and $\sim 6$ suggesting an increase in number and/or in luminosity of LAEs with redshift. Right panel: UV luminosity functions of LBGs located at redshift $z \sim 4, 5, 6$ and 7-8 (Bouwens et al., 2007). The opposite evolutionary trends of LAEs is found for LBGs, where the UV LF decreases with redshift.

11 billion years ago) before decreasing rapidly to the low present-day value.

3.2.2 The Ly$\alpha$ and UV Luminosity functions of galaxy populations

Both the UV and Ly$\alpha$ luminosity functions of distant star-forming galaxies (LFs) prove to be two precious observational tools for our understanding of the evolution of distant galaxies with redshift. In particular, the Ly$\alpha$ ones are also widely used by astronomers to probe the history and the epoch of the cosmic reionization of the Universe (section 3.2.3).

The luminosity function of a population of galaxies (i.e. for instance LAEs) describes the number density of galaxies (i.e. the number of galaxies per comoving $Mpc^3$) showing a luminosity between $L$ and $L + dL$. Comparing the luminosity functions of galaxies at different redshift allows astronomers to identify an evolution in number or in luminosity of galaxies with time. As shown in figure 3.6, the observed UV luminosity functions (derived between 1300 Å and 1600 Å, in rest-frame) of distant galaxies have a similar shape at any redshift. This shape is well approximated by the Schechter function
The different parameters that describe the Schechter function (i.e. $\alpha$, $L^*$ and $\phi^*$) can be used to compare more easily the evolution of the UV and Ly$\alpha$ luminosity function of galaxies at different redshifts.

Due to the detection of a very large number of high-redshift starburst galaxies since the end of the 1990s, many groups have taken an active interest in constructing both the UV and Ly$\alpha$ luminosity functions of LAEs and LBGs at different redshift $z$ with reasonable accuracy (Malhotra and Rhoads, 2004; Shimasaku et al., 2006; Kashikawa et al., 2006; Bouwens et al., 2007, 2008; Ouchi et al., 2008, 2010). In particular, as shown by Ouchi et al. 2008 (see figure 3.6, left panel), the evolution of the UV luminosity function of LAEs shows a clear increase in number and/or UV luminosity between $z \sim 3-4$ and 5.7. But, on the other hand, the UV luminosity function of LBGs (see figure 3.6, right panel) tends to show an opposite evolutionary trends of LAEs, namely, a decrease in number and/or luminosity with increasing redshift. Assuming no clear evolution in UV luminosity of LAEs and LBGs with redshift, such a result would imply that the ratio in number density LAEs/LBGs would increase with redshifts (and that Ly$\alpha$ emission should be more common in the SED of remote young galaxies at early epochs). Qualitatively, such a trend has been confirmed after studying spectroscopically different samples of UV-continuum selected galaxies (LBGs) at various redshifts. Indeed, while Reddy et al. (2008) found a LAE fraction of 8% at $z \sim 2$, Shapley et al. (2003) and Noll et al. (2004) concluded that 25% of UV-continuum selected galaxies were LAEs at $z \sim 3$. Although different results have been obtained by independent groups at higher redshifts (due to different selection effects or systematic errors), an increase in the LAE fraction with redshift is always obtained. In particular, LBGs galaxies with $4 < z < 5$ tend to show a LAE fraction of $\sim 36\%$ (Nool et al. 2004) and the ones at $z \sim 6$ show a fraction up to 60% - 80% (Vanzella et al. 2006; Shimasaku et al. 2006).

3.2.3 Probing the epoch of the cosmic reionization of the Universe

As mentioned above, the Ly$\alpha$ luminosity function (LF(Ly$\alpha$)) of distant star-forming galaxies constitutes a very useful observational tool to probe the history of the cosmic reionization of the Universe.

After crossing a cold and neutral period without any sources of visual radiation (the dark age), this long period of the history of the Universe had continued until the formation of the first stars and galaxies ($z \sim 10 - 30$) which
emitted energetic enough photons to ionize the surrounding neutral hydrogen gas of the IGM. This process marked the beginning of the cosmic reionization of the Universe (see figure 2.1). Unfortunately, no observation has identified either the sources at the origin of the cosmic reionization of the Universe or the exact chronology of this process so far.

Until now, different observations have provided many constraints on the epoch of the reionization. Firstly, the Ly$\alpha$-forest and the Gunn-Peterson effect observed on the SEDs of distant quasars (see section 2.2.4) indicate that the IGM was highly ionized at $z \sim 5.7$ (Gallerani et al. 2008). This suggests that the reionization of the IGM took place before $z \sim 6$. Secondly, another constraint can be provided by the polarization of the Cosmic Microwave Background (CMB), which is produced by Thompson scattering of CMB photons on the free electrons of the IGM. Thus, the analysis of the CMB polarization allows to derive directly the ionization fraction of hydrogen $x_{HI}$ in the IGM and the exact epoch of the reionization. According to Spergel et al. (2007), the CMB observations by WMAP indicates an early reionization of the Universe at about $z \sim 11$.

Another tracer of the epoch of reionization is the Ly$\alpha$ emission line of LAEs at high-redshift. This method is based on the fact that the Ly$\alpha$ photons are very sensitive to the neutral hydrogen gas and can therefore undergo a
strong attenuation getting through a neutral IGM. Therefore, a clear decrease in the Ly\(\alpha\) luminosity of LAEs is expected at the redshift \(z_{\text{reion}}\) of the cosmic reionization due to the strong attenuation undergone by the Ly\(\alpha\) photons in the neutral IGM. However, such approach assumes no evolution of the physical properties of LAEs with redshift. This assumption allows astronomers to interpret any decrease of the Ly\(\alpha\) luminosity function as an increase in the IGM opacity. Following this method, Ouchi et al. (2010) analyze a sample of 207 LAEs at \(z \sim 6.6\) and found a decrease of \(\text{LF}(\text{Ly}\alpha)\) of 30\% between \(z = 5.7\) to \(z = 6.6\) in the case of pure luminosity evolution (see figure 3.7). Nevertheless, comparing the evolution of the \(\text{LF}\,(\text{Ly}\alpha)\) with various reionization models including analytic, semi-analytic, and radiative transfer models, Ouchi et al. (2010) concluded that the IGM was not highly neutral at \(z = 6.6\) \((x_{\text{HI}} < 0.20)\), indicating that the major reionization process took place early, at \(z > 7\). These conclusions are consistent with the ones reached from other observations, as discussed above.

The Ly\(\alpha\) line profile of LAEs can also be used to identify some effects of the cosmic reionization. As shown by Haiman (2002), the Ly\(\alpha\) line of a LAE embedded in an IGM prior to the reionization epoch can be still detected if it is surrounded by a large intergalactic HII region\(^1\). In this configuration, only the Ly\(\alpha\) photons shifted to the red side of the line center would be able to get through the IGM and be detected by an observer. As a consequence, a particular Ly\(\alpha\) line profile would emerge, showing a redshifted emission and strong asymmetry. Furthermore, another proof of the cosmic reionization would be the observation of a clear anti-correlation between the width of Ly\(\alpha\) line profile and the Ly\(\alpha\) luminosity of LAEs, if these galaxies lie in a neutral IGM (Haiman and Cen, 2005). This effect is simply due to the fact that fainter LAEs, preferably residing in smaller HII regions, are affected by stronger Ly\(\alpha\) scattering within the IGM.

Comparing their observations with the model of Haiman and Cen (2005), Ouchi et al. (2010) did not find any clear evolution of the Ly\(\alpha\) line profiles between \(z \sim 5.7\) and 6.6 (see figure 3.8, right panel), nor any anticorrelation between the Ly\(\alpha\) luminosity and the width of the Ly\(\alpha\) line profiles. These results indicate that the reionization process took place earlier (at \(z > 7\)), which is well consistent with the conclusions obtained from the analysis of the \(\text{LF}(\text{Ly}\alpha)\) of LAEs.

\(^1\)This large HII region corresponds to a large ionized region produced by the ionizing photons \((\lambda < 912 \, \text{Å})\) emitted by the LAE. The galaxy is thus located at the center of this large HII region.
Figure 3.8: Cosmological simulations (from a large-scale dark-matter simulation; Bolshoi simulation, by Anatoly Klypin and JOEL Primack) that show the filamentary distribution of the barionic matter (red channel) in the early epochs of the Universe. While the distribution of all filaments follows the one of the dark-matter, the barionic gas is progressively infalling by gravity towards the more massive dark-matter halos, where galaxies are forming. The inset is a zoomed-in, high-resolution image of a smaller part of the "cosmic web" (3 million parsec across), from the cosmological simulation that includes barionic gas and dark matter. Galaxies are forming in the highly contrasted central region. Source: Cantalupo et al. (2014).

3.2.4 Studying the circumgalactic medium of galaxies

Besides using the Lyα line for studying both the evolution of galaxy properties and the epoch of the cosmic reionization, the Lyα line offers a unique probe of the extended atomic hydrogen gas that surround galaxies at high-redshift.

The environment of high-redshift galaxies is likely full of neutral hydrogen gas. Indeed, as shown in figure 3.8, cosmological simulations of structure formation in the Universe suggest that galaxies were formed in massive dark-matter haloes, themself connected each other by long filaments of hydrogen that were progressively infalling towards the most massive haloes over the cosmic time. Such a structure of the early Universe is usually called the "cosmic web". Measuring the properties of the neutral hydrogen gas located in the environment of galaxies (i.e. inside the Circumgalactic Medium, or CGM)
would provide therefore important information for different purposes, such as understanding either the galaxy formation and evolution or the formation of large structures in the Universe.

While the filaments of the "cosmic web" have never been observed directly (their existence remains only the results of computer simulations), the properties of the HI gas located in the CGM of galaxies is still poorly understood from an empirical angle. In order to measure the properties of circumgalactic HI halos (i.e. the HI mass, density, distribution and kinematics), we must find a way of observing it. A direct method would consist in observing the 21cm emission line of the circumgalactic neutral hydrogen atoms. However, while such observations are relatively easy in the local Universe, such attempts remain either extremely challenging or impossible at very high-redshift. Then, another method used by astronomers for mapping the circumgalactic HI of individual galaxies consists in using any strong resonant lines of hydrogen, such as Ly$\alpha$ line. The idea of this method consists in taking advantage of the very high probability of scattering of the Ly$\alpha$ line on HI atoms. Therefore, while the central galaxy is considered as a source of Ly$\alpha$ photons, these photons are expected to scatter on the circumgalactic HI atoms and "illuminate" this surrounding medium of galaxies. Such scattering effect produced the so-called "Ly$\alpha$ halo" around star-forming galaxies (see figure 3.9, right panel; Ostlin et al., 2009).

Based on a numerical approach, Dijkstra and Kramer (2012) succeed to reproduce the large Ly$\alpha$ halos surrounding several $z \sim 2.65$ LBGs (Steidel et al., 2011). From their numerical work, they could constrain for the first time the properties of the cold circumgalactic HI gas (radius, velocity, HI mass, density). In particular, their results highlighted the strong feedback of the stellar-formation of galaxies on the CGM, where the reproduction of the Ly$\alpha$ halos around LBGs require outflows in which the HI gas decelerate at large radii after their initial acceleration (the HI gas being outflowing at a radial velocity up to $V_{\text{exp}} = 400 \text{ km} \cdot \text{s}^{-1}$ from the central starburst).

Besides producing an extended Ly$\alpha$ haloes by pure scattering around star-forming galaxies, Ly$\alpha$ photons can also be produced by recombination within the circumgalactic gas that surrounds bright quasars. Indeed, the very strong ionizing power of quasars can ionize the HI gas located in both the galaxy and in the circumgalactic medium. As shown in figure 3.9 (left panel), Cantalupo et al. (2014) discovered a very extended Ly$\alpha$ halo of 460 physical kpc of diameter around the quasar UM287 located at $z \sim 2.3$. This large Ly$\alpha$ halo, whose Ly$\alpha$ emission is produced by fluorescence of the circumgalactic HI atoms, is extended well beyond the virial radius of any plausible associated dark matter halo which confirms the first detection of a "cosmic web" filament. From their analysis, Cantalupo et al. (2014) conclude that the amount of cold gas observed
Figure 3.9: Mapping of the circumgalactic hydrogen gas surrounding galaxies and quasars using the Ly$\alpha$ line. **Left panel:** Deep imaging of the Ly$\alpha$ emission (blue color) around the $z = 2.3$ quasar UM287 (at the center of the image), obtained with the Keck telescopes (Cantalupo et al., 2014). The ionizing radiation from the quasar makes the surrounding intergalactic gas glow, revealing the morphology and physical properties of a "cosmic web" filament. **Right panel:** Color composite image of the nearby star-forming galaxy ESO 338-04 ($z = $), as observed with the HST (Östlin et al., 2009). While both the green and the red channels show the UV continuum emission at 1500 Å (rest-frame) and the nebular $H^\alpha$ emission of the galaxies, the blue color shows the continuum-subtracted Ly$\alpha$ emission observed from this object. Let’s remark the extended Ly$\alpha$ emission (i.e. Ly$\alpha$ halo) that surround ESO 338-04.

in the nebula is at least ten times larger than what is expected from cosmological simulations. Such a result suggests that a population of intergalactic gas clumps with sub-kpc sizes might be missing within current numerical models, providing therefore useful test-bed to refine the current model of structure formation in cosmological simulations.

### 3.2.5 Identifying the first generation of stars

Another illustration of the great potential of the Ly$\alpha$ line in cosmology research concerns the search for the first generation of stars in the early Universe. As predicted by the current theories, the first generation of stars are expected to form by gravitational contraction of primordial gas clouds either within small dark matter halos at redshifts $z \sim 10 - 60$ (Trenti and Stiavelli, 2009) or within more massive halos hosting some of the first galaxies at $z < 15$ (Johnson et al., 2008; Stiavelli and Trenti, 2010). This first generation of stars is commonly called population III.

The roles that astronomers allocate to population III stars in cosmology
Figure 3.10: This figure shows the theoretical intrinsic SED including Hydrogen and Helium recombinasion lines for zero metallicity population III stars (Far-UV and optical fields). The solid line takes into account both the nebular and the stellar contributions to the SED. We can notice the presence of strong He II lines ($\lambda = 1640, 3203$ and $4686$ Å, thick red dashed lines) and the importance of the Ly$\alpha$ line. source: [Schaerer, 2002].

are important, either for explaining the metal enrichment of the most metal-poor stellar populations of the local Universe (i.e. population II stars) or for explaining the cosmic reionization of the Universe. However, despite intense research, the existence of population III stars remains entirely hypothetical. While the first population III stars (formed beyond $z \sim 10$) seem too faint to be detected, even with the future generation of telescopes ([Greif et al., 2009], [Rydberg et al., 2012]), the existing telescopes could be used to detect the second generation of Population III stars (the ones formed at $z < 15$) using their particular Ly$\alpha$ spectral signatures that set them apart from usual objects ([Schaerer, 2002], [Zackrisson et al., 2011]).

During their formation, the particular chemical composition of the population III stars (i.e. only composed of hydrogen and helium) tends to suppress the fragmentation of the first collapsing gas clouds that gives rise to them. Therefore, population III stars are expected to be very massive ($10 M_\odot < M$
Figure 3.11: This figure shows the temporal evolution of the Ly$\alpha$ equivalent width EW(Ly$\alpha$) for instantaneous bursts and different metallicities (those expected for population III stars): $Z = 0$ (short-dashed line), $Z = 10^{-7}$ (solid line) and $Z = 10^{-5}$ (dotted line). The expected values of EW(Ly$\alpha$) for a constant star formation history (SFR = const.) and metallicities $Z < 10^{-5}$ are plotted on the right using open squares. Source: Schaerer (2003).

