The Bright Side of the Dark Universe:
Lyα emission from the Intergalactic Medium

A dissertation submitted to

ETH ZURICH

for the degree of

Doctor of Sciences

presented by

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2008
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Abstract

The analysis of absorption systems in the spectra of high-z quasars has represented so far the only practical way to study the Intergalactic Medium (IGM). Unfortunately, this method is almost always one-dimensional.

The aim of this thesis is to explore in detail an alternative approach: the detection and study of the IGM in Ly$\alpha$ emission. This emission is mostly produced via hydrogen recombinations in the IGM ionized by an external background, as originally proposed by Hogan & Weymann (1987). Detection of the Ly$\alpha$ emission would provide a three-dimensional picture of the IGM and proto-galactic clouds at high redshift.

As a first step, in order to predict the observable properties of this emission, I developed and combined two radiative transfer models (one for the ionizing continuum and a full 3D Monte Carlo for the Ly$\alpha$ photons) with the results of an hydrodynamical simulation of structure formation at redshift three. The results, presented in Chapter 2, show that the velocity field and the complex topology of the IGM clouds have a substantial effect on the surface brightness and the shape of the Ly$\alpha$ emission. In particular, optically thick regions in vicinity of a quasar emit much less than expected from the widely used static, plane-parallel model. These findings are able to explain previous null detections and constitute the bases for the design of successful observing campaigns.

The prediction of the theoretical model have been used to carry out a spectroscopic survey for the IGM Ly$\alpha$ emission, presented in Chapter 3, around a quasar at redshift three. Using the FORS2 instrument at the Very Large Telescope (VLT), we detected 13 Ly$\alpha$ sources sparsely sampling a large volume around the quasar. The observed properties of these objects suggest that several of the detected sources may have an intergalactic origin. Moreover, their number density is in agreement with the expectations from theoretical models. The distance of most of the candidates from the quasar gives also a constraint on the quasar age, implying a lower limit of 30 Myr. One of the best candidates is sufficiently far behind the quasar to imply a lifetime of at least 60 Myr. Although there are uncertainties in interpretation (due both to observational limitations and theoretical uncertainties), this study provides one of the first statistical samples of Ly$\alpha$ clouds around a high-redshift quasar, opening a new window in the study of the IGM and the first stages of the galaxy-formation process.

Finally, in Chapter 4, I present a new method to directly detect and map the neutral IGM during the Reionization Epoch using the Ly$\alpha$ emission produced within the Ionization-fronts of the highest-redshift quasars. This emission, mainly produced by HI collisional excitation, should trace the bulk...
of neutral hydrogen in the IGM before the end of reionization, similarly to future 21-cm tomography. Using detailed radiative transfer simulations (based on a new radiative transfer code presented in the Appendix), I show that the expected signal should appear as a single line emission (with a width of few hundred km per second) with a typical brightness of the order of $10^{-20} \text{erg s}^{-1} \text{cm}^{-2} \text{arcsec}^{-2}$, depending on the quasar properties and redshift. The signal should be already detectable with current facilities by means of moderate/high resolution spectroscopy, shedding new light on the reionization history and the properties of the highest-redshift quasars.
Sommario

L’analisi degli spettri dei quasar ad alto redshift ha rappresentato fin ora l’unico mezzo pratico di studiare il Mezzo Intergalattico (IGM). Sfortunatamente, questo metodo è quasi sempre unidimensionale.


Come primo passo, ho sviluppato e combinato due modelli di trasporto radiativo (uno per i fotoni ionizzanti e un Monte Carlo tridimensionale per i fotoni Ly\(_\alpha\)) con i risultati di una simulazione idrodinamica di formazione delle strutture a redshift tre. I risultati, presentati nel Capitolo 2, mostrano che il campo di velocità e la complessa topologia delle sorgenti hanno un effetto significativo sulla radiazione emergente. In particolare, regioni otticamente spesse in prossimità di un quasar emettono molto meno di quanto prevedevano precedenti modelli statici e con geometrie semplificate. Questi risultati permettono di spiegare gli insuccessi di precedenti campagne osservative e costituiscono la base per pianificare nuove osservazioni.

Successivamente, ho utilizzato i risultati del modello teorico per la ricerca di emissione Ly\(_\alpha\) dall’IGM in prossimità di un quasar a redshift tre. Le osservazioni, presentate nel Capitolo 3, sono state effettuate in spettroscopia utilizzando lo strumento FORS2 al Very Large Telescope e hanno portato alla scoperta di 13 sorgenti Ly\(_\alpha\). Almeno metà degli oggetti scoperti presentano caratteristiche che sembrano confermare la loro natura intergalattica. Inoltre, la loro densità numerica è compatibile con i risultati del modello teorico. La distanza della maggior parte delle sorgenti dal quasar dà anche informazioni sull’età minima del quasar stesso, stimabile attorno ai 30 milioni di anni. Uno dei candidati più promettenti si trova ad una distanza tale da suggerire un’età minima del quasar di 60 milioni di anni. Sebbene vi possano essere ancora alcune incertezze sulla reale natura di questi oggetti (dovute sia ai limiti osservativi sia alle incertezze legate ai modelli), questo studio fornisce il primo insieme statistico di plausibili sorgenti Ly\(_\alpha\) intergalattiche attorno ad un quasar ad alto redshift. Per tale motivo, può rappresentare l’inizio di una nuova strada nello studio del Mezzo Intergalattico e delle prime fasi della formazione delle galassie.

Infine, nel Capitolo 4, presento un nuovo metodo per rivelare l’idrogeno neutro intergalattico durante la reionizzazione usando l’emissione Ly\(_\alpha\) pro-
dotta nei fronti di ionizzazione dei primi quasar. Questa radiazione, generata principalmente dalle collisioni tra elettroni liberi e atomi di idrogeno, può tracciare la presenza di idrogeno neutro (anche a densità media) in un modo simile alle future osservazioni a 21-cm. Usando un nuovo modello di trasporto radiativo (presentato in Appendice), mostro che il segnale dovrebbe presentarsi come una singola linea di emissione con una luminosità dell’ordine di \(10^{-20}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\). Questa emissione potrebbe essere rivelata anche con i telescopi esistenti e gettare nuova luce sulla storia della reionizzazione del Mezzo Intergalattico e le proprietà dei primi quasars.
Chapter 1

Introduction

The vast majority of the visible radiation in the Universe originates from galaxies and quasars. However, even though they may visually appear like islands of light in a dark sea, the space between them is not empty. It is certain that there is diffuse intergalactic gas in the rare and rich clusters of galaxies, as indicated by X-ray observations, in the form of a hot, $10^8$ K plasma. In such objects, the mass of the so called Intracluster Medium (ICM) is at least as great as the mass in the visible parts of the cluster galaxies.

Is there any definite evidence for an Intergalactic Medium (IGM) outside of galaxy clusters? And, if present, what are its origins, physical properties and the relation to the galaxies? Answering these questions is one of the more tantalizing problems of modern cosmology. In this chapter, I will briefly review the history of the search for this diffuse and elusive gas, our current understanding, and the main topic of this thesis: the future of the IGM studies in a new light, namely, its own.

1.1 The search for the IGM: historical background

The search for the IGM began at the end of the 1950s, before our current model for the origin of the Universe, the Big Bang theory, was completely established. After the first great observational discovery of modern cosmology – the expansion of the Universe – made by Hubble in 1929, it was soon realized that the Universe must have experienced a very hot, radiation-dominated phase in its early stage. In the late 1940s, Gamow tried to explain the origin of the chemical elements in the Universe during this hot-phase by primordial nucleosynthesis. However, he realized that this process is not able to produce significant amounts of elements heavier than Helium. The problem of
the synthesis of the metals observed in the present-day Universe was solved later by Hoyle and collaborators, accounting for the elements produced by nucleosynthesis in stars. A very important prediction derived from Gamow studies was made by Alpher and Herman: the cooled remnant of the hot early phase should be present in the Universe as a background of black-body radiation with temperature about 5 K. This remnant, the Cosmic Microwave Background (CMB), was discovered in 1965 by Penzias and Wilson, confirming the prediction of the Big Bang model.

These discoveries provided (and still provide) the framework within which to tackle the problems of structure and galaxy formation. Primordial hydrogen and helium first materialized in the form of an extremely hot and diffused ionized gas. After three hundred thousand years from the Big Bang the gas cooled down and recombined. The last scattered radiation at this epoch appears today as the CMB. Gravitational processes shaped the large-scale structure of the Universe, possibly confining the pre-galactic gas and giving origin to the galaxies. Unless galaxy-formation was an extraordinary efficient process, sweeping up all the primordial gas, there should still exist traces of this medium.

A few years before the discovery of the CMB, Field (1959) tried to detect the absorption features generated by intergalactic neutral hydrogen along the line-of-sight between us and the radio galaxy Cygnus A. Like this first case, all the observational studies in the last decades are based on the same principle: the line-of-sight absorption of the light generated by a background source in correspondence of the wavelength of a neutral hydrogen resonant line. In his attempt, Field failed to detect the absorption corresponding to the hyperfine hydrogen transition with a wavelength of 21 cm. It was only with the discovery of the first Quasi-Stellar Object (QSO), called 3C9, in 1963 that the astronomers started to have greater chances of detecting the IGM. In a seminal paper of 1965, Gunn & Peterson argued that, if the Universe were indeed filled with neutral hydrogen, all the photons emitted blueward of the QSO’s Lyα emission line (1216 Å in the QSO rest-frame) should have been absorbed and never make it to our detectors. However, they measured only a small decrement in the spectrum of the QSO 3C9 shortward of its Lyα emission line. This result meant either that galaxy formation consumed all but a tiny residual of the primordial hydrogen, or that the gas between the galaxies was reionized.

As it was soon pointed out by Bahcall & Salpeter (1965), individual Lyα absorption features should appear from neutral hydrogen concentrated into cosmological structures. Shortly thereafter, discrete lines were observed (Lynds & Stockton 1966, Burbidge et al. 1966), giving rise to a long debate regarding their precise origin. The simultaneous detection of higher
order Lyman lines (e.g., Baldwin et al. 1974) confirmed the suggestion by Lynds (1970) that most of the absorption lines constitute a population of Lyα systems, now called the Lyα forest, rather than metal lines. The basic observational properties of the Lyα forest were established with the first quantitative spectroscopy on the high-redshift quasars in the late 1970s and early 1980s. Making use of the new sensitive electronic detectors and 4-m telescopes, the work by Sargent et al. (1980) set the stage for the standard picture of the Lyα forest. Giving their low metallicity, large rate of incidence (i.e., the number of absorbers per unit redshift along the line-of-sight) and their weak clustering compared to the galaxies, Lyα forest systems were found to be consistent with a new population of objects: intergalactic gas clouds.

1.2 The Modern IGM

The last two decades have seen a large progress in our knowledge of the IGM thanks to the advent of 8-10 m class telescopes (particularly the Keck and the Very Large Telescope) and high-performance computers. Individual lines in the Lyα forest, resolved in high resolution spectra, show line shapes reasonably well approximated by Voigt profiles\(^1\) (Carswell et al. 1984). From Voigt profile fitting, it is then possible to derive three basic observables: the column density \(N_{\text{HI}}\), the line width (indicated in terms of the Doppler parameter \(b\)) and the redshift \(z\) of the absorption system. The absorption features are broadly classified into three main types, according to their column density: Lyα forest \((N_{\text{HI}} < 10^{17.2} \text{ cm}^{-2})\), Lyman Limit Systems (LLSs; \(10^{17.2} \leq N_{\text{HI}} < 10^{20.3} \text{ cm}^{-2}\)), and Damped Lyα Systems (DLAs; \(N_{\text{HI}} > 10^{20.3} \text{ cm}^{-2}\)). This classification is based on the shape of the absorption features. The lowest column density systems in the forest are by far the most common and well fitted by Doppler line profiles. On the other side, the much rarer DLAs have sufficiently high column-density to show the radiation damping wings of the Lorentz line profile, thus requiring the Voigt profile for accurate fitting. The intermediate column-density systems, the LLSs, produce a characteristic drop in the continuum of the foreground source in correspondence of the hydrogen ionization edge, or Lyman limit (912Å in the atom rest frame). Although these features are treated as distinct objects, the classification is not strictly exclusive. A DLA will also produce a drop at the Lyman continuum edge, and a LLS produces an absorbing feature at the Lyα wavelength (1216Å in the atom rest frame). However, as we will see below,

\(^{1}\)The combination of a Gaussian profile (resulting from Doppler broadening) and the natural Lorentz profile of the line, see equation (2.8).
1.2. The Modern IGM

A large number of surveys for quasar intervening absorption systems have been carried out in the last decade (see the recent review of Meiksin 2007 for an exhaustive and up-to-date list). Systems with \( N_{\text{HI}} < 10^{12} \text{ cm}^{-2} \) have not been detected yet, while an upper cut-off at \( 5 \times 10^{21} \text{ cm}^{-2} \) has been suggested by Prochaska et al. (2005). It was already recognized by Tytler (1987), and recently confirmed (Janknecht et al. 2006) that the distribution function of the column densities is extremely close to a single power law with index \( \beta = -1.6 \). Such a finding, over the large dynamic range involved, may suggest a single formation mechanism for the absorbers. The Doppler parameters are typically in the range \( 10 < b < 100 \text{ km s}^{-1} \), with the vast majority between 15-60 km s\(^{-1}\) (Hu et al. 1995; Kim et al. 1997; Kirkman & Tytler 1997). The Doppler parameter can be related to the temperature \( T \) of the gas via the relation \( b = (2k_B T/m_{\text{H}} + b_{\text{turb}}^2)^{0.5} \), where \( k_B \), \( m_{\text{H}} \) and \( b_{\text{turb}} \) are, respectively, the Boltzmann constant, the atomic mass and the Doppler contribution given by turbulent motions. The interpretation of the Doppler parameter distribution is complicated by several factors. However, neglecting the factor \( b_{\text{turb}} \), the measured values can be used to put constraints on the upper limits of the absorber temperatures. In this case, the range 20-60 km s\(^{-1}\) corresponds to temperatures of \( 2.4 \times 10^4 - 3.8 \times 10^4 \text{ K} \), consistently with the expectations from a photo-ionized medium at moderate overdensities (Meiksin 1994; Hui & Gnedin 1997).

From the theoretical point of view, the challenge was to understand how such a population of clouds, with varying column densities and velocity widths, could arise. In view of the Cold Dark Matter (CDM) model of cosmogony (for which the majority of the mass in the Universe resides in non-baryonic matter interacting only via gravity), structure formation in the Universe produces self-gravitating, collapsed “haloes” - the sites of galaxy formation - connected by filaments of material at lower density. These lower mass objects could not form galaxies but could retain hydrogen and thus give rise to the absorption systems. This network of filamentary structures, the so called “cosmic web” (Bond et al. 1996), had been found in the first numerical simulations of structure formation in the mid 1990s. An example from a more recent numerical simulation (Cantalupo et al. 2005) is shown in Figure (1.1).

The Ly\(\alpha\) forest is believed to be a signature of the cosmic web, in particular of the rarefied and highly ionized gas expanding with the Hubble flow and exposed to the ionizing radiation of galaxies and quasars. Early simulations broadly reproduced the main statistical properties of the lower column density systems in the Ly\(\alpha\) forest (e.g., Cen et al. 1994; Hernquist et al. 1996;
1.2. The Modern IGM

Figure 1.1 An example of the “cosmic web” from a hydrodynamical simulation of structure formation at redshift $z = 3$ with radiative transfer (Cantalupo et al. 2005). The box size is 10 comoving Mpc/h. The image represents a projection of the neutral hydrogen density along the line-of-sight. The tenuous, cyan filaments correspond to the lower column-density systems, i.e. the Ly$\alpha$ forest. The yellow and red colors indicate column-densities in the range of LLSs and DLAs.

Katz et al. 1996; Miralda-Escudé et al. 1996). These simulations and analytical arguments based on the observations (Meiksin & Madau 1993) suggested that a large fraction of the baryons in the Universe at redshift $z > 1.5$ are contained in the IGM.

The nature of higher column-density systems, LLSs and DLAs, is less clear. They represent the few islands or structure in the Universe where most of the neutral hydrogen is concentrated and shielded from the ionizing radiation from stars and quasars that produce the highly ionization of the Ly$\alpha$ forest.

DLAs are suspected of containing the gas that formed the bulk of the stars in present day galaxies (Wolfe et al. 1995) and thus it is believed that they are directly connected with the galaxy formation process. However, it is still unclear if they are galaxy already in place (e.g. Prochaska & Wolfe 1998) or are still in the form of protogalactic clouds (e.g., Haehnelt, Steinmetz &
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Rauch 1998). The relatively high metallicity measured from coincident metal absorption systems in correspondence of several DLAs suggests that some of them originate in already enriched regions of the Universe, i.e. in galactic environments. On the other hands, a non-negligible fraction of DLAs shows metallicity close to the low values measured in the Ly$\alpha$ forest (cf. Prochaska 2003 and Simcoe et al. 2004), suggesting that DLAs include systems of different origin.

Concerning the LLSs, there is still a lack of systematic studies to disentangle their origin. A limited number of observational studies conducted so far suggested that LLSs are the progenitors of (or already in place) gaseous halos of normal galaxies (Tytler 1982; Steidel 1990) or small clouds located in proximity (or within) the halo of high redshift galaxies (Prochaska 1999; Misawa et al. 2004). On the other hand, attempts to identify the LLSs with large galaxies were not entirely successful (Mo & Miralda-Escudé 1996). Theoretical models identify LLSs with either low-mass dark matter halos filled with neutral and self-shielded gas (Katz et al. 1996; Abel & Mo 1998) or with uncollapsed gas outside of the halos (Maller et al. 2003). Like in the case of DLAs, LLSs probably include systems with both intergalactic and galactic origins as also suggested by recent numerical simulations (Kohler & Gnedin 2007; Razoumov et al. 2007).

Following the last decade of studies, it is becoming increasingly apparent that the separation of the IGM, galaxies and QSOs into distinct entities is an artificial construct: galaxies and QSOs originated from the IGM and their radiation and outflows impacted on it. Unraveling the formation and structure of the IGM may thus serve as a crucial step in the solution of the much more complex problem of galaxy formation.

Recently, new observational and theoretical efforts have been also concentrated on the study of the very high-redshift IGM\footnote{see section 4.1 for a more detailed review.}: at some point, before the galaxies and QSO filled the Universe with ionizing radiation, the Universe was full of neutral hydrogen. Understanding when and how the IGM was “reionized” to the level observed in the present day Universe is one of the principal unsolved problems of cosmological structure formation.

1.3 The search for the IGM in a new light

All the observational results on the IGM mentioned so far have been obtained from the study of absorption systems in QSO spectra. Although very powerful, this method has a non-negligible disadvantage: we can only get one-dimensional information on the intervening absorption systems, either
galactic or intergalactic. Only in a few cases, using projected pairs of QSOs, we can have two (or multiple) lines of sight passing through the same object.

Directly mapping in three dimensions the IGM and the absorption systems found in the QSO spectra would represent a major breakthrough in our knowledge of the structure formation in the Universe. Already in 1987, Hogan & Weymann argued that the Lyα forest should appear not only in absorption in the QSO spectra but also in Lyα emission: whatever is the physical state of these systems, if they are in photo-ionization equilibrium with an external ionizing background, they will emit Lyα photons as a consequence of hydrogen recombinations. However, given the low density of the gas responsible for the Lyα forest, this emission (called “fluorescent”) should be extremely faint, much below current observational limits. Higher column density systems, LLSs and DLAs, are expected to be optically thick to the external ionizing radiation and brighter fluorescent Lyα emitters. If they are self-shielded, it turns out that (assuming a slab geometry and an uniform external radiation field) about 60% of the external ionizing background is converted into Lyα emission, as shown by Gould & Weinberg (1996).

These studies suggested that the “search for the IGM” is not only possible looking in absorption but also in emission. The aim of this thesis is to model and to reveal this emitting “Lyα side” of the IGM. In the following, I briefly describe the content of the thesis.

1.3.1 Modelling fluorescent Lyα emission

In Chapter 2, I present a new model to predict the properties of fluorescent Lyα emission from the redshift three IGM. The method is based on the combination of hydro-dynamical simulations of structure formation (to obtain the density and velocity field of the IGM) and two radiative transfer model that we developed: a simplified ray-tracing scheme for the continuum ionizing radiation and a full 3D Montecarlo method for the scattering of Lyα photons. I discuss in detail the effect induced by the IGM velocity field and the complex density distribution of the emitters. These effects substantially change the apparent shape and spectral emission of fluorescent Lyα emission previously predicted by the (widely used) static, plane-parallel model.

1.3.2 Detecting the fluorescent IGM

In Chapter 3, I describe a blind search for fluorescent Lyα emission around a QSO at redshift 3 that we carried out on the Very Large Telescope (VLT) based on the predictions of our theoretical model. I discuss in detail the technique and the results of our search: 13 line-emitters that represent one
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of the first statistical samples of plausible fluorescent candidates around a high-redshift QSO.

1.3.3 Probing Reionization with Lyα emission

In Chapter 4, I present a new method to directly map neutral hydrogen during the Reionization Epoch using the IGM Lyα emission. In particular, I show how the Lyα emission produced within the Ionization-fronts of the highest-redshift QSOs can be used to trace the neutral hydrogen on very large angular scale around the QSOs. I present detailed calculations (based on a new radiative transfer scheme presented in the Appendix) of the expected surface brightness and spectral shape of the Lyα emission. The signal should be already detectable with current facilities, opening a new window in our knowledge of the high-redshift Universe.

Chapters 2, 3 and 4 have been published as papers in *The Astrophysical Journal*. The Appendix forms the basis of a manuscript to be submitted soon.
Chapter 2

Modelling Fluorescent Ly$\alpha$ emission from the $z \sim 3$ Intergalactic Medium

Abstract

We combine a high-resolution hydro-simulation of the ΛCDM cosmology with two radiative transfer schemes (for continuum and line radiation) to predict the properties, spectra and spatial distribution of fluorescent Lyα emission at $z \sim 3$. We focus on line radiation produced by recombinations in the dense intergalactic medium ionized by UV photons. In particular, we consider both a uniform background and the case where gas clouds are illuminated by a nearby quasar. We find that the emission from optically thick regions is substantially less than predicted from the widely used static, plane-parallel model. The effects induced by a realistic velocity field and by the complex geometric structure of the emitting regions are discussed in detail. We make predictions for the expected brightness and size distributions of the fluorescent sources. Our results account for recent null detections and can be used to plan new observational campaigns both in the field (to measure the intensity of the diffuse UV background) and in the proximity of bright quasars (to understand the origin of high column-density absorbers).

2.1 Introduction

Hydrogen absorption-line systems observed shortward of Ly$\alpha$ emission in quasar spectra constitute an important probe of the physical state of the intergalactic medium at high-redshift. These spectral features are shaped by the combined action of gravity, hydrodynamics and photoionization processes which determine the local density and the velocity field of neutral hydrogen within the absorbers. Numerical simulations suggest that the so called Lyman-\textalpha forest is generated by diffuse, sheetlike and filamentary structures with a mean density which is between 1 and 10 times higher than the cosmic average (Cen et al. 1994; Zhang, Anninos & Norman 1995; Hernquist et al. 1996; Miralda-Escudé et al. 1996). These low-column-density systems are highly ionized by the extragalactic background of Lyman continuum photons generated by young stellar populations and quasars. At the opposite extreme, Lyman-limit (LLS, $N_{\text{HI}} > 10^{17.2} \text{ cm}^{-2}$) and damped Lyman-\textalpha (DLA, $N_{\text{HI}} > 10^{20.3} \text{ cm}^{-2}$) systems correspond to concentrations of atomic hydrogen which are optically thick to the cosmic ionizing background. Numerical simulations suggest that they arise in dense gas clouds with a meatball topology. On cosmological scales, they appear to form a collection of isolated clouds which trace the cosmic web.