< 100 $M_\odot$; e.g. Clark et al. 2011), with a very short lifetime (t < $2 \times 10^7$ yrs for M = 9 $M_\odot$). Furthermore, the very high effective temperature of population III stars, on the order of $T > 10^5$ K, implies a very high flux shortward of the Lyman-limit (at $\lambda < 912$ Å). As a result, such stars are surrounded by a resulting HII region with several characteristic spectral properties (see figure 3.10). Indeed, a multitude of Hydrogen and Helium recombination lines are expected from this surrounding nebula, such as an extremely large Ly$\alpha$ line and noticeable He II lines (1640, 4686 Å). As shown in figure 3.11, the Ly$\alpha$ rest-frame equivalent width displayed by Population III stars could be higher than 1000 Å, while normal stellar population models predict a maximum value of 240 Å (i.e. population I stars). For the HeII$\lambda$1640 line, a large range of equivalent widths up to 80 Å have been predicted for very young and pure population III stars (schaerer03, Raiter 10, Hayes11).

Interestingly, several surveys have already revealed the existence of EW(Ly$\alpha$) higher than 240 Å in the spectra of a large fraction of high-redshift LAEs. In
particular, among the LAEs detected in the large LALA survey at $z = 4.5$, approximately $60\%$ of them exhibited $\text{EW}(\text{Ly}\alpha) > 200$ Å, with a median value of 450 Å (Malhotra and Rhoads, 2002). Shimasaku et al. (2006) also found a sample of 28 LAEs at $z \sim 5.7$ showing a median equivalent width of $\text{EW}(\text{Ly}\alpha) \sim 233$ Å. This observed value proves to be anomalously large if we take into account the transmission of the IGM at this redshift (0.3 - 0.5; Dijkstra et al., 2007), increasing this value by a factor of 3. Finally, more recently Kashikawa et al. (2012) detected a LAE with an extremely large $\text{EW}(\text{Ly}\alpha)$ of $\sim 900$ Å at $z = 6.5$. Although these large Ly$\alpha$ equivalent widths seem to be consistent with the presence of population III stars in the host galaxies, this explanation proves to be dismissed by other observations. Indeed, supplementary observations of the LALA survey have shown the absence of the significant HeII$\lambda 1640$ line in all the sample, dismissing the presence of Population III stars in these galaxies (Dawson et al., 2004; Nagao et al., 2008).

Nowadays, the origin of these very large $\text{EW}(\text{Ly}\alpha)$ remains unclear. Some observations have tested the scenario that an Active Galactic Nuclei (AGN) may explain these very large values. But this hypothesis has also been dismissed by some observations of the LALA survey in X-rays, where no more than 5% of LAEs host an AGN (Wang et al., 2004). Nowadays, several alternatives exist to explain these high $\text{EW}(\text{Ly}\alpha)$. We can first mention the numerical studies of Roy et al. (2010), Xu et al. (2011) and Yajima and Li (2012) who studied the Ly$\alpha$ radiative transfer in spherical galactic clouds of dust-free gas and found that the Ly$\alpha$ radiation may be appreciably delayed compared to the UV continuum, resulting in a higher $\text{EW}(\text{Ly}\alpha)$. Indeed, unlike UV continuum, Ly$\alpha$ photons typically experience many scattering process in the cloud due to its resonant nature, resulting in a time delay of the Ly$\alpha$ emission. Nevertheless, the most popular explanation to these high $\text{EW}(\text{Ly}\alpha)$ seems to be a complex effect of Ly$\alpha$ radiative transfer in a clumpy ISM, as originally proposed by Neufeld (1991). We will come back to this scenario in chapter 4 and in both paper I and II we present at the end of this thesis.
4. Studying Lyman-\(\alpha\) radiative transfer in star-forming galaxies

In the previous chapters, the problem of the Ly\(\alpha\) radiative transfer in star-forming galaxies has not been raised in detail. While the Ly\(\alpha\) line features of distant starburst galaxies (luminosity, EW, line profile) are widely used by astronomers to derive either the physical properties of distant galaxies or the ionization state of the IGM, these features prove to be strongly affected by the complex transport experienced by the Ly\(\alpha\) photons inside the ISM of galaxies. It is therefore vital that these problems be understood as well as possible. This is exactly the aim of this thesis. Throughout this chapter, we first give a large overview of the physical parameters that enter in the Ly\(\alpha\) radiative transport in the ISM of star-forming galaxies. In particular, we will focus on the effects produced by each ISM quantity on Ly\(\alpha\), as revealed by deep observations of low-redshift star-forming galaxies. Second, we focus on the Ly\(\alpha\) line of high-redshift galaxies. We will describe here both the main distortion that the Ly\(\alpha\) line experiences within their ISM and the main physical parameters it is possible to derive by understanding the Ly\(\alpha\) radiative transfer. Finally, we present a pioneer and ambitious observational project that will allow us to go deeper into the study of the Ly\(\alpha\) transport in the ISM of nearby galaxies. This project, called LARS, has taken part in my PhD research program.

4.1 Identifying the ISM quantities that enter in the Ly\(\alpha\) transport from observations of nearby star-forming galaxies

The first theoretical models of Partridge and Peebles (1967) and Meier (1976) predicted that high-redshift star-forming galaxies should be detectable thanks to their strong Ly\(\alpha\) emission line. More precisely, this population of distant galaxies was expected to be detectable with the existing technology prior to the 1970s, because relatively bright in Ly\(\alpha\) (with an intrinsic Ly\(\alpha\) line containing \(\sim 7\%\) of the total bolometric luminosity of the host galaxy; Patridge & Peebles 1967) and numerous (with a possible surface density in the order of \(10^4\) - \(10^5\) deg\(^{-2}\) at \(z \sim 5\); Pritchet 1994). However, the first attempts to
detect high-redshift galaxies in Lyα gave quite meager results with no significative detection in Lyα between $2 < z < 5$ (Djorgovski and Thompson, 1992; Pritchet, 1994). The very rare Lyα emitting galaxies detected in such a redshift range were always associated in some way with AGNs (either hosting an active nuclei or being a companion of a high-z quasar; Chambers et al. 1990; Djorgovski et al. 1985, 1987; Lilly 1988; McCarthy et al. 1987). As a result, in the early 1990s, it turned out that the Lyα line of distant star-forming galaxies was either fainter than those predicted or simply absent from the SED of those galaxies. All these incoherence questioned therefore the real effectiveness of the Lyα line in detecting high-redshift galaxies.

In order to understand this strong discrepancy between the models and the observations, astronomers have taken an active interest in studying the Lyα line of low-redshift star-forming galaxies (Meier and Terlevich, 1981; Neufeld, 1990; Charlot and Fall, 1993; Kunth et al., 1998; Mas-Hesse et al., 2003; Östlin et al., 2009; Hayes et al., 2013). Thanks to the high resolution observations of those nearby analogues of the remote young galaxies by means of UV space
telescopes (i.e. the International Ultraviolet Explorer IUE, and thereafter the Hubble Space Telescope HST), these studies have highlighted both the importance of the Lyα resonant scattering and the relevant ISM parameters at the origin of the strong Lyα attenuation in nearby galaxies (see figure 4.1). These investigations have thus allowed to explain the apparent lack of a strong Lyα emission line in the SED of high-redshift star-forming galaxies: the Lyα flux just appears fainter than those expected and it is during this last decade, thanks to the advent of very large optical telescopes and very sensitive cameras, that all LAEs known to date have been detected (Hu and Cowie, 1998; Hu et al., 2010; Cowie and Hu, 1998; Kudritzki et al., 2000; Rhoads et al., 2000; Taniguchi et al., 2003, 2005; Shimazaki et al., 2006; Gronwall et al., 2007; Nilsson et al., 2007; Guaita et al., 2010; Ouchi et al., 2003, 2008, 2010).

The Lyα radiative transfer in the ISM of nearby star-forming galaxies turns out to be very complex. Because of its resonant nature, the emergent features of the Lyα line is very sensitive to many ISM quantities (HI column density, dust attenuation, neutral hydrogen kinematics, gas geometry and inclination of disk galaxies). In this section we summarize our current knowledge of the effects of each ISM parameter on both the strength and the shape of the emergent Lyα line of nearby star-forming galaxies.

4.1.1 Dust attenuation

In the 1980s and 1990s, the lack of detection of high-redshift galaxies in Lyα was originally attributed to the strong dust attenuation that the Lyα line must undergo inside the ISM of galaxies (Meier and Terlevich, 1981; Pritchet, 1994; Deharveng et al., 1985; Calzetti and Kinney, 1992). This was expected as a result of the resonant scattering process experienced by the Lyα photons which implies longer path length and then higher probability of being absorbed by dust grains inside the ISM.

The first UV observations of nearby star-forming galaxies were carried out with the UV space telescope IUE in the 1980s and 1990s. From these pioneer observations, the first results agreed with this scenario. In particular, Charlot and Fall (1993) and Terlevich et al. (1993) combined different observations of the IUE satellite (i.e. blue compact galaxies and HII galaxies located at $0.01 < z < 0.06$) and found a clear anti-correlation between EW(Lyα) and the metallicity [O/H] of the selected galaxies (see figure 4.2, left panel). The authors thus concluded that the most likely explanation for the weakness of the Lyα emission line from nearby galaxies was attenuation by dust (assuming nevertheless that the metallicity and the dust content are well correlated each other and independent of the galaxy environment, which is not true in general; Atek et al. 2014).
Figure 4.2: Left panel: compilation of IUE data showing an anti-correlation between the Ly\(\alpha\) equivalent width EW(Ly\(\alpha\)) and the metallicity [O/H] (Charlot and Fall (1993)). The authors of this study concluded to a clear anti-correlation between EW(Ly\(\alpha\)) and the dust content of these galaxies. Right panel: this figure shows the evolution of EW(Ly\(\alpha\)) as a function of the color excess E(B-V) measured from 21 nearby starburst galaxies observed by the IUE satellite (Giavalisco et al., 1996). The color excess is derived from the Balmer decrement \(H\alpha / H\beta\). Clearly, no corelation exists between the strength of the Ly\(\alpha\) line and the dust attenuation in nearby star-forming galaxies, suggesting that other ISM parameter seem to intervene in the obscuration and the escape of Ly\(\alpha\) photons in a galaxy.

However, a few years later, other observational results reached another conclusion than Charlot and Fall (1993), suggesting that other ISM quantities might intervene in the attenuation of the Ly\(\alpha\) line. First of all, Kunth et al. (1994) and Thuan et al. (1997) spectroscopically observed two different galaxies, IZw18 and SBS 0335-052 (see figure 4.1, right panel), known to be the most metal-poor star-forming galaxies of the local Universe. While the conclusion of Charlot and Fall (1993) may suggest the presence of a strong Ly\(\alpha\) emission line in the SED of these objects (because not affected by dust extinction), it is rather a pronounced Ly\(\alpha\) absorption line that appeared in the spectra. In parallel to these observations, the same conclusion was reached by Giavalisco et al. (1996), who studied a local sample of 21 starburst galaxies observed with the IUE satellite (some of them being studied previously by Charlot and Fall 1993 and Terlevich et al. 1993). Nevertheless, instead of using the oxygen abundance [O/H] as a dust indicator, Giavalisco et al. (1996) used two more direct estimates of the mean dust attenuation foreground the ionized gas in galaxies: the Balmer decrement \(H\alpha / H\beta\) and the UV spec-

\footnote{The Balmer decrement, which corresponds to the flux ratio \(H\alpha / H\beta\), is a direct...}
tral slope $\beta$. Following this approach, Giavalisco et al. (1996) found no clear correlation between Ly$\alpha$/H$\beta$ or EW(Ly$\alpha$) and the reddening E(B-V) of these local galaxies (see figure 4.2, right panel). Furthermore, even correcting both the Ly$\alpha$ and H$\beta$ lines for dust extinction, the line ratio Ly$\alpha$/H$\beta$ proved to be still lower than the intrinsic one ($\sim 27$), suggesting that Ly$\alpha$ photons suffered greater attenuation than non-resonant lines. All these results highlighted that other ISM parameters than the dust extinction intervened in the escape of Ly$\alpha$ photons from star-forming galaxies. In particular, Giavalisco et al. (1996) proposed that the spatial distribution of both the gas and dust inside the ISM of galaxies may have a significant effect on the attenuation of the Ly$\alpha$ line (see section 4.1.4).

Nowadays, the advent of newly space telescopes (such as GALEX and HST) have enabled the study of larger samples of nearby UV-selected galaxies at $z < 1$ (Deharveng et al., 2008; Cowie et al., 2010; Scarlata et al., 2009; Atek et al., 2009a). That has allowed astronomers to make better conclusions of a statistical nature concerning the dependency of the Ly$\alpha$ escape to the dust attenuation. As shown by Atek et al. (2014), a clear trend is now obtained between the Ly$\alpha$ escape and the dust extinction, but a large dispersion still suggests the influence of other physical parameters in the attenuation of the Ly$\alpha$ line inside the ISM of nearby starburst galaxies. This trend is shown in figure 4.3, where the Ly$\alpha$ escape fraction $f_{\text{esc}}$(Ly$\alpha$) of numerous nearby Ly$\alpha$-emitting galaxies (from different surveys) is compared to the nebular dust attenuation E(B-V)$_{\text{Neb}}$ (derived from the Balmer decrement H$\alpha$/H$\beta$). This result confirms both the decrease of the Ly$\alpha$ strength with increasing the dust extinction and the fact that Ly$\alpha$ photons suffer greater attenuation than the neighboring UV continuum photons (modeled by the red dashed line in Fig. 4.3).

estimate of the dust attenuation undergone by nebular lines in a galaxy. As the wavelength dependency of the dust attenuation makes always the H$\alpha$ line less attenuated than the H$\beta$ line, a comparison between both the observed line ratio H$\alpha$/H$\beta$$_{\text{obs}}$ and the intrinsic one (H$\alpha$/H$\beta$)$_{\text{int}}$ $\sim 2.86$ in HII regions) allows us to derive the color excess E(B-V) suffered by the nebular emission of the galaxy.

1The Ly$\alpha$ escape fraction corresponds to the fraction of Ly$\alpha$ photons that manage to escape from the galaxy and is calculated following the relation: $f_{\text{esc}}$(Ly$\alpha$) = f(Ly$\alpha$)$_{\text{obs}}$/f(Ly$\alpha$)$_{\text{int}} = f(Ly\alpha)_{\text{obs}}/(8.7 \times f(H\alpha)_C)$, where f(Ly$\alpha$)$_{\text{obs}}$ is the observed Ly$\alpha$ flux and f(H$\alpha$)$_C$ is the H$\alpha$ flux correction for dust extinction. The factor 8.7 corresponds here to the most likely intrinsic line ratio Ly$\alpha$/H$\alpha$ in HII regions (Case B of recombination, Osterbrock (1989)).
Figure 4.3: Ly$\alpha$ escape fraction as a function of the nebular dust extinction for different samples of nearby Ly$\alpha$-emitting galaxies ($z\sim0.3$) Ly$\alpha$-galaxies of Atek et al. (2014) in black circles, $z\sim0$ IUE galaxies in blue triangles, $z\sim0.3$ sample of Scarlata et al. 2009, Cowie et al. 2011 sample in red circles and $z\sim0$ galaxies of Atek et al. 2008 with purple squares). The solid black line corresponds to best fit to the relationship $f_{\text{esc}}(\text{Ly}\alpha)-\text{E}(B-V)$, and the yellow area covers the 1$\sigma$ uncertainties of the fit. The dashed red line corresponds to the expected attenuation law at the Ly$\alpha$ wavelength, as derived from the Cardelli et al. (1989) extinction law. Note that the negative values of E(B-V) corresponds in reality to E(B-V) = 0.

4.1.2 HI gas kinematics

Among the other ISM parameters that enter in the escape of Ly$\alpha$ photons from galaxies, the role played by the neutral gas kinematic was revealed during the 1990s by Kunth et al. (1994), Lequeux et al. (1995) and Kunth et al. (1998). In particular, for 8 local star-forming galaxies observed with the Goddard High Resolution Spectrograph (GHRS), on board the HST, Kunth et al. (1998) found 4 bright Ly$\alpha$-emitters (see figure 4.4 left panel) and 4 galaxies showing a pronounced Ly$\alpha$ absorption line. When Ly$\alpha$ appeared in emission, a systemic blueshift of Low Ionized State (LIS) metal absorption lines with respect to Ly$\alpha$ was observed (see figure 4.4 right panel), indicative of outflows in the neutral medium. Furthermore, the shape of the Ly$\alpha$ emission lines proved to be asymmetric, confirming the presence of outflowing neutral hydrogen ma-
Figure 4.4: Left panel: Ly$\alpha$ line profiles emerging from 4 nearby starburst galaxies of the sample of (Kunth et al., 1998). Each spectrum is plotted in velocity scale where the zero point corresponds to the systemic velocity as derived from the optical emission lines. These different Ly$\alpha$ emission line profiles have a P-Cygni profile, confirming the presence of strong outflows in the host galaxies ($V_{\text{exp}} \sim 200 - 300$ km/s).

Right panel: Shift of both UV O[I] and Si[II] absorption lines (LIS absorption lines) relative to the systemic redshift. We can notice that each line is blueshifted, indicative of an expanding neutral ISM which helps Ly$\alpha$ photons to escape the galaxy.

Nowadays, the same conclusions of Kunth et al. (1998) have been reached by Wofford et al. (2013) when observing the Ly$\alpha$ line of 20 H$\alpha$-selected galaxies at $<z> = 0.03$. In this sample, seven galaxies prove to be Ly$\alpha$ emitters, with moderate rest-frame EW(Ly$\alpha$) between 1 and 12 Å. From this
study, two main results tend to summarize our current knowledges about the effects of the ISM kinematics on the Ly$\alpha$ escape. On the one hand, while all Ly$\alpha$-emitters of Wofford et al. (2013) show an outflowing ISM, the Ly$\alpha$-absorbers of the sample exhibit an almost static ISM from the HII regions. This result is consistent with the conclusion of Kunth et al. (1998). On the other hand, when fast outflow velocities are measured, a large diversity of Ly$\alpha$ escape fraction is still observed by Wofford et al. (2013), revealing the effects of other ISM quantities on Ly$\alpha$ (dust attenuation and HI content). Therefore, all these results indicate that an outflowing ISM seems to be a necessary, but not a sufficient condition, for allowing Ly$\alpha$ photons to escape from nearby star-forming galaxies.

4.1.3 HI column density

A third ISM parameter that must intervene in the escape of Ly$\alpha$ photons from nearby star-forming galaxies is the total HI mass, or more precisely the HI column density $N_{HI}$ of the ISM. Given the physics of the Ly$\alpha$ line (see chapter 5), the more the HI column density, the higher the optical depth of the ISM for Ly$\alpha$ photons. Therefore, an increase in the total HI mass in a galaxy should imply a longer path length and a higher probability of being absorbed by dust grains in the ISM.

Besides this theoretical point of view, very few resolved HI observations of nearby star-forming galaxies (from which the Ly$\alpha$ radiative transport was intensively studied) have been carried out so far. Such a lack of observational data still prevents us from reaching a robust conclusion on the real effect of the HI mass on the Ly$\alpha$ line of star-forming galaxies.

Nevertheless, very few observational and numerical studies have reached some conclusions that support the theoretical trend discussed above between the Ly$\alpha$ strength and the HI content of galaxies. So far, these works mostly focus on isolated star-forming galaxies of the local Universe. First of all, Atek et al. (2009b) studied IZw 18, a very metal-poor galaxy discussed in section 4.1.2. The SED of this galaxy exhibits a strong and broad Ly$\alpha$ absorption line (see figure 4.5) which is surprising given the very low dust extinction of this galaxy. Using the 3D Lya Monte Carlo code (MClya) of Verhamme et al. (2006), Atek et al. (2009b) could reproduce the Ly$\alpha$ spectrum of IZw 18 and derived some relevant ISM parameters, such as the dust extinction, the HI column density and the outflow velocity of the HI gas. Independently to the geometrical configurations explored in their simulations, the Ly$\alpha$ line profile of IZw 18 was always reproduced with a small amount of dust ($E(B-V) \approx 0.05$), a very high $N_{HI} = 3.6 \times 10^{21}$ cm$^{-2}$ and an almost static ISM (see figure 4.5). Atek et al. (2009b) thus concluded that the high HI mass was responsible
The derived parameters of the Ly$\alpha$ fit are: $N_{HI} = 6.5 \times 10^{21}$ cm$^{-2}$, $E(B-V) = 0.05$ and $v=0$ km s$^{-1}$. The blue dotted line represents the input spectrum of the simulation. The intrinsic Ly$\alpha$ equivalent width adopted here is $EW_{int}(Ly\alpha)=60$ Å.

for the strong Ly$\alpha$ absorption line of IZw 18. Indeed, the derived HI column density $N_{HI}$ is very high and comparable to the ones of DLAs (known to be ones of the most massive galaxies rich in neutral hydrogen of the Universe). This implies a longer path length for Ly$\alpha$ photons and higher probability of being absorbed by a very small amount of dust grains.

More recently, Pardy et al. (2014) presented new HI imaging and spectroscopy of a small sample of 11 nearby UV-selected star-forming galaxies (LARS galaxies, see section 4.3). These observations were carried out in radio wavelengths with the 100m Green Bank Telescope (GBT) and enabled to estimate the total HI mass of the galaxies from the 21 cm emission line of neutral hydrogen[1](rest-frame wavelength). In parallel to these radio observations, these galaxies were also imaged and spectroscopically observed in Ly$\alpha$ with HST. The combination of both observations allowed Pardy et al. (2014) to find an anti-correlation between the Ly$\alpha$ properties ($f_{esc}(Ly\alpha)$ and $EW(Ly\alpha)$) and

$^{1}$The 21cm emission line of neutral hydrogen corresponds to an hyperfine electronic transition of the HI ground state produced when the spin of the electron changes.

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**Figure 4.5:** Best fit of the observed Ly$\alpha$ line profile of IZw 18. The dark line represents the observed SED of IZw 18, obtained from spectroscopic observations carried out with STIS, on board the HST. The red dashed line shows the best fit of the Ly$\alpha$ line profile of the galaxy. It is obtained assuming using the 3D Ly$\alpha$ Monte Carlo code of Verhamme et al. (2006) and modeling IZw 18 by spherical shell of HI and dust surrounding a central source of Ly$\alpha$ and UV photons. The derived parameters of the Ly$\alpha$ fit are: $N_{HI} = 6.5 \times 10^{21}$ cm$^{-2}$, $E(B-V) = 0.05$ and $v=0$ km s$^{-1}$. The blue dotted line represents the input spectrum of the simulation. The intrinsic Ly$\alpha$ equivalent width adopted here is $EW_{int}(Ly\alpha)=60$ Å.
the total HI mass in the sample. This result seems to support the theoretical trend, but larger statistical samples would be needed in order to confirm it.

4.1.4 ISM geometry

In parallel to these intense observations of nearby galaxies, both semi-analytical and numerical studies have highlighted the effects produced by the ISM geometry on the emergent strength of the Ly$\alpha$ line (Neufeld 1991; Hansen and Oh, 2006).

Overall, several numerical studies have shown that a clumpy and dusty ISM (where hydrogen and dust are distributed in clumps around sources of photons) is always more transparent to Ly$\alpha$ and non-resonant photons compared to an equivalent homogeneous ISM of equal dust content (Boisse, 1990; Hobson and Scheuer, 1993; Witt and Gordon, 1996, 2000; Hansen and Oh, 2006). Therefore, it is known that any photon takes advantage of the weak opacity of the interclump medium to escape more easily from a clumpy ISM than any homogeneous dusty one.

However, more interestingly, a clumpy ISM might be at the origin of a particular effect on the Ly$\alpha$ line, as originally suggested by Neufeld (1991). Under certain conditions on the ISM, it has been proposed that the Ly$\alpha$ photons might escape from a clumpy ISM more easily than the non-resonant UV continuum photons. The result for the emergent Ly$\alpha$ line is an enhancement of the equivalent width EW(Ly$\alpha$). As shown in figure 4.6, this scenario assumes that both the Ly$\alpha$ and the UV continuum photons travel inside a clumpy ISM, where all neutral hydrogen and dust are mixed together in clumps (leaving the interclump medium empty or extremely ionized). On the one hand, Ly$\alpha$ photons would be able to scatter off of the surface of clumps (because scattering on the HI atoms located on the surface of the clumps), having their journey confined in the dustless interclump medium. On the other hand, the UV continuum photons would penetrate into the clumps and would suffer greater dust extinction than the Ly$\alpha$ photons. Nowadays, this model is commonly used by astronomers to explained the origin of the very large EW(Ly$\alpha$) sometimes observed in the SED of high-redshift LAEs (Kashikawa et al., 2012; Shimasaku et al., 2006).

However, although studied thereafter by Hansen and Oh (2006), the exact physical conditions under which this model may work in reality remain still unclear today. This problem needs to be understood in order to figure out both the way Ly$\alpha$ photons travel inside real clumpy ISMs and the origin of the unphysically high EW(Ly$\alpha$) observed from distant galaxies. The Neufeld’s scenario is the subject to the first two papers of this thesis (i.e. paper I and II).
Figure 4.6: The Neufeld scenario (Neufeld, 1991). In this scenario, both the hydrogen and the dust are mixed together in clumps in the ISM. The interclump medium is however assumed empty (or extremely ionized) allowing Lyα and UV photons to propagate freely in the interclump medium. In such an ISM, the Lya photons should scatter off of the surface of clumps (scattering against the HI atoms localized on the surface), whereas UV photons would penetrate into the clumps where they would suffer greater extinction than the Lyα photons. Therefore, Lyα photons would escape more easily such an ISM than the UV photons, implying an enhancement of the Lyα equivalent width EW(Lyα) (the observed EW(Lyα) being higher than the intrinsic one).

4.1.5 Summary

The current number of nearby star-forming galaxies samples is significantly enough to reach robust conclusions on the effects produced by each ISM quantity on the regulation of EW(Lyα) and f_{esc}(Lyα). Overall, four relevant ISM parameters clearly enter in the complex Lyα radiative transport in nearby star-forming galaxies: the dust extinction, the HI column density, the ISM kinematics and the neutral gas geometry. Much attention are now devoted to obtain a possible "order of precedence" between these different quantities. Regarding our current knowledge on the effect of each parameter on the Lyα line, the following scenarios might be proposed:

- **From extremely optically thick ISMs:** Due to the high optical depth of the ISMs, either an outflow or a clumpy ISM (i.e. showing a low covering fraction) may allow Lyα photons to escape from galaxies. In second precedence, the dust attenuation and the HI column density may vary the transparency of the ISM for Lyα photons.
- **From moderate optically thick ISMs**: Ly$\alpha$ photons may take advantage of the low HI coverage of the ISMs to escape from such galaxies. The Ly$\alpha$ line might therefore behave more like a non-resonant line. Therefore, it might be expected that the effect of the dust attenuation on the Ly$\alpha$ line’s strength should be dominant compared to the ones of both the kinematics and the covering fraction of the neutral gas.

### 4.2 Investigating the Ly$\alpha$ radiative transport in high-redshift star-forming galaxies

In the previous subsection, we have seen that deep and wide observations of low-redshift star-forming galaxies have provided significant information on the processes that regulate the Ly$\alpha$ line’s features within the ISM of nearby galaxies. Regarding now the question at hand in astrophysics, that is understanding the radiative transport undergone by Ly$\alpha$ photons in the ISM of high-redshift galaxies, such a process is more challenging to study and remains poorly understood from an empirical angle. In this section, we summarize first our current knowledges in the effects produced by the most relevant ISM parameters of high-redshift galaxies on the strength of the Ly$\alpha$ line. Second, we focus on the large diversity of Ly$\alpha$ line profiles observed in the SED of high-redshift galaxy populations, stressing in particular on the different ISM properties it is possible to infer from the analysis of these different line shapes.

#### 4.2.1 Any differences to the Ly$\alpha$ transport inferred in low-redshift galaxies ?

Due to the large distances involved for high-redshift galaxies, the radiative transport experienced by Ly$\alpha$ photons within the ISM of these objects remains poorly understood from an empirical point of view. Indeed, such distances creat two main observational limitations that prevent astronomers from deriving accurately the ISM quantities involved in the Ly$\alpha$ radiative transfer:

- The very low observed UV and optical continuum surface brightness\(^1\) of individual high-redshift galaxies complicates the measurement of some fundamental ISM quantities (dust content, HI content, gas kinematics, ...). These problems are typically solved through staking analyses, which destroys almost all information relating to the diversity of the galaxy populations.

\(^1\)The surface brightness (SB) corresponds to radiation flux per solid angle. It is usually expressed in flux units per arcsecond (erg s$^{-1}$ cm$^{-2}$ arcsec$^2$) UV and optical wavelengths.

52
• The current impossibility to obtain critical complementary information in a wide wavelengths range when observing distant star-forming galaxies (as only the Ly$\alpha$ line, as well as the faint UV continuum are accessible to ground-based telescopes when observing high-redshift galaxies).

As a consequence, only the measurement of the *stellar dust extinction* $E(B-V)_{\text{Stel}}$ of individual galaxies can be inferred directly from the observed slope of their UV continuum radiation (and not the *nebular dust extinction* $E(B-V)_{\text{Neb}}$ which can be derived from both the non-resonant H$\alpha$ and H$\beta$ emission lines and remain only accessible to ground-based telescopes for redshifts below $z = 2.6$; K-band limit). Regarding the diagnostics of neutral gas kinematics, this requires very deep UV continuum spectroscopy to infer low ionization absorption lines against the very faint UV continuum of galaxies. Such attempts remain very challenging and very expensive for galaxies at $z > 4$ (it is currently out of reach beyond that). Finally, direct observations of HI by its emission at 21cm remains impossible to measure beyond the local Universe due to the current sensitivity limits of the radio telescopes. Given all these observational complications when observing high-redshift galaxies, we understand why much efforts are put on low-redshift galaxies to figure out the complex Ly$\alpha$ radiative transfer inside the ISM of galaxies (with the aim to be able to extrapolate these processes to high-redshift objects).