Optically thick clouds are expected to emit fluorescent Ly$\alpha$ photons produced in hydrogen recombinations (Hogan & Weymann 1987; Gould & Weinberg 1996). This emission is concentrated in the outer parts of the clouds where hydrogen is significantly ionized by the external UV background ($\tau_{\text{LL}} \sim 1$). However, Ly$\alpha$ photons cannot directly escape the clouds because of the large optical depth in the center of the line ($\tau_{\text{Ly} \alpha} \approx 10^4 \tau_{\text{LL}}$). Each photon thus suffers a large number of resonant scatterings (more precisely: absorptions and re-emissions) by neutral hydrogen atoms in the ground state. Each scattering adds a small Doppler shift to the frequencies of the photons due to the thermal (and turbulent) motions of the atoms. Therefore, photons execute a random walk both in frequency and in physical space until their frequencies are shifted sufficiently away from the line center and they are able to escape the medium in a single flight (Zanstra 1949).

Monte Carlo simulation (e.g. Ahn, Lee & Lee 2001; Zheng & Miralda-Escudé 2002 and references therein) is the most popular method for addressing the radiative transfer problem. Analytical solutions only exist for highly symmetric systems. For instance, the emerging spectrum from a plane-parallel and static homogeneous slab is characterized by two sharp peaks in the Doppler wings of the line (Neufeld 1990 and references therein). The plane-parallel solution approximately holds also for self-shielded systems where the ionized layer which surrounds the neutral region is thin with re-
spect to the characteristic radius of the cloud. In this ideal case, optically thick systems act as efficient mirrors which convert nearly 60% of the impinging ionizing flux into Lyα photons (Gould & Weinberg 1996).

Direct imaging of fluorescent sources would lead to a major advance in our understanding of galaxy formation. Determining the size distribution of LLS at $z \gtrsim 3$ would be crucial to distinguish whether they arise from photoionized clouds in galactic halos (Steidel et al. 1995; Mo & Miralda-Escudé 1996) or in minihaloes formed prior to reionization (Abel & Mo 1998). At the same time, the intensity of the cosmic UV background could be inferred from the observed brightness of the fluorescent emission.

With present-day technology, the detection of fluorescent emission from high-redshift gas condensations is challenging, but not impossible. At $z \sim 3$, the intensity of the diffuse ionizing background (e.g. Haardt & Madau 1996) corresponds to a Lyα surface brightness of the order of $10^{-20}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$. It is then not surprising that blind searches have only produced a number of null results (Lowenthal et al. 1990; Martínez-Gonzalez et al. 1995; Bunker, Marleau & Graham 1998). Positive fluctuations in the ionizing background can be used to increase the signal. For instance, clouds lying close to a bright quasar are exposed to a stronger UV flux (with respect to an “average” cloud) and are then expected to be brighter in fluorescent Lyα. Previously to the present work, Francis & Bland-Hawthorn (2004) presented a deep narrow-band search for Lyα emission in a field which lies next to the quasar PKS 0424-131. Based on quasar-absorption-line statistics and on simple models for fluorescent emission (Gould & Weinberg 1996), they expected to detect more than 6 clouds but none were seen. These null results highlight the need for a more sophisticated analysis of fluorescent Lyα emission in realistic environments.

In this chapter, we present accurate models of the fluorescent Lyα emission from LLSs at redshift $z \sim 3$. Our study proceeds in three steps. First, we perform a hydrodynamical simulation of structure formation to compute the cosmological distribution of the baryons at $z = 3$. A simple radiative transfer scheme is then used to propagate the ionizing radiation through the computational box and to compute the distribution of neutral hydrogen and of recombinations. Finally, a three-dimensional Monte Carlo code is used to follow the transfer of Lyα photons. As ionizing radiation, we first consider the diffuse background generated by the UV emission of galaxies and quasars (Haardt & Madau 1996). We then discuss an inhomogeneous case where the ionizing flux from a quasar (which lies in the foreground of the gas clouds) is superimposed to the uniform background. Our detailed numerical analysis shows that simplified models (e.g. Gould & Weinberg 1996) tend to overpredict the Lyα flux emitted from optically thick regions.
The structure of the chapter is as follows. We describe our numerical techniques in §2.2 and present our results in §2.3 where we also discuss the implications of our analysis for present and future observations. Finally, we discuss the limitations of our approach in §2.4 and we conclude in §2.5.

2.2 Method

2.2.1 Cosmological simulation

The cosmological simulation, provided by F. Miniati, follows the formation and evolution of the large-scale structure in a “concordance” ΛCDM model by means of an Eulerian, grid based Total-Variation-Diminishing hydro+N-body code (Ryu et al. 1993). The cosmological parameters used in the simulation are the followings: mass density Ω_0 = 0.3 (with a baryonic contribution Ω_b = 0.04), vacuum-energy density Ω_Λ = 1 − Ω_m = 0.7, and Hubble constant H_0 = 100 h km s^{-1} Mpc^{-1} with h = 0.67. The simulation is started at redshift z = 60 and follows the evolution of Gaussian density fluctuations characterized by a primordial spectral index n = 1 and “cluster-normalization” σ_8 = 0.9 (with σ_8 the rms linear density fluctuation within a sphere with a comoving radius of 8 h^{-1} Mpc). This is consistent with the most recent joint analyses of temperature anisotropies in the cosmic microwave background and galaxy clustering (e.g. Tegmark et al. 2004 and references therein). The computational box has a size of 10 h^{-1} Mpc where the dark matter distribution is traced by 256^3 particles and the gas component is evolved on a comoving grid with 512^3 zones. The nominal spatial resolution for the gas (the mesh size) is ~ 20 h^{-1} kpc (comoving) with the mean baryonic mass in a cell being ~ 10^5 h^{-1} M_☉. On the other hand, each dark matter particle has a mass of 5 × 10^6 h^{-1} M_☉. All the results presented in this work are derived from the z = 3 output of a simulation which does not include radiative cooling of the gas. The limitations of this assumption are briefly discussed in §2.4. We defer a detailed analysis of the radiative case to future work.

2.2.2 Radiative transfer of UV radiation

In order to compute the distribution of neutral hydrogen within a snapshot of the computational box, we need to simultaneously solve the radiative transfer problem for UV radiation and the rate equations describing the balance between the ionization and recombination rates.

For simplicity, we assume that hydrogen is in ionization equilibrium and
use the “on the spot” approximation (Baker 1962):

\[
(1 - x) n_H \int_{\nu_0}^{\nu_{up}} \frac{d\nu}{h_p \nu} \sigma_{\nu} \int_{4\pi} d\Omega J_\nu(\Omega) = x^2 n_H^2 \alpha_B(T) \tag{2.1}
\]

where \(h_p, x, n_H, \sigma_{\nu}, T\) and \(\alpha_B\) respectively denote the Planck constant, the hydrogen ionized fraction, volume number density, ionization cross section, temperature and case B recombination coefficient (for which we use the fit by Hui & Gnedin 1997). The intensity of ionizing radiation per unit frequency and solid angle is given by \(J_\nu\) (in erg cm\(^{-2}\) s\(^{-1}\) sr\(^{-1}\) Hz\(^{-1}\)). The frequency integral in equation (2.1) extends from the hydrogen ionization threshold, \(h_p \nu_0 = 13.6\) eV, to a maximum frequency \(\nu_{up}\) (which is, formally, infinite).

A sufficiently good approximation for our propose is to assume \(\nu_{up} = 4 \nu_0\), (i.e. set the intensity of radiation to zero at frequencies above the ionization threshold for HeII). First of all, only a very few percent of energy available for Ly\(\alpha\) emission is lost during the process of HeII recombination (because, for the HM spectrum, only few percent of the ionizing photons have \(\nu > 4 \nu_0\)). Second, since He II recombines faster than HI (and the intensity of radiation at the HeII Lyman limit is lower than at \(\nu_0\)), the HeII becomes self-shielded at a larger radius with respect to HI (e.g. Miralda-Escudé & Ostriker 1990). This implies that HeI-ionizing photons are absorbed in the outer regions of the gas concentrations where H is nearly fully ionized. The only effect that could significantly change the HII recombination rate in the presence of ionized He is the increase of the electron density with respect to the HII density in equation (2.1). Given the helium abundance by number (typically \(\sim 8\%\)), this can imply a correction factor in the right-hand side of equation (2.1) \(\sim 1.16\) in the regions where the He is fully ionized. In §2.2.3, we explain how we include this correction in the calculation of the HII recombination rate. Eventually, given the small helium abundance by number, we ignore any correction to equation (2.1) due to the presence of He atoms and ions, other than the correction in §2.2.3.

In each cell of the simulation, the diffuse ionizing background is approximately described by following the radiative transfer along 6 “light-rays” which propagate parallel (and antiparallel) to the main axes of the computational box. With this numerical trick we can treat anisotropic backgrounds (created, for instance, by shadowing effects) with a minimal request of CPU time. In order to implement a photon conserving scheme, we substitute the left-hand side in equation (2.1) by the number of ionizing photons deposited by each of the six rays (labeled by the index \(i\)) per unit volume and time in a given cell. Let us define \(\tau_i(\nu)\) as the optical depth that the \(i\)-th ray has to travel (from a given starting point in the box, see below) to reach the surface of the cell and \(\Delta \tau(\nu)\) as the optical depth between the two cell face
2.2. Method

Given the input ionizing radiation $J_{\nu,i}^{in}$ before it is filtered by the gas distribution in the box and the cell-size (in physical units) $L$, we can easily write the left-hand side in equation (2.1) as:

$$\frac{4\pi}{6} \sum_{i=1}^{6} \int_{\nu_0}^{\nu_{up}} \frac{J_{\nu,i}^{in}}{h_{\nu,i}^{\nu}} e^{-\tau_{i}(\nu)} \frac{1-e^{-\Delta\tau(\nu)}}{L}$$

(2.2)

where the sum is taken over the six rays.

To describe the diffuse UV background, we assume that $J_{\nu,i}^{in} = J_{\nu}^{HM}$ with $J_{\nu}^{HM}$ the intensity of radiation derived at $z = 3$ by Haardt & Madau (in preparation\(^2\), hereafter HM) considering the emission from observed quasars and galaxies after it is filtered through the Ly$\alpha$ forest. We assume that underdense cells are exposed to the full, isotropic background. On the other hand, overdense cells see an anisotropic radiation field which is computed by using equation (2.2) to propagate the input background starting from the surface where $\rho = \bar{\rho}$. The intensity of radiation (and thus $x$) in each overdense cell depends on the ionized fraction of the surrounding region. To solve the non-local equations, we start our calculations by assuming that the whole simulation box is optically thin (i.e. it is exposed to the input radiation field) and we iterate the radiative transfer and ionization-equilibrium calculations until convergence (within 1%) is reached in each overdense cell.

We use a similar approach to discuss the anisotropic radiation field generated by a quasar lying in the foreground of the simulation box along the observer's line of sight. For simplicity, we assume that the quasar lies distant enough from the simulated region that its emission can be modeled as a train of plane waves impinging onto a face of the simulation box. We also assume, for simplicity, that the quasar input spectrum is identical to that of the cosmic background. This will not affect our result because the quantity that determines the Ly$\alpha$ emission rate is simply the number of ionizing photons, i.e. the integral of the spectral emission over the Lyman Limit, not the shape of the spectrum. We then write the quasar ionizing flux (erg cm$^{-2}$ s$^{-1}$ Hz$^{-1}$) as $F_{\nu} = \pi b J_{\nu}^{HM} \delta_{ii}$ with $\delta_{ij}$ the Kronecker symbol and $b$ a dimensionless constant. This is equivalent to using $J_{\nu,i}^{in} = 1.5 b J_{\nu}^{HM} \delta_{ii}$ in equation (2.2). In this case, we compute the optical depth starting from the face of the simulation box which is first reached by quasar light (i.e. along the direction $i = 1$).

A self-consistent calculation of the gas temperature requires a joint treatment of radiative transfer and hydrodynamics which is still beyond present-day computing capabilities. Assuming that the photoionized gas is in thermal

\(^2\text{http://pitto.mib.infn.it/ haardt/refmodel.html}\)
2.2. Method

equilibrium, we find that \( T \simeq 1 - 3 \times 10^4 \) K for the typical densities in the shielding layers \((100 \lesssim \rho / \bar{\rho} \lesssim 300)\). However, shock heating can easily drive the gas temperature to \(10^5 - 7\) K. This is particularly important for the low-density regions \((\rho \lesssim 100 \bar{\rho})\) where cooling processes are inefficient and the shocked material remains hot (Theuns et al. 1998). In our analysis, we assume that \( T = 2 \times 10^4 \) K everywhere. This is an excellent approximation for highly overdense regions \((\rho \gtrsim 100 \bar{\rho})\) where the cooling time is shorter than the Hubble time and the gas temperature rapidly approaches the equilibrium solution (Theuns et al. 1998). Anyway, since the recombination coefficient \( \alpha_B \) has only a weak dependence on \( T \), fixing the temperature to \(2 \times 10^4\) K in the whole simulation box does not seriously affect our results.

Note that, at \( T = 2 \times 10^4\) K, the hydrogen recombination timescale is \( t_{\text{rec}} = 2.26 (\bar{\rho}/\rho) \times 10^{10} \) yr. Ionization equilibrium will approximately hold only where \( t_{\text{rec}} \) is shorter than the characteristic quasar lifetime \((\sim 10^8\) yr, Porciani, Magliocchetti & Norberg 2004), i.e. for \( \rho \gtrsim 200 \bar{\rho} \). At lower densities, our assumption of ionization equilibrium will then overestimate the hydrogen ionized fraction. This is not a problem for our study since, in the vicinity of a quasar, the ionizing flux is strong enough to nearly completely ionize the low-density intergalactic medium. It is worth noticing, however, that regions with \( \rho < 200 \bar{\rho} \) will emit their recombination radiation after the quasar has switched off and will not be detectable in a survey centered onto a bright quasar.

2.2.3 The clumping factor

Hydro-simulations have a finite spatial resolution and cannot describe the gas distribution on arbitrarily small scales. In other words, they provide a coarse grained representation of the density field. However, the hydrogen recombination rate scales proportionally to the square of the local (i.e. fine grained) number density and is sensitive to small-scale inhomogeneities (clumpiness) within a simulation cell. In order to keep track of this discrepancy, we rewrite the mean recombination rate within a cell as

\[
x^2 \mathcal{C} \langle n_H \rangle^2 \alpha_B(T) \tag{2.3}
\]

where the average is taken over a simulation cell and

\[
\mathcal{C} = \frac{\langle n_H^2 \rangle}{\langle n_H \rangle^2} \tag{2.4}
\]

denotes the clumping factor of the gas. In principal, the latter quantity can be estimated by comparing simulations with different resolutions and consistent initial conditions.
We assume that $C$ is constant everywhere and we fix its value by imposing that the number density (per unit redshift) of LLSs in our simulation matches the observational data (Péroux et al. 2003) \(^3\). This normalization procedure, which requires $C \simeq 6$, partially overcomes the limitations of our simulation (limited resolution and any missing physics). In particular, $C$ takes into account also a factor in the electron density due to the partial or total ionization of the He as discussed in \(\S\)2.2.2.

### 2.2.4 Ly$\alpha$ emission

Using equation (2.3), we compute the hydrogen recombination rate in each cell of the simulation. In order to convert this quantity into an emission rate for Ly$\alpha$ photons, we need to evaluate how many recombinations ultimately lead to a $^2P \rightarrow ^1S$ transition. For $T = 2 \times 10^4$ K, nearly 44% of the atoms directly recombine to the ground level while 35% of the remaining cases ultimately produce excited atoms in the $^2S$ state which decays to $^1S$ via two-photon emission (both fractions are weakly dependent on the gas temperature, see e.g. Osterbrock 1989). Therefore, if the gas is optically thin to UV photons (Case A approximation), only a fraction $\epsilon_{\text{thin}} = \alpha_{2P}^{\text{eff}} / \alpha_A \sim 0.36$ (where $\alpha_{2P}^{\text{eff}}$ is the effective recombination coefficient from level $^2P$ to $^1S$ and $\alpha_A$ is the Case A total recombination coefficient) of the recombinations yield a Ly$\alpha$ photon. However, in the optically thick case, continuum photons produced by recombinations to the ground level can be captured by neutral atoms and produce additional Ly$\alpha$ radiation. The asymptotic yield in the extremely thick case (Case B approximation, where no continuum photon can leave the cloud) is $\epsilon_{\text{thick}} = \alpha_{2P}^{\text{eff}} / \alpha_B \sim 0.65$ (where $\alpha_B$ is the Case B total recombination coefficient). We use this value to compute the emission rate of fluorescent Ly$\alpha$ photons in the simulation box\(^4\).

### 2.2.5 Resolving the optical depth

When we apply the method described above to our simulation, we find that the shielding layers (where the transition between optically thin and optically thick regions occurs) are poorly resolved (see Figure 2.1). Typically, they consist of very few cells each with a single-cell optical depth (at the Lyman Limit) $\Delta \tau_{\text{cell}} \gtrsim 1$. However, for a proper treatment of the radiative transfer

---

\(^3\)Note that the spectral resolution of the observational data roughly corresponds to our box size. Therefore we can safely compute the hydrogen column density by integrating $v_{\text{HI}}$ along the entire box.

\(^4\)In section 4.2.1, we derive an accurate fitting relation for the $\epsilon_{\text{thick}}$ parameter valid for a broad range of temperatures.
2.2. Method

Figure 2.1 Fraction of recombinations taking place in cells with a single-cell optical depth (at the Lyman Limit) $\Delta \tau_{\text{cell}}$ larger than a given value $\Delta \tau_{\text{ion}}$. Dashed and solid lines, respectively, refer to the original and the adaptively refined simulation boxes. Note that a proper treatment of the radiative transfer problem requires that the Ly$\alpha$ photons are generated within cell with $\Delta \tau_{\text{cell}} \lesssim 1$ (see text).

problem, more stringent requirements on the grid spacing must be met. In particular, the Ly$\alpha$-emitting regions must be resolved with $\Delta \tau_{\text{cell}} \lesssim 1$. If not, both the spatial distribution of recombinations and the escape probabilities of Ly$\alpha$ photons along different directions (see §2.2.6) are spuriously altered.

To solve this problem, we adaptively refine the Ly$\alpha$ emitting regions by interpolating the original density and velocity fields of the input simulation. We use the solution of the radiative-transfer problem for the original (unrefined) grid to select the regions to interpolate and the factor of refinement. Given the memory limitations of the available machines, we use a $100^3$ cells sub-box (which is particularly rich of structures) of the original simulation and we interpolate every cell with a significant recombination rate ($> 0.1\%$ of the maximum) and $\Delta \tau_{\text{cell}} > 1$. The level of refinement is scaled proportionally to $\Delta \tau_{\text{cell}}$ (up to a factor of 32 in each dimension) in order to have a subgrid of cells with $\Delta \tau_{\text{cell}} \lesssim 1$. Eventually, we re-compute the radiative transfer for the adaptively refined grid. Figure 2.1 shows that the fraction
of recombinations originated in cells with $\Delta \tau_{\text{cell}} > 1$ decreases from 30% to 7% as a result of this refinement. Moreover, in the finer grid, only a negligibly small number of recombinations takes place in extremely thick cells ($\Delta \tau_{\text{cell}} > 10$) compared with 12% of the original grid.

As discussed in §2.2.3, we account for unresolved substructure in our simulation box by using a non-vanishing clumping factor in the equation of ionization equilibrium. Density variations within a parent cell of the original simulation due to the refinement procedure described above could, in principal, significantly contribute to the clumping factor. If this is the case, we should then adopt a value $C < 6$ for the refined simulation to reproduce the observed abundance of LLSs. We find that the clumping associated with the refinement is severe in the densest zones of the simulation (which typically lie in the self-shielded regions and do not contribute to the Ly$\alpha$ flux) but amounts to only a few per cent in the most rapidly recombing cells. For these, we can then safely adopt $C = 6$ also for the refined box. Note that in our model we use the on the spot approximation, i.e. we assume that every ionizing photon generated by a HII recombination is absorbed in the same cell in which is generated. This is no longer a good approximation if the single-cell optical depth is smaller than 1, as we try to obtain by the refinement. In this case the recombination ionizing photons can be absorbed (producing eventually a Ly$\alpha$ photon) in a different cell with respect to the cell where they are created. How this can affect our results? Numerically, about 50% of the Ly$\alpha$ photons can be generated by ionizing photons from recombination. In the self-shielded regions, that are the regions in which we are interested in, ionizing radiation from recombination can slightly extend the spatial emission region in the inner and outer part of the shielding layer (with a slight effect on the spectral emission shape). Instead, for the cells in the central part of the shielding layer we statistically expect that the “loss” of Ly$\alpha$ photons is balanced by the recombination from ionizing photons incoming from the surrounding cells.

### 2.2.6 Ly$\alpha$ radiative transfer

We now combine the results of the previous sections (namely, a set of arrays containing the Ly$\alpha$ emission rate, the HI density and the gas velocity field as a function of spatial position) to compute the spectra and the projected image on the plane of sky of the fluorescent sources. The radiative transfer of resonant Ly$\alpha$ photons is modeled using a three-dimensional Monte Carlo scheme analogous to that employed by Zheng & Miralda-Escudé (2002, see also Ahn, Lee & Lee 2001). The method follows a large number of photon trajectories as they are scattered within the HI density and velocity distri-
2.2. Method

**Emission of Lyα photons**

We assume that Lyα photons are isotropically emitted with frequency $\nu_0$ in the frame of the recombining atoms (the natural linewidth is negligibly small for our purposes). In the cosmic frame (e.g. for an observer lying at the center of the simulation box and which participates to the free expansion of the universe), the frequencies of the resonant photons appear Doppler shifted by the projected velocities of the atoms along the photon trajectories. The velocity of a hydrogen atom with respect to the cosmic frame is given by the superposition of the Hubble flow with the bulk motion of the gas (i.e. the peculiar velocity of the fluid in the corresponding cell of the simulation) and a random thermal velocity:

$$v = H(z)r + v_{\text{gas}} + v_{\text{th}}$$

(2.5)

with $r$ the atom position with respect to the center of the simulation box. The component of $v_{\text{th}}$ along the direction of the emitted photon is generated by extracting a Gaussian deviate out of a distribution with zero mean and dispersion $\sigma_{\text{th}} = (k_B T/m_H)^{1/2} = 12.8 (T/2 \times 10^4 \text{K})^{1/2} \text{km s}^{-1}$ (with $k_B$ the Boltzmann constant and $m_H$ the atomic mass).

**Absorption**

The photon frequency can be conveniently expressed in terms of the variable

$$x = \frac{\nu - \nu_0}{\Delta}$$

(2.6)

which measures the frequency shift from the Lyα line center in units of the Doppler width, $\Delta = \sqrt{2} \nu_0 \sigma_{\text{th}}/c$, where $c$ denotes the speed of light. The mean scattering cross section of Lyα photons in the fluid frame is

$$\sigma_{\text{Ly} \alpha}(x) = \sqrt{\pi} f_{\text{Ly} \alpha} \frac{e r_e}{\Delta} H(a, x)$$

(2.7)

where $f_{\text{Ly} \alpha}=0.416$ is the Lyα oscillator strength, $r_e = 2.82 \times 10^{-15}$ m is the classical electron radius and

$$H(a, x) = \frac{a}{\pi} \int_{-\infty}^{+\infty} \frac{e^{-y^2}}{(x - y)^2 + a^2} \, dy$$

(2.8)

is the Hjerting-Voigt function. For the relatively low-densities we are interested in, atomic collisions are not important and the damping coefficient $a$
2.2. Method

can be expressed in terms of the spontaneous decay rate $\Gamma$ as $a = \Gamma / (4\pi \Delta) = 3.3 \times 10^{-4} (T/2 \times 10^4 \text{K})^{-1/2}$.

We use equation (2.7) to determine the distance covered by each photon before it is scattered by an atom. We first extract a random deviate, $R$, from an exponential distribution function and then we integrate the product $n_{\text{HI}} \sigma_{\text{Ly} \alpha}(x)$ along the photon direction of motion until the resulting optical depth equals $R$. If the photon still lies within the computational volume, we select the velocity of the scatterer. Note that, in order to be able to absorb line radiation, an atom must have a velocity component along the trajectory of the incoming photon, $v_\parallel$, which closely matches the Doppler shift. From equation (2.8), it follows that, in the fluid frame, $x_\parallel = v_\parallel / (\sqrt{2} \sigma_{\text{th}})$ is characterized by the following probability distribution

$$P(x_\parallel) = \frac{a}{\pi H(a,x)} \frac{e^{-x_\parallel^2}}{(x - x_\parallel)^2 + a^2}.$$  

We use the method presented by Zheng & Miralda-Escudé (2002) to generate deviates which follow this statistic. The perpendicular component of the thermal velocity in the scattering plane, $x_\perp$, is then extracted from a Gaussian distribution with a temperature-dependent dispersion as described above.