Despite these observational limitations, some information on the ISM physical properties of high-redshift galaxies have already been obtained from the analysis of large samples of LAEs and LBGs. Combined with the study of their Ly$\alpha$ emission, the effects of some ISM quantities on the Ly$\alpha$ escape can now be constrained:

• **Effect of dust extinction on Ly$\alpha$:** working exclusively on stacked data of large samples of LAEs and LBGs, Shapley et al. (2003) derived the mean dust attenuation of large subsamples of $z \sim 3$ UV-selected galaxies ($\sim 1000$ LBGs in the total sample). These galaxies samples showed a significant anti-correlations between the Ly$\alpha$ equivalent width and the dust extinction. More recently, a similar result was reached by Korney et al. (2010) and Hayes et al. (2010) who found a clear anti-correlation between the Ly$\alpha$ escape fraction and the dust content of $z \sim 2 - 3$ star-forming galaxies. The results of Hayes et al. (2011) also confirms this interpretation when comparing the redshift evolution of $f_{\text{esc}}$(Ly$\alpha$) between $z = 0$ and $z = 8$ to the one of the dust attenuation $E(B-V)$ in individual galaxies (for H$\alpha$ and UV selected galaxies, see figure 4.7). In particular, between $z = 0$ and 6, the evolution of the mean $f_{\text{esc}}$(Ly$\alpha$) can be purely explained by an increase of the dust content in galaxies with time. In conclusion, the dust extinction in high-redshift galaxies seems
Figure 4.7: Evolution of the Lyα escape fraction $f_{\text{esc}}(\text{Ly} \alpha)$ as a function of the redshift $z$. Different samples of Hα-emitters and Lyman break galaxies (see the caption) have been used in this analysis. The solid red line shows the best fitting power-law to points between redshift 0 and 6, which takes an index of $\alpha = 2.6$ and is clearly a good representation of the observed points over this redshift range. In particular, it intersects with the $f_{\text{esc}}(\text{Ly} \alpha)=1$ line (dotted line) at redshift $z=11.1$. Interestingly, the observed evolution of $f_{\text{esc}}(\text{Ly} \alpha)$ is consistent with the one of the dust extinction with time.

to play an important role in the regulation of the observed strength of the Lyα line.

- **Effect of gas kinematics on Lyα**: no robust correlation has already been obtained between the outflow velocity of LAEs and LBGs and other Lyα quantities so far ($f_{\text{esc}}(\text{Ly} \alpha)$, EW(Lyα), L(Lyα); Shapley et al. 2003, Verhamme et al. 2008). Nevertheless, as observed in low-redshift galaxies, some indications tend to reveal that large scale outflows/inflows have a noticeable effect on the Lyα line’s strength of high-redshift galaxies. In particular, most of the distant LAEs and LBGs exhibit an asymmetric Lyα line profile with redshifted peaks (see figure 4.8, left panel). Such a result is clearly indicative of the presence of a large scale outflow among Lyα-emitting galaxies at high-redshift. Further deep observations of large sample of Lyα-emitting and Lyα-absorbers at high-redshift will be needed in order to explore a possible trend between the ISM gas velocity and other Lyα parameters.

- **Effects of $N_{HI}$ and the ISM geometry on Lyα**: while LAEs and LBGs show clear evidence of galactic outflows, the effects of other ISM pa-
rameters, such as the HI mass, dust content and the ISM geometry seems to play a dominant role in the escape of Lyα photons at high-redshift. Such ISM quantities may indeed explained the large diversity of Lyα-strength observed between LAEs and LBGs, where the presence of a bright (weak) Lyα line in the SED of LAEs (LBGs) seem to be the result of their low (high) HI mass and dust content.\cite{Verhamme2008, Shibuya2014}.

In summary, all significant and possible trends found between ISM quantities and Lyα properties of high-redshift seem to go in the same way than the ones observed at low-redshift. Further deep observations of large sample of high-redshift Lyα-emitters and Lyα-absorbers will be needed in order to explore the exact effects produced by each ISM parameter on the Lyα line’s features.

4.2.2 The diversity of the Lyα line profiles: probing the ISM properties of high-redshift galaxies

As mention above, because of the factors which contribute to the Lyα radiative transfer inside the ISM of star-forming galaxies, the Lyα line profile encodes much information on the physical properties of individual galaxies: dust attenuation, gas kinematics, HI column density and geometry of the ISM. It is therefore particularly interesting to study the Lyα line in the SEDs of high-redshift star-forming galaxies in view of all precious information it is possible to derive on the ISM of these objects.

Overall, LAEs and LBGs exhibit a large diversity of Lyα line profiles. In figure 4.8, we give an example of the most common Lyα emission line profiles observed from these distant galaxy populations. Due to the complex radiative transport experienced by the Lyα line inside the ISM, each Lyα line profile results from particular ISM properties of the host galaxy. For each line profile, we summarize here the typical physical conditions ($V_{exp}$, $N_{HI}$, E(B-V)) which prevail in the ISM of these distant galaxies:

- **Asymmetric line profiles** (left panel): Most of LBGs and LAEs show an asymmetric Lyα line profile (P-Cygni type profile), characterized by a steep blue wing, an extended red wing and, sometimes, a peak located at the middle of the red wing. Following numerical models which study the transport of the Lyα photons in 3D shell geometries (Verhamme et al., 2006), such asymmetric line profiles are characteristic of an expanding ISM with a velocity of about $V_{exp}$ $\sim$ 200 - 300 km.s$^{-1}$. Such strong outflows allow to Doppler shift out of resonance all Lyα photons whose
Figure 4.8: Examples of observed Lyα emission line profiles of LBGs (Verhamme et al., 2008). LAEs show the same variety of line profiles. Three different types of profiles are observed (black line) and can be reproduced by numerical models studying the Lyα radiative transfer in shell and bubble geometries (blue line; see figure 4.5). 1) Left panel: Most of the LBGs (and LAEs) for which spectra of sufficient resolution have been obtained show asymmetric profiles, with an extended red wing. Such a line profile is characteristic of an expanding ISM with a high expansion velocity of $V_{exp} \sim 200 - 300$ km/s. 2) Middle panel: Part of the LBGs (and LAEs) show double-peak profiles. This shape is characteristic of a static ISM ($V_{exp} \approx 0$ km/s). 3) Right panel: in LBGs and LAEs it exists some intermediate cases showing asymmetric double peak line profiles. Such a profile is usually characteristic of an expanding ISM with moderate expansion velocities (typically $V_{exp} \leq 100$ km/s).

- **Double-peaked line profiles** (middle panel): Part of LBGs and LAEs show a double-peak Lyα line profile, characterized by two symmetric peaks centered around the center of the intrinsic Lyα line. Such a line profile is characteristic of a galaxy whose its neutral ISM is static from the hydrogen nebula giving rise to Lyα photons (i.e. no large scale outflow/inflow).

- **Intermediate cases** (right panel): Some LBGs and LAEs also show profiles which appear intermediate between the above two cases. Such line profiles seem characteristic of an expanding ISM with a moderate expansion velocity (i.e. $V_{exp} \leq 100$ km/s; Verhamme et al., 2006).

Regarding both the HI column density and the dust extinction of LBGs and LAEs, some information can be obtained by fitting the Lyα line profile of galaxies, as shown in Fig. 4.8. First, it seems that LBGs have larger HI
column densities $N_{HI}$ than LAEs. This can be revealed by the width difference between the Ly$\alpha$ emission lines of LBGs and LAEs (i.e. FWHM (Ly$\alpha$) $< 500$ km/s for LAEs; Rhoads et al. 2003, Venemans et al. 2004). Indeed, several observations have shown that the HI column density $N_{HI}$ seems to correlate with the width of the line (Tapken et al., 2007). If this correlation between $N_{HI}$ and FWHM truly holds in high-redshift star-forming galaxies, Verhamme et al. (2008) deduces a maximum column density of $N_{HI} < (2-4) \times 10^{20}$ cm$^{-2}$ for LAEs. Second, the analysis of the Ly$\alpha$ line profiles of LAEs and LBGs also suggest that LBGs are dustier than LAEs (Verhamme et al., 2008). All these results seem consistent with the conclusions of Pentericci et al. (2007) who suggests that LBGs are more massive (and also older and dustier) than LAEs.

These information on the ISM of galaxies result from the modeling of Ly$\alpha$ radiative transfer in the framework of galaxy simulations (Ahn et al., 2001, 2002; Cantalupo et al., 2005; Verhamme et al., 2006; Hansen and Oh, 2006; Laursen et al., 2009a,b). While such numerical investigations are fundamental for a better understanding of the Ly$\alpha$ transport in the ISM of star-forming galaxies, they enable to reproduce the Ly$\alpha$ line profile and the UV continuum observed in the SED of distant galaxies. In this way, useful information can be derived on the physical properties of LBGs and LAEs.

4.3 The LARS sample: going deeper into the study of Ly$\alpha$ radiative transfer in nearby galaxies

As explained in the previous sections, our knowledge in the complex transport experienced by Ly$\alpha$ photons inside the ISM of star-forming galaxies has grown remarkably during the last twenty years. In particular, thanks to deep observations of nearby star-forming galaxies, astronomers have been able to identify the main ISM quantities that enter in the complex Ly$\alpha$ transport and comprehend their effects on this strong hydrogen recombination line.

However, there are still many uncertainties and unknowns concerning important topics on Ly$\alpha$, such as understanding the exact effects produced by each ISM quantity, inferring clear qualitative and quantitative correlations between the Ly$\alpha$ properties and the ISM ones, or apprehending the tipical Ly$\alpha$ morphology from Ly$\alpha$-emitters (i.e. are Ly$\alpha$-emitters always accompanied by large Ly$\alpha$-halos? are the properties of these Ly$\alpha$-halos always correlated to the ones of the host galaxies?). All these unknows are mostly due to the small sample of nearby galaxies that have been imaged in Ly$\alpha$ with very high resolution so far (nowadays, only six nearby galaxies have Ly$\alpha$ imaging available; Ostlin et al. 2009).

In order to go deeper into the study of Ly$\alpha$ radiative transport inside the
ISM of nearby star-forming galaxies, we set up a project called LARS during my PhD program (i.e. for Lyman-alpha Reference Sample). This pioneering and very ambitious observational project consisted of a sample of fourteen nearby UV-selected star-forming galaxies, all of them being imaged and spectroscopically observed with the HST in cycle 18, 19 and 20 (P.I. Ostlin, program 12310). Below, we present in more details the galaxies that compose the LARS sample, as well as the large array of data and the main scientific goals of the LARS project.

4.3.1 The sample

The LARS sample is composed of 14 star-forming galaxies at redshift between 0.028 and 0.18. These redshifts are high enough to avoid any overlapping between the Ly$\alpha$ radiation of the galaxy targets and the strong geocoronal Ly$\alpha$ emission line (from the Earth’s geocorona). We show in figure 4.9 the composite images of the LARS galaxies, as obtained from our HST imaging.

All these targets were selected from the cross-correlated GALEX general release 2 and Sloan Digital Sky Survey (SDSS) DR6 catalogues. More precisely, two main criteria regarding both the H$\alpha$ and UV luminosities were used to select the most convenient star-forming galaxies in these two catalogues (Östlin et al., 2014). First of all, we imposed a cut at EW(H$\alpha$) > 90 $\AA$ to ensure an active star-formation activity within each object (i.e. a strong Ly$\alpha$ production). AGNs were removed from the sample in order to focus exclusively on star-formation dominated systems. Then, we also constrained our selection by populating an UV luminosity range above $10^9$ L$_\odot$. Finally, let’s also notice that we allowed for a maximum foreground FUV extinction of about 30% in order to prevent any strong dust attenuation of the MW on the SED of these nearby galaxies. This gave some constraints on the coordinates of the galaxy targets (Right Ascension and Declination).

Morphologically, the LARS sample shows a large diversity of star-forming galaxies: edge-on disk galaxies (LARS #5, #11), face-on disk galaxies (LARS #8), irregular galaxies (LARS #1, #4, #6), compact galaxies (LARS #14), dwarf-like galaxies (LARS #2) and merging systems (LARS #3, #7, #10, #12, #13). This large diversity makes the LARS sample an interesting test-bed for understanding the possible effects produced by galaxy morphologies/viewing-angle on the properties of the emergent Ly$\alpha$ line (EW, luminosity, line profile).

4.3.2 Imaging and spectroscopic observations

A large set of imaging and spectroscopic data were obtained for each galaxy of the LARS sample. Besides using the HST for imaging (in far-ultraviolet and optical frequencies) and spectroscopy, a large array of telescopes were used
Figure 4.9: The LARS sample. We show here the composite image of the LARS galaxies, as obtained from the HST observations. The resolution of these images is 0.04''/pix. For each target galaxy, we indicate its assigned ID and its redshift $z$. We use here the same color code than in Fig. 4.1: the green channel shows the FUV continuum emission, the red one shows the continuum-subtracted H$\alpha$ emission line and the blue color shows the Ly$\alpha$ one.
Figure 4.10: Left panel: ACS/SBC bandpass combinations used to observe the LARS galaxies. We add to this figure two modeled spectra of star-forming galaxies: the blue spectrum at low-redshift and the red one at high-redshift is. The geocoronal Ly$\alpha$ line, shown by the dot-dashed vertical line at 1216 Å is not transmitted by the ACS/SBC long-pass filters. Right panel: effective Ly$\alpha$ bandpasses yielded by our combination of ACS/SBC filters shown on the left panel. Bandpasses are labeled, as are the synthesized narrowbands that result from the subtraction of adjacent long-pass filters. The combinations F125LP-F140LP and F140LP-F150LP sample Ly$\alpha$ at redshifts $z = 0.028 - 0.109$ (i.e. LARS #1-#12) and $z = 0.134 - 0.190$ (i.e. LARS #13 and #14), respectively. Source: Östlin et al. (2014)

to observe LARS galaxies into various electromagnetic fields (from X-rays to radio frequencies).

Each LARS galaxy was first imaged with the HST from Far-ultraviolet (FUV) to optical (8000 Å) in rest-frame wavelengths. In optical, the use of the Wide Field Camera 3 (WFC3) provided optical broadband imaging in U, B and I bands to cover most of the optical continuum emission from the galaxies. We supplemented these broadband data with two narrowband imaging that isolated both the H$\alpha$ and H$\beta$ lines of the targets. In this way, very useful information on both the intrinsic Ly$\alpha$ production and nebular extinction $E(B-V)_{Neb}$ could be derived for each galaxy. In FUV wavelengths, three HST/SBC broadbands were used to cover both the Ly$\alpha$ line and the neighboring FUV continuum of the LARS galaxies (ACS/SBC F125LP, F140LP and F150LP filters). As shown in figure 4.10, the Ly$\alpha$ line of each galaxy was isolated using a combination of two FUV filters that generated a synthetic narrow bandpass (i.e. depending on the redshift of the galaxy, either the combination F125LP-F140LP for LARS#1-#12 and F140LP-F150LP for LARS#13 and #14). This hydrogen line was hereafter continuum-subtracted using a new SED-fitting method that used all available FUV and optical data of the galaxies (Hayes et al., 2009).

In order to get useful complementary information on the LARS galaxies,
a large set of imaging and spectroscopic data have been obtained into a wide wavelengths range. In particular, Pardy et al. (2014) carried out deep observations of the LARS galaxies were carried out into radio wavelengths with the 100m Green Bank telescope (GBT). These observations enable us to infer the neutral hydrogen content of the targets from the 21cm emission line of hydrogen. Furthermore, we got a large set of imaging data in Far-infrared (FIR) wavelengths from both the Hershel and IRAS space telescopes. These different data may provide useful and robust information on the dust properties of the galaxies, such as the total dust content (i.e. directly derived from the analysis of the FIR continuum of the galaxies) and the dust-to-gas ratio (i.e. the ratio between both the dust and the HI contents). Finally, mostly to go deeper into the HST observations in FUV and optical radiation of the LARS galaxies, a large set of imaging data from the Nordic Optical Telescope (NOT) was obtained for each galaxy target. Several soft X-rays imaging from the Chandra space telescope are also available for some galaxies of the sample.

Regarding the spectroscopic observations of the LARS galaxies, these ones have been mostly carried out in FUV and optical wavelengths. We can essentially mention three important spectroscopic observations of the LARS galaxies: using the Cosmic Origin Spectrograph (COS, on board the HST), the PMAS spectrograph and the SDSS database. Using COS, we obtained the SED of the LARS galaxies in a narrow FUV wavelengths range (from 1160 Å to 1470 Å, observed wavelengths). These spectroscopic data, which cover both the Lyα line and the neighboring FUV continuum emission of the galaxies, enable to study the Lyα line profile and to infer useful information on the ISM gas kinematics from pronounced Low ionization lines (LIS) that appear in absorption into the FUV stellar continuum. Finally, both the PMAS and SDSS observations provided different spectra of the galaxy targets into optical wavelengths. Whereas the SDSS observations provide an integrated spectrum of each galaxy in the spectral range [3800 , 9200] Å, integral field spectroscopic observations were carried out with the PMAS spectrograph in the wavelength range [5874 , 7700] Å. The latter provides useful information concerning the Hα line kinematics/width, as well as an abundance map for each galaxy.

4.3.3 Scientific goals

Given our large array of observational data, the LARS sample provides an interesting test-bed for our understanding of both the Lyα radiative transport in star-forming galaxies and the reinterpretation of all high-redshift Lyα studies.

The LARS project is based on several scientific goals. First of all, regarding the Lyα morphology of Lyα-emitting galaxies, the high resolution of the

1PMAS spectrograph, at the Calar Alto 3.5m telescope (Spain)
HST observations allow us to qualitatively and quantitatively compare it to stellar and non-resonant nebular morphologies. Therefore, a deep study of potential Lyα-halos and its relation with physical properties of the host galaxies is possible.

Concerning the Lyα transport inside the ISM of star-forming galaxies, detailed studies consist in reexploring the possible relation between the Lyα properties (luminosity, escape fraction, EW) and other ISM and stellar quantities (dust content, gas kinematics, metallicity, HI column density, stellar mass, stellar age, ...). Such observational works will allow us to confirm/dismiss some correlations already known, as well as to highlight new ones (such as the effects of the HI content on Lyα, which is mostly unknown due to the lack of resolved HI observations of nearby Lyα-emitting galaxies).

As explained in section 4.1.4, the combined effect of dust and ISM geometry (homogeneity and clumpiness) on Lyα is poorly understood from an empirical point of view. For the first time, the high resolutions of our HST data will allow us to observationally study these effects, as well as the possibility of enhancing the Lyα equivalent width as proposed by Neufeld (1991).

Finally, let’s mention that the large diversity of galaxy morphologies in the LARS sample allows us to investigate the potential effect of this parameter on Lyα. In particular, recent high-resolution numerical simulations on isolated star-forming disk galaxies of Verhamme et al. (2012) have revealed possible strong inclination effects of disk galaxies on various Lyα properties (EW, fesc and Lyα spectrum). Indeed, whereas Lyα photons are expected to easily escape from face-on disk galaxies, the situation would become more complicated when the same galaxy is seen edge-on from the observer. The high HI column density of the galaxy disk would make the galaxy completely opaque to Lyα radiation, leading to a strong decrease of the Lyα visibility (fesc and EW), transforming a strong intrinsic Lyα emission line into a pronounced observed Lyα absorption line for the observer. We study this effect in the last paper of this thesis (i.e. Paper IV), where we carried out a complete observational study of the edge-on disk galaxy Mrk1486 (LARS#5) and its surprising strong Lyα emission line.
5. The physics of the Lyman-α line

In this chapter we describe the physics of the Lyα line in more details. Unless otherwise specified, each type of interaction and scattering process discussed below has been included in the Lyα radiative transfer code MCLya developed by Verhamme et al. (2006) and used throughout my PhD research. First of all, we give a more detailed summary of the Lyα line formation mechanisms and its intrinsic features in the HII regions of starburst galaxies. Then, we focus on the physics of the different interactions undergone by Lyα photons when travelling inside the ISM of galaxies (i.e. interactions with neutral Hydrogen, dust, Deuterium atoms and atomic collisions).

5.1 The Lyα line formation mechanisms and its intrinsic features in starburst galaxies

5.1.1 Lyα line formation mechanisms

In the Universe, the Lyα line is always produced in dense, warm, ionized and turbulent regions in which all Hydrogen recombination lines are formed either by collisional excitations or through recombination of Hydrogen atoms. Overall, four different sources of radiation are known to produce a bright Lyα emission line in the Universe. We list here the nature of these different sources and the mechanisms giving rise to their Lyα emission.

**Star-forming galaxies** are the most widespread objects producing a bright Lyα emission line in the Universe. This radiation is mostly formed by recombination of Hydrogen atoms, whose their ionization might have two different origins in star-forming galaxies. On the one hand, young and very massive stellar objects make a significant contribution to the total ionizing radiation (the ionizing Far-UV radiation emitted by O and B type stars is mostly absorbed by the surrounding ISM from which nebular lines form). On the other hand, stellar feedback from supernovae, stellar winds or galactic outflows may entail collisional ionization that occurs in shocks inside the ISM. This process may correspond to another important source for ionizing photons in star-forming galaxies.
Active Galactic Nucleus (AGNs) are also powerful and bright sources in Ly$\alpha$. Due to the strong ionizing power of their central black hole, AGNs show hardly sharp intrinsic ionizing spectrum that leads to the formation of vast galactic and extragalactic HII regions around them. As a consequence, these HII regions form stronger Ly$\alpha$ emission lines through recombination of Hydrogen atoms than starburst galaxies (Charlot and Fall 1993).

At very high redshift, intense Ly$\alpha$ emission lines may also be produced within large clouds of neutral Hydrogen in accretion in dark matter halos (such a process is expected to occur during the formation of primordial galaxies in the early Universe). As the gravitational collapse of those neutral clouds goes on, the temperature of the gas must increase, leading to a strong Ly$\alpha$ emission line by cooling radiation of Hydrogen atoms (Fardal et al. 2001; Yang et al. 2006). However, there have been only few reports of this kind of Ly$\alpha$ emission so far (i.e. from Ly$\alpha$-blobs, Nilsson et al. 2006, Scarlata et al. 2009).

Finally, we can also mention the phenomenon of "fluorescence" which produces a relatively weak Ly$\alpha$ emission line on the edge of the Hydrogen clouds located in the outer layer of galaxies. Indeed, each galaxy is exposed to a strong ionizing UV radiation emitted by the IGM (known to be warm and composed of a ionized and tenuous gas). This radiation can therefore ionize the neutral Hydrogen atoms located at the edge of the galaxies, leading to the formation of a faint Ly$\alpha$ emission by recombination.

5.1.2 The intrinsic Ly$\alpha$ line of star-forming galaxies

As mentioned above, the Ly$\alpha$ line of star-forming galaxies is mostly produced through recombination of Hydrogen atoms in the HII regions that surround the most massive and hottest stars of these objects (O and B type stars). During the lifetime of these massive stars, from few Myrs to $\sim 40$ Myrs, free protons and electrons of the ionized nebula collide and recombine, forming all recombination lines of HI atoms though the cascade of the electron to the ground state. In order to understand the formation of the Ly$\alpha$ line, we have to consider the different orbitals of the second energy level of the HI atoms. It consists indeed of three different substates, commonly named 2S$_{1/2}$, 2P$_{1/2}$ and 2P$_{3/2}$ (see Fig. 1.1). According to the electronic dipole selection rules, the only electronic transitions allowed are from the 2P-states to the ground-state, emitting a Ly$\alpha$ photon. Whereas, the transition from the 2S$_{1/2}$ orbital to the ground state does not produce any Ly$\alpha$ radiation. This transition emits two photons into the continuum and is commonly called the "two photon" emission (Breit and Teller, 1940).

Regarding the intrinsic Ly$\alpha$ luminosity $L$(Ly$\alpha$) in HII regions, simple con-
**Figure 5.1:** Predicted temporal evolution of the Ly$\alpha$ equivalent width $\text{EW(} \text{Ly}\alpha \text{)}$ of the nebular emission ($\text{EW(} \text{Ly}\alpha \text{)} > 0$) and the stellar absorption ($\text{EW(} \text{Ly}\alpha \text{)} < 0$) for instantaneous burst (solid and long-dashed lines) and constant star formation (short dashed, dotted, and dash-dotted). The dash-dot lines show the total $\text{EW(} \text{Ly}\alpha \text{)}$ (nebular + stellar) for constant star formation, the short-dashed lines show the nebular emission component and the long-dashed ones reveal the stellar absorption component. Three different metallicities are shown in this figure: $Z = 0.02$ (solar metallicity, black), 0.004 (red) and 0.0004 (blue). A Salpeter IMF is assumed in these models. Let’s remark that the Ly$\alpha$ line appears in emission in all cases (i.e. $\text{EW(} \text{Ly}\alpha \text{)} > 0$ Å), except for an instantaneous burst where $\text{EW(} \text{Ly}\alpha \text{)}$ becomes negative after $\sim 50$ Myrs. *Source:* Schaerer and Verhamme (2008)

Considerations lead $L(\text{Ly}\alpha)$ being directly proportional to the number of ionizing photons emitted by the ionizing stars (Schaerer, 2003):

$$L(\text{Ly}\alpha) = \frac{2}{3}(1 - f_{\text{esc}})h\nu_0Q_H \text{ erg.s}^{-1}$$

(5.1)

where $Q_H$ is the total flux of ionizing photons reward of 912 Å (in unit s$^{-1}$), $f_{\text{esc}}$ is the fraction of Lyman continuum photons that do not participate to hydrogen ionization in the HII region, and $\nu_0$ is the rest-frame frequency of the Ly$\alpha$ photons. The factor $2/3$ is related to the case B of the recombination theory (Osterbrock, 1989). It is assumed here that all photons emitted through the recombination of HI atoms are always re-absorbed into the HII
region (i.e. it is the optically thick regime, the most likely configuration in HII regions). Under this condition, the orbitals of the second energy level of HI atoms (i.e. 2S_{1/2}, 2P_{1/2} and 2P_{3/2}) are equally populated, implying that two-third of the recombinations in HII regions lead to the emission of a Ly\(\alpha\) photon (Spitzer, 1978; Osterbrock, 1989). This indicates the high strength of the Ly\(\alpha\) line in starburst galaxies. Besides becoming the strongest recombination line of Hydrogen atoms emitted in HII regions, the Ly\(\alpha\) line can also become the dominant emission line of the SED of star-forming galaxies at very low metallicities (Schaerer, 2003).

- **Relative strength of the intrinsic Ly\(\alpha\) line:**

The equation 5.1 shows that the strength of the Ly\(\alpha\) line is primarily dependent on the ionizing flux \(Q_H\) of the underlying stellar population, which depends on both the stellar metallicity \(Z\) and the age of the stellar source (Charlot and Fall, 1993; Schaerer, 2003). We illustrate in figure 5.1 the temporal evolution of the intrinsic Ly\(\alpha\) equivalent width \(EW(Ly\alpha)\), assuming different stellar metallicities \(Z\) and different star formation histories for the host galaxy (Schaerer, 2003). In all cases, the Ly\(\alpha\) line is very strong at the beginning of the stellar formation, with \(EW(Ly\alpha)\) being able to reach either 240 Å (for normal stellar metallicities; i.e. population I stars) or 360 Å (for very metal-poor stars; i.e. population II stars).

The relative strength of the Ly\(\alpha\) line also decreases with time, due to both the aging of the stellar population and the decrease of the Lyman continuum flux \(Q_H\). However, the decrease of \(EW(Ly\alpha)\) will be more or less pronounced according to the star-formation history. Two different cases appear. For galaxies showing a constant star formation, the Ly\(\alpha\) equivalent width decreases before reaching an asymptotic value of 80 - 100 Å after \(\sim 50\) Myrs (i.e. \(log(\text{age}) > 7.70\)). For an instantaneous burst (that occurs at \(t = 0\)), the first stellar generation is the only source of ionizing photons within the galaxy. A quick decrease of \(EW(Ly\alpha)\) is therefore observed until reaching 0 Å after 10 Myrs into the nebula (i.e. no Ly\(\alpha\) photons emitted from the HII region). The total \(EW(Ly\alpha)\) becomes nevertheless strongly negative after 50 Myrs due to the stellar Ly\(\alpha\) absorption of the old B type stars of the galaxy.

- **Shape of the intrinsic Ly\(\alpha\) line:**

Regarding now the shape of the newly formed Ly\(\alpha\) line in HII regions, this one corresponds to a gaussian with a width given by a convolution of the natural, thermal, and turbulent broadening. From a theoretical point of view, the width of the Ly\(\alpha\) line is essentially due to both the thermal and turbulent broad-
ening in such ionized nebula. Taking only into account the thermal contribu-

\[ \Delta v_D = \left( \frac{v_{Ly\alpha}}{c} \right) \sqrt{2kT/m}, \]

where \( v_{Ly\alpha} \) is the rest-frame Ly\( \alpha \) line frequency, \( c \) is the
speed of light, \( T \) is the temperature of the gas, \( k \) is the Boltzmann constant and \( m \) is
the average mass of the gas’s particles.

The thermal broadening is measured by the Doppler width \( \Delta v_D \). It is defined as
\[ \Delta v_D = \left( \frac{v_{Ly\alpha}}{c} \right) \sqrt{2kT/m}, \]

However, given that the turbulence may also dominate over thermal motions, well
higher widths may be observed in reality. From an observational point of view,
some information regarding the intrinsic width of the Ly\( \alpha \) line can be given by
observations of the H\( \alpha \) line of galaxies. This non-resonant Hydrogen line is
indeed produced in the same locations as Ly\( \alpha \), so can be used as a probe. In
this way, after correction of any internal motion of ISM clouds in nearby star-
forming galaxies, Yang et al. (1994) found a lower limit for the H\( \alpha \) line width
of \( \sim 30 \) km.s\(^{-1}\). Higher values up to 100 km.s\(^{-1}\) are also found in nearby and
high-redshifts galaxies. Such a line width is indeed consistent with the mea-

\[ \Delta v_D = \left( \frac{v_{Ly\alpha}}{c} \right) \sqrt{2kT/m}, \]

surement of the velocity dispersion of CO and H\( \alpha \) lines in the starburst galaxy
cB58 (Teplitz et al. 2000; Baker et al. 2004), the velocity dispersion measured
in several starbursts at \( z \sim 2 \) by Erb et al. (2003), and in SMM J2135-0102 at
\( z = 2.32 \) by Swinbank et al. (2011).

As largely discussed throughout this thesis, the observed strength, width
and shape of the Ly\( \alpha \) line of star-forming galaxies are nevertheless extremely
different from the intrinsic ones. Indeed, the complex transport experienced
by Ly\( \alpha \) photons within the ISM or the IGM determines the emergent features
of the Ly\( \alpha \) line. As we will see below, Ly\( \alpha \) photons undergo many kinds of
interactions: scattering against HI atoms or destruction by dust, H\( _2 \) molecules,
Deuterium atoms and atomic collisions. Numerical simulations must take all
of these into account to reproduce Ly\( \alpha \) radiative transfer in galactic environ-
ment.

5.2 Interaction between Ly\( \alpha \) photons and neutral Hydro-
gen

Given the resonant nature of the Ly\( \alpha \) electronic transition, Ly\( \alpha \) photons are
very likely to interact with HI atoms. Each interaction between a Ly\( \alpha \) photon
and a HI atom leads to a phase of absorption and of re-emission. The latest
one modifies many properties of the incoming Ly\( \alpha \) photon: its frequency, di-
rection of propagation and degree of polarization. Throughout this subsection
we describe in more details these different changes.

\[ \Delta v_D = \left( \frac{v_{Ly\alpha}}{c} \right) \sqrt{2kT/m}, \]

The thermal broadening is measured by the Doppler width \( \Delta v_D \). It is defined as
\[ \Delta v_D = \left( \frac{v_{Ly\alpha}}{c} \right) \sqrt{2kT/m}, \]

67
5.2.1 Absorption process

The absorption probability of a Ly\(\alpha\) photon by a HI atom (the electron of this atom being in the ground state \(1S_{1/2}\)) is measured by the cross-section of absorption \(\sigma(\nu)\). We describe below the expression of \(\sigma(\nu)\) in the observer’s frame (i.e. a frame other than the absorbing HI atom) and estimate the absorption probability of a Ly\(\alpha\) photon in a typical ISM HI cloud.