**Re-emission**

A new direction for the photon is then randomly selected according to a phase function, $P(\cos \theta)$ (with $\theta$ the scattering angle), determined by atomic physics. Resonant scattering has an isotropic angular distribution, $P = 1$, while wing scattering is characterized by the Rayleigh phase function, $P = 3(1 + \cos^2 \theta)/4$ (Stenflo 1980). We find that the two angular distributions give consistent outputs. All the results presented in this work are obtained assuming isotropic re-emission.

To determine the new photon frequency, we assume that the scattering process is coherent in the reference frame of the scatterer (partially coherent scattering). This is appropriate when the excited atom undergoes no collisions before re-emission and the radiative damping coefficient is small (Avery & House 1968). Both conditions apply to Lyα radiation emitted by gas in the typical conditions of the shielding regions in the intergalactic medium. Once the scattering angle and the photon velocity of the scatterer are specified, it is straightforward to compute the frequency shift of the re-emitted photon in the fluid frame:

$$x = (x_{\text{in}} - x_\parallel) + x_\parallel \cos \psi + x_\perp \sin \psi$$  

(2.10)
2.3. Results

where $x_{in}$ is the frequency shift of the incoming photon and $\psi$ is the angle between the initial and final direction of the scattered photon. A Lorentz transformation is finally used to compute the frequency shift in the cosmic frame.

The set of calculations described above is iterated until the photon escapes the computational box.

**Ly$\alpha$ spectra**

To produce spectra (and narrow-band images) of the fluorescent emitters, we compute the surface-brightness of the computational box along the observer’s line of sight (hereafter, the $x$-axis). At each scattering, the probability that a photon will be re-emitted along this direction is

$$\frac{1}{4\pi} P(\cos \theta_x) e^{-\tau_x}$$

(2.11)

where $\theta_x$ is the angle between the incoming photon and the $x$-axis and $\tau_x$ denotes the Ly$\alpha$ optical depth of the scattering site along the observer’s line of sight $^5$. For each photon and for each scattering, we sum this quantity to a counter in correspondence of the projected position of the scattering site and of the photon frequency. We thus obtain a three-dimensional array containing the surface brightness of fluorescent Ly$\alpha$ photons as a function of 2 spatial coordinates plus frequency. Note that a simulated photon tends to remain for many scatterings in a rather small region before it eventually escapes. This means that photons contribute only to a few pixels surrounding their emission site.

Following Zheng & Miralda-Escudé (2002), we test our implementation of the Monte Carlo scheme against the analytical approximation by Neufeld (1990) for the optically thick, plane-parallel case. Figure 2.2 shows that our code accurately reproduces the analytical solution which becomes exact in the limit of extremely large optical depths.

2.3 Results

In order to have an acceptable compromise between spectral resolution and CPU time, we only apply the Monte Carlo radiative transfer to the adaptively refined grid corresponding to a $100^3$ region of the original simulation box. To achieve a good signal-to-noise ratio, we generate $10^6$ photon trajectories for

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$^5$This optical depth includes the effects of neutral hydrogen lying in the foreground of the computational box.
2.3. Results

Figure 2.2 Lyα spectrum emitted by a uniform slab with a midplane source with optical depth τ₀. The results of our Monte Carlo code (solid histograms) are compared with an analytical approximation (Neufeld 1990) which becomes exact in the limit τ₀ → ∞ (dotted lines). A temperature of T = 10 K is assumed.

every simulation. We thus obtain high resolution spectra for each pixel of the resulting image that can be combined to simulate slit, line-emission integral field or narrow-band observations.

2.3.1 Diffuse background and static gas

We first discuss the ideal case of a static gas distribution illuminated with a uniform and isotropic background of ionizing radiation. This is obtained by artificially setting to zero the velocity field of the gas within our refined box.

In the left panels of Figures 2.3 and 2.4, we respectively show the HI column density distribution and the narrow-band images (∼90 Å in the observed frame, centered at λ = (1 + z) · 1216 Å = 4864 Å) of the selected
2.3. Results

Figure 2.3 Column-density distribution of neutral hydrogen at $z = 3$. In the left panel, the gas is exposed to a diffuse UV background generated by the population of galaxies and quasars. In the right panel, the ionizing flux from a foreground quasar, located a short distance in front of the region and corresponding to a boost factor $b = 6$ (see equation (3.1)) is superimposed to the diffuse background.

region illuminated with the diffuse UV background. The color code in Figure 2.4 gives the fluorescent Ly$\alpha$ emission rate (photons per unit time, surface and solid angle) in units of the impinging rate of ionizing photons times $\epsilon$ (i.e. the fraction of the recombinations yielding a Ly$\alpha$ photon):

$$R_{HM} = \epsilon_{\text{thick}} \int_{v_0}^{4v_0} \frac{J_{HM}}{h_P \nu} d\nu = 2.44 \times 10^4 \text{ cm}^{-2} \text{ s}^{-1} \text{ sr}^{-1}$$

(2.12)

with $\epsilon_{\text{thick}} \approx 0.65$. For an observer at redshift $z = 0$, this corresponds to a Ly$\alpha$ surface brightness of

$$SB_{HM} = 3.67 \times 10^{-20} \text{ erg cm}^{-2} \text{ s}^{-1} \text{ arcsec}^{-2}.$$  

(2.13)

The brightest fluorescent sources correspond to compact gas clouds with a meatball topology. This is because the diffuse UV background is bright enough to fully ionize gas concentrations with $\rho \lesssim 100 \bar{\rho}$. In general, the shielding regions either lie within virialized structures or correspond to dense gas shells which are accreting onto collapsed objects. As we will see below, the velocity field of the infalling gas produces specific signatures in the Ly$\alpha$ spectra.
2.3. Results

The compact fluorescent sources lie along the filaments and sheets which characterize the distribution of neutral hydrogen on cosmological scales. For ease of reading, we label the three largest structures (which each have a diameter of $\sim 0.4$ comoving Mpc) with the letters A, B and C (see Figure 2.3). Cloud C is composed of two sub-units and is a part of an elongated structure which extends towards cloud B. Similarly, a filamentary plume of gas bridges clouds A and B.

Simple reasoning based on the plane-parallel model for line transfer suggests that, in the absence of photon sinks (e.g. dust), self-shielded (isotropically-illuminated) objects should shine with a surface brightness of $S_{BH}(Hogan & Weymann 1987; Gould & Weinberg 1996)$. In our static simulation (Figure 2.4, left panel), the SB of self-shielded objects closely matches the predictions of this simple plane-parallel model. The SB distribution in the simulation (dotted histogram in Figure 2.5) shows a narrow peak at this expected value. In general, the SB scales proportionally to $N_{HI}^{1/2}$ in the optically thin regions and asymptotically approaches its maximum value for self-shielded objects (see the top-left panel in Figure 2.6). The brightest lines of sight in fluorescent Ly$\alpha$ correspond to optically thick systems with column densities $N_{HI} \gtrsim 10^{18}$ cm$^2$ which are thus associated with LLSs and DLAs. All the photons of the ionizing background are converted into Ly$\alpha$ radiation within the shielding layers of these optically thick systems. In the absence of other sources of ionizing radiation, it is impossible to produce a stronger Ly$\alpha$ flux. This explains why the brightest objects in the left panel of Figure 2.4 have a uniform SB and sharp boundaries which correspond to the regions with $N_{HI} \simeq 10^{18}$ cm$^2$ in the left panel of Figure 2.3.

2.3.2 Including the gas velocity field from the hydro-simulation

We are now ready to discuss the more realistic case where we include the gas velocity field of the hydro-simulation. The corresponding Ly$\alpha$ emission rate is shown in the right panel of Figure 2.4. The overall pattern is similar to the static case, but a number of striking differences are noticeable. Namely: i) the SB of self-shielded objects is no longer uniform (e.g. the right-hand side of Cloud A is nearly a factor of 2 fainter than the left-hand side); ii) the boundaries of the emitting regions are less sharp and self-shielded objects are surrounded by large, low-SB halos; iii) self-shielded objects can be significantly fainter (or, very rarely, brighter) than in the static case.

The top-right panel in Figure 2.6 shows that the gas velocity field introduces additional scatter into the SB - $N_{HI}$ relation with respect to the static
2.3. Results

Figure 2.4 Narrow-band images (≈ 90 Å, centered on 4864 Å) of fluorescent Lyα emission at $z = 3$ for static gas clouds (left) and accounting for the gas velocity field (right). Both images correspond to the column density distribution presented in the left panel of Figure 2.3. The white boxes indicate the location of the slit spectrographs used to obtain the energy distributions presented in Figure 2.7.

The brightest lines of sight still correspond to $N_{\text{HI}} \gtrsim 10^{18}$ cm$^2$ but now two regions with the same column density can be associated with brightnesses which differ up to a factor of 5. In consequence, the SB distribution of optically thick regions is broader and it is slightly shifted to fainter fluxes with respect to the static case (see the peak of the solid histogram in Figure 2.5). We find that the median SB of the self-shielded objects amounts to nearly 75% of the value predicted by Gould & Weinberg (1996). At the same time, a larger fraction of the sky has SB < SB$_{\text{HM}}$ compared to the static case. (the power-law part of the solid histogram in Figure 2.5). As we will show below, this excess is caused by foreground scattering of the Lyα photons and is related to the presence of extended Lyα halos around self-shielded objects.

A better understanding of the “velocity-field effect” can be achieved by comparing the spectra of the fluorescent emission in the static and in the general case. In the left and central panels of Figure 2.7, we show the corresponding spectral energy distributions of the Lyα photons. These have been obtained positioning four slit spectrographs (width ≃ 0.9 arcsec and variable length) on top of the three brightest sources as shown in the right panel of Figure 2.4. In a static gas distribution, spectra have a characteristic double
2.3. Results

Figure 2.5 Surface brightness distribution of fluorescent sources ionized by a diffuse UV background (solid), by the additional contribution of a quasar with “boost” factor $b = 2$ (dashed) and $b = 6$ (dot dashed). The dotted line is analogous to the solid one but is obtained by artificially setting to zero the gas velocity field.
2.3. Results

Figure 2.6 The Lyα surface brightness of each pixel of the simulated images is plotted against the corresponding column density of neutral hydrogen. In the top panels, the intergalactic medium is ionized by a diffuse background. In particular, the top-left frame refers to a static gas distribution. In the bottom panels, a quasar with boost factor $b = 2$ (bottom-left) and $b = 6$ (bottom-right) is superimposed to the diffuse background. Dotted lines mark the expected SB for a plane-parallel slab while dashed lines indicate the minimum column density for LLSs (short-dashed) and DLAs (long-dashed).
humped shape and are symmetric with respect to the line center. On the other hand, in the general case the energy distribution is no longer symmetric. In fact, particular configurations of the velocity and density fields are able to strongly suppress one of the wings of the Lyα line and significantly lower the observed SB of the self-shielded objects. In the particular case of Cloud A, a low-density concentration of neutral hydrogen is infalling onto the Lyα emitting region. The relative velocity (along the line of sight) corresponds to $\sim 4\sigma_{th}$ and thus to a very high optical depth. Therefore, most of the photons that, in the static case, leave the shielding layers along the line of sight in the red Doppler wing will scatter within the infalling cloud and escape in other directions lowering the observed surface brightness. These photons will then form the extended Lyα halos which surround the brightest objects in Figure 2.4. The phase-space distribution of neutral gas in the vicinity of the emitting regions thus plays a fundamental role in reshaping the Lyα spectral energy distribution. In broad terms, infalling material diminishes the red wing of the spectrum, while gas which is receding from the emitting region (which could also mean that the shielding layer is infalling onto a central object more rapidly than the surrounding gas) damps out the blue peak of the spectrum. On the other hand, if both peaks are detectable, their separation is nearly independent from the detailed properties of the emitting regions and is set by the velocity dispersion of the original cloud. In fact, in analogy with the plane-parallel case, the escape probability of a Lyα photon peaks at a frequency which only depends on the optical depth of its emission site and on the temperature of the medium. For a typical self-shielded cloud ($\tau_{LL} \gtrsim 1$), the spectrum peaks at $\sim \pm 4\sigma$ (which corresponds to a minimum separation of $\sim 150 \text{ km s}^{-1}$ or $\sim 2.5 \text{ Å}$ for $\sigma_{th} = 12.8$, value that can increase up to $\sim 8\text{ Å}$ for a system with total velocity dispersion $\sim 60 \text{ km s}^{-1}$).

The two-dimensional spectra shown in the central panel of Figure 2.7 clearly show that the gas velocity field within and in the vicinity of the shielding layers has a complicated structure which does not show the characteristic pattern of ordered rotation or symmetric infall considered by Zheng & Miralda-Escudé (2002).

### 2.3.3 Quasar plus diffuse background

We now discuss a case of anisotropic illumination, obtained by superimposing the ionizing flux from a quasar to the diffuse UV background. The quasar is imagined to lie a short distance in front of the computational box as seen by us, and thus enhances the UV illumination experienced by faces of gas clouds exposed to it. Note that the “boost” factor $b$, that we defined in
2.3. Results

Figure 2.7 Two-dimensional spectra obtained “observing” our simulations with the slits shown in the right panel of Figure 2.4. Different columns refer to different simulations. In particular, from left to right: diffuse background and static gas distribution (§2.3.1), diffuse background and including the gas velocity field (§2.3.2), adding to the diffuse background a quasar with $b = 6$ (§2.3.3). The labels in the top left corner indicate a particular slit spectrograph as in Figure 2.4.
2.3. Results

§2.2.2, is determined by the intrinsic luminosity of the quasar and by its actual separation from the simulated region. At a physical distance $r$ from a quasar with monochromatic luminosity $L_\nu = L_{\text{LL}} (\nu/\nu_{\text{LL}})^{-\alpha}$, we find

$$b = 15.2 \frac{L_{\text{LL}}}{10^{30} \text{erg s}^{-1} \text{Hz}^{-1}} \frac{0.7}{\alpha} \left( \frac{r}{1 \text{ Mpc}} \right)^{-2}.$$  \hspace{1cm} (2.14)

The resulting $N_{\text{HI}}$ distribution (assuming a boost factor $b = 6$) is shown in the right panel of Figure 2.3. The corresponding narrow-band image (obtained accounting for gas velocities) is presented in the left panel of Figure 2.8. As expected, the self-shielded regions (and thus the fluorescent sources) are smaller with respect to the isotropic background case due to the extra-ionizing radiation produced by the quasar. This also makes the fluorescent sources brighter (dot-dashed histogram in Figure 2.5) since more recombinations will be produced to balance a stronger ionization rate. Based on the (plane-parallel) slab model, where Ly$\alpha$ photons are emitted following a cosine law (Gould & Weinberg 1996), one would have naively expected an increase in the Ly$\alpha$ surface brightness towards the observer by a factor $1 + b = 7$ with respect to the diffuse background case. However, Figures 2.5 and 2.6 clearly indicate that the slab model overestimates the SB of the self-shielded objects. This is not due to shadowing effects. In fact, the attenuation of the quasar flux by diffuse gas lying in front of the fluorescent clouds is generally negligible. Comparing with a static simulation, we also find that gas motions can only explain a small part of this discrepancy. In fact, in the presence of a quasar, foreground scattering is reduced due to the lower neutral fraction present in low density gas and narrow-band images tend to be more uniform than in the case of isotropic illumination. On the other hand, the slab approximation no longer applies when the size of the shielding layers is comparable with the radius of a cloud. In this case, Ly$\alpha$ photons produced at a particular point leave the cloud with a different angular distribution with respect to the plane-parallel case. For approximately spherical clouds and in the presence of uniform illumination, this effect is suppressed for symmetry reasons. However, when the ionizing flux is anisotropic, the Ly$\alpha$ SB does depend quite strongly on the geometry of the shielding layers.

To study how the SB of self-shielded objects along the quasar direction, $\text{SB}_\parallel$, depends on the impinging flux, we performed a series of simulations with increasing $b$. Our results are summarized in Figure 2.9, where we express $\text{SB}_\parallel$ in terms of an “effective boost factor” defined by

$$\text{SB}_\parallel = (1 + b_{\text{eff}}) \text{SB}_{\text{HM}}.$$  \hspace{1cm} (2.15)

This holds for normal incidence. In general, the surface brightness of a slab which forms an angle $\theta$ with the incident quasar flux corresponds to a factor $1 + b \cos \theta$. 

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Points with errorbars mark the 25th, 50th and 75th percentiles of $1+b_{\text{eff}}$ among the DLAs. The solid line represents the best-fitting relation

$$1 + b_{\text{eff}} = 0.74 + 0.50 b^{0.89},$$

while the dashed line shows the predictions of the slab model. Note that the geometric effect becomes more and more important as $b$ is increased.

Where do the “missing” Ly$\alpha$ photons go? In the right panel of Figure 2.8, we show the fluorescent emission along a line of sight perpendicular to the direction of quasar illumination (assuming $b = 6$ as in the left panel). In this case, the plane-parallel model predicts that the self-shielded objects should emit at SB$_{\text{HM}}$. In our simulations, however, the shielding layer deeply penetrates in the clouds along the quasar direction and the slab model does not apply. In consequence, self-shielded objects are much brighter than a slab along this line of sight. Typically, SB$_\perp \simeq 0.5$SB$_\parallel$ for $b \gg 1$ while SB$_\perp \simeq$ SB$_\parallel$ for $b \ll 1$. In other words, Ly$\alpha$ photons generated by the quasar ionizing flux are emitted within a wide solid angle. As a consequence of this partial isotropization, self-shielded clouds are fainter than expected (based on the slab approximation) along the quasar direction and brighter in the perpendicular directions.

Finally, in the bottom panels of Figure 2.6, we show the SB - $N_{\text{HI}}$ scatter-plot for anisotropic illumination (when observer, quasar and the simulation box are aligned). It is worth noticing that, while the SB keeps nearly constant for LLSs, on average, it steadily increases with $N_{\text{HI}}$ for DLAs. This phenomenon can be explained by as follows. Let us assume that self-shielded objects are nearly spherically symmetric. Then, i) the ionizing flux from the quasar depends on the incident angle with respect to the local density gradient in the clouds; ii) this cosine approaches unity for the central projected regions of self-shielded objects; iii) the column density reaches the highest values along these lines of sight.

### 2.3.4 Size distribution of Ly$\alpha$ sources

Knowing the size distribution of fluorescent Ly$\alpha$ sources is fundamental to planning an observational campaign for their detection. Regrettably, our refined box is too small (its size being $\sim 2 h^{-1}$ comoving Mpc) to provide a statistically representative sample of optically thick sources. On the other hand, performing the line transfer on the $10 h^{-1}$ Mpc box would require an excessive amount of computer time. For these reasons, we decided to propagate only the ionizing radiation through the $10 h^{-1}$ Mpc box and to use the scatterplots in Figure 2.6 to convert the neutral-hydrogen column densities
Figure 2.8 Narrow-band images (∼ 90 Å, centered on 4864 Å) of fluorescent Lyα emission from our simulation box at z = 3. In both cases, the intergalactic medium is ionized by a diffuse background and by a quasar with boost factor $b = 6$. The image on the left (right) is obtained by observing our simulation box from a line of sight parallel (perpendicular) to the direction of quasar illumination. The left frame corresponds to the column density distribution presented in the right panel of Figure 2.3.

into Lyα fluxes. In fact, independently of the value of $b$, all lines of sight with $N_{\text{HI}} > 10^{18} \text{ cm}^{-2}$ are approximately associated with a constant Lyα surface brightness (within a factor of 2 uncertainty caused by the gas motion and cosine effects discussed above). We then adopt this threshold value to derive the size distribution of fluorescent objects. In Figure 2.10, we present our results for an isotropic ionizing background ($b = 0$). Solid and dashed histograms respectively refer to objects with $N_{\text{HI}} > 10^{18} \text{ cm}^{-2}$ and to DLAs. It is worth remembering that we fixed the value of the clumping factor in our simulation so as to reproduce the observed sky covering factor of LLSs. In consequence, if a significant fraction of the real systems have a characteristic size which is smaller than our numerical resolution, our simulation will overpredict the number of large systems in order to preserve the required normalization.

In Figure 2.11, we plot the number density of self-shielded objects as a function of $b$. We use three different thresholds for the source size: 3 (which corresponds to barely resolved objects), 20 and 80 arcsec$^2$. In all cases, the number of sources rapidly drops with increasing $b$. In fact, higher values of
2.3. Results

Figure 2.9 Lyα surface brightness of optically thick clouds [expressed in terms of the effective boost factor defined in equation (2.15)] as a function of the impinging quasar ionizing flux [expressed in terms of the quasar boost factor, $b$, defined in equation (3.1)]. Points with errorbars denote the 25th, 50th and 75th percentiles of $b_{\text{eff}}$ for the DLAs. The solid line represents the best-fitting relation given in equation (2.16). Predictions of the static, plane-parallel model are plotted with a dashed line.

$b$ characterize regions which are closer to a given quasar (see eq. (3.1)) and, obviously, correspond to a lower number density of self-shielded objects.

From this figure, it is also possible to determine the number density of sources which are brighter than a certain threshold value $(1 + b_{\text{min}}) SB_{\text{HM}}$. Let us consider a Lyα source which is optically thick to ionizing radiation at a given distance from a quasar. Let us also imagine that we can move the cloud towards the quasar thus increasing the $b$ factor. As long as the cloud keeps optically thick, $SB_{\parallel}$ monotonically increases. However, there exists a particular value of the boost factor, $b_{\text{ss}}$, at which the cloud is no longer able to self-shield. Therefore, for $b \gtrsim b_{\text{ss}}$, $SB_{\parallel}$ keeps roughly constant. Thus, the number of self-shielded objects at a given $b$ coincides with

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7The fraction of recombinations yielding a Lyα photon decreases from $\epsilon_{\text{thick}} \sim 0.65$ to $\epsilon_{\text{thin}} \sim 0.36$ when a cloud becomes optically thin. Therefore, we expect a fully ionized cloud to be a factor of $\sim 2$ fainter in Lyα with respect to the optically thick case.
2.3. Results

Figure 2.10 Differential size distribution of optically thick clouds (solid histogram) and DLAs (shaded histogram) in a simulation where the intergalactic medium is exposed to a diffuse ionizing background. The shaded histogram has been slightly shifted in the horizontal direction to improve readability.
2.3. Results

Figure 2.11 Physical number density of fluorescent Lyα sources (with size $A$ indicated by the labels) as a function of the impinging quasar flux [expressed in terms of the boost factor $b$ defined in equation (3.1)]. Errorbars are derived assuming Poisson statistics. Triangles and circles have been slightly displaced in the horizontal direction to improve readability.
the number of sources (which are not necessarily optically thick) with $\text{SB} \gtrsim [1 + b_{\text{eff}}(b)] \text{SB}_{\text{HM}}$. In other words, the number of sources which are brighter than a given threshold can be computed with the following procedure. First, convert the threshold SB into an effective boost factor, $b_{\text{thr}}^{\text{eff}}$. Second, invert equation (2.16) to find the value of $b_{\text{min}}$ such that $b_{\text{eff}}(b_{\text{min}}) = b_{\text{thr}}^{\text{eff}}$. Third, use $b = b_{\text{min}}$ in Figure 2.11 to determine the number density of the sources. Fourth, use equation (3.1) to find the volume within which it is possible to have $b > b_{\text{min}}$.

### 2.3.5 Comparison with previous observational data

We can use the above to compare the predictions of our models with the observational results by Francis & Bland-Hawthorn (2004, hereafter FBH). These authors performed a deep narrow-band search for fluorescent Ly$\alpha$ emission in the vicinity of the $z = 2.168$ quasar PKS 0424-131 ($L_{\text{LL}} = 1.67 \times 10^{30}$ erg s$^{-1}$Hz$^{-1}$, $\alpha \simeq 0.7$). At the 5$\sigma$ confidence level (corresponding to a surface brightness of $4.7 \times 10^{-19}$ erg cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ for sources larger than 100 arcsec$^2$ and to $9.6 \times 10^{-18}$ erg cm$^{-2}$ for unresolved sources) no source was been detected. Based on the observed abundance of LLSs, FBH expected to find $\sim 6$ fluorescent clouds with a size of 100 arcsec$^2$. This estimate, however, does not take into account the ionizing radiation from the quasar.

Assuming that our results at $z = 3$ are approximately valid at the quasar redshift, \(^8\) we find that the sensitivity limits of FBH correspond to $b_{\text{min}} \sim 11.2$ for sources which are larger than 100 arcsec$^2$. Assuming that the ionizing background keeps roughly constant in the redshift interval $2 < z < 3$, from equation (3.1) we find that this corresponds to a distance from the quasar of $r_{\text{max}} \sim 1.5$ (physical) Mpc. This is the maximum distance from the quasar at which an optically thick cloud could have been detected. Based on our simulations, we expect to find, on average, $1 - 2$ objects within a sphere of radius $r_{\text{max}}$ around the quasar. However, FBH limited their search to distances smaller than 1 Mpc thus reducing the sampled volume by a factor 3.4 with respect to the theoretical limit. In this case, the expected number of sources ranges between 0.3 and 0.6. Therefore, the probability of detecting (at least) one source with one single observational run is $0.25 < P < 0.45$ (assuming Poisson statistics). Our simulations clearly show that the results by FBH are thus perfectly consistent with our understanding of the intergalactic medium at high-$z$ \(^9\).

\(^8\)We simply assume that the Ly$\alpha$ surface brightness scales as $(1 + z)^{-4}$, i.e. $\text{SB}(z = 2.168) = 2.54 \text{SB}(z = 3)$.

\(^9\)The detection limit for unresolved sources is less interesting. It corresponds to $b_{\text{min}} \sim$
2.4. Uncertainties

There are caveats to the simple calculations described above. For instance, we have assumed that all the \( \text{Ly} \alpha \) sources lying within a distance \( r_{\text{min}} \) from the quasar are brighter than \( b_{\text{min}} \). This assumption tends to over-estimate the number of detectable objects. In fact: i) self-shielded clouds lying in front of the quasar are much fainter and hardly detectable (their SB actually depends on the angle between the line of sight and the quasar direction); ii) fully ionized clouds in the foreground of the quasar tend to be a factor of \( \epsilon_{\text{thick}}/\epsilon_{\text{thin}} \approx 1.8 \) fainter than assumed above; iii) if the age of the quasar is shorter than the hydrogen recombination timescale no fluorescent sources will be detectable (see the discussion at the end of §2.2). On the other hand, we have assumed that our simulation box is representative of the gas distribution surrounding a quasar. Since optically selected quasars at high-\( z \) tend to sit within the most massive dark-matter halos formed at that epoch (Porciani et al. 2004), it is reasonable to expect that matter clusters (and moves with larger peculiar velocities) around them. Therefore, we could have underestimated the number densities of fluorescent sources lying close to a quasar.

Despite of the approximations listed above, we believe that our results provide the most reliable estimates for the abundance of fluorescent \( \text{Ly} \alpha \) sources at high-\( z \) carried out to date. Optimized sampling strategies are certainly required to observe these objects. Our simulations then represent a fundamental tool to plan observations around a given quasar.

2.4 Uncertainties

2.4.1 Radiative cooling

While numerical simulations are a useful tool to guide our understanding, they cannot be considered a perfect model of reality. A potential limit of our simulation is the lack of radiative cooling. While this is not a concern for the diffuse intergalactic medium, it becomes worrisome for highly overdense regions. Fluorescent \( \text{Ly} \alpha \) sources have intermediate overdensities \( (\rho/\bar{\rho} \sim 200) \) and are likely to be in equilibrium with the UV ambient radiation. We thus expect them to be mildly affected by cooling processes. In any case, most of the results discussed in this paper are nearly independent of the details of the gas distribution. Both the velocity and the geometric effects will be present anyway. On the other hand, the size distribution of the sources

\[ b_{\text{max}} \approx 250 \text{kpc}. \]

The number of expected sources in the associated volume of \( \sim 0.06 \text{Mpc}^3 \) is therefore negligibly small.

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388 (assuming that equation (2.16) can be extrapolated to such high values of \( b \)) and
might be more affected by the cooling processes. It is also worth stressing that there is no way of accounting for the effects of cooling and heating in a self consistent way. In fact, simulations where radiative transfer is fully coupled with hydrodynamics are still not viable with current supercomputers. Moreover, other poorly understood processes (like energy and momentum feedback) play an important role. Therefore, even a simulation including gas cooling would imply a similar level of approximation.

2.4.2 Resolution and sub-structure

Is the finite resolution of our simulation affecting our results? Multiple metal lines are often associated with single DLAs (e.g. Prochaska & Wolfe 1997) thus suggesting the presence of a clumpy medium. Unresolved sub-structure in our simulation might reduce the velocity effect and modify the outcoming spectra. The adopted value of $C$ implies that at least 1/6 of the volume is in dense clumps. If these sub-structures have a diameter which is comparable to the cell size, we only expect a minor modification of our results. In fact, the gas velocity in the simulation should closely approximate the motion of these clumps. The only effect is then a slight Doppler-shift of the entire Ly$\alpha$ spectrum of each cell. The opposite case, where each cell contains a large number of small substructures (Abel & Mo 1998), can be approximately discussed by considering an additional contribution to the thermal velocity dispersion. Assuming a value of $\sigma_{\text{th}} \sim 50 \text{ km s}^{-1}$ (corresponding to roughly half the virial velocity of the host halos, Haehnelt, Steinmetz & Rauch 1998), we find that the velocity effect may be suppressed making the spectra in better agreement with the slab model. Note, however, that the existence of a sea of small subclumps is disfavored by observations. In fact, this scenario would produce broad absorption features instead of the multiple metal systems associated with single DLAs (cfr. Haehnelt, Steinmetz & Rauch 1998; McDonald & Miralda-Escudé 1999). In any case, the velocity dispersion within our simulated DLAs is of the order of 100 km s$^{-1}$, in good agreement with observational data.

2.4.3 Additional sources and dust

Beyond fluorescent emission, additional Ly$\alpha$ radiation might be produced in the inner regions of the clouds. Within gravitationally collapsed objects, the gas tends to dissipate its internal energy by emitting line photons (e.g. Haiman, Spaans & Quataert 2000; Fardal et al. 2001; Furlanetto et al. 2005). Similarly, internal star formation could act as a copious source of Ly$\alpha$ photons, but, whereas fluorescent emission is expected to extend over several
tens of kiloparsec, the Ly\(\alpha\) emission from star forming region should be more concentrated near the centers of galaxies (Furlanetto et al. 2005). We have focused here on the fluorescent emission generated by recombinations and these extra sources of line photons are not considered in our analysis. We will present a comprehensive model of Ly\(\alpha\) emitters in a future work.

At the same time we did not consider the destruction of Ly\(\alpha\) photons by dust grains. Little is known about the dust properties within the intergalactic medium at \(z \sim 3\) even though there is some evidence for the presence of dust in DLAs (Fall & Pei 1993). Nevertheless, the associated absorption of fluorescent photons is likely to be minimal due to the relatively low \(N_{\text{HI}}\) of the shielding layer (e.g. Gould & Weinberg 1996). On the other hand, absorption is expected to be more severe for Ly\(\alpha\) photons produced close to and within the star-forming regions where dust is likely to be more abundant and the Ly\(\alpha\) escape probability is lower.

### 2.5 Summary

We have presented a new method to produce realistic simulations of fluorescent Ly\(\alpha\) sources at high redshift. We started by simulating the formation of baryonic large-scale structure in the ΛCDM cosmology. A simple radiative transfer scheme was then used to propagate ionizing radiation through the computational box and to derive the distribution of neutral hydrogen. Finally, the transport of Ly\(\alpha\) photons generated by hydrogen recombinations was followed using a three-dimensional Monte Carlo code. As ionizing radiation, we first considered the smooth background generated by galaxies and quasars. Then, as a second case, we superimposed to the background the UV flux produced by a quasar lying in the vicinity of the simulation box.

Our detailed numerical treatment improves upon previous work which was either based on rather crude approximations for the transfer of resonantly scattered radiation (Hogan & Weymann 1987; Gould & Weinberg 1996) or on highly symmetric semi-analytical models for the gas distribution (Zheng & Miralda-Escudé 2002). Our results show that simple models (e.g. Gould & Weinberg 1996) tend to overpredict the Ly\(\alpha\) flux emitted from optically thick clouds. In fact, we identified two effects that reduce the fluorescent Ly\(\alpha\) flux (and modify the spectral energy distribution) with respect to the widespread static and plane-parallel model.

**Velocity effect** – The velocity field inside and around the shielding layers of a gas cloud influences the emerging line profile. The symmetry of the double humped spectrum is lost and, in most cases, one of the two peaks is severely suppressed. On average, the SB of a cloud is reduced by 25% with
respect to the static situation.

*Geometric effect* – For anisotropic illumination and in the presence of a strong ionizing flux, the thickness of the shielding layer is comparable to the size of the gas cloud. In this case, the angular distribution of the emerging radiation is very different than in the plane-parallel approximation. For instance, close to a quasar, a cloud emits much less than predicted by the slab model in the direction of the quasar and much more in the other directions.

The importance of these effects (in particular of the angular redistribution of Ly$\alpha$ photons) depends on the intensity of the impinging radiation. In equation (2.16), we provided a fitting function for the maximum Ly$\alpha$ brightness of optically thick sources as a function of the incident ionizing flux. In Figure 2.11, we presented our predictions for the number density of fluorescent sources with different sizes.

These results are able to explain previous null detections (e.g., Francis & Bland-Hawthorn (2004)) and represent a fundamental tool for planning successful observations of fluorescent Ly$\alpha$ emission at high-redshift, as we show in Chapter 3.
Chapter 3

Detecting Fluorescent Lyα emission around the z=3 QSO 0420-388\(^1\)

Abstract

We report the results of a survey for fluorescent Lyα emission carried out in the field surrounding the z = 3.1 quasar QSO0420-388 using the FORS2 instrument on the VLT. We first review the properties expected for fluorescent Lyα emitters, compared with those of other non-fluorescent Lyα emitters. Our observational search detected 13 Lyα sources sparsely sampling a volume of \(\sim 14000\) comoving Mpc\(^3\) around the quasar. The properties of these in terms of i) the line equivalent width, ii) the line profile and iii) the value of the surface brightness related to the distance from the quasar, all suggest that several of these may be plausibly fluorescent. Moreover, their number is in good agreement with the expectation from theoretical models. One of the best candidates for fluorescence is sufficiently far behind QSO0420-388 that it would imply that the quasar has been active for (at least) \(\sim 60\) Myrs. Further studies on such objects will give information about proto-galactic clouds and on the radiative history (and beaming) of the high-redshift quasars.

3.1 Introduction

The analysis of absorption systems in the spectra of high-redshift quasars has represented for several decades the only practical way to obtain information

\(^1\)This chapter is based on Cantalupo, Lilly & Porciani 2007, ApJ, 657, 135
about the properties of the intergalactic medium (IGM). The Ly$\alpha$ forest gives an unique insight into the one-dimensional distribution of low density hydrogen along the quasars’ line of sight. Higher column-density features, i.e. the Lyman-limit systems (LLS) and the damped Ly$\alpha$ systems (DLA), correspond to denser concentrations of atomic hydrogen and, for this reason, can be associated with galaxy formation. Unfortunately the information from quasar absorption spectra is almost always one-dimensional.

An interesting alternative to absorption studies is to try to detect the IGM in emission rather than in absorption. The absorption of ionizing photons should be associated with the emission of fluorescent Ly$\alpha$ photons, as originally proposed by Hogan & Weymann (1987). Detection of the fluorescent emission would provide a three-dimensional picture of the neutral IGM and proto-galactic clouds at high redshift.

In Chapter 2, we constructed models of fluorescent emission combined with hydrodynamical simulations. These simulations were normalized so as to produce the correct statistics for Lyman limit absorption systems. For clouds that are optically thick to the ionizing radiation (i.e. Lyman limit systems and above), the surface brightness of the fluorescent emission is set by the strength of the ionizing background. Unfortunately, the intensity of the UV background at $z \sim 3$ (e.g. Haardt & Madau 1996) corresponds to a maximum Ly$\alpha$ surface brightness (SB) of $\sim 3 \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. Detecting such a low surface brightness is very challenging with present-day instrumentation. Blind searches in the field have only produced a number of null results (Lowenthal et al. 1990; Martínez-Gonzalez et al. 1995; Bunker, Marleau & Graham 1998).

The surface brightness of fluorescent emission will be higher if the local ionizing background is increased, e.g. for gas clouds lying close to a bright quasar. In Chapter 2, we examined this effect and showed that it could boost the fluorescent emission to detectable levels over a large volume, i.e. of order 30,000 comoving Mpc$^3$ for a sufficiently bright quasar. The penalty for this boost is that the extra photo-ionization increases the total hydrogen column density that is required to reach a given neutral column density, i.e. to produce the maximum fluorescent surface brightness. This is the analogue of the proximity effect seen in quasar absorption spectra. It means that maximally fluorescent sources near to a quasar will be systems that, in the absence of the quasar, would be DLAs rather than LLS. DLAs have hydrogen column densities comparable to a sightline through the disk of present day spiral galaxies and a total gas mass similar to the mass in stars and gas within galaxies at the present epoch (Wolfe et al. 1995). For these reasons, DLAs are widely believed to be the gas reservoirs from which the present galaxies formed. However, it is still unclear if DLAs are galaxies already in
place (e.g. Prochaska & Wolfe 1998) or are still in the form of protogalactic clouds (e.g. Haehnelt, Steinmetz & Rauch 1998). They typically contain very little of the molecular hydrogen usually associated with star formation (e.g. Ledoux et al. 2003, but see also Zwaan & Prochaska 2006). Moreover, metallicity measurements show a large range from 1/10 solar to a value close to that measured for the Lyα forest (cfr. Prochaska et al. 2003 and Sincoe et al. 2004). It is likely that DLAs include systems of different origins.

In addition to studying the intergalactic medium, the detection and measurement of fluorescent Lyα emission from clouds at different distances and orientations from the quasar, would in principle allow the study of the history and angular distribution of the ultraviolet emission from quasars. Both questions are of considerable topical interest in the context of unified models of active galactic nuclei (see e.g. Antonucci 1993).

In this Chapter, we describe a blind survey for fluorescent Lyα emission carried out around the z ∼ 3.1 quasar QSO0420-388, one of the brightest quasars at high redshift for which the Lyα line lies within an existing narrow-band filter of the VLT-FORS2 instrument.

Previous searches for fluorescence around quasars have had either null results at z ∼ 2.2 (Francis & Bland-Hawthorn 2004) or only one (or marginally two) possible detection at z ∼ 4.3 (Francis & McDonnell 2006). In the first case, the null result is perfectly consistent with our model of fluorescent Lyα emission presented in Chapter 2. In the second case, the very close association of the system with the quasar itself make the identification with fluorescence difficult (see §3.2.5 for details). Other possible fluorescent sources have been detected serendipitously in connection with absorbing systems in quasar pairs (Fynbo et al. 1999, Adelberger et al. 2005). However, the metallicity of the systems and the presence of a substantial continuum emission probably indicates the presence of star-formation within the clouds. Lyα emission at high redshift can of course be produced by internally ionized clouds, either from an associated young stellar population or from processes involving the gas itself (e.g., cooling). Several observations during the last decade have shown that these emitters are quite common in the high-redshift universe (for a review see Taniguchi et al. 2003) and enhanced by clustering effects around bright sources like AGNs and, in particular, radio-galaxies (e.g., Venemans et al. 2005 and references therein). In searching for fluorescence, we must thus take into account the presence of this population.

The layout of the Chapter is as follows. In §3.2 we compare the characteristics of fluorescent Lyα emission with those of other sources of Lyα emission at high redshift, in order to determine which properties can best be used to recognize fluorescent emission. Although fluorescent sources should have characteristic equivalent widths (extremely high), surface brightness
and spectral profiles, none of these provides a unique diagnostic. We conclude this section by reviewing recent claims in the literature for detected fluorescence. In §3.3 we describe our own new observations and the data reduction. We then isolate a set of Lyα emitting candidates around the target quasar. In §3.4, we discuss in detail the properties of the individual sources in the context of the expected fluorescent characteristics, and compare their number density with both our own models for fluorescence and with those of other non-fluorescent Lyα sources. We conclude that it is likely, but not certain, that some of the detected sources that we have detected are indeed fluorescent. In §3.5 we summarize.

3.2 Recognition of fluorescent emission

Besides fluorescent emission, Lyα can be produced by several kinds of internal sources, e.g., photo-ionization from a young stellar population or active nucleus (LAE, Lyα emitter [galaxies]), or from cooling of shock-heated gas. Many observations during the last decade have shown that Lyα emitters are quite common in the high-redshift universe (e.g., Cowie & Hu 1998; Pascalelle, Windhorst & Kell 1998; Fynbo et al. 2003) and enhanced by clustering effects around objects like AGNs and, in particular, radio-galaxies (e.g., Le Fevre et al. 1996; Pascarelle et al. 1996; Venemans et al. 2005) which likely reside in high density regions of the Universe.

In this section, we review the characteristic properties that in principle could identify a source as fluorescent: i) the equivalent width (EW), ii) the emission profile, iii) the surface brightness (SB), and iv) the number density of emitters. We will take advantage of the model presented in Chapter 2, in which a combination of a high-resolution hydrodynamic simulation and two radiative transfer schemes was used to predict the properties, spectra and number density of fluorescent Lyα emitters at $z \sim 3$.

3.2.1 Equivalent Widths

In the fluorescent case, the Lyα emission originates from pure gaseous clouds externally photo-ionized. Therefore, any continuum emission comes only from recombination processes: mainly two-photon continuum and free-bound recombinations to the ground level. However, given the low value of the emission coefficient corresponding to these processes, the continuum level around the Lyα wavelength is very faint, resulting in an extremely high EW. The case of Lyα emission originating from cooling shock-heated gas will be similar.
If the Ly$\alpha$ emission results from photo-ionization by embedded young stars, we expect a significant contribution to the UV continuum emission from the stellar population. In this case, the Ly$\alpha$ EW depends on the age, initial mass function (IMF), metallicity and dust content of the star-formation burst. Synthesis population models (see e.g., Schaerer 2003 and references therein) show that high EWs can be produced for very young bursts in metal-poor and dust-free galaxies. Upper limits for very metal-poor models ($0 < Z < 10^{-7}$) range from EW~ 800Å (for a very young population with an age of 2 Myr) to EW~ 200Å (for a 10 Myr old star-formation burst). Synthesis models of star-forming galaxies with moderate ages (> 10 Myr) and with metallicity (and IMF) closer to the normally observed values have EW in the range 50 – 200 Å (Charlot & Fall 1993). Surveys of Ly$\alpha$ emitters at $z \sim 3$ usually show a distribution of EW in the range from 15 – 100Å, with a few objects extending to higher values (up to 200-300Å). High-EW objects can also be associated with AGN activity.

### 3.2.2 Emission line profiles

The properties of the Ly$\alpha$ line have been widely studied analytically under certain approximations (e.g., Neufeld 1990 and references therein). In particular, for an extremely opaque and plane-parallel medium, it is possible to demonstrate that the emerging profile consists of two symmetric peaks separated by a velocity shift of $\Delta v \sim 2(\ln \tau_{\text{Ly}\alpha})^{1/2} \sqrt{2}\sigma_{\text{th}}$ (where $\tau_{\text{Ly}\alpha}$ and $\sigma_{\text{th}}$ are, respectively, the central-line optical depth of Ly$\alpha$ photons and the thermal velocity dispersion of the medium).

Since fluorescent photons originate from externally ionized clouds, their typical $\tau_{\text{Ly}\alpha}$ should correspond to $\tau_{\text{Ly}\alpha} \sim 2 \times 10^4$ (assuming a temperature of $T = 2 \times 10^4$ K). Therefore, in the above approximations, fluorescent emission should be characterized by two symmetric peaks separated by $\Delta v \sim 8.9\sigma_{\text{th}}$.

However, detailed simulations of fluorescent emission in more realistic situations show that the inclusion of velocity fields inside and around the clouds influences the emerging line profile. In most cases, the symmetry of the double-humped profile is lost and one of the two peaks is severely suppressed (see Figure 2.7 in Chapter 2). Furthermore, if the gas consists of several small clumps, a turbulent velocity term should be added to the thermal velocity dispersion, increasing the separation of the peaks. On the other hand, if the turbulent velocity of the emitting region is large compared with that of the intervening layers, the symmetry of the line profile may be restored.

While the double peaked nature of fluorescent emission can be modified, the single Ly$\alpha$ lines generated by internal photo-ionization at low optical
3.2. Recognition of fluorescent emission

depth can be partially absorbed by infalling or expanding gas. As a result, the emergent profile can again consist of multiple components.

We conclude that these practicalities mean that the analysis of the emission line profile alone cannot provide a watertight signature of fluorescence.

3.2.3 Surface Brightness

With a simplified slab geometry (e.g., Hogan & Weymann 1987, Gould & Weinberg 1996) of a semi-infinite and static medium, fluorescent (self-shielded) clouds should act like “mirrors”: illuminated by an external source they return the incident ionizing photons in the form of Ly\(\alpha\) line emission with an efficiency of \(\sim 65\%\). In this case, the Ly\(\alpha\) surface brightness is uniform and its value is easily predicted once the impinging ionizing flux is known, and vice-versa.

In the case of a locally enhanced ionizing flux, e.g., from a nearby quasar, the fluorescent surface brightness would be expected in this simplified geometry to be higher. We introduce a “boost factor” \(b\), that is defined to be the increase in the predicted surface brightness relative to that induced by the UV background at \(z \sim 3\) (\(SB_{\text{bg}} = 3.67 \times 10^{-20}\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\)), i.e., \(SB = (1 + b)SB_{\text{bg}}\). The value of \(b\) corresponds to:

\[
b = 15.2 \frac{L_{LL}}{10^{30}\text{erg s}^{-1}\text{Hz}^{-1}} \frac{0.7}{\alpha} \left( \frac{r}{1\text{Mpc}} \right)^{-2} \tag{3.1}
\]

at a physical distance \(r\) from a quasar with monochromatic luminosity \(L_{\nu} = L_{LL}(\nu/\nu_{LL})^{-\alpha}\) (see figs. 2.6, 2.9 and §2.3.3 for further details).

When velocity fields and a more realistic gas distribution are taken into account, we have shown in Chapter 2 that the surface brightness may be reduced. In particular, for anisotropic illumination (i.e. fluorescence induced by a quasar), the expected surface brightness in the direction of the incoming flux can be much lower than expected in the slab approximation. The importance of this effect, which we called the “geometric effect”, depends on the relative size of the shielding-layer with respect to the cloud radius, and therefore on the gas density profile and the intensity of the impinging radiation. In Chapter 2, we found that the fluorescent surface brightness from self-shielded clouds is still predictable in good approximation from the empirical relation:

\[
SB = (0.74 + 0.50 b^{0.89})SB_{\text{bg}} \tag{3.2}
\]

where \(b\) represents the ideal “boost factor” described above.

The SB predicted in this way represents a fundamental upper-limit constraint: emitters with higher SB must receive a ionizing contribution from
3.2. Recognition of fluorescent emission

other sources and, therefore, are with high probability internally ionized clouds. However, several uncertainties remain to be taken into account. In particular, the exact distance from the quasar may be uncertain due to peculiar motions (and uncertainty in the precise systemic redshift of the quasar). Anisotropy or time-variability in the quasar emission will also modify the surface brightness. In fact this latter effect offers the possibility, if other indicators indicate a fluorescent origin of the emission, that their surface brightnesses can be used to study the angular distribution and temporal history of the quasar UV emission.

3.2.4 The number density of emitters

The covering factor of fluorescent sources on the sky within a volume is directly related to the number density of optically thick absorbers seen in quasar spectra. This fact was used in Chapter 2 to normalize our simulations. Two complications enter in the present case. First, the regions around quasars are likely to have higher than average density. Second, the enhanced ionizing radiation will produce a higher photo-ionization in a given cloud, reducing the column density of neutral hydrogen. The high surface brightness fluorescence will still come from systems which would be seen as LLS if there was a background quasar, but these are systems that would have been seen as DLA if the extra ionizing radiation had not been present. The fluorescence near to a quasar is thus closely linked to the “proximity effect” (e.g., Bajtlik, Duncan & Ostriker 1988). Since statistics of LLS near QSOs are not constrained, we must rely on theoretical models to determine their covering factor.