- **Absorption cross section in the atomic frame:**

In the classical photon-atom interaction model\(^1\), the absorption cross-section \(\sigma_{at}(\nu)\) in the rest frame of a static HI atom is a function of the incoming photon frequency \(\nu\) ([Monier (2006), chap. 4.4]):

\[
\sigma_{at}(\nu) = \frac{e^2 \pi f_{12}}{m_e c} \left( \frac{\Gamma / 4\pi^2}{(\nu - \nu_0)^2 + (\Gamma / 4\pi)^2} \right) \quad (cm^2)
\]

(5.2)

This is a Lorentzian function, where \(e\) is the elementary charge, \(m_e\) the electron mass, \(c\) the speed of light, \(f_{12} = 0.4162\) the oscillator strength of the Ly\(\alpha\) transition, \(\nu_0 = 2.47 \times 10^{15}\) Hz the frequency of the Ly\(\alpha\) line at the line center (related to the wavelength \(\lambda_{\text{Ly}\alpha} = 1215.67\ \text{Å}\)) and \(\Gamma = A_{12} = 6.265 \times 10^8\ \text{s}^{-1}\) the Einstein coefficient of spontaneous emission for the electronic transition of the Ly\(\alpha\) line (i.e. the probability of spontaneous emission per second). This Lorentzian function describes the natural broadening of the Ly\(\alpha\) line. The cross-section \(\sigma_{at}(\nu)\) is thus centered at the Ly\(\alpha\) line frequency \(\nu_0\) and decreases sharply over a very small frequency range \(\Delta\nu\) around \(\nu_0\) (\(\Delta\nu = 6.265 \times 10^8\ \text{Hz}\)).

- **Absorption cross-section \(\sigma(\nu)\) in the observer’s frame:**

The equation 5.2 is only valid in the rest frame of a static HI atom. In reality, a HI atom that is exposed to a certain temperature \(T\) undergoes a random thermal motion with respect to an observer. As a consequence, a strong Doppler shift should occur in the atomic frame, shifting the intrinsic absorption profile (eq. 5.2) at a frequency \(\nu\) other than the one of the Ly\(\alpha\) line center \(\nu_0\). If we describe the thermal motion of the HI atom by the Maxwellian distribution, the cross-section \(\sigma(\nu)\) in an observer’s frame is a convolution of the cross-section \(\sigma_{at}(\nu)\) with the velocity distribution of the HI atom:

\(^1\)The photon-atom interaction can be seen as an electromagnetic wave interacting with an oscillating dipole.
Figure 5.2: Schematic representation of the motions of both the absorbing HI atom (black dot) and the incoming Lyα photon (blue wave). The HI atom travels in a random direction with respect to the one of the Lyα photon. The projection of the velocity vector of the HI atom $\vec{V}$ is noted $V_z$.

$$\sigma(\nu) = \int_{-\infty}^{\infty} \sigma_{\text{at}} (\nu (1 - \frac{V_z}{c})) P(V_z) \, dV_z$$  \hspace{1cm} (5.3)$$

where $V_z$ is the projection of the velocity $\vec{V}$ of the HI atom along the direction of propagation of the incoming Lyα photon$^1$. $P(V_z)dV_z$ is the probability to find the HI atom in the velocity range $[V_z; V_z + dV_z]$ and $\nu$ is the frequency of the incoming Lyα photon in the observer’s frame. The term $\nu (1 - V_z/c)$ in equation 5.3 corresponds therefore to the frequency of the Lyα photon in the atomic frame. Using the Maxwellian distribution, the probability $P(V_z)dV_z$ is given by:

$$P(V_z)dV_z = \frac{1}{\sqrt{\pi V_{th}}} e^{-\frac{V_z^2}{V_{th}}} \, dV_z$$  \hspace{1cm} (5.4)$$

where $V_{th} = (2k_B T/m_H)^{1/2} = 12.85(T/10^4)^{1/2} \text{ km.s}^{-1}$ is the thermal velocity dispersion of the HI atom (i.e. the most probable speed of the HI atom) and $T$ the temperature of the gas expressed in Kelvin. The thermal motion of HI atoms has for main effect to widen the width of the Lyα absorption profile. In this way, we can introduce the Doppler frequency broadening of the Lyα absorption profile $\Delta \nu_D$ that is given by $\Delta \nu_D = (V_{th}/c) \nu_0$. The turbulence has also an effect on the broadening of the Lyα absorption profile, leading to a more general Doppler frequency broadening $\Delta \nu_D = (b/c) \nu_0$, where $b = (V_{th}^2 + V_{turb}^2)^{1/2} \text{ km.s}^{-1}$.

Before deriving the final expression for the cross-section $\sigma(\nu)$ (eq. 5.3), we introduce some other useful variables. First of all, instead of the frequency $\nu$ of the incoming Lyα photon, let’s consider the dimensionless parameter $x$:

$^1$We assume here that the incoming Lyα photon travels along the axis $z$ of a cartesian grid in the observer’s frame (Fig. 5.2).
\[ x = \frac{v - v_0}{\Delta v_D} \quad (5.5) \]

This parameter measures the shift of the frequency \( v \), in frequency \( \Delta v_D \), from the line center \( v_0 \). Then, we also introduce the Voigt parameter \( \alpha \), which measures the ratio between the natural and the thermal widths of the Ly\( \alpha \) line:

\[ \alpha = \frac{\Gamma/4\pi}{\Delta v_D} = 4.7 \times 10^{-4} \times T_4^{1/2} \quad (5.6) \]

where \( T_4 \) is the temperature in units of \( 10^4 \) K. Including these different variables in the equation 5.3, the total cross-section \( \sigma(x) \) in the observer’s frame is given by:

\[ \sigma(x) = \frac{\sqrt{\pi}e^2}{m_e c} f_{12} \frac{H(\alpha,x)}{\Delta v_D} \quad (5.7) \]

where \( H(\alpha,x) \) is the Hjerting function. It describes the Voigt absorption profile of the cross section \( \sigma(x) \) and is defined as:

\[ H(\alpha,x) = \frac{\alpha}{\pi} \int_{-\infty}^{\infty} \frac{e^{-y^2}}{(y-x)^2 + \alpha^2} \, dy = \begin{cases} \sim e^{-x^2} & \text{core} \\ \sim \frac{\alpha}{\sqrt{\pi}x} & \text{wing} \end{cases} \quad (5.8) \]

where we use the dimensionless variable \( y = V_z/V_{th} \). The critical frequency \( x_c \) that marks the transition between core and wing in the Hjerting function depends on the value of the Voigt parameter \( \alpha \) (i.e. on the temperature \( T \) to which the HI atom is exposed). For \( \alpha \) in the range \( [10^{-2},10^{-6}] \) the transition occurs in the frequency range \( [2.5,4] \) (Verhamme et al., 2006), whereas for \( \alpha = 4.7 \times 10^{-4} \) (corresponding to a temperature \( T=10^4 \) K, typical of the thermal conditions of neutral Hydrogen clouds of a real ISM) the transition occurs at \( x_c \approx 3.3 \).

From the equation 5.7, we notice that the broadening of the absorption profile of the Ly\( \alpha \) line is essentially due to the Doppler broadening in most of the HI clouds of an ISM. Indeed, the usual temperatures measured in neutral HI clouds of a real ISM (i.e. \( T \approx 10^4 \) K in the Warm Neutral Medium, McKee & Ostriker 1977) leads to a Doppler broadening \( \Delta v_D \approx 1.05 \times 10^{11} \) Hz. This value is three orders of magnitude higher than the natural width of the Ly\( \alpha \) line (\( \Gamma = 6.265 \times 10^8 \) Hz) and one order of magnitude higher than the frequency difference between the 2P-states of the second energy level of the Hydrogen atom (2P\(_{1/2}\) and 2P\(_{3/2}\), \( \Delta v = 10^{10} \) Hz).

At the Ly\( \alpha \) line center, the cross-section \( \sigma(v_0) \) reaches \( 5.9 \times 10^{-14} \) cm\(^2\), which is several orders of magnitude higher than the one of ionizing photons \( (\sigma(912 \, \text{Å}) = 6.3 \times 10^{-18} \) cm\(^2\)) and the one of other recombination lines of the Hydrogen atom. Therefore, among all photons likely to interact with neutral
Hydrogen atoms, Lyα photons appear as the most probably ones.

- **Optical-depth \( \tau_x \) and probability of absorption:**

The optical depth \( \tau_x \) experienced by a Lyα photon that is propagating through a cloud of neutral Hydrogen is given by:

\[
\tau_x(L) = \int_0^L \sigma(x) n_H(z) \, dz \tag{5.9}
\]

where \( L \) is the physical size of the HI cloud along the direction of propagation of the Lyα photon, \( n_H(z) \) is the Hydrogen density at the abscise \( z \) along this direction and \( \sigma(x) \) is defined in equation 5.7. Combining all equations defined above, it can be shown that (Verhamme et al., 2006):

\[
\tau_x(L) = 1.041 \times 10^{-13} T_4^{-1/2} N_{HI} H(a,x) \sqrt{\pi} \tag{5.10}
\]

where \( N_{HI} \) is the neutral Hydrogen column density measured along the direction of propagation of the photon. At the Lyα line center (\( x = 0 \)), the optical depth of a static HI medium is given by:

\[
\tau_0(L) = 3.31 \times 10^{-14} T_4^{-1/2} N_{HI} \tag{5.11}
\]

The optical depth \( \tau_x \) is related to the probability \( P(x) \) of a Lyα photon of frequency \( x \) to be absorbed by a HI atom in the Hydrogen cloud: \( P(x) = 1 - e^{-\tau_x} \). From the equation 5.11, we notice that a HI cloud becomes optically thick to Lyα photons from \( N_{HI} = 3 \times 10^{13} \text{ cm}^{-2} \) (assuming here \( T = 10^4 \text{ K} \) in the HI medium). Such HI column density is very low compared to the ones usually measured in the HI clouds observed in the ISM of galaxies. In the Milky way, the measurement of the total HI column density of neutral Hydrogen clouds located in the local ISM reveals column densities going from \( 10^{18} \text{ cm}^{-2} \) to few \( 10^{21} \text{ cm}^{-2} \) (Heiles and Troland 2003; Stanimirović et al., 2007). Such a HI column density range implies a probability of Lyα photons absorption of unity in any HI cloud of a real ISM. It is then very unlikely to see a Lyα photon escaping from galaxies without interacting with any HI atom (except those escaping between holes that may appear between HI clouds). This is especially true given that massive stars (O and B type stars) and their surrounding HII region are still embedded in their natal giant molecular clouds (Churchwell 1990; Gouliermis et al. 2012). Therefore Lyα photons have at least to get through such dense HI clouds before traveling inside the ISM.
5.2.2 Re-emission process

After absorbing a Ly\(\alpha\) photon, the excited HI atom sees its electron going from the ground state \(1S_{1/2}\) to one of the 2P orbitals of the second energy level (\(2P_{1/2}\) or \(2P_{3/2}\)). Due to the very short lifetime of the electron in a 2P-state, around \(t = 1/A_{12} \approx 10^{-8}\) s (with \(A_{12}\) the Einstein coefficient of spontaneous emission for the Ly\(\alpha\) transition), the return of the electron to the ground state is considered as immediate\(^1\). This transition emits a new Ly\(\alpha\) photon by spontaneous emission. Nonetheless, let’s remark that the re-emission of a Ly\(\alpha\) photon may be suppressed if any collision/interaction occurs during this short time scale (see section 5.4.2).

In the framework of the re-emission of a Ly\(\alpha\) photon, the outgoing photon is different from the incoming one in the observer’s frame. In particular, the frequency, the direction of propagation and the degree of polarization may change, as we explain further.

- Angular redistribution:

  The angular redistribution of the re-emitted Ly\(\alpha\) photon is not isotropic in the atomic frame. It mostly depends on 1) the electronic transition involved in the re-emission process and 2) the frequency \(x\) at which the incoming Ly\(\alpha\) photon is absorbed by the HI atom.

  Overall, whereas the scattering event \(1S_{1/2} \rightarrow 2P_{1/2} \rightarrow 1S_{1/2}\) leads to an isotropic re-emission of the Ly\(\alpha\) photon, the sequence \(1S_{1/2} \rightarrow 2P_{3/2} \rightarrow 1S_{1/2}\) produces a dipolar redistribution of the re-emitted Ly\(\alpha\) photon (Chandrasekhar, 1960; Ahn et al., 2002; Dijkstra and Loeb, 2008). The frequency \(x\) of the incoming photon plays also a role in the final angular redistribution. It is indeed different for core and wing scattering. For a Ly\(\alpha\) photon absorbed in the core of the absorption profile (i.e. for \(x < 3.3\), assuming here \(T = 10^4\) K in the HI gas), the photon is scattered at resonance via one of the two orbitals of the 2P state (\(2P_{1/2}\) or \(2P_{3/2}\)). Summing over all possible Ly\(\alpha\) transitions\(^2\), the averaged scattering phase function\(^3\) \(p(\theta)\) undergone by the re-emitted Ly\(\alpha\) photon can be described as a superposition of Rayleigh and isotropic scattering with corresponding weight 1/3 and 2/3 (Dijkstra and Loeb, 2008):

\(^1\)Given the very short time scale on which the spontaneous emission occurs, the Ly\(\alpha\) "absorption - re-emission" process is rather called "Ly\(\alpha\) scattering" by simplicity.

\(^2\)Given the multiplicity of each 2P state (i.e. equal to \(2J+1\), with \(J\) the total angular momentum quantum number), the scattering of a Ly\(\alpha\) photon via the \(2P_{3/2}\) state is twice more likely than the scattering via the state \(2P_{1/2}\).

\(^3\)The angular phase function \(p(\theta)\) gives the probability of the re-emitted photon being scattered at an angle \(\theta\) relative to the incoming photon.
\[ p(\theta) = \frac{11}{12} + \frac{3}{12} \cos^2(\theta) \] (5.12)

In the wing of the absorption profile, Stenflo (1980) shows that the Ly\(\alpha\) scattering cannot be splitted into the 2P\(_{1/2}\) or the 2P\(_{3/2}\) state separately, but into a superposition of both states. A quantum mechanics approach of this problem proves that this superposition (Rayleigh scattering and the isotropic scattering) introduces quantum interferences, yielding to the following angular phase function \(p(\theta)\):

\[ p(\theta) = \frac{3}{4} + \frac{3}{4} \cos^2(\theta) \] (5.13)

The angular phase function \(p(\theta)\) in the wing of the Ly\(\alpha\) absorption profile corresponds to a pure Rayleigh scattering.

- **Degree of polarization:**

The polarization degree of the incoming Ly\(\alpha\) photon also changes with the scattering process. As the angular redistribution, the photon polarization depends on 1) the electronic transition involved in the scattering process and 2) the frequency \(x\) of absorption. In general, the transition from the 2P\(_{1/2}\) state gives completely unpolarized Ly\(\alpha\) photons, while the one from 2P\(_{3/2}\) leads to a maximum degree of polarization of 3/7 for an angular re-emission of 90° (Chandrasekhar 1960). Using the same calculation than above, it turns out that scatterings of Ly\(\alpha\) photons in the wings (i.e. for \(x > 3.3\)) show a degree of polarization three times higher than the ones produced by scatterings in the core (Dijkstra and Loeb 2008).