The procedure to calculate the expected number of fluorescent emitters around a quasar, outlined in §2.3.4, consists of three steps: i) convert the surface brightness sensitivity limit of the survey (SBlim) into a minimum boost factor bmin inverting Eq.(3.2), ii) use b = bmin in Figure 2.11 to determine the physical number density of fluorescent sources with SB ≥ SBlim; iii) given the values of LLL, α for the selected quasar, invert Eq. 3.1 using b = bmin to find the maximum distance (rmax), and thus the volume, where the fluorescent SB ≥ SBlim. As an example, a sensitivity of SBlim ∼ 10^{-18} erg s^{-1} cm^{-2} arcsec^{-2} corresponds to a fluorescent (physical) number density of dN/dV ∼ 0.3 ± 0.1 Mpc^{-3} (for sources with area A ∼ 4 arcsec^2), neglecting any density enhancement around the quasar.

This may be compared with the number density of other Lyα sources around z ∼ 3 quasars. Recent surveys indicate that the number of Lyα emitters around radio-galaxies at that redshift can be enhanced by a factor ∼ 3 with respect to the field. In particular, Venemans et al. (2005; here-
3.2. Recognition of fluorescent emission

after V05) found an emitter number density of $0.26 \pm 0.04$ Mpc$^{-3}$ around the $z \sim 3.13$ radio-galaxy MRC0316-257, in a survey with sensitivity of the order of $SB_{\text{lim}} \sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. In the view of the AGN unified model (see e.g., Antonucci 1993), the environment of radio-loud quasars should be similar to that of radio-galaxies. Moreover, we do not expect a significant contribution from fluorescent sources to the number density found by V05, given the shape of their survey and the direction of the (probable) UV emission-cone from MRC0316-257.

3.2.5 Fluorescent candidates in the literature

In this section, we briefly describe previous surveys for fluorescent emission and review the results of these in the light of our discussion above. Given the difficulties in the detection of fluorescence induced by the UV-background alone, previous surveys have centered around quasars, as in our case.

Francis & Bland-Hawtorn (2004) reported an attempt to find fluorescence around a quasar at redshift $\sim 2.17$ basing their expectations on the simplified analytical models (Gould & Weinberg 1996). In particular, they were expecting to find at least 6 fluorescent emitters within their sampled region of 1 Mpc around the quasar, but they saw none. However, this result is perfectly consistent with the expectation of our more realistic model of fluorescent emission (see §2.3.5 for details).

Adelberger et al. (2006) reported the serendipitous discovery of a possible fluorescent emitter associated with a DLA at redshift $\sim 2.8$. In particular they found the emitter in the spectrum of a Lyman-break object located 49" from a much brighter quasar. The object consists of two peaks with separation $\Delta V \sim 500$ km s$^{-1}$ and its SB seems to be compatible with the fluorescence induced by the quasar, even though the required boost factor is extremely high ($b \sim 2000$, in the ideal case of a slab). However, the object is clearly detected in their $G$ and $R$ images (with an observed magnitude $G_{\text{AB}} = 26.8 \pm 0.2$) resulting in a rest-frame equivalent width $EW_0 = 72 \pm 20$ Å. Therefore, this candidate is more plausibly an internally ionized source. A similar detection, associated with a lower redshift DLA system ($z \sim 1.9$) in the spectrum of a close quasar-pair, was reported by Fynbo et al. (1999). In this case a continuum counterpart is not clearly detected, although the subtraction of the PSF of the bright quasars makes this difficult. However, the extreme proximity of the quasar responsible of the possible fluorescent emission ($\sim 20$ kpc), indicates a plausible physical connection between the two objects.

Finally, Francis & McDonnell (2006) claimed the detection of a fluorescent object located just 0.8" from a quasar at $z = 4.28$. Their object is spectrally
and spatially unresolved and the flux is poorly constrained because of the proximity of the quasar. There is a lower limit for the equivalent width of $\text{EW}_0 > 19\AA$. Given the vicinity of the quasar ($\sim 5 - 50$ physical kpc) and the uncertainties in the flux and size measurement, comparison with the theoretical SB is hard, although they note that the predicted luminosity is $\sim 400$ times greater than observed, if the object is fluorescent. The sampled area around the quasar is very small ($5'' \times 7''$ in projection) because of the Integral Field Spectrometer used, making any statistical comparison difficult.

### 3.3 Observations and data analysis

In this section we describe our own survey for fluorescent emission around QSO0420-388, including the data reduction and the selection of the Ly$\alpha$ candidates.

#### 3.3.1 VLT spectroscopy and imaging

Observations were taken during four visitor-mode nights on the VLT 8.2 m telescope Antu on November 28 - December 1, 2005. The FORS2 spectrograph was used in multi-object spectroscopy mode (MXU) at standard resolution ($0.25 \times 0.25$ arcsec$^2$ pixel$^{-1}$) to build a “multi-slit plus filter” (Crampton & Lilly 1999) configuration centered on the $z = 3.1$ QSO [HB89]0420-388.

For all the observations, we used the 1400V grism giving a dispersion of $0.61\ \text{Å}$ pixel$^{-1}$, in combination with the narrow band filters OIII+50 and OIII/3000+51. The resolution ($R=2100$, corresponding to $\sim 150$ kms$^{-1}$) is large enough to resolve the doublet [OII]$\lambda\lambda3726, 3729$, which helps to distinguish a Ly$\alpha$ emission from low redshift contaminants. The use of the narrow band filters allowed us to put 14 slits (each $6.8'$ long and $2''$ wide) parallel to each other and separated by $25''$ without a significant overlapping of the spectra on the CCD. The total area covered by the slits in the mask corresponds to $3.17$ arcmin$^2$. The same mask was used for all the observations, but with two different filters and two different spatial orientations: i) slits parallel to North-South direction, ii) slits parallel to East-West direction.

The use of two different narrow band filters and two mask orientations was chosen in order to increase the sampled volume in redshift and projected space. For our setup, the central wavelength of the filters OIII+50 and OIII/3000+51 is, respectively $5001 \text{Å}$ and $5045 \text{Å}$ with a FWHM of 57$\text{Å}$ and 59$\text{Å}$, corresponding to a total redshift range $z = 3.089 - 3.173$ for Ly$\alpha$. Filter OIII/3000+51 was used for both the mask orientations ($0^\circ$ and $90^\circ$ rotations) and filter OIII+50 for just one orientation ($0^\circ$ rotation).
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For each configuration, a series of several dithered exposures of 1800s each, stepped along the slit by 5 arcsec, were obtained for a combined exposure time of 7 hours (filter OIII+51 and 0° rotation), 9.5 hours (filter OIII+50 and 0° rotation) and 6.5 hours (filter OIII+51 and 90° rotation). On the third night we also obtained a V-band image of the same field for a total exposure time of 2 hours. It consisted of 120 dithered exposures of 60 secs each, and it was obtained under photometric sky conditions. An overview of the observations and of the different configurations is summarized in Table 3.1.

3.3.2 Data reduction

The spectroscopic and photometric data were reduced using standard packages (IRAF - Image Reduction and Analysis) and additional IDL routines written by the authors.

The data reduction consisted of several steps including bias subtraction, spectral distortion correction, flat-fielding (using “sky-flats” obtained from the scientific images themselves) and sky subtraction. The individual sky-subtracted images were then combined to obtain the three scientific images corresponding to the three different configurations (see Table 3.1). The combination of the images was performed with an averaged sigma clipping algorithm in order to minimize the effect of bad pixels and cosmic rays. A pixel-by-pixel noise map associated with each science image was generated from the statistics of the pixels in the multiple image combinations.

Spectro-photometric calibration was based on observations of different spectro-photometric standard stars for each night of observation. The magnitude zero-points derived from several standard stars were consistent with each other within 0.02 magnitudes. A small Galactic extinction correction of $A_L(V) = 0.079$ mag (Schlegel et al. 1998) was applied.

The result of the data reduction was three final “spectroscopic” multi-slit images (S1, S2 and S3; corresponding to the different configurations of mask orientation and filters summarized in Table 3.1) plus the V-band image (IMA) of the same field. The ensuing steps included: i) the detection of line emission in S1, S2 and S3; ii) the identification of possible continuum counterparts of the line emission in the V-band image; iii) the selection of probable Lyα emission with a criterion based on the rest-frame equivalent width of the line.
3.3. Observations and data analysis

3.3.1 Table 3.1. Summary of the observations and setups.

<table>
<thead>
<tr>
<th>Setup name</th>
<th>Date</th>
<th>Mode</th>
<th>Filter</th>
<th>Mask rot.</th>
<th>Seeing</th>
<th>Exp. time</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>11/29</td>
<td>MXU</td>
<td>OIII/3000+51</td>
<td>0°</td>
<td>1°.0</td>
<td>25 200 s</td>
</tr>
<tr>
<td>S2</td>
<td>11/30 &amp; 12/01</td>
<td>MXU</td>
<td>OIII/3000+51</td>
<td>90°</td>
<td>1°.0</td>
<td>34 200 s</td>
</tr>
<tr>
<td>IMA</td>
<td>12/01</td>
<td>Imaging</td>
<td>Bessel V</td>
<td>-</td>
<td>1°.0</td>
<td>7 200 s</td>
</tr>
<tr>
<td>S3</td>
<td>12/02</td>
<td>MXU</td>
<td>OIII+50</td>
<td>0°</td>
<td>0°.7</td>
<td>23 400 s</td>
</tr>
</tbody>
</table>

3.3.3 Line emission detection

The detection of line emission candidates was performed with the help of the software package SExtractor (Bertin & Arnouts 1996). In order to make the detection process more efficient, we first removed from each image the regions corresponding to the brightest continuum spectra (typically stars and local bright galaxies). Such regions were automatically identified for each slit by summing the flux over the spectral band and applying a sigma-clipping algorithm to the resulting 1-dimensional array. We removed all the regions where the integrated signal was greater than 3 times the standard deviation for that slit. The excluded regions were, respectively, ∼4% and ∼9% of the total image for the 0° and 90° rotation configurations.

The resulting images and corresponding noise-maps (obtained in the reduction process described above) were then processed by SExtractor. In order to allow the most general search, we varied the three most relevant parameters, i.e. the smoothing filter, the minimum detection threshold and the minimum detection area (i.e. the number of connected pixels). We used always standard filters (Gaussian, top hat) plus our own filters with a shape designed to increase the S/N of the double peaked emission. The minimum detection threshold and the number of connected pixel was varied, respectively, from 0.3 to 1.5, and from 3 to 30 pixels. Each combination of the three detection parameters produced a separate catalog of line emission candidates, for a total of 1344 catalogs for each dataset. We refer to these as “positive” catalogues.

We then applied exactly the same procedure on the original images after they had been multiplied by −1 to produce a negative image. Any emission objects detected in these “negative” catalogues must of course be spurious. We therefore kept only those “positive” catalogs for which the corresponding “negative” catalogue (generated with the same SExtractor parameters) contained no detected sources. Notice that this procedure assumes Gaussian (rather than Poisson) noise. This is a good approximation since the noise is sky-dominated and the sky level is high. The final step consisted of merging together the lists of objects in these surviving catalogues, removing the
3.3. Observations and data analysis

duplications.

The output we had from SExtractor, at this stage was the central position and approximate size of the candidate line-emission for each of the three spectroscopic images. These were used as a first guess of the photometric aperture in the calculation of the line and continuum flux (as explained in the next sections).

3.3.4 Identification of possible continuum counterparts

For each candidate detected in the spectroscopic images, we identified the corresponding region in the V-band image and calculated the continuum flux $f_V$. The size of the photometric aperture was fixed at the slit width (2") perpendicular to the slit, and the size of the detected object in the spectrum, in the direction along the slit. The location of these apertures was obtained from accurate relative astrometry of the brightest continuum objects which were detected both in the spectra and the V image. The errors on $f_V$ were estimated from integrating on random positions within the image. The resulting 1σ limiting magnitude for a typical aperture of $2'' \times 2''$ was about 27.7 mag.

3.3.5 Selection of Lyα candidates

In order to select candidate Lyα emitters we used a method based on the line rest-frame equivalent width:

$$EW_0 = \frac{F_{\text{line}}}{C_{\text{line}}(1 + z)}$$  \hspace{1cm} (3.3)

where $F_{\text{line}}$ is the flux of the emission line, $C_{\text{line}}$ is the continuum, if present, at the same wavelength of the line and $z$ is the redshift of the emitter. Since the value of $C_{\text{line}}$ is too faint to be reliably measured from the spectra, we base it on the V-band flux density $f_V$ assuming a power law continuum with slope $\beta$. Including the contribution of the line-emission, the flux density measured in the V-band is, to first approximation:

$$f_V = \frac{F_{\text{line}} \cdot \epsilon_V(\lambda_{\text{line}})}{\int \epsilon_V(\lambda) d\lambda} + C_{\text{line}} \left[ \frac{\lambda_{\text{eff},V}}{\lambda_{\text{line}}} \right]^{\beta},$$  \hspace{1cm} (3.4)

where $\epsilon_V$, and $\lambda_{\text{eff},V}$ are, respectively, the efficiency and the central wavelength (5561.9Å) of the V-band filter. From Eq. (3.4) we derive:

$$EW_0 = \frac{F_{\text{line}}}{f_V - f_{\text{line},V}} \left( \frac{\lambda_{\text{eff},V}}{\lambda_{\text{line}}} \right)^{\beta} (1 + z)^{-1}$$  \hspace{1cm} (3.5)
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where

\[ f_{\text{line}, V} = \frac{F_{\text{line}} \cdot \epsilon_V(\lambda_{\text{line}})}{\int \epsilon_V(\lambda)d\lambda} \]  (3.6)

represents the equivalent flux density in the V image given by the line emission alone.

The line flux \( F_{\text{line}} \) is calculated within an aperture on the spectrum (as explained in §3.3.3). Instead, the value of \( \epsilon_V(\lambda_{\text{line}}) \) is interpolated from the measured transmission curve of the V-band filter. We have not tried to take into account the absorption of the continuum bluewards of \( \lambda_{\text{line}} \), because Ly\( \alpha \) always falls in the blue wing of the V-band. We cannot estimate the value of the slope (\( \beta \)) for each source, and so a flat spectrum (\( \beta = -2 \)) was assumed for all the objects. The actual value of \( \beta \) has little effect on EW_0 - i.e. changing to \( \beta = -1 \) (or \( \beta = -3 \)) changes the EW by only \( \sim 10\% \).

In order to compare our results with the other surveys for Ly\( \alpha \) emitters, we selected objects with \( EW_0 > 15\mu\text{A} \) as candidate Ly\( \alpha \) line (see e.g. Venemans et al. 2005 and reference therein). For candidates with \( f_V < f_V(1\sigma) \) we obtain a lower limit to EW_0 by assuming \( f_V = f_V(1\sigma) \).

3.3.6 Results

Each candidate lying above the equivalent width threshold (assuming the redshift given from the Ly\( \alpha \) line) was visually inspected in order to remove spurious objects like leftover cosmic rays. This resulted in a list of 14 candidates, of which 12 are compatible to be Ly\( \alpha \) lines while the remaining 2 show a double peaked emission that can also be compatible with the [OII] doublet. One of these two candidates has a 2\( \sigma \) detection in the V-band image and was rejected as a probable OII emitter. The other one, labeled #13, does not show any continuum counterpart above 1\( \sigma \) (corresponding to an equivalent width greater than 70\( \mu\text{A} \) for OII) and, for this reason is included in the Ly\( \alpha \) sample. One other OII emitter, for which the identification is considered secure (see caption of Figure3.2 for more details), was found by visual inspection of the regions containing a bright continuum that were excluded from the analysis at the beginning (see section 3.3.3).

The fraction of contaminants in our sample is thus 1/14 \( \sim 7\% \), similar to the fraction (\( \sim 6.5\% \)) of low redshift interlopers found in other surveys of Ly\( \alpha \) emitters at \( z = 3.1 \) (e.g., Steidel et al. 2000; Venemans et al. 2005). In the following section we will discuss in detail the main characteristics of the 13 Ly\( \alpha \) candidates and, in §3.5, their possible fluorescent origin.
3.3. Observations and data analysis

Table 3.2. Position and redshift of the Ly$\alpha$ candidates and the QSO.

<table>
<thead>
<tr>
<th>Object</th>
<th>Position</th>
<th>$z^a$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\alpha_{\text{J2000}}$</td>
<td>$\delta_{\text{J2000}}$</td>
</tr>
<tr>
<td>1</td>
<td>04:22:18.53</td>
<td>−38:45:15.6</td>
</tr>
<tr>
<td>3</td>
<td>04:22:27.56</td>
<td>−38:43:24.8</td>
</tr>
<tr>
<td>4</td>
<td>04:22:27.55</td>
<td>−38:42:14.5</td>
</tr>
<tr>
<td>5</td>
<td>04:22:23.36</td>
<td>−38:45:32.1</td>
</tr>
<tr>
<td>7</td>
<td>04:22:19.31</td>
<td>−38:43:35.8</td>
</tr>
<tr>
<td>8</td>
<td>04:22:04.06</td>
<td>−38:45:52.1</td>
</tr>
<tr>
<td>9</td>
<td>04:22:01.97</td>
<td>−38:45:59.2</td>
</tr>
<tr>
<td>10</td>
<td>04:22:23.35</td>
<td>−38:44:42.0</td>
</tr>
<tr>
<td>11</td>
<td>04:21:59.87</td>
<td>−38:43:21.0</td>
</tr>
<tr>
<td>12</td>
<td>04:22:16.87</td>
<td>−38:42:27.6</td>
</tr>
<tr>
<td>13</td>
<td>04:22:21.08</td>
<td>−38:43:35.8</td>
</tr>
<tr>
<td>QSO</td>
<td>04:22:14.76</td>
<td>−38:44:50.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

$^a$ typical error in the redshift estimation is 0.0015

$^b$ estimated by Osmer et al. 1994

$^c$ estimated by Lanzetta et al. 1993
### 3.3. Observations and data analysis

Table 3.3. Spectro-photometrical properties of the Ly\(\alpha\) candidates

<table>
<thead>
<tr>
<th>Object #</th>
<th>(F_{\text{line}} \pm 1\sigma) (10^{-18}) b</th>
<th>(f_{\nu} \pm 1\sigma) (10^{-20}) c</th>
<th>(\text{EW}_0) A</th>
<th>(\text{SB})</th>
<th>Fluorescent?(^a)</th>
<th>(\text{EW}) (\text{EP}) (\text{SB})</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>58.27 ± 6.67</td>
<td>6.55 ± 5.90</td>
<td>(\geq 370)</td>
<td>15.81 ± 2.73</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>2</td>
<td>18.81 ± 1.20</td>
<td>3.43 ± 3.69</td>
<td>(&gt; 150)</td>
<td>(\geq 9.72)</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>3</td>
<td>12.98 ± 1.35</td>
<td>16.70 ± 3.32</td>
<td>(16^{+6}_{-4})</td>
<td>5.80 ± 1.06</td>
<td>-</td>
<td>+</td>
</tr>
<tr>
<td>4</td>
<td>11.33 ± 1.41</td>
<td>1.46 ± 4.43</td>
<td>(&gt; 65)</td>
<td>2.68 ± 0.78</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>7.30 ± 0.81</td>
<td>4.76 ± 4.06</td>
<td>(\geq 36)</td>
<td>2.65 ± 0.49</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>6.36 ± 0.68</td>
<td>8.86 ± 4.06</td>
<td>(15^{+17}_{-4})</td>
<td>1.93 ± 0.40</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>7</td>
<td>5.31 ± 0.82</td>
<td>0.86 ± 4.06</td>
<td>(&gt; 30)</td>
<td>2.71 ± 0.50</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>8</td>
<td>4.70 ± 0.67</td>
<td>0.59 ± 4.43</td>
<td>(&gt; 24)</td>
<td>1.84 ± 0.49</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>4.21 ± 1.16</td>
<td>0.65 ± 5.17</td>
<td>(&gt; 18)</td>
<td>(\geq 2.40)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>4.06 ± 1.01</td>
<td>-5.65 ± 3.69</td>
<td>(&gt; 25)</td>
<td>(\geq 2.34)</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>3.49 ± 1.05</td>
<td>-1.98 ± 3.69</td>
<td>(&gt; 21)</td>
<td>(\geq 3.52)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>2.65 ± 0.56</td>
<td>3.17 ± 3.32</td>
<td>(&gt; 18)</td>
<td>(\geq 1.79)</td>
<td>+</td>
<td>-</td>
</tr>
<tr>
<td>13</td>
<td>2.62 ± 0.45</td>
<td>2.34 ± 2.58</td>
<td>(&gt; 23)</td>
<td>(&gt; 70)</td>
<td>1.46 ± 0.39</td>
<td>+</td>
</tr>
</tbody>
</table>

Previous fluorescent Ly\(\alpha\) candidates in literature:

- AA1\(^a\): 21.0 ± 5.0 \(10^{-18}\) b, 72.2 ± 20 \(10^{-20}\) c, 110.0 ± 26.00 \(\text{EW}\) \(\text{EP}\) \(\text{SB}\)
- FD1\(^b\): \(\geq 15.0\) \(10^{-18}\) d

\(^a\) in view of the indicators discussed in §3.2 (where EP stays for emission-line profile)

\(^b\) erg s\(^{-1}\) cm\(^{-2}\)

\(^c\) erg s\(^{-1}\) cm\(^{-2}\) A\(^{-1}\)

\(^d\) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\)

\(^e\) if \(z_{\text{QSO}} = 3.110\)

\(^f\) if the line is OII at \(z = 0.36\)

\(^g\) Adelberger et al. 2006, candidate at \(z = 2.842\)

\(^h\) Francis & McDonnell 2006, candidate at \(z = 4.279\)
Figure 3.1 2D-spectra (in S/N units) of the 13 Ly$\alpha$ candidates (right panels) and the corresponding V-band image of the slit with the object positions (white boxes in left panels). The dispersion direction in the spectra is parallel to the x-axis. The scale of the panels is $32\AA \times 10''$ for the spectra and $4'' \times 10''$ for the images. The white boxes represent the apertures used to calculate the line and V-band flux. The values of flux and $1\sigma$ noise for each aperture is shown in Table 3.3 (see text for details).
3.4 Properties of Lyα candidates

The spatial distribution and the main spectro-photometric properties of the 13 Lyα candidates are summarized in Tables 3.2 and 3.3. The 2-dimensional spectra in S/N units together with the corresponding slit positions in the V-band image are shown in Figure 3.1, while the flux calibrated 1-dimensional spectra are shown in Figure 3.3. The photometric apertures used to calculate the line and continuum fluxes are represented by the white boxes in Figure 3.1.

Only two objects (#3 and #6) have an integrated continuum flux in the V-band image that is well above 1σ for the corresponding photometric aperture. However, in only one of these (#6) there is a source clearly detected at the expected position. In other cases (i.e. #1, #3 and #5), the presence of close objects in the V-band image may have affected the photometry. For the objects with \( f_V \lesssim 1\sigma \), we estimate a lower limit for EW_0, assuming \( f_V = 1\sigma \). Thus, only one of our candidates is clearly ruled out as a fluorescent emitter based on its EW_0.

The spectral shape of the emission lines appears to be sharp and, in most of the cases, consists of only one clear peak. One candidate (#4) clearly shows the presence of two peaks separated by \( \sim 8\AA \). Both peaks were independently detected by SExtractor at \( S/N > 5 \). Candidates #3 and #6 also show a lower S/N (\( \gtrsim 3 \)) second peak at a slightly different spatial position. Candidate #13 was detected as a single emission line but
subsequent study of the unsmoothed spectra revealed the presence of two emission lines separated by $3 - 4\text{Å}$. In other words, about a third of the sample show some evidence for double line structure.

The estimation of the SB for Lyα candidates is complicated by their small sizes, which typically range between the seeing disk and 3 arcsec. For this reason, we have simply used the flux in the peak pixel, divided by the product of the pixel and the slit size (i.e. $0''.25 \times 2''$) as a rough estimation of the surface brightness, that will, for the unresolved objects, be a lower limit. Object #4 shows a clear flat-topped profile over about $1''.25$, and for this object we estimate the surface brightness directly.

3.4.1 Note on candidate #1

Candidate #1 was detected in a part of the spectrogram in which the spectra of two slits overlap. It was assigned to the blue edge of the appropriate slit because it lays closer to its central wavelength. We cannot completely rule out the possibility that it belongs instead to the red edge of the adjacent slit. At the assumed position, candidate #1 was situated close to a bright star that was subtracted before calculating $f_V$.

3.5 Discussion

Are any of our detected objects fluorescent? We know from §3.2 that a good fluorescent candidate should have: i) very high EW, ii) possibly (but not necessarily) a double-peaked profile, iii) a precise value of its surface brightness. We would also like to see the number density of objects to roughly match the density calculated in §3.2, allowing for the uncertainty in clustering.

As a quick reference, we associated to each candidate in Table 3.3 a “+”(or “−”) if the corresponding indicator clearly suggests (or disfavors) a fluorescent origin for the Lyα emission. Regarding the first criterion we notice that, given the sensitivity limits of our V-band image, only the two brightest emitters (#1 and #2) have high upper limits to their EW (see Table 3.3) - and it would be extremely difficult to establish the required EW observationally. The low values of the EW for #3 and #6 indicate a likely non-fluorescent origin for the emission.

Two objects (#4 and #13) display a very clear signature of double-peaked emission. Candidate #4 is compatible with fluorescence if $\sigma_{th} \sim 60 \text{ km s}^{-1}$. Instead, object #13 is compatible both with fluorescent Lyα (with $\sigma_{th} \sim 20 \text{ km s}^{-1}$) and OII emission at $z = 0.36$. However, the high EW, the intensity
Figure 3.3 1D calibrated spectra of the 13 Ly$\alpha$ candidates. The flux (in units of $10^{-18}$ erg s$^{-1}$ cm$^{-2}$ A$^{-1}$) is obtained integrating within the aperture represented by the white boxes in the left panels of Figure 3.1. The dashed lines represent the 1$\sigma$ noise level.
3.5. Discussion

Figure 3.4 Observed surface brightness of the 13 Lyα candidates against their three-dimensional comoving distance from the quasar for two different quasar redshifts. The expected SB from self-shielded clouds, as calculated by the theoretical models presented in Chapter 2, is shown by the solid line. The total errors in the predicted SB should take into account the scatter around the model relation and the uncertainties on the derived value of the quasar luminosity ($L_{LL}$) and spectral shape ($\alpha$). To give an idea of the effect of these uncertainties in the predicted SB we overplot the expected fluorescent SB for a Lyman Limit flux of $2 \times L_{LL}$ (upper dashed line) and $0.5 \times L_{LL}$ (lower dashed line). The limiting case of fluorescent emission from a static slab is represented by the dotted line. Open circles indicate the candidates with a V-band counterpart with flux greater than $1\sigma$ for the correspondent photometric aperture (see text for details). The horizontal error bars take into account a peculiar velocity shift of $\pm 250 \text{ km s}^{-1}$. All the candidates with a SB equal or lower than the theoretical expectations curves are compatible with fluorescence induced by the quasar.
3.5. Discussion

ratio of the peaks (i.e. that the blue peak is brighter than the red peak) all disfavor the association with [OII] emission.

The comparison of the expected fluorescent surface brightness with the estimated surface brightness of the individual candidates is shown in Figure 4. Unfortunately the systemic redshift of the quasar is uncertain – $z = 3.110$ is given by Osmer et al. 1994, and $z = 3.123$ by Lanzetta et al. 1993. The expected surface brightness from self-shielded clouds (solid line) is calculated from Eq. (1), using the corresponding value of $L_{\text{LL}}$ ($\sim 10^{32} \text{ergs}^{-1} \text{Hz}^{-1}$) and $\alpha (0.61 \pm 0.02)$ for our quasar (extrapolated from Kuhn et al. 2001). Only the most distant objects (#4, #5 and #6) have an estimated surface brightness that seems to be too high to be due from fluorescence induced by the quasar, unless the quasar was brighter in the past. Notice that two of these (#5 and #6) both have $f_V \gtrsim 1\sigma$ (and are represented by open-circle symbols in Figure 3.4), and #6 in particular has already an EW that disfavors a fluorescent origin. In general, we can notice that the case $z_{\text{QSO}} = 3.110$ allows a better fit of the expected relation between surface brightness and distance for the detected objects. In this case, at least 7 – 8 candidates have a SB in good agreement with the theoretical expectations.

The theoretical curves shown in Figure 3.4 are calculated assuming isotropic and time-invariant emission from the quasar. The candidates beyond the quasar could have been illuminated by a different UV flux with respect to the value measured by us. In particular, gas clouds at 20 comoving Mpc from the quasar (within which most of our candidates were found) should be responding to the ionizing flux of the quasar that was emitted or order $\sim 3 \times 10^7$ yrs before the epoch of observation. At 40 comoving Mpc, where candidates #4, #5 and #6 lie, the time delay is two times larger, i.e. $\sim 6 \times 10^7$ yrs, close to the expected life-time of the quasar (e.g., Porciani, Magliocchetti & Norberg 2004).

Turning the argument around, the effect of the time delay may represent a direct way to measure the radiative history of quasars, if the fluorescent origin of the sources can be proved. If we assume that our object #4 is truly fluorescent, which is plausible given the high EW and the clear double-peaked profile, its surface brightness would provide us with direct proof that the quasar was shining $\sim 10^8$ yr ago with an ultraviolet luminosity 6-10 times higher than the present measurements. Confirmation of the fluorescent origin of object #4 would for this reason be especially interesting.

In conclusion, what we can say about the fluorescent nature of our detected objects? Unfortunately, there is no definitive evidence of fluorescence. The EW can be poorly constrained for most of our candidates, requiring extremely deep broad-band images (for ground observations). The SB-distance relation (as well as the emission-line profile), given all the theoretical and ob-
servational uncertainties discussed above, is only an approximate indicator.

Nevertheless, collecting all the indication so far, we can highlight 5 of the 13 objects which are most probably not fluorescent, i.e. #3 (low-EW), #5 (too high SB), #6 (both low-EW and too high SB), #11 and #12 (both objects are unresolved, in front of the quasar and with SB at the limit for fluorescence). However, given their higher upper limit on the EW (mainly because of their high line-flux) and their SB, objects #1 and #2 (if $z_{\text{QSO}} = 3.11$) could be good candidates for fluorescence. As noted above, object #4 could also be a good candidate, because the profile is flat in the center and the presence of a double-peaked profile, compatible with fluorescence if $\sigma_{\text{th}} \sim 60$ km s$^{-1}$. Finally, objects #7, #8, #10, #12 and #13 have SBs compatible with fluorescent emission (for both quasar redshifts), but the EW is poorly constrained.

As a final remark, it is worth stressing that self-shielded fluorescent emitters around a quasar could also be detected in absorption as the equivalent of DLAs in the field (see §3.1 for further details). Therefore, the existence of such a fluorescent population could in principle support the association of DLAs with proto-galactic gas clouds (e.g., Haehnelt, Steinmetz & Rauch 1998). However, even if all fluorescent emitters around a quasar are DLAs, this does not imply the converse, allowing the possibility of a different origin for a part of these absorbing systems, like disk galaxies already in place (e.g., Prochaska & Wolfe 1998).

### 3.5.1 The number density of emitters

Given our sensitivity limits ($\text{SB}_{\text{lim}} \sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ for a typical aperture of $2'' \times 2''$) and the assumed value of $L_{\text{LL}}$ and $\alpha$ for our quasar, we can use the procedure discussed in §3.2 to derive the expected number of fluorescent and not-fluorescent sources in our volume. We find a physical number density of fluorescent emitters of $dN/dV \sim 0.3 \pm 0.1$ Mpc$^{-3}$, detectable within $r_{\text{max}} \sim 4.7$ physical Mpc from the quasar. Given the projected area covered by our slits in all three configurations ($\sim 1.4$ physical Mpc$^2$), we therefore should be able to detect fluorescent emission within a total volume $V \sim 13$ physical Mpc$^3$. The shape of this volume is approximatively a cuboid, being constrained from the limited field of view of the detector ($6'8 \times 6'8$, corresponding to a physical Mpc scale of $3.2 \times 3.2$ at this redshift). Therefore the number of expected fluorescent emitters within $r_{\text{max}}$ from the quasar is $\sim 4 \pm 1$. Notice, however, that this number does not take into account: (i) the expected enhancement of the number density of objects around the quasar due to clustering effects, (ii) any reduction due to beaming of the quasar emission - although we note that we would expect
the illuminated cone to include the line of sight and thus to be more or less aligned with the accessible volume. In this context, we looked to see whether foreground and background candidates were located on different sides of the quasar, possibly indicating beaming, but found no evidence of this.

By comparison, we expect \( \sim 6 \) non-fluorescent sources in our total sampled volume if it is similar to the radio galaxy environment studied by V05. Despite the small statistics and with all the many uncertainties, these numbers agree very well with the detected number of objects in our survey. It may be a coincidence, but it is certainly consistent with the indication that about half of our detected sources may have a fluorescent origin.

### 3.6 Summary

Based on our model of fluorescent Ly\( \alpha \) emission presented in Chapter 2, we carried out a Ly\( \alpha \) survey around the \( z \sim 3.1 \) quasar QSO 0420-388 to search for signatures of fluorescence. We used a “multi-slit plus filter” technique to sparsely sample a volume of \( \sim 14000 \) comoving \( \text{Mpc}^3 \) around the quasar (directly sampling \( \sim 1700 \) comoving \( \text{Mpc}^3 \)).

We found 13 emission line sources, selected on equivalent width, which are likely to be Ly\( \alpha \) at a redshift close to the quasar. In order to try to distinguish fluorescent objects from internally ionized clouds, we measured three possible signatures of fluorescence: i) the line equivalent width, ii) the line profile, iii) the surface brightness. We also calculated the expected number of fluorescent and non-fluorescent sources from theoretical models and recent Ly\( \alpha \) surveys.

From a theoretical point of view, the best constraints would be a very high EW and, within some limitations, the relation of the surface brightness with the distance from the quasar. Instead, the line profile cannot give precise information on the nature of the sources - a double-peaked profile is a possible indication of fluorescence, but it can be absent, or be present in non-fluorescent sources.

Regarding the origin of the detected sources, there are good reasons to suspect that 5 objects are probably not-fluorescent, and this estimate is in good agreement with the number density of such sources around radio galaxies. Of the remaining 8 objects, two or three of them are quite good fluorescent candidates, based on moderately high upper limits to their EW, and, in some cases, the presence of extended emission with a flat SB and a double-peaked profile. The remaining 5 – 6 candidates are consistent with fluorescence, but their upper-limits on the EW are low enough to provide little real constraint.
3.6. Summary

On the basis of our model, we were expecting 3\(\sim\)5 fluorescent sources in the inner region around the quasar, and, from other surveys of Ly\(\alpha\) emitters around AGNs, we were expecting \(\sim\)6 non-fluorescent sources in the total sampled volume. These estimates are certainly consistent with the idea that about half of our detected sources could be fluorescent.

In this case, the distance of most of the candidates from the ionizing source would imply that the quasar has been active for at least 30 Myr, with a UV luminosity similar (within a factor of a few) to the present day value. In particular, one of the best candidates for fluorescence is sufficiently far behind the quasar to imply a life-time of \(\gtrsim\)60 Myr.

Although there are uncertainties in interpretation, due to both observational limitations and theoretical uncertainties (and no doubt a range of phenomena in Nature), the current study provides one of the first statistical samples of possible fluorescent emitters around a high-redshift quasar. Future studies on this category of objects will give information about the properties of proto-galactic clouds and, furthermore, on the emission properties (i.e. spatial and temporal variations) of high-redshift quasars.
Chapter 4

Mapping HI during Reionization in Ly$\alpha$ emission$^1$

Abstract

We present a new method to directly map the neutral-hydrogen distribution during the reionization epoch and to constrain the emission properties of the highest-redshift quasars (QSOs). As a tracer of HI, we propose to use the Ly$\alpha$ radiation produced by quasar ionization fronts (I-fronts) that expand in the partially ionized intergalactic medium (IGM) before reionization is complete. These Ly$\alpha$ photons are mainly generated by collisional excitations of hydrogen atoms in the boundary of the rapidly expanding HII region. The observable signal is produced by the part of the I-front that lies behind the QSO with respect to the observer. The expected Ly$\alpha$ flux depends on the properties of both the QSO (e.g., its total ionizing rate and spectral hardness) and the surrounding medium (e.g., the local density and the mean hydrogen neutral fraction). Combining two radiative transfer models (one for the QSO ionizing radiation and one for the Ly$\alpha$ photons), we estimate the expected Ly$\alpha$ spectral shape and surface brightness (SB$_{\text{Ly}\alpha}$) for a large number of configurations where we varied both the properties of the ionizing QSO and of the surrounding medium. We find that the expected signal is observable as a single (broad) emission line with a characteristic width of 100 – 200 km s$^{-1}$. The expected SB$_{\text{Ly}\alpha}$ produced at redshift $z \simeq 6.5$ within a fully neutral region (at mean density) by a typical QSO I-front lies in the range $10^{-21} - 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ and decreases proportionally to $(1 + z)^2$ for a given QSO age. QSOs with harder spectra may produce a significantly brighter emission at early phases. The signal may cover up to a

$^1$This chapter is based on Cantalupo, Porciani & Lilly, 2008, ApJ, 672, 48
few hundred square arcmin on the sky and should be already detectable with current facilities by means of moderate/high resolution spectroscopy. The detection of this Lyα emission can shed new light on the reionization history, the age and the emission properties of the highest-redshift QSOs.

### 4.1 Introduction

The epoch of reionization (EoR) marks the time at which the first luminous sources ionized the mostly neutral intergalactic medium (IGM). Uncovering when and how the EoR took place represents one of the most fundamental questions of modern cosmology and considerable efforts are being made to understand this era.

The recent polarization measurements of the cosmic microwave background (CMB) by the WMAP satellite suggest that the universe was mostly neutral at redshift $z \gtrsim 14$ (Page et al. 2006). On the other hand, at $z < 5$, hydrogen absorption features in the spectra of luminous quasars are resolved into individual Lyα forest lines (e.g., Rauch 1998) as expected in a highly ionized IGM. At $z \gtrsim 6$, quasar spectra start showing complete Gunn-Peterson absorption troughs (GPT) which might suggest a rapid increase in the neutral fraction of cosmic hydrogen (Becker et al. 2001; Fan et al. 2003; White et al. 2003). However, the Lyα transition has a large cross-section and the presence of GPTs only requires very low values for mean neutral fraction of cosmic hydrogen: $\langle x_{HI} \rangle \gtrsim 10^{-3}$ (Fan et al. 2002; Songaila 2004; Oh & Furlanetto 2005).

Stronger constraints on $\langle x_{HI} \rangle$ can be obtained from the detailed spectral shape of the GPT, i.e. from the size of the HII region produced by the QSO itself (White et al. 2003; Mesinger & Haiman 2004; Wyithe & Loeb 2004; Yu & Lu 2005; Fan et al. 2006; Maselli et al. 2006; Bolton & Haehnelt 2007). The physical scales of these regions are typically inferred to be $\sim 5$ Mpc at $z > 6$ (Fan et al. 2006), an order of magnitude larger than the HII bubbles expected from clustered star-forming galaxies (Furlanetto, Zaldarriaga & Hernquist 2004). The size of the HII region around a QSO depends on the neutral density of the surrounding medium but also on the source luminosity and age (more specifically, on its light curve). With some knowledge of the QSO parameters it is then possible to constrain the value of $\langle x_{HI} \rangle$. Whyte et al. (2005) applied this method to seven QSOs at $6 \lesssim z \lesssim 6.42$ and derived $\langle x_{HI} \rangle \gtrsim 0.1$. Similarly, from the size of the Lyα and Lyβ troughs of a QSO at $z = 6.28$, Mesinger & Haiman (2004) found $\langle x_{HI} \rangle \gtrsim 0.2$. On the contrary, Fan et al. (2006) did not find strong evidence for a mean hydrogen neutral fraction as high as 0.1 at $z = 6.4$. Apart from systematics, the main
uncertainty of this method lies in the estimate of the QSO age. As a matter of fact, the current observed sizes seem to be equally consistent with both a significantly neutral and a highly ionized surrounding IGM (e.g., Bolton & Haehnelt 2007).

Additional (indirect) information about the ionized fraction of the IGM can be obtained from the luminosity-function evolution of Ly$\alpha$ emitting galaxies (LAE) at $z > 6$ (Miralda-Escudé 1998; Madau & Rees 2000; Haiman 2002; Santos 2004; Taniguchi et al. 2005; Furlanetto et al. 2006; Malhotra & Rhoads 2006; Kashikawa et al. 2006), and from their clustering properties (McQuinn et al. 2007). The key idea is that the observed Ly$\alpha$ flux from high-$z$ galaxies should strongly depend on the neutral fraction of their surrounding medium. However, these observations are challenging and difficult to interpret. Any change in the luminosity function due to the EoR must be distinguished from an intrinsic physical evolution of the sources, as well as the effects of dust or galactic winds. Similarly, clustering signatures of the EoR can only be detected by comparing the spatial distribution of a given galaxy population (e.g., Lyman-break galaxies) with that of the sub-sample of LAEs (see Fan, Carilli & Keating 2006 for a recent review).

A very promising method for studying the EoR is the detection of the redshifted 21-cm emission from neutral hydrogen (Madau, Meiksin & Rees 1997; see Furlanetto, Oh & Briggs 2006 for a recent and exhaustive review). This technique has received a lot of attention recently as a concrete possibility of studying the detailed history of the EoR. From the technical point of view, however, it requires an extremely challenging measure: the intrinsic 21-cm signal, detected as a brightness-temperature fluctuation against the CMB, is at least four orders of magnitude smaller than the emission from our Galaxy. Other important foregrounds include radio recombination lines, terrestrial interference and ionospheric distortion. The hope is to separate the fluctuating spectral features due to 21-cm emission from the smooth spectrum of the foregrounds. Anyway, given the difficulties of high signal-to-noise imaging, attention has been focused on statistical measurements, like the power-spectrum analysis. First-generation facilities (as LOFAR and MWA, now under construction) should only detect a statistical signature of reionization. For a direct detection of the three-dimensional structure of HI and HII regions (the so called “21-cm tomography”) we will probably have to wait for a subsequent generation of radio arrays with much larger collecting area (e.g., SKA).

Are there other possibilities to directly detect the high-$z$ IGM in emission? Ly$\alpha$ is the strongest hydrogen emission line. This transition (from the 2P to the 1S level of atomic hydrogen) has a spontaneous emission coefficient $A_{21} = 6.25 \times 10^8$ s$^{-1}$. An efficient mechanism to populate the $n = 2$ level, with
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consequent Lyα emission, is the HII recombination process. Unfortunately, the recombination rate is typically very low and recombination radiation from optically thin hydrogen in the high-redshift IGM cannot be detected with current instruments (see e.g., Hogan & Weymann 1987; but also Baltz, Gnedin & Silk 1998).

As we discussed previously in this thesis, optically thick and self-shielded HI clouds exposed to strong UV radiation are expected to re-emit a significant part of the impinging flux in the form of “fluorescent” Lyα emission. However, self-shielded clouds correspond to overdense regions with relatively small sizes that may trace just a small fraction of the neutral hydrogen distribution during the EoR.

Under favorable conditions, the excitation of atomic hydrogen due to collisions with energetic electrons populates the \( n = 2 \) level in a much more efficient way than recombinations. In this Chapter, we show that the corresponding Lyα emission can be efficiently used to map the neutral hydrogen distribution during the EoR. This emission should be already detectable with current observational facilities and could be used to shed light on the bulk of neutral hydrogen during the EoR.

The layout of the Chapter is as follows. In §4.2 we summarize the basic physics of Lyα emission from recombination and collisional excitation processes. In §4.3 we show that collisional excitations should efficiently produce Lyα emission within the ionization fronts of high-redshift QSOs. We also explain how it is possible to map the distribution of neutral hydrogen behind the QSO using this emission. In §4.4 we present more sophisticated models of Lyα emission based on numerical simulations including a detailed treatment of radiative transfer. In §4.5 we discuss the dependence of our results on model parameters and possible detection strategies. Finally, in §4.6, we summarize our results. The reader who is not interested into the technical details of the model can safely read §4.5.2 right after §4.3 (focussing also on Figures 4.7 and 4.8).

Throughout this Chapter, we adopt a standard, flat ΛCDM cosmological model with mass-density parameter \( \Omega_m = 0.24 \), a baryonic contribution of \( \Omega_b = 0.044 \), and a present-day Hubble constant of \( H_0 = 100 \; h \; \text{km s}^{-1} \; \text{Mpc}^{-1} \) with \( h = 0.73 \). We also adopt the notation “pMpc” to indicate proper distances measured in Mpc.

4.2 The physics of Lyα emission

There are two main channels that drive the production of Lyα photons in the IGM: i) recombination processes and ii) collisional excitations by free
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electrons. Both mechanisms directly arise from the ionization of the hydrogen atom.

4.2.1 Lyα from recombinations

When an electron is captured by a free proton, it can either directly populate the ground 1\(^2\)S level (with the emission of a Lyman continuum photon) or an excited state from which it cascades by downward transitions to the 1\(^2\)S level (with the emission of a continuum photon plus several transition lines). Cascades that populate the 2\(^2\)P state decay to the 1\(^2\)S level by emitting a Lyα photon, while cascades to the 2\(^2\)S level subsequently decay via two-photon emission.

Electrons that populate \(n \geq 3\) levels may also decay to the ground state with the emission of another Lyman-series line (with no two-photon or Lyα emission). However, even in the low-density IGM, the typical Lyman-line emitting regions have quite large optical depths (∝) in the Lyman resonance lines (Osterbrock 1989). Therefore, a good approximation (unless the medium is fully ionized) is to assume that every Lyman-line photon from \(n \geq 3\) levels is converted into lower-series photons plus either Lyα or two-photon radiation (Case B approximation, Baker & Menzel 1938). In this case, it is convenient to write the effective Lyα emission coefficient from recombinations as:

\[
\alpha_{\text{Lyα}}^\text{eff}(T) = \epsilon_{\text{Lyα}}^B(T) \alpha_B(T),
\]

where \(\alpha_B(T)\) is the hydrogen total recombination coefficient excluding recombinations to the ground level, and \(\epsilon_{\text{Lyα}}^B(T)\) (≡ \(\epsilon_{\text{thick}}\)) is the fraction of those recombinations producing Lyα photons (see also section 2.2.4). Combining the tabulated values by Pengelly (1964; for \(T > 10^3\) K) and Martin (1988; for \(T < 10^3\) K), we have derived the following fitting formula for \(\epsilon_{\text{Lyα}}^B(T)\) (accurate to the 0.1% in the temperature range \(100\) K < \(T < 10^5\) K):

\[
\epsilon_{\text{Lyα}}^B(T) = 0.686 - 0.106 \log(T_4) - 0.009 \cdot (T_4)^{-0.44},
\]

where \(T_4 = T/10^4\) K. Note that the value of \(\epsilon_{\text{Lyα}}^B(T)\) varies very little with temperature, ranging between 0.68 and 0.61 for \(T_4 = 1 - 5\). The temperature dependence of \(\alpha_{\text{Lyα}}^\text{eff}(T)\) is shown in Figure 4.1 as a dashed line.

The volume Lyα emissivity due to radiative recombinations is given by:

\[
\frac{4\pi j_{\text{Lyα}}}{\hbar \nu_{\text{Lyα}}} = n_e n_p \alpha_{\text{Lyα}}^\text{eff}
\]

where \(j_{\text{Lyα}}\) is the emissivity (energy radiated per unit time, volume and solid angle), \(\hbar \nu_{\text{Lyα}} = 10.2\) eV is the energy of a Lyα photon and \(n_e, n_p\)
are, respectively, the electron and proton number densities. Note that the coefficient $\alpha_{\text{eff}}^{\text{Ly} \alpha}$ is independent from the assumption regarding the fate of Lyman-continuum photons. Wherever these photons are absorbed, and also in the case they escape the medium, the local values of $n_e$ and $n_p$ will change accordingly, modifying the Ly$\alpha$ emissivity.