- **Frequency redistribution:**

While the frequency redistribution of Ly\(\alpha\) photons is coherent in the atomic frame\(^1\)(i.e. the frequency \(x\) before and after scattering is the same in the atomic frame), in reality, in the scattering with a HI atom, a Ly\(\alpha\) photon transfers a very small fraction of its energy to the atom (by analogy to the Compton scattering between an electron and a photon). This effect is usually called the recoil effect. As a consequence, the energy of the Ly\(\alpha\) photon should decreases during the scattering process, yielding an output frequency \(\nu_{\text{out}}\) higher than the one of the incident photon \(\nu_{\text{ini}}\). However, the difference \(\nu_{\text{out}} - \nu_{\text{ini}}\) (i.e. \(\nu_{\text{out}} - \nu_{\text{ini}} < 1.6 \times 10^8 \text{ Hz}\)) is negligible compared to the frequency redistribution of the Ly\(\alpha\) photon due to the thermal motion of the HI atoms (see text). The recoil effect can be therefore neglected and the frequency redistribution can be considered as coherent in the atomic frame.

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Figure 5.3: Frequency redistribution of Lyα photons in the observer’s frame. All curves take into account both the natural and the Doppler broadening of the Lyα line and are averaged over all re-emission directions. For each curve, an incoming Lyα photon of frequency $x$ is absorbed by a HI atom ($x = 0, 1, 2, 3$ and $4$ in the observer’s frame). The curves show the re-emission probability $P(x)$ of the outgoing Lyα photon. This figure is based on an isotropic angular redistribution of the re-emitted Lyα photon (i.e. corresponding to the scattering event $1S_{1/2} \rightarrow 2P_{1/2} \rightarrow 1S_{1/2}$).

In the observer’s frame, the frequency redistribution of a Lyα photon depends on 1) the re-emission direction of the Lyα photon and 2) the speed of the HI atom. The complexity of the frequency redistribution finds some analytical solutions: the two functions $R_{II}$ of Hummer (1962). These two functions describe the frequency redistribution of a re-emitted Lyα photon for a dipolar angular redistribution (for the sequence $1S_{1/2} \rightarrow 2P_{3/2} \rightarrow 1S_{1/2}$) and an isotropic angular redistribution (for the sequence $1S_{1/2} \rightarrow 2P_{1/2} \rightarrow 1S_{1/2}$). In figure 5.3 we illustrate the function of Hummer (1962) for the isotropic angular redistribution case. From this figure, the angular redistribution of a Lyα photon in the observer’s frame can be described in the following way:

- For an incoming Lyα photon of frequency $x_{ini}$ in the core of the absorb-
tion profile (i.e. \(x_{ini} \leq 3.3\)), the frequency of the outgoing Ly\(\alpha\) photon will be in the range \([-x_{ini};x_{ini}]\). Indeed, in the core of the absorption profile, a Ly\(\alpha\) photon is likely to be absorbed by moving HI atoms that see the frequency \(x_{ini}\) exactly at the Ly\(\alpha\) line center in their own frame (see figure 5.4). As the re-emission of the Ly\(\alpha\) photon is coherent in the atomic frame, it is re-emitted at the line center from the HI atom. Therefore, considering all possible atom speeds and all directions of re-emission, the frequency range of the outgoing Ly\(\alpha\) photons is roughly \([-x_{ini};x_{ini}]\) in the observer’s frame.

- For a Ly\(\alpha\) photon of frequency \(x_{ini}\) in the wing of the absorption profile (i.e. \(x_{ini} > 3.3\)), the frequency redistribution is almost coherent in the observer’s frame (i.e. the outgoing photon frequency \(x_{out}\) is approximately equal to the one of the incoming Ly\(\alpha\) photon \(x_{ini}\)). Indeed, a Ly\(\alpha\) photon of frequency \(x_{ini}\) seen in the wing of the Ly\(\alpha\) absorption profile is unlikely to be absorbed by a moving HI atom at resonance (see figure 5.4). Instead, they are very likely to be absorbed in the wing of the absorption profile by a static HI atom. Nonetheless, the Ly\(\alpha\) frequency redistribution is coherent in the atomic frame, so it also remains unchanged in the observer’s frame.

5.2.3 The Ly\(\alpha\) radiative transfer in HI media

- The transport of Ly\(\alpha\) photons through HI media:

In the previous subsections, we highlight both the very high scattering probability of Ly\(\alpha\) photons and the strong impact the re-emission process has on the frequency, the direction of propagation and the polarization degree of the Ly\(\alpha\) photons. In this subsection, we explain the way Ly\(\alpha\) photons travel inside optically thick HI media and how Ly\(\alpha\) photons may escape from the ISM of galaxies.

Unlike other lines, the scattering of resonant Ly\(\alpha\) photons in optically thick HI media is not a pure random walk, but a coupled spatial and frequency space one. In other words, while non-resonant lines try to escape from optically thick media by moving in space (until they reach the edge of the cloud after experiencing a multitude of scatterings), Ly\(\alpha\) photons rather escape straight by taking advantage of the frequency shift they undergo when scattering against HI atoms. Therefore, it is when the Ly\(\alpha\) photon frequency is shifted enough to the wing of the Ly\(\alpha\) absorption profile (where the opacity is lower) that the photon escape from neutral Hydrogen media or the ISM of
Figure 5.4: Probability that a Ly\(\alpha\) photon of frequency \(x_{\text{ini}}\) is absorbed by a HI atom such that it appears at a frequency \(x_{\text{at}}\) in the atomic frame (Dijkstra and Loeb 2008). We assume a temperature of \(T = 10^4\) K, so the core-wing scattering transition occurs at \(x \sim 3.3\). We consider two different Ly\(\alpha\) photons: the ones seen in the core \((x_{\text{ini}} = 3.3,\) solid line\) and the ones seen in the wing \((x_{\text{ini}} = -5.0,\) dashed line\) of the Ly\(\alpha\) absorption profile. For \(x_{\text{ini}} = 3.3\), Ly\(\alpha\) photons are absorbed at resonance \((x_{\text{at}} = 0)\) or in the wing at \(x_{\text{at}} \approx 3.3\) (by static HI atoms). However, for \(x_{\text{ini}} = -5.0\), Ly\(\alpha\) photons are unlikely to be absorbed at resonance (as very few HI atom are fast enough to Doppler shift the frequency \(x_{\text{ini}}\) at resonance). These photons are mostly absorbed in the wing of static HI atoms, at \(x_{\text{at}} \approx -5.0\).

A galaxy (Adams 1972). Given this basic mechanism, two different cases can be distinguished.

- **A medium with a moderate optical depth** \(\tau_0\) (i.e. \(\tau_0 < 10^3\)) becomes highly optically thick at the line center, but remains optically thin in the wings of the absorption profile (eq. 5.10). Through this medium, a Ly\(\alpha\) photon always starts scattering locally against HI atoms (since it is initially emitted in the core of the Ly\(\alpha\) absorption profile). However, after many scatterings, a fast HI atom (a HI atom with a velocity in the wing of the Maxwellian distribution) can absorb the Ly\(\alpha\) photon. In such a case, the Ly\(\alpha\) photon is shifted off resonance in the re-emission and it can directly escape from the HI medium (because now seen in the wing of the Ly\(\alpha\) absorption profile, where the opacity is lower).

- **In a medium with an extremely high optical depth** \((\tau_0 > 10^3/\alpha,\)
Neufeld et al. 1990), the previous process becomes mostly inefficient for Lyα photons because the wing of the Lyα absorption profile is now optically thick. In such a case, Lyα photons travel in space and change frequency in the course of the multitude scatterings they experience in the HI medium. This process continues until the Lyα photons either reach a favorable region for escaping the medium (i.e. a region having either a low HI density, strong gas kinematics, ... ) or are significantly shifted into the wings at high frequency \(x_{esc}\), such as the optical depth \(\tau(x_{esc})\) is lower than unity.

Such understanding of the Lyα radiative transport has come after a long period of theoretical work that aimed to understand both the scattering and escaping processes experienced by Lyα photons in optically thick HI media (Unno, 1955; Field, 1959; Osterbrock, 1962). During the 1950s and 1960s, it was believed that the scattering of Lyα photons was a pure random walk. This scenario (based on a coherent scattering of Lyα photons) implied that Lyα photons could only escape from HI media once they reached the edge of the cloud by scattering against HI atoms. However, since the average number of scatterings needed would be very high in this case (i.e. \(N_{sc} = \tau_0^2\), Osterbrock 1962), the probability of seeing Lyα photons escaping from any optically thick and static HI medium would be almost zero. This result seemed to indicate that no Lyα emission could escape from any astronomical objects. Then, for the first time, Adams (1972) proposed that Lyα photons may travel in a different way: unlike other lines, Lyα photons could escape from extremely optically thick media after experiencing different series of excursions to the wings of the Lyα absorption profile. This scenario explains how resonant photons can escape from optically thick media. Indeed, unlike pure random walk scenarios, in this case the mean number of scattering Lyα photons needed for escaping is lower (i.e. \(N_{sc} = \tau_0\), Adams et al, 1972). This implies both a longer mean free path and a higher probability of Lyα photons escaping from optically thick HI media.

- **Analytical and numerical studies of Lyα transport:**

Given the way Lyα photons travel inside HI media, we can understand the formation of the double-peak profile that the Lyα line exhibits when escaping from static HI clouds (see figure 5.5). Such a line profile has been analytically explained by Neufeld (1990) in the limit of a source of radiation located in a very optically thick, uniform density and isothermal slab. As shown in figure 5.5, all Lyα photons (originally emitted at the line center \(x = 0\)) are redistributed into the wings. The frequency of the maximum of each peak is \(x_{max}\).
Figure 5.5: Emergent predicted Ly$\alpha$ line profiles for a monochromatic source embedded in a static HI medium with various HI column density $N_{HI}$ (i.e. various $\tau_0$). In this figure is compared the emergent spectra obtained from Monte Carlo radiative transfer simulations (solid histograms, Tasitsiomi (2006)) and the ones predicted analytically by Neufeld (1990) (dashed histograms). The emergent line has a double-peak line profile where the separation between the two peaks increases as $\tau_0$ increases in the medium. Source: Tasitsiomi (2006)

$$\tau_0 = 10^4$$

$$\tau_0 = 10^5$$

$$\tau_0 = 10^6$$

$$x = \Delta \nu / \Delta \nu_d$$

$= \pm 0.88(a\tau_0)^{1/3}$ and the average number of scattering is $N_{sc} = 0.91\tau_0$ (Harrington, 1973). As mentioned above, both the frequency and the separation between the two peaks tend to increase as the optical depth $\tau_0$ of the medium increases. Indeed, it is more complicated for Ly$\alpha$ photons to emerge from a media showing high $\tau_0$. Therefore, the photon frequencies must move farther away in order to escape from the HI clouds.

Like the analytical approach developed by Neufeld (1990), all analytical solutions known to date are only applicable to certain specific and idealized conditions when studying the Ly$\alpha$ radiative transfer in HI media. It therefore appears that the numerical approach remains the only method available to comprehend the complex transport of the Ly$\alpha$ line in galaxies and cosmological values.
5.3 Interaction between Lyα photons and dust

When traveling inside the ISM, Lyα photons may also interact with dust. When this interaction occurs, a Lyα photon can be either absorbed and scattered by the dust grain. The total probability of interaction of a Lyα photon with dust depends on the total cross-section $\sigma_d$, which is the sum of the scattering cross section $\sigma_s$ and the absorption cross section $\sigma_a$:

$$\sigma_d = \sigma_s + \sigma_a$$ (5.14)

The cross sections $\sigma_a$ and $\sigma_s$ are both defined as $\sigma_{a,s} = \pi R^2 Q_{a,s}$, with $R$ the mean radius of a dust grain (assuming here that the dust grain is spherical) and $Q_a$ and $Q_s$ are the absorption and scattering efficiency respectively ($Q_a = Q_s = 1$ at UV wavelengths, Verhamme et al. 2006). Furthermore, both parameters $Q_a$ and $Q_s$ intervene in the definition of the albedo of the dust grains. This dimensionless parameter, noted $A$, describes the probability for a photon of being scattered instead of absorbed by the dust. It is the ratio between the scattering efficiency $Q_s$ and the total efficiency of interaction: $A = Q_s/(Q_a+Q_s) \approx 0.50$ for the Lyα and the adjacent UV continuum photons (Witt and Gordon 2000; Draine 2003). With a typical grain size of $R \approx 10^{-6}$ cm (Draine 2003) and the measured values of $Q_a$ and $Q_s$ at Lyα and UV wavelengths, we get a total cross section of $\sigma_d \approx 7 \times 10^{-12}$ cm$^2$ for Lyα photons. At the Lyα line center, $\sigma_d$ is therefore an order of magnitude lower than the HI atom absorption cross section $\sigma(\nu)$ (eq. 5.7). However, despite its low probability, the interaction between Lyα photons and dust may occur at the line center. Indeed, the overall probability of such an interaction increases due to the resonant scattering of Lyα photons. In the wing of the line, the interaction with dust has also great chances to occur as the dust cross-section $\sigma_d$ starts exceeding the HI absorption one ($\sigma(\nu)$).

The scattering of a Lyα photon with a dust grain has also a non negligible impact on some properties of the incoming photon, such as the frequency, the direction of propagation and the degree of polarization. Below, we describe some of these changes further.

- angular redistribution:

The Henyey and Greenstein (1941) analytical function approximate the photons angular redistribution in radiative transfer models as:

$$\phi(\theta) = \frac{1 - g^2}{4\pi(1 + g^2 - 2g\cos(\theta))^{3/2}}$$ (5.15)

where $g = <\cos(\theta)>$ is the only parameter of the scattering phase function.
Table 5.1: Dust parameters \((a \text{ and } g)\) taken from \cite{WittGordon2000} and adopted for \(\text{Ly} \alpha\) line photons, and continuum photons at UV and optical wavelengths (close to the B and V-band).

<table>
<thead>
<tr>
<th>Photons</th>
<th>(\lambda) (Å)</th>
<th>(\tau_d/\tau_V)</th>
<th>(a)</th>
<th>(g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{Ly} \alpha)</td>
<td>1215.67</td>
<td>6.74</td>
<td>0.460</td>
<td>0.770</td>
</tr>
<tr>
<td>UV</td>
<td>1235.0</td>
<td></td>
<td>0.495</td>
<td>0.633</td>
</tr>
<tr>
<td>B-band</td>
<td>4350.0</td>
<td>1.38</td>
<td>0.495</td>
<td>0.633</td>
</tr>
<tr>
<td>V-band</td>
<td>5550.0</td>
<td>1.00</td>
<td>0.490</td>
<td>0.607</td>
</tr>
</tbody>
</table>

\(\phi(\theta)\). This parameter strongly evolves with the photon frequency \(x\), as revealed by the analysis of the observed surface brightness of different reflexion nebulae \cite{Draine2003, Gordon1994, WittGordon2000, Calzetti1995, GibsonNordsieck2003}. Overall, the angular redistribution of photons is not isotropic in the frame of a dust grain. This has been revealed by the positive values of the phase function parameter \(g\) measured for the dust grains of the Milky Way (MW), the Small Magellanic Cloud (SMC) and the Large Magellanic Cloud (LMC). This implies a higher probability of being forward-throwing relative to the incoming photons \cite{Draine2003, WittGordon2000}.