### 4.2.2 Ly$\alpha$ from collisional excitations

Free electrons can interact one or more times with neutral hydrogen atoms before eventually recombining. Given the relatively low densities of the IGM, we can imagine the free electrons colliding with hydrogen in the ground state and transferring to it a fraction of their energy. If this energy (i.e., the electron temperature) is high enough, the collision will excite the atomic levels with subsequent decay via line emission. The efficiency of the process is strongly temperature dependent. In particular, the collisional excitation coefficient for the transition from the ground level (1) to the level $nl$ is given by:

$$ q_{1, nl} = \frac{8.629 \times 10^{-6} \Omega(1, nl) e^{-E_{1,n}/k_B T} \Omega(T)}{\omega_1} \Omega \text{cm}^3 \text{s}^{-1}, \quad (4.4) $$

where $\Omega(1, nl)$ is the temperature dependent effective collision strength, $\omega_1$ is the statistical weight of the ground state and $E_{1,n}$ is the energy difference between the ground and the $nl$ level. We define the effective collisional excitation coefficient for Ly$\alpha$ emission as:

$$ q_{\text{eff}}^{\text{Ly} \alpha} = q_{1,2p} + q_{1,3s} + q_{1,3d} \quad (4.5) $$

where we consider excitation processes up to the level $n = 3$ that will eventually produce Ly$\alpha$ radiation (in Case B approximation). The contribution from higher levels is completely negligible for the electron temperatures we are interested in. Similarly, we neglect angular-momentum-exchanging processes from proton and electron collisions (e.g., the 2s-2p and 2p-2s transition) that, in principle, might boost or suppress Ly$\alpha$ emission. The typical densities of the IGM are too low for these transitions to be important (Osterbrock 1989). We use the polynomial fits of Giovanardi, Natta & Palla (1987) to compute $q_{\text{eff}}^{\text{Ly} \alpha}$. The result is shown as a solid line in Figure 4.1.

The total Ly$\alpha$ emissivity coming from radiative recombinations and collisional excitations is thus given by:

$$ 4\pi j_{\text{Ly} \alpha} = n_e n_p \alpha_{\text{Ly} \alpha}^{\text{eff}} + n_e n_{\text{HI}} q_{\text{eff}}^{\text{Ly} \alpha}, \quad (4.6) $$
4.2. The physics of Lyα emission

Figure 4.1 Effective Lyα production rate from recombination processes ($\alpha_{Ly\alpha}^{\text{eff}}$, dashed line) and collisional excitations ($q_{Ly\alpha}^{\text{eff}}$, solid line) as a function of the gas (electronic) temperature.
4.3 Lyα emission from quasar ionization fronts during reionization

where \( n_{\text{HI}} \) is the neutral hydrogen density. Higher ionization fractions favour Lyα emission from radiative recombinations, while higher temperatures increase the contribution from collisional excitations provided that a significant fraction of hydrogen atoms remain neutral. Therefore, collisional excitation significantly contributes to the total Lyα emissivity in relatively hot regions where \( n_e \sim N_{\text{HI}} \), i.e. where the neutral fraction \( (x_{\text{HI}}) \) is about 0.5. In particular, if the temperature of these regions is in the range \( 2 - 5 \times 10^4 \) K, collisional excitation may increase the total Lyα signal of several orders of magnitudes with respect to radiative recombinations.

4.3 Lyα emission from quasar ionization fronts during reionization

The two requirements for efficient Lyα production via collisional excitation (\( T \sim a \text{ few} \times 10^4 \) K and \( x_{\text{HI}} \sim 0.5 \)) are met within the ionization fronts (I-fronts) produced by powerful UV sources with a hard spectrum (like QSOs) located in a mostly neutral IGM. An I-front constitutes the transition region between the inner HII zone and the outer (predominantly neutral) IGM. In this transition layer, the hydrogen neutral fraction varies by several orders of magnitudes within a length scale determined by the mean free path of the ionizing photons. The thickness of the I-front is generally negligible with respect to the characteristic radius of the HII region. Sources with harder spectra produce thicker I-fronts (for a given IGM density) because of the frequency dependence of the photo-ionization cross-section. If the I-front is not in photo-ionization equilibrium, ionization fractions evolve with time and the transition zone moves outward (the HII region expands). The propagation of the I-front produced by powerful UV sources like QSO can be highly relativistic, racing ahead of the hydrodynamic response of the ionized gas for the entire lifetime of the source (Shapiro & Giroux 1987).

4.3.1 A simple estimate of the Lyα signal

As shown in equation (4.6), the volume emissivity of Lyα radiation within the I-front depends on the electron, proton and HI densities, and on the local temperature. Detailed modelling of these quantities within an expanding I-front requires an accurate numerical solution of the radiative transfer problem and is postponed to the next section. However, we can give an order-of-magnitude estimate of the expected amplitude of the signal following a simple analytical reasoning.
4.3. Lyα emission from quasar ionization fronts during reionization

Let us assume that a bright QSO turns on at redshift $z_{in} > 6$, before the reionization process is complete, and produces a rapidly expanding I-front that completely ionizes the surrounding IGM. Let us further assume, for simplicity, that the IGM is at mean cosmic density, the hydrogen neutral fraction varies linearly (from 0 to 1) with distance within the thickness of the I-front, and that the I-front temperature is uniform. The actual value of the I-front temperature depends on the detailed balance between photoheating and cooling processes (see, e.g., Miralda-Escude & Rees 1994). In the following we estimate the expected Lyα signal for a given I-front temperature and medium density. Typical values for this temperature can be inferred from the far-UV spectral indices of QSOs (see e.g., Telfer et al. 2002) and lie in the range $2 - 4 \times 10^4$ K if the IGM is at mean cosmic density (see e.g., Abel & Haehnelt 1999). At these temperatures we can neglect Lyα emission due to radiative recombinations and write the integrated Lyα flux at the inner edge of the I-front as:

$$I_{Ly\alpha} \approx \frac{1}{\pi} \int_{1-\text{front}} n_{\text{HI}}(r)n_e(r)q_{\text{Ly}\alpha}(T)dr$$

$$\approx \frac{1}{\pi} n_H^2 C \chi_e \left(\frac{S}{6}\right) q_{\text{Ly}\alpha}(T), \quad (4.7)$$

where $C \equiv \langle n_H^2 \rangle / \langle n_H \rangle$ is the hydrogen clumping factor, $\chi_e$ the factor that accounts for the contribution of ionized helium to the electron density, and $S$ denotes the thickness of the I-front. The factor $1/6$ derives from the integration of $x_{\text{HI}}(1 - x_{\text{HI}})$ over the front, while the factor $1/\pi$ accounts for the angular distribution of the emitted photons (Gould & Weinberg 1996). The actual value of $S$ depends on several factors, including the spectrum of ionizing radiation $F_\nu$ and the local density. As a first-order approximation, we can assume that the size of the I-front is given by the mean free path of the ionizing photons with mean frequency $\langle \nu \rangle = \int_{\nu_0}^{\infty} F_\nu d\nu / \int_{\nu_0}^{\infty} (F_\nu / h_\nu) d\nu$ (with $\nu_0$ the hydrogen ionization threshold and $h_\nu$ the Planck constant), i.e. $S \simeq (n_H \sigma_{\nu})^{-1}$, where $\sigma_{\nu}$ is the (frequency dependent) photo-ionization cross-section. Substituting $S$ in equation (4.7), replacing the hydrogen density with $n_H = n_{H,0}(1 + z)^3$ (where $n_{H,0}$ is the comoving mean number density), and including the redshift dimming, we obtain the observed integrated surface brightness (SB) in photons:

$$\Phi_{Ly\alpha} \approx f_{\text{esc}} C \chi_e n_{H,0} q_{\text{Ly}\alpha}(T) / \sigma_{\nu} \quad (4.8)$$

The appropriate scaling relations based on other parameters, like the QSO age, ionizing rate and local overdensity will be derived in §4.5.
4.3. Lyα emission from quasar ionization fronts during reionization

where $f_{\text{esc}}$ is the fraction of Lyα photons that manage to escape from the I-front along the line of sight. Remarkably, the observed SB (in photon number) does not depend on the QSO redshift for a given temperature of I-front.

How strong is this signal? The exact value of $f_{\text{esc}}$ is difficult to estimate as it depends on several factors, including the size of the HII region and the value of the residual HI in proximity of the I-front. Detailed calculations (see §4.4) suggest that $f_{\text{esc}} \sim 0.5$. Typical values of the clumping factor at $z > 6$, estimated from simulations (e.g., Gnedin & Ostriker 1997), are of order of $C \sim 30$. Therefore, assuming $\langle \nu \rangle \simeq 3 \nu_0$, $\chi_e = 1.2$ and fixing the temperature to $T \simeq 3 \times 10^4$ K, we obtain:

$$\Phi_{\text{Lyα}} \simeq 200 \text{ photons s}^{-1} \text{ cm}^{-2} \text{ sr}^{-1},$$

(4.9)

at the top of Earth’s atmosphere, or, equivalently:

$$SB_{\text{Lyα}} \simeq 10^{-20} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ arcsec}^{-2},$$

(4.10)

for a QSO at $z \sim 6.5$.

Although much fainter than the limit fluxes of present-day surveys for Lyα emitters at $z \sim 6.5$ ($\sim 10^{-18}$ erg s$^{-1}$ cm$^{-2}$ for apertures of order of few arcsec$^2$; Tran et al. 2004; Kashikawa et al. 2006), the emitting region can cover several hundred comoving Mpc$^2$. This corresponds to several hundred arcmin$^2$ on the sky at $z \sim 6.5$ and makes the signal detectable with current facilities by means of moderately-high resolution spectroscopy.

Observations of this emission would provide direct evidence for the presence of an I-front, shedding light on the properties of both the ionizing source and the surrounding medium. In particular, as we will show in §4.5, the angular shape of the apparent I-front can constrain the QSO age and its angular emission properties.

4.3.2 Lyα map of the HI distribution during reionization

Detecting the Lyα emission from the I-front makes it possible to directly map the distribution of neutral hydrogen behind the QSO at the location of the I-front. In fact, the distribution of the Lyα signal on the sky traces the local density of HI as it was before the arrival of the I-front. We will illustrate this with a simple example. Let us consider two patches of the IGM (at mean

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3The detectability of this signal with present and future instruments will be discussed in §4.5.2.
4.4 Modelling the Ly$\alpha$ signal

density) that are simultaneously reached by the QSO I-front. Right before
the arrival of the front, one of them is still neutral ($x_{\text{HI}}^a = 1$) and the other
is significantly ionized ($x_{\text{HI}}^b < 0.1$) by a local faint source. Let us further
assume that the local source in the second region has a softer spectrum than
a QSO and thus that the (initial) temperature of the free electrons is low,
$T \lesssim 10^4$ K. While the I-front crosses the two regions, energetic electrons
are released by hydrogen atoms and collisional excite the remaining neutral
hydrogen. The Ly$\alpha$ emissivity reaches a maximum at the center of the I-front
where the actual neutral fraction is about $0.5x_{\text{HI}}$ and the temperature peaks.
However, the mean energy of the free electrons and the number density of
neutral-hydrogen atoms in the second region are both reduced by a factor
$x_{\text{HI}}^a/x_{\text{HI}}^b > 10$ with respect to the first region: the Ly$\alpha$ emissivity is thus
reduced by more than a factor of 100.

A schematic description of how this effect can be used to map the HI
distribution is shown in Figure 4.2 for a uniform IGM. The locally ionized
regions will appear as “holes” in the 2-dimensional Ly$\alpha$ map. Given the
large angular extension of the HII region, mapping the Ly$\alpha$ emission from
the I-front behind a high-redshift QSO can effectively constrain the topology
and the history of the reionization process.

4.4 Modelling the Ly$\alpha$ signal

The rate equations that regulate the temperature and the ionization-fraction
profiles inside the expanding I-front cannot be solved analytically. These
quantities depend on the local ionizing spectrum that is determined by non-
local radiative-transfer (RT) effects. For instance, higher energy photons will
be absorbed at higher column densities, causing an effective hardening of the
ionizing spectrum at larger distances from the source. Therefore, detailed
modelling of the Ly$\alpha$ emissivity requires a full RT transfer calculation for
the ionizing radiation.

4.4.1 Continuum Radiative Transfer

To follow the radiative transfer of the continuum ionizing radiation from the
QSO, we use a three-dimensional, photon-conserving, and time-dependent
code based on a ray-tracing algorithm (see Appendix A). This code has been

\footnote{This strictly applies to young QSOs with I-fronts that are expanding at ultrarelativistic
speeds. For older QSOs, the front will move faster in the regions pre-ionized by other local
sources and will produce bright Ly$\alpha$ emission from the entire (irregular) boundary of the
HI region.}
Figure 4.2 This schematic cartoon illustrates how to map the HI distribution using the Ly$\alpha$ emission from the I-front of an high-z QSO. The QSO and the observer are on the left side. The ionizing photons, in the plane of the figure, propagate from left to right and create an I-front wherever they encounter a partially neutral region. Within the I-front, the interactions between neutral hydrogen and the energetic electron released by photo-ionization produce Ly$\alpha$ photons via collisional excitation (yellow stripes). The Ly$\alpha$ emission escapes the I-front through the HII region in the direction of the observer. The regions already ionized by local sources (bounded by the dashed lines) do not produce Ly$\alpha$ via collisional excitations and will appear as holes in the 2-D Ly$\alpha$ map, similarly to a 21-cm tomography. This strictly applies to a young QSO with a relativistically expanding I-front. For older quasars, the entire boundary of the HI region can emit Ly$\alpha$ photons.
4.4. Modelling the Lyα signal

developed to study the propagation of I-fronts in cosmological simulations and it includes an adaptive refinement scheme of the computational grids (in space and time) on the front. Among other features, it accounts for the presence of multiple ionizing sources and for the propagation of ionizing radiation produced by recombinations. The time-dependent rate equations include the evolution of HI, HeI and HeII. The gas temperature is computed including the energy input due to photoionizations and collisional ionizations of the three species and all the relevant cooling processes (recombinations, collisional excitations/ionizations, dielectronic recombination of HeII, bremsstrahlung, Compton and Hubble cooling).

For simplicity, in the present study, we consider a single (steady) ionizing QSO surrounded by a uniform (cosmologically expanding) medium. We follow the evolution of the I-front over a few $10^8$ yr, i.e up to distances of 70-140 comoving Mpc from the source (depending on the QSO luminosity). The adaptive mesh refinement (AMR) scheme allow us to resolve the I-fronts with a large number of (optically-thin) cells of a few comoving kpc at all times. A more general configuration based on the density and velocity fields extracted from a hydro-dynamical simulation will be analyzed in future work.

4.4.2 Finite light-travel time effects

High-redshift QSOs are expected to produce relativistically expanding I-fronts for an important fraction of their lifetime (Shapiro et al. 2006). This is difficult to follow with most RT codes (see Iliev et al. 2006 for a recent compilation), including our own, in which the ray-tracing algorithm assumes an infinite light speed and ionization fronts tend to propagate faster than light at early times. A quick fix is obtained by limiting the ray-tracing up to a maximum distance but this would lead to the loss of photon conservation. We thus decided to follow a novel approach. For a steady ionizing source in a uniform medium, the correct speed of the I-front at a given radius, $v_I(r_1)$, can be expressed in terms of its counterpart obtained assuming an infinite speed of light, $v_{I,NR}(r_1)$, by the relation

$$v_I(r_1) = \frac{v_{I,NR}(r_1)}{1 + v_{I,NR}(r_1)/c},$$

regardless of the difference in physical times at which the I-front reaches the radius $r_1$ (White et al. 2003; Yu 2005; Shapiro et al. 2006). Therefore, we can get the correct velocity of the I-front by redefining the time variable as follows. We associate to each time step used in the radiative transfer code $\Delta t_{NR}$ an actual time step $\Delta t_R$ simply given by:

$$\Delta t_R = \Delta t_{NR}(1 + v_{I,NR}/c).$$

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Note that this is an approximate solution, since the optical depth of the photons is still computed at the time of their emission and does not take into account the changes taking place in the medium during their propagation time.

4.4.3 The apparent evolution of the I-front

The observed shape of the I-front (i.e. the relation between the QSO age, $t$, and the I-front distance from the QSO, $r_I(t)$, as a function of the viewing angle $\theta$ defined in Figure 3) will differ from the proper shape because of finite light-travel effects (see equations (1)-(3) in Yu 2005). In fact, the photons we receive from the part of the I-front that is moving towards us travel a smaller distance than the photons emitted behind the quasar.

In Figure 4.4, we show the time-evolution of the apparent I-front position for three different values of $\theta$ and $\langle x_{\text{HI}} \rangle$ (the mean neutral fraction of the medium surrounding the ionization source before the latter turns on). This is the output of a simulation where a luminous QSO (with a total ionizing rate $\dot{N}_\gamma = 10^{57}$ ph s$^{-1}$, and far-UV energy spectral index $\alpha = -1.7$) turns on at $z_{in} = 6.5$ in an uniform medium at mean density with a clumping factor $C = 35$. This parameter set is consistent with observations of QSOs showing a GPT at $z > 6$ (Yu & Lu 2005). From now on, the evolution of the I-front in a fully neutral medium ($\langle x_{\text{HI}} \rangle = 1$) surrounding this source will constitute our reference model.

The time-evolution of the I-front position obtained from our code is in good agreement with the approximate analytical solution by Yu (2005) and Shapiro et al. (2006). For a given QSO ionizing rate, the apparent position of the I-front closest to the observer (red short-dashed line in Figure 4) is very sensitive to both the QSO age and $\langle x_{\text{HI}} \rangle$. This is not the case for the apparent position of the Ly$\alpha$ emitting I-front behind the QSO (blue long-dashed line in Figure 4), that determines fairly well the QSO age (at least for $\langle x_{\text{HI}} \rangle \gtrsim 0.1$). Combining the information from the Ly$\alpha$ emitting I-front and the position of the GPT in the QSO spectrum, we can significantly constrain both the QSO age and $\langle x_{\text{HI}} \rangle$.

At any given time, it is useful to define the “contact” radius ($R_t$) as the position where the I-front closest to the observer ($\theta = 0$) is reached by the photons emitted by the I-front behind the quasar ($\theta = \pi$). This quantity determines the strength of the damping-wing absorption for the observed Ly$\alpha$ signal from the I-front at $\theta = \pi$. The evolution of the contact radius for our reference model is shown in the bottom right panel of Figure 4.4. Note that $R_t$ keeps nearly constant at early times and grows afterwards. Therefore, even when the rest-frame radius of the HII region is extremely...
Figure 4.3 Schematic view of the apparent I-front shape (solid line) around an isotropically emitting QSO. The dotted circles represent the I-fronts in the QSO rest-frame at different epochs. The departure from the spherical shape is due to the relativistic expansion speed of the I-front combined with finite light-travel effects. The apparent shape is rotationally symmetric along the quasar line of sight. The positions of the apparent and rest-frame I-front coincide for $\theta = \pi/2$, while the apparent expansion of the I-front at $\theta = 0$ is superluminal.
Figure 4.4 Time-evolution of the apparent I-front distance from the QSO (in physical Mpc) as a function of the angle \( \theta \) (defined as in Figure 4.3) and the mean neutral fraction of the environment \( \langle x_{\text{HI}} \rangle \) (measured before the arrival of the I-front) obtained with our radiative transfer code including finite light-travel effects. Dotted lines are for reference and indicate propagation at the speed of light (black) and \( \propto t^{1/3} \) (red). The bottom right panel shows the evolution of the “Contact” radius, i.e. the position where the I-front closest to the observer (\( \theta = 0 \)) is reached by a photon emitted by the I-front behind the quasar (\( \theta = \pi \)). Note that the apparent \( \theta = \pi/2 \) and the rest-frame I-front expansions are identical. All the panels assume a QSO that turns on at \( z_{\text{in}} = 6.5 \) with total ionizing rate \( \dot{N}_\gamma = 10^{57} \text{ ph s}^{-1} \), far-UV spectral index \( \alpha = -1.7 \), and a clumping factor \( C = 35 \). These parameters are compatible with observed QSOs showing a Gunn-Peterson trough at \( z > 6 \) (Yu & Lu 2005).
small, the Ly$\alpha$ photons produced behind the QSO (and emitted towards us) will encounter the edge of the ionized bubble when it has grown up to a much larger scale, substantially reducing the damping wing absorption.

### 4.4.4 Ly$\alpha$ emissivity from the I-front

Using the time evolution of the I-front derived in the previous section, we want now to compute the Ly$\alpha$ signal produced at given distance (or, equivalently, QSO age) from the central source.

In Figure 4.5 we show the temperature and ionization profiles for our reference model at two different epochs in the QSO rest-frame. At early times (left panel), the HII/HI transition is very sharp and the temperature (red, long-dashed line) slowly decreases going outwards until it suddenly drops down in the neutral region. In particular, there is a small peak in the temperature profile at the position of the I-front ($x_{\text{HI}} \sim 0.5$, where $T \sim 3 \times 10^4$ K) due to the radiative transfer effects that increase the hardness of the ionizing spectrum. The HeII region extends outward of the HII zone, contributing to the free electron density (blue dotted line) and to the temperature. At later stages (right-panel), the HII/HI transition is less sharp and the inner HII region is colder, $T \sim 10^4$ K. However, the temperature peak at the I-front is more pronounced, reaching a value of $T \sim 2 \times 10^4$ K. The HeIII region is now well inside the HII zone, with an important effect on the temperature profile (note the temperature drop at $\sim 3$ pMpc).

In Figure 4.6 we show the evolution of the Ly$\alpha$ emissivity from collisional excitations (black solid line), and radiative recombinations (blue, short-dashed line). As expected, Ly$\alpha$ photons generated by collisional excitations are only produced on the I-front, while those produced by radiative recombinations are emitted within the entire HII region. Photons from collisional excitations dominate the total Ly$\alpha$ emissivity, but their contribution diminishes with time as a consequence of the decreasing I-front temperature (red long-dashed line).

### 4.4.5 Ly$\alpha$ Radiative Transfer

The density of neutral hydrogen within the I-front is high enough to make the medium extremely optically-thick ($\tau_{\text{Ly}\alpha} \gtrsim 10^4$ at the line center) to the Ly$\alpha$ photons generated via collisional excitations. Moreover, the residual neutral hydrogen along the line of sight may substantially change the observed Ly$\alpha$ line shape and flux. A numerical treatment of the transfer of resonant line radiation is required to fully account for these effects. We thus compute the observed properties of the Ly$\alpha$ emission from both collisional excitations and
4.4. Modelling the Ly$\alpha$ signal

Figure 4.5 Radial (rest-frame) temperature and ionization profiles for our reference model at two different expansion epochs. Solid, dotted and dash-dotted lines respectively show the HI, HeII and HeIII fractions. The long-dashed line indicates the temperature expressed in units of $T_5 = (T/10^5 \text{ K})$. The short-dashed line represents the ratio $n_e/n_{\text{HI}}$ which is larger than 1 inside the HII region because of the contribution of partially or totally ionized Helium. Note that the scales and the x-ranges of the two plots are very different.
4.4. Modelling the Lyα signal

Figure 4.6 Lyα emissivity from collisional excitations (black solid line) and recombinations (blue short-dashed line) for our reference model at different expansion epochs of the QSO I-front. For reference, we also show the evolution of the temperature profiles (red long-dashed line).
4.4. Modelling the Lyα signal

radiative recombinations using an updated version of the three-dimensional Lyα Monte Carlo code presented in Chapter 2. In particular, the new version includes two improvements. First, it uses a more precise (and computationally less expensive) analytical fit of the Voigt-Hijertig function proposed by Tepper-Garcia (2006). Second, it performs the line transfer in a medium with a spatially varying temperature. The presence of temperature gradients not only changes the Lyα emissivity but also the shape of the absorption cross-section and thus the scattering process. In particular, a Lyα photon generated in a region with high temperature can more easily penetrate a colder zone before getting eventually absorbed. Thus, the photons produced in the (warm) I-front will diffuse more in the neutral (cold) region than expected for a single-temperature medium.

Given the small thickness of the I-front compared with the radius of the HII region, we can work in the plane-parallel approximation. In the absence of Hubble expansion and assuming no absorption from residual HI in the ionized region, the Lyα spectrum emerging from the I-front would be characterized by the symmetric, double-peaked emission typical of plane-parallel, uniform-density media (e.g., Neufeld 1990). In this case, Lyα photons would be emitted with a cosine law over a net solid angle of \(\pi\) (see e.g., Gould & Weinberg 1996). However, both the Hubble expansion and the presence of residual HI increase the number of scatterings for the photons in the blue peak which are then absorbed and re-emitted over a wider solid angle and frequency interval. The net effect is a suppression of the blue peak in the spectrum. The strength of this suppression depends on the residual HI fraction and, therefore, on the I-front distance from the QSO (or, equivalently, on the QSO age). In most cases, the HI residual fraction is high enough to erase the blue peak. On the other hand, the damping wing absorption from HI lying outside the ionized region only reduces the Lyα line flux by a few per cent at all epochs (without altering the line-shape).

In the left panel of Figure 4.7, we show the evolution of the observed Lyα spectra obtained from the I-front profiles and emissivities presented in Figure 4.6. At early stages, the blue peak is still detectable but, in general, it is strongly suppressed. Therefore, the emission consists of a single redshifted peak with an asymmetric tail on the red side (i.e., towards the direction of the cold neutral gas). The broadening of the observed peak is significant compared with the sharpness of the emissivity in Figure 4.6. Both the suppression of the blue-peak and the damping-wing absorption from external HI reduce the integrated surface brightness with respect to the static,

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5This neglects peculiar velocities that, in general, modify the spectral shape of either the red or the blue peak, as shown in Chapter 2.
4.4. Modelling the Ly$\alpha$ signal

Figure 4.7 Spectral evolution of the Ly$\alpha$ emission from the expanding I-front (behind the QSO) for our reference model. The different lines correspond to the five different epochs for which the emissivities are shown in Figure 4.6. The spectra have been obtained with our Ly$\alpha$ RT code for a non-relativistic front (left) and including relativistic expansion (right). Absorption by (residual) HI along the line of sight is included.

plane-parallel case. Our simulation suggests that the observable integrated SB roughly corresponds to 58 per cent of the ideal case (solid line in Figure 4.8).

4.4.6 Ly$\alpha$ Radiative Transfer and Relativistic I-fronts

In the previous section we treated the I-front as static, i.e. we assumed that the Ly$\alpha$ photons leave the I-front on a time scale which is short with respect to the characteristic ionization time of the IGM. This assumption, however, is not valid for young QSOs when the I-front expansion is ultra-relativistic. In this case, as the Ly$\alpha$ photons scatter, the medium becomes optically thinner and the optically-thick edge of the I-front moves outward. If the I-front speed is close to the speed of light, the Ly$\alpha$ photons find themselves inside the HII region after few scatterings. Once there, they will be scattered over a wider solid angle (4$\pi$ at maximum) with respect to the semi-infinite slab case. Therefore, ultra-relativistic I-fronts should emit a Ly$\alpha$ flux which is reduced by up to a factor of 4 with respect to the static plane-parallel emission and up to a factor of 2 with respect to the non-relativistic case discussed in the
4.5 Discussion

The parameters of the ionizing source in our reference model have been chosen based on observations of QSOs showing a GP trough at \( z \sim 6 \). In this case, the Ly\( \alpha \) SB produced by the I-front which propagates within a neutral patch of the IGM at mean density always lies between \( 10^{-21} - 10^{-20} \) erg s\(^{-1}\) cm\(^{-2}\) arcsec\(^{-2}\) (see Figure 4.8). How does the Ly\( \alpha \) SB change with varying the QSOs and the surrounding medium properties? Moreover, what is the redshift dependence of our results? In order to answer these questions, we performed a series of simulations in which we kept fixed all the parameters of the reference model but one. The resulting SBs (for a neutral patch of the IGM at mean density) are shown in Figure 4.9. In each panel, we indicate on the top-left the varying parameter (see caption for details) and the reference model is always represented by the black solid line. The SB is obtained from the integrated emissivity and corrected for absorption and RT effects, as described in §4.4. The correction for the relativistic I-front expansion in the Ly\( \alpha \) RT is not included. However, as shown in §4.4.6, the decrease in the integrated SB is at maximum a factor of 2 when the expansion is ultra-relativistic and it is negligible at later stages.

From the top-left panel in Figure 4.9, we notice that, for a given QSO age, \( t_Q \), the expected Ly\( \alpha \) SB is roughly proportional to \( N_\gamma^{1/3} \), unless the I-front expansion is still ultra-relativistic (i.e. \( t_Q \lesssim 5 \) Myr for our reference model). Note that this corresponds to a linear scaling with the ionizing flux at the I-front position. After the ultra-relativistic period, and before recombinations
Figure 4.8 Integrated Ly\(\alpha\) SB of the expanding I-front (behind the QSO) of our reference model at different expansion epochs, as obtained by our Ly\(\alpha\) RT simulations (solid circles). The dashed line represents the expected SB from a plane-parallel (and optically thick) medium given by the integrated Ly\(\alpha\) emissivity inside the I-front (\(SB_{\text{Ly}\alpha}^{\text{pp}}\)). The solid line represents \(0.58 \times SB_{\text{Ly}\alpha}^{\text{pp}}\). Finally, the solid triangles show the result of our Ly\(\alpha\) RT that includes the effect of the I-front relativistic expansion (see text for details).
Figure 4.9 Expected Lyα Surface Brightness produced by the QSO I-front as it crosses an initial neutral region of the IGM at mean density. In each panel, the reference model (i.e., total ionizing rate $\dot{N}_\gamma = 10^{57} \, \text{ph s}^{-1}$, far-UV spectral index $\alpha = -1.7$, initial redshift $z_{in} = 6.5$, clumping factor $C = 35$) is represented by the black solid line. The effect of the variation of one parameter with respect to the reference model is shown in each panel with the red dotted and the blue dashed lines representing, respectively: $\dot{N}_\gamma = 10^{56}$ and $\dot{N}_\gamma = 10^{58}$ (upper-left panel); $\alpha = -2.5$ and $\alpha = -1.0$ (upper-right panel); $C = 20$ and $C = 50$ (bottom-left panel); $z_{in} = 8$ and $z_{in} = 10$ (bottom-right panel). The corresponding SB for a region with initial neutral fraction $x_{HI}$ and overdensity $(1 + \delta)$ will scale approximately like $x_{HI}^2 (1 + \delta)^{1/2}$ (see text for details). Note that the observed SB at very early stages (e.g., $t_Q \lesssim 5$ Myr for the reference model) may be substantially lower than the values shown in the figure because of the high-relativistic expansion of the I-front (see text for details).
4.5. Discussion

start to play a significant role, the time evolution of the Ly$\alpha$ SB is well represented by a power law (SB $\propto t_Q^{-1}$) independently of the QSO luminosity. The slope of the power law is mainly determined by the spectral index of the QSO spectrum (see top-right panel in Figure 4.9), as expected by the strong temperature dependence of the collisional-excitation rate. In particular, we found that the SB evolves proportionally to $t_Q^{-(\alpha+2.7)}$. Varying the clumping factor ($20 < C < 50$) has little effect on the SB evolution (bottom-left panel in Figure 4.9). This is because the increase in the collisional excitation rate due to a more clumpy medium is partially balanced by the fact that the medium becomes colder (mainly because of the cooling from collisional excitations themselves). This self-regulation is more efficient as the I-front slows down.

Finally, in the bottom-right panel of Figure 4.9, we show that the expected SB$_{\text{Ly}\alpha}$, for a given $t_Q$, decreases proportionally to $(1+z)^{-2}$ (instead of $(1+z)^{-1}$ as expected for a medium with fixed temperature, see §4.3.1). Note that, in order to evidence this relation, the y-axis of the figure has been properly normalized.

In the models discussed so far we only considered the Ly$\alpha$ SB generated within a neutral patch of the IGM at mean density. As we already shown in §4.3, the expected emission is proportional to the square of the initial neutral fraction ($x_{\text{HI}}$) (i.e., the medium neutral fraction before the arrival of the I-front). In order to estimate how the expected SB changes with the local overdensity ($\delta \equiv (\rho - \rho_0)/\rho_0$), we performed a series of simulations placing slabs with different values of $(1+\delta)$ at a given distance from the QSO. We found that, in overdense regions ($\delta \lesssim 50$), the expected Ly$\alpha$ SB is nearly proportional to $(1+\delta)^{1/2}$. In summary, assuming $20 \lesssim C \lesssim 50$, the Ly$\alpha$ SB produced by a QSO I-front is of the order of:

$$SB_{\text{Ly}\alpha} \sim 10^{-20} \cdot x_{\text{HI}}^2 (1+\delta)^{1/2} \cdot \left[\frac{t_Q}{10\text{Myr}}\right]^{-1} \times \left[\frac{\dot{N}_\gamma}{10^{57}\text{s}^{-1}}\right]^{1/3} \left[\frac{1+z}{7.5}\right]^{-2} \text{erg s}^{-1}\text{cm}^{-2}\text{arcsec}^{-2}, \quad (4.13)$$

for $\alpha \simeq -1.7$, $5 \lesssim t_Q \lesssim 100$ Myr, and $\delta \lesssim 50$. Note, however, that QSOs with harder ionizing spectra ($\alpha \simeq -1$) produce significantly brighter I-fronts (blue dashed line in Figure 9).

We do not consider here the Ly$\alpha$ SB produced within more overdense regions. In this case, a proper treatment should also consider hydrodynamical effects. Fluorescent Ly$\alpha$ emission from overdense ($\delta > 100$) regions could be as bright as the I-front emission at mean density. However, these dense
regions will appear significantly more compact. An extensive study of the Ly\(\alpha\) emission produced by overdense regions and the effect of IGM inhomogeneities will be presented in a future work.

### 4.5.1 Uncertainties and limitations

For very young QSOs, when the expansion-speed of the I-front (\(v_I\)) is very close to the speed of light, our model might overestimate the actual Ly\(\alpha\) emission. In this case, the photo-ionization time scale (\(t_{\text{ion}}\)) at the I-front (roughly given by \(t_{\text{ion}} \sim S/v_I\), where \(S\) is the I-front thickness) can be shorter than the collisional-excitation time scale \(t_{\text{CE}} \sim (Cn_{\text{HI}}q(T))^{-1}\). In our reference model, this effect is important for \(t_Q \lesssim 5\) Myr (and earlier at higher redshifts). In overdense regions the I-front is slower and collisional excitations are faster with respect to the IGM at mean density. Therefore, the Ly\(\alpha\) emission produced in these regions is less sensitive to this effect. On the other hand, I-fronts expanding around young quasars lie very close to the source. For instance, the I-front behind a bright QSO at \(z \sim 6.5\) with \(t_Q \sim 5\) Myr appears at a proper distance of 1 Mpc (see Figure 4.4). If the opening angle of the QSO emission cone is \(45^\circ\) (with respect of the line of sight), the total projected area covered by the I-front will extend over \(\sim 12\) arcmin\(^2\) (or \(\sim 60\) arcmin\(^2\) if the quasar emits isotropically). Therefore, older QSOs provide a larger projected area for detecting the I-front emission and a better constraint on the properties of both the quasar emission and the surrounding IGM. Moreover, older and luminous QSOs produce HII bubbles that are larger than possible pre-existing ionized regions generated from clustered star-forming galaxies.

Our RT simulations do not consider X-ray radiation produced by the QSO. However, X-ray photons travel unimpeded well beyond the position of the emitting I-front and do not modify the properties of the Ly\(\alpha\) signal. In the presence of pre-existing X-ray background, the initial gas temperature will be higher than assumed in our models (\(T \sim 100\) K) and this will slightly increase the Ly\(\alpha\) emission from collisional excitations (provided that the medium is still significantly neutral before the arrival of the I-front).

For simplicity, we have assumed a steady ionizing emission rate for the quasars. We also did not account for the possible contribution of other local sources that can change the apparent shape of the QSO I-front and the properties of the surrounding medium (see e.g., Yu 2005; Yu & Lu 2005; Wyithe & Loeb 2007; Lidz et al. 2007). Addressing these effects requires performing high-resolution RT within a fully cosmological simulation and is beyond the scope of the present study.
4.5.2 Detectability

To date, eight QSOs have been detected at redshift $z > 6.1$ (Fan et al. 2003, 2004; Willot et al. 2007) and all of them have significant ($\Delta z > 0.1$) dark absorption troughs in their spectra in proximity of the QSO redshift. Although this is not necessarily evidence for a surrounding neutral medium, these objects represent the best targets for detecting the I-front Ly$\alpha$ emission.

Let us take, as a practical example, the case of QSO J1148+5251. This quasar has the most accurate redshift measurement ($z = 6.419 \pm 0.001$, Walter et al. 2003) and shows complete Ly$\alpha$-Ly$\beta$ troughs corresponding to an apparent proximity region of $R_s \sim 5$ physical Mpc (Wyithe et al. 2004, Yu & Lu 2005). Assuming that the medium surrounding the QSO was still significantly neutral ($\langle x_{\text{HI}} \rangle > 0.1$) before the QSO turned on, from the estimated ionizing rate ($N_{\gamma} \sim 2 \times 10^{57}$ ph s$^{-1}$, see e.g., Yu & Lu 2005) we expect $8 \lesssim t_Q \lesssim 30$ Myr (see Figure 4.4). This corresponds, for a QSO spectral index $\alpha = -1.7$, to $0.5 \lesssim SB_{\text{Ly} \alpha} \lesssim 1.5 \times 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$ (see equation (4.13) and Figure 4.9) for a neutral patch of the IGM at mean density.

Is this signal detectable? Although faint (about 3 orders of magnitude below the sky background), the expected emission may extend over a projected area on the sky up to a few hundred square arcmin. By means of moderately-high resolution spectroscopy ($R=1000-3000$) and integrating the signal over a fraction of the slit length, single neutral patches of the IGM (even at mean density) can be already detected from the ground with current facilities and long integration times ($T \sim 40$ hr) if they extends over few arcminutes scales (or smaller for slightly overdense regions). For instance, the expected signal-to-noise ($S/N$) ratio corresponding to the above example and for a ground-based observation (in the atmospheric window at $\sim 0.9 \mu m$) will be of the order of:

$$S/N \sim 7 \times C_t \left[ \frac{D}{8 \text{ m}} \right] \left[ \frac{\zeta}{0.8} \right] \left[ \frac{f}{0.25} \right]^{1/2} \times \left[ \frac{\Delta s}{3 \Lambda} \right]^{-1/2} \left[ \frac{T}{40 \text{ hr}} \right]^{1/2} \left[ \frac{\Delta \Omega}{180 \text{ arcsec}^2} \right]^{1/2}, \quad (4.14)$$

where $C_t$ is the slit covering factor (i.e. the fraction of the slit where the Ly$\alpha$ emission is present), $D$ is the telescope diameter, $\zeta$ the atmospheric transmission, $f$ the system efficiency, $\Delta s$ the spectral bin, $T$ the integration time and $\Delta \Omega$ the area of the sky covered by the slit. For a slit width of 1", the above $S/N$ implies that we can detect a single neutral patch of the IGM (i.e., $C_t = 1$) at mean density if it has at least a linear size of $l \sim 3'$ (corresponding to $\sim 1$ pMpc at $z \sim 6.4$).
4.6 Summary

Even if single neutral patches cannot be detected, a proper integration over the total slit length (that can be substantially increased, for instance, using a multi-slit plus filter technique, see Chapter 3) may reveal at least the position of the Ly\(\alpha\) emitting I-front. Once the I-front has been located, we can use its apparent distance from the QSO to determine the QSO age and to constrain the value of \(\langle x_{\text{HI}} \rangle\) (see Figure 4). Possible limitations are given by the unknown opening angle of the QSO emission (that can reduce the projected area over which the I-front may extend) and the difficulties of subtracting the sky lines.

A significant improvement is expected from the next generation of space telescopes like JWST, although the background (i.e., the Zodiacal light) will still be 2 orders of magnitude brighter than the expected signal. With JWST, we will be able to detect single neutral patches of the IGM on smaller scales than allowed from the ground. Moreover observations will not be limited to the narrow redshift ranges permitted by the atmospheric windows. For a given QSO age, the Ly\(\alpha\) SB decreases proportionally to \((1 + z)^2\) (instead of the usual \((1 + z)^4\)). The next generation of space telescopes will thus be able to map HI distribution during the EoR in a broad redshift range.

4.6 Summary

We have presented a new method to directly map the neutral hydrogen distribution during the reionization epoch, and to measure the age of the highest-redshift QSOs. We have shown that collisional excitations are an efficient mechanism to produce Ly\(\alpha\) photons, even in the low density IGM, provided that nearly 50 per cent of the hydrogen is neutral and the local temperature is as high as \(T \gtrsim 2 \times 10^4\) K. These conditions are achieved within the I-fronts produced by luminous UV sources, like QSOs, as they expand into the surrounding IGM. The observable Ly\(\alpha\) photons are those emitted by the I-front behind the QSO (with respect to the observer). These photons can cross the large HIII region lying in front of their emission point without being significantly scattered. The emerging signal traces the HI distribution at the location of the QSO I-front (similarly to future 21-cm tomography) since the expected SB roughly scales as the square of the (initial) local HI fraction. The angular distribution of the Ly\(\alpha\) emission and its distance from the QSO constrains both the properties of the source (i.e. the QSO opening angle and age) and of the surrounding medium (i.e., the average neutral fraction).

Using detailed radiative transfer simulations that include finite light-speed effects, we have shown that the expected emission appears as a single (broad) line with a width of 100 – 200 km s\(^{-1}\). The Ly\(\alpha\) SB of a typical
QSO I-front that propagates at $z_Q = 6.5$ within a fully neutral patch of the IGM at mean density lies in the range $SB_{Ly\alpha} \sim 10^{-21} - 10^{-20}$ erg s$^{-1}$ cm$^{-2}$ arcsec$^{-2}$. QSOs with very hard spectra ($\alpha \sim -1$) produce a significantly brighter signal at early phases ($t_Q \lesssim 10$ Myr). Interestingly, for a given QSO age, the Ly$\alpha$ SB of the I-front scales as $(1 + z_Q)^{-2}$.

The signal from neutral patches of the IGM extending over a few arcmin scales is already detectable by current ground facilities with the use of moderately/high resolution spectroscopy. The next generation of space and ground based telescopes will allow us to draw high signal-to-noise maps of the HI distribution with higher angular resolution. Combining this information with a measure of the I-front position, we will be able to simultaneously constrain the reionization history and the emission properties of the highest-$z$ QSOs.
4.6. Summary
Concluding remarks and future prospects

Almost fifty years passed from the first attempt to detect and prove the existence of a medium between the galaxies (Field, 1959). Since then, the study of the Intergalactic Medium has made large progresses, becoming one of the most important and active field in modern cosmology. The origin of this progress is mostly due to the improvement in the observing facilities, while the basic technique to detect the IGM – absorption studies – has remained almost the same since it was first proposed by Gunn & Peterson (1965). Absorption studies allowed generations of astronomer to study the “dark side” of the IGM in a very powerful way. Unfortunately, this method has some shortcomings. For instance, in most of the cases, it is only possible to get one-dimensional information on the intervening absorption systems.

The aim of the present work has been to open a new window in the detection and study of the IGM thanks to its Ly$\alpha$ emission, following the suggestions of Hogan & Weymann (1987) and Gould & Weinberg (1996). Accurate modelling of this “bright side” of the IGM required the development of new numerical techniques (Chapter 2) to overcome the simplification of previous models. The theoretical predictions have been fundamental in order to design a successful observational campaign (Chapter 3). The fruit of this work is the first statistical sample of IGM Ly$\alpha$ clouds around a high-redshift quasar: a new population of objects that may represent the missing link between the IGM and the early stages of the galaxy-formation process.

The use of a bright quasar as the “illuminating source” and the best current facilities like the FORS2 camera at the Very Large Telescope allowed us to explore this “new side” of the IGM in a relatively brief observing time. Our study may thus open the way to large and systematic observational campaigns around high-redshift quasars. Recent observations made with the Keck telescope in the field surrounding another bright quasar at redshift $z \sim 2.8$ (C.C. Steidel 2008, private communication) found very similar results: several Ly$\alpha$ clouds with a number density and observed properties consistent
with our findings. A possible shortcoming in the use of bright quasars is that the extra photo-ionization increases the column-density threshold required for the cloud to be self-shielded. This means that only the densest part of the IGM can be detected with this method. On the other hand, the environment and the properties of the quasars (e.g., the age and the shape of the emission) can be constrained with the Lyα emission from the surrounding IGM. Next future facilities with a large collecting area (e.g., the Extremely Large Telescope) may allow us to directly image the IGM at lower density illuminated solely by the cosmic UV background, away from bright quasars.

From a theoretical point of view, more sophisticated models are needed to understand the origin and the physical properties of the Lyα sources in the current and future observational campaigns. Fluorescent emission is only one of the possible mechanism able to “illuminate” the IGM. Cooling emission and internal star formation could substantially contribute to the total population. Moreover, the propagation of the quasar Ionization-fronts inside the dense IGM clouds may produce additional Lyα emission induced by hydrodynamical effects, with HI collisional excitations as an important driver for the generation of Lyα photons. In order to study these effects, we need accurate, time and temperature-dependent radiative transfer models. Moreover, a direct coupling with hydro-codes is required. In the Appendix, I presented a new code that will constitute the base for the necessary theoretical and numerical development in the study of the IGM Lyα emission and the first stages of the galaxy-formation process.

The study of the IGM is entering a new era that promises to settle a number of outstanding questions regarding the early Universe. Currently, large theoretical and observational efforts are directed to revealing the circumstances that led to the IGM reionization. The Gunn-Peterson effect in the spectra of the $z > 6$ quasars is at the moment the only direct, but very weak, constraint on the possible evolution of the IGM neutral fraction. Future 21-cm observations are the promising way to directly map the cosmic HI during the Epoch of Reionization (EoR). Unfortunately, given the weakness of this emission, we have probably to wait a few decades before extremely large radio facilities (e.g., SKA) could be able to make a direct HI “tomography”. In Chapter 4, a new possible way to directly map the HI during the EoR has been presented: the Lyα emission produced within the Ionization-fronts of the highest-redshift quasars may reveal the distribution of the cosmic HI.

An interesting result has been recently obtained with a very deep, spectroscopic search for Lyα emission at redshift three by Rauch et al. (2008): a new populations of faint and extended line-emitting objects, consistent with the LLSs and DLAs observed in absorption, without a detectable continuum counterpart. In this case, a low star-formation activity, perhaps supplemented by cooling, appears to dominate the Lyα emission.
Concluding remarks and future prospects

(behind the quasar), similarly to a future 21-cm “tomography”. Unlike radio observations, a Ly$\alpha$ map of the IGM during the EoR may be feasible already with the current optical facilities or with the next generation telescopes (e.g., JWST) $^7$. The discovery of this signal would represent a crucial step to understand when and how the first source of ionizing radiation, galaxies and quasars, reionized the Universe.

From the local Universe to the EoR, revealing the origins and the physical properties of “the diffuse matter in the space between the galaxies would be of great interest in several branches of astrophysics” (Field, 1959). Now, after decades of “darkness”, the IGM has began to reveal its bright side.

$^7$Moreover, cross-correlations between the Ly$\alpha$ and the radio signal from facilities available in the next few years (LOFAR, MWA) may help to establish statistically significant detections.
Concluding remarks and future prospects
Appendix A

Cosmological Radiative Transfer of Ionizing Photons

In this appendix, I describe a new 3D cosmological radiative transfer code, called StART (block-Structured Adaptive Radiative Transfer), based on a ray-tracing, photon-conserving and adaptive (in space and time) algorithm for multi-mesh simulations. In particular, StART has been designed specifically to work in combination (presently, in post-processing) with Adaptive Mesh Refinement hydrodynamical simulations. Among other features, StART is based on a new cell-by-cell approach in the ray-tracing scheme that allows high accuracy for multi-grid structures and high computational performance. The code follows the propagation of ionizing radiation from an arbitrary number of sources and from the diffuse recombination radiation of hydrogen and helium. The chemical state of six species (HI, HII, HeI, HeII, HeIII, e) and electron temperatures are computed with a time-dependent, non-equilibrium chemistry solver. The code uses the newest and best poten-}

tialities of the FORTRAN95/2003 language and consists of more than 10,000 lines in a modular structure.

In the following, I present the main characteristics, the new algorithms and the validating tests of the code.

A.1 Basic equations

The cosmological radiative transfer equation in comoving coordinates (e.g., Norman, Paschos & Abel 1998) is given by

\[
\frac{1}{c} \frac{\partial I_\nu}{\partial t} + \frac{\hat{n} \cdot \nabla I_\nu}{\ddot{a}} - \frac{H(t)}{c} \left( \nu \frac{\partial I_\nu}{\partial \nu