However, it still remains many uncertainties on the scattering properties of dust grains in the UV field (i.e. albedo \(A\) and \(g\)). More precisely, two problems appear. First, although the function of \cite{HenyeyGreenstein1941} provides a good approximation to the observed phase function at wavelengths between 0.4 \(\mu\)m and 1.0\(\mu\)m, this function cannot be applied to reproduce the angular phase \(\phi(\theta)\) at shorter wavelengths (i.e. for \(\lambda < 0.27\); Draine et al., 2003). Second, the observational measurements of the dust scattering properties (\(A\) and \(g\)) in the MW, SMC and LMC exhibit large variations in the UV field.

Given these problems, we have made different assumptions on the dust properties in all papers presented at the end of this thesis (i.e. Paper I, II and IV). In particular, using the Monte Carlo code MCLya for our numerical simulations, we have modelling the dust scattering in the UV field through either the phase function of \cite{HenyeyGreenstein1941} or an isotropical angular redistribution. We list in table 5.2 the mean dust scattering properties we have considered in our numerical simulations (the values of \(g\) correspond to the ones we have used when considering the phase function of Heney and Greenstein; Witt & Gordon 2000). However, such assumptions have not any consequences on the results obtained throughout this thesis. Indeed, given the main quantities of interest in our different papers (i.e. gas kinematics, HI column density, ISM geometry), the destruction of the \(\text{Ly} \alpha\) and UV continuum photons by the dust does not strongly depend on the exact dust properties. We expect indeed
that other poorly known properties of an ISM (i.e. the velocity field, the HI column density and ISM geometry) on the Lyα radiative transfer are more important than the detailed dust properties (Laursen et al., 2009a).

- frequency redistribution:

The Lyα photons frequency redistribution by dust is coherent in the dust frame. However, as discussed previously for the photons frequency redistribution by Hydrogen, the frequency of the outgoing Lyα photon may change in the observer’s frame because of 1) the direction of re-emission of the Lyα photon and 2) the speed of the dust grain.

5.4 Other interactions

Lyα photons can experience other interactions when traveling inside the ISM. We consider two different interactions in this section: interaction with Deuterium atoms and atomic collisions. Besides explaining the effects of each interaction on Lyα photons, we also explain in more detailed how they are integrated in the Lyα radiative transfer code MCLya (Verhamme et al., 2006) we have used throughout this thesis.

5.4.1 Interaction with Deuterium

The Deuterium atom is an isotope of Hydrogen and is composed of a proton and a neutron. Lyα photons can be absorbed by Deuterium atoms at a frequency blueward the Hydrogen Lyα line center. The Deuterium Lyα absorption line center is blueshifted by 82 km.s\(^{-1}\) with respect to that for Hydrogen (i.e. \(\Delta v = 6.75 \times 10^{11}\) Hz between Hydrogen and Deuterium Lyα absorption lines). When studying the Lyα radiative transfer in numerical simulations, the Deuterium optical depth \(\tau_{D,x}\) must to be added to the Hydrogen \(\tau_x\) one. As shown by Dijkstra et al. (2006), the Deuterium optical depth \(\tau_{D,x}\) simply corresponds to the Hydrogen optical depth \(\tau_0\) (eq. 5.11) blueshifted to 82 km/s and reduced by the Deuterium abundance [D/H]. More precisely, we have \(\tau_{D,x} = \sqrt{2} \times [D/H] \tau_0 = 4.4 \times 10^{-5} \tau_0\), where [D/H] \(\sim 3 \times 10^{-5}\) (Burles and Tytler, 1998). The contribution of Deuterium to the Hydrogen optical depth (\(\tau_{D,x}/\tau_0\)) is shown in figure 5.6 (left panel) as a function of the frequency \(x\). In a gas exposed to a temperature \(T = 10^4\) K, Deuterium clearly dominates the Hydrogen optical depth blueward of the Lyα line center.

On the right panel of the figure 5.6 we show the typical imprint of Deuterium on a Lyα line profile emerging from a static HI media. A clear absorp-
Figure 5.6: Left panel: contribution of Deuterium (with a cosmological abundance of [D/H] = 3 \times 10^{-5}) to the Ly\(\alpha\) opacity for a gas at T = 10^4 K. The horizontal axis represents the radiation frequency expressed in terms of the dimensionless parameter x (eq. 5.5). The black-dotted line is for Hydrogen Ly\(\alpha\) line, the red-solid line is for Deuterium only and the blue-dashed line is their sum. For x in the range = 5-8, Deuterium dominates the opacity. Right panel: emerging Ly\(\alpha\) line profile with the imprint of the Deuterium on the blue side of the Ly\(\alpha\) line (assuming a cosmological abundance of Deuterium [D/H] = 3 \times 10^{-5}). This line profile has been obtained from a static sphere of Hydrogen showing a HI column density of 1.2 \times 10^{19} \text{cm}^{-2}. Source: Dijkstra et al. (2006).

The effect of Deuterium on the Ly\(\alpha\) transport has been included in the Monte Carlo Ly\(\alpha\) radiative transfer code MCLya (Verhamme et al., 2006) we have used throughout this PhD research program.

5.4.2 Collisions

As already mentioned above, HI atoms can collide during the scattering of Ly\(\alpha\) photons. Overall, atomic collisions have three different effects on both the absorbing HI atom and the scattered Ly\(\alpha\) photon (Tasitsiomi, 2006):

- **Redistribution of the electron within the first excited state**: During a
collision between an HI atom and a free proton, the electron of the HI atom can be shifted into another state of the first excited state. More precisely, the following electronic transitions are possible: $2\text{P} \rightarrow 2\text{S}$, $2\text{S} \rightarrow 2\text{P}$ or $2\text{P} \rightarrow 2\text{P}$. While the first possible transition leads to the destruction of the Ly$\alpha$ photon by a "two-photon" emission (from the decay of the $2\text{S}_{1/2}$ state), the second implies the emission of an extra Ly$\alpha$ photon by the absorbing HI atom. The third transition re-emits a Ly$\alpha$ photon changing its angular redistribution.

- **De-excitation from the first excited state**: During a collision between an HI atom and a free electron, the excited electron of the HI atom may decay from the state $n=2$ to the ground state without emitting any Ly$\alpha$ photon.

- **Broadening of the absorption line profile**: Mostly observed after a collision with other particles than electrons and protons (atoms, ions, ...), the electron energy levels may be distorted. This phenomenon leads to a broadening of the Ly$\alpha$ absorption profile (eq. 5.7), leading to an incoherent re-emission of a Ly$\alpha$ photon in the atomic frame.

In the first case, the $2\text{P} \rightarrow 2\text{S}$ transition is the most likely under low proton number densities ($n_p < 10^4 \text{ cm}^{-3}$), while the transition $2\text{S} \rightarrow 2\text{P}$ overpasses at high proton density. However, given both the low proton and electron densities of HII regions and neutral Hydrogen clouds in galaxies (i.e. $n_p \leq n_e \leq \sim 400 \text{ cm}^{-3}$ in HII regions; Beckman et al. 2013), the rate of collisions of HI atoms with electrons and protons is very low in reality (Osterbrock 1989). Therefore, the first type of collisions mentioned above can be neglected under normal physical conditions in star-forming galaxies. The same conclusion can be formulated for the collisions of type 2 and 3 as their collisional cross sections are even lower than the cross section of the case 1.

All collisional events mentioned in this section have been neglected in the Ly$\alpha$ radiative transfer code MCLya. Therefore, we always assume a re-emission and a coherent frequency redistribution (in the atomic frame) of Ly$\alpha$ photons when absorbed by a HI atom.
Summary and contribution to the Papers

In the next sections we first summarize both the scientific context and the aims of each of the four papers included in this thesis. Then, I also explain in more details my contribution to these different studies.

- **Paper I**: Since the 1990s, and the early analytical and observational works of Neufeld (1991) and Giavalisco et al. (1996), the ISM geometry and its clumpiness are expected to play a significant role in the radiation transport of the Lyα line in star-forming galaxies. In particular, clumping can in principle alter both the transfer and the opacity of the ISM to Lyα, as shown early by Neufeld (1991), and has often been invoked to explain anomalously strong Lyα equivalent width EW(Lyα) observed at high-redshift (Shimasaku et al., 2006; Kashikawa et al., 2012; Rhoads et al., 2003). However, while only a few detailed numerical studies of the effects of ISM clumpiness on Lyα has so far been undertaken, no observational study of these effects has been carried out until now.

Throughout this paper, we performed a detailed radiation transfer calculations using the 3D Monte Carlo code MCLya of Verhamme et al. (2006) and Schaerer et al. (2011) to examine and understand the main effects of clumpy ISM structures on the Lyα line and UV continuum radiative transfer. Our aim was to identify the main effects produced by a clumpy ISM on both the transport and the observed properties of the Lyα line of star-forming galaxies (strength, EW(Lyα) and line profile). As an application of this study, we also examined the physical conditions under which the Neufeld model (Neufeld, 1991) can work in a clumpy ISM.

I performed all numerical simulations presented in this paper, as well as their complete analysis. Furthermore, I have made all plots and I have written all the paper.

- **Paper II**: This paper is based on Paper I. Here, we mostly focused on the Neufeld model and the possible origins of unusually high equivalent widths of the Lyα line observed from star-forming galaxies at high-redshift. Our aims were to investigate under which physical conditions the Neufeld model may work in a clumpy ISM and to propose alternative scenarios that may also lead to artificial enhancements of EW(Lyα). Throughout this study, we used another radiative transfer numerical code, named MoCaLaTa (Laursen et al., 2009b) and more restraint physical conditions for the clumpy media in which the Lyα radiation transport was studied. The results presented in this paper
were consistent with the ones presented in Paper I, which confirmed the robustness of all our results.

I worked in collaboration with the main author of this paper (Peter Laursen) and I participated in both the analysis and the discussion of the paper.

- Paper III: The Lyman Alpha Reference Sample (LARS) is a sample of 14 nearby star-forming galaxies that were imaged and spectroscopically observed in high-resolutions with the Hubble Space Telescope (HST) in cycles 18, 19 and 20 (P.I. Ostlin, program 12310). Throughout this paper, we presented the first results regarding the Lyα output of the star-forming galaxies based on our HST imaging.

We first presented the intensity images in Lyα, Hα and FUV, and maps of Lyα equivalent width, Lyα/Hα and Hα/Hβ for each galaxy of the LARS sample. Comparing the Lyα morphology of these galaxies to the ones of Hα and FUV continuum radiation, we revealed the presence of an extended Lyα-halo around most of the Lyα-emitting galaxies of the sample. Second, we reexplored all relations between the Lyα line properties (Luminosity, Lyα escape fraction, EW(Lyα) and the line ratio Lyα/Hα) and other ISM and stellar quantities derived from either HST imaging or different spectroscopic data.

My contribution to this paper consisted in reducing all HST data of the LARS sample and deriving all maps of the continuum-subtracted Lyα line, Hα line and other physical quantities of the galaxies.

- Paper IV: Throughout the evolution of galaxies, many of their properties have rapidly changed with time, such as their mass, their size, their abundance in heavy elements and, especially, their morphologies. Whereas all young galaxies at redshift beyond z = 4 exhibits an irregular morphology (Beckwith et al., 2006), the fraction of regular and disk galaxies has increased with decreasing redshift (especially for z < 2; Ferguson et al. 2000; Papovich et al. 2005). Interestingly, recent numerical simulations of isolated star-forming disk galaxies have suggested a strong dependency of the Lyα properties on the inclination of the disk (as explained in section 4.3.3; Verhamme et al. 2012, Behrens et al. 2014). In other words, from edge-on to face-on, we should go from an absorption Lyα line to a strong Lyα emission line. Whereas such a dependency is only the result of numerical simulations, the LARS sample provides us the opportunity to investigate this effect because composed of edge-on and face-on disk galaxies.

In particular, the fifth galaxy of the LARS sample (named Mrk1486) exhibits very surprising Lyα properties that seem to go against all numerical predictions. Indeed, this galaxy shows one of the highest Lyα luminosity (L_{Lyα} = 1.11 \times 10^{42} \text{ erg s}^{-1}), Lyα equivalent width (EW(Lyα) = 35 \text{ Å}) and Lyα escape
fraction ($= 0.174$) of the LARS sample, suggesting an easy escape of Ly$\alpha$ photons from the disk of Mrk1486. Therefore, a particular mechanism seems to be at work in Mrk1486 that help Ly$\alpha$ photons to easily escape from the core of the galaxy. The aim of this paper was to examine and understand both the sites of production and the Ly$\alpha$ transport inside Mrk1486.

We carried out a detailed study of the HST imaging and a radiation transfer calculations to reproduce the Ly$\alpha$ line profile of the galaxy. All numerical simulations were performed using the 3D Ly$\alpha$ Monte Carlo code MCLya, a large grid of simulations used in Paper I and a relatively complex 3D geometry of HI and dust that modeling the ISM structure of LARS#5.

Throughout this paper I performed all HST data reduction, all numerical simulations, as well as their complet analysis. Furthermore, I have made all plots and I have written all the paper.
Acknowledgments

First of all I would like to thank my supervisor Göran Östlin and my co-supervisor Erik Zakrisson for their scientific support throughout the five years of my PhD. I am very grateful to Göran for having given me the opportunity to travel a lot, especially for observing, one of the most exciting dreams of any young astronomer.

My thanks go also to all people at the astronomy department for the very nice atmosphere in which I have carried out my PhD. Among those people, a particular thanks to Illa, Emanuel, Kai Yan, Gianni, Utte, Sarah, Thoger, Andreas, Johannes, Saghar, Hannes, Francesco, Katia, Hiva, Tine, Matteo, Johanne and Carolina for all great times and parties we have had together during these last few years. You have been a second family to me in Stockholm and great friends, I will never forget you. It will be always a great pleasure to meet you during the next few years. Moreover, I should also focus my thanks to the most amazing, friendly and helpful office-mates I have had during my PhD: Thoger Rivera-Thorsen and Anders Jerkstrand. Thanks a lot guys for the very nice chats, scientific discussions and friendship we have shared throughout my PhD. Working by your side has always been a great source of motivation to me.

Scientifically speaking, I will never forget the original answer some PhD students at the department used to give to the question: "how do we detect high-redshift Lyα-emitting galaxies using a telescope?". Instead of explaining the general procedure that consists in using a large telescope and a narrow-band filter, some colleagues of mine used to answer: "the first step would consist in sending Florent to La Palma Observatory... then, he can start the normal procedure". A big thank to Andreas for having allowed me to go observing more than seven times to La Palma for his own projects. It has been a great, rich and unique experience to me. In particular, big thanks to Lucia with who I observed most of the time and from who I learnt a lot, Thoger with who I tested how to break down a 2.5 meters telescope in the middle of the run, and Illa for the very nice, busy and interactive observing nights we had together.

I also want to thank all people of the galaxy group at the department, for the interesting discussions, helps and collaborations. It has been a great honor and an immense pleasure to work within such a very nice and very active scientific group.

Enfin, je tiens a remercier d’une facon toute particuliere mes parents et mon frere Damien. Sans leur aide et toute le soutient qu’ils m’ont apporte durant ces vingt huit premières années, je n’aurais surement pas pu atteindre
le niveau doctorat aujourd’hui. Nos vingt-six années de vie commune ont été absolument merveilleuses et pleine de joie. C’est une chance et un grand honneur d’avoir grandi à vos côtés. Une nouvelle page de ma vie s’ouvre à présent. C’est avec une grande joie que je l’aborde, mais aussi un grand plaisir de continuer ce chemin avec vous.
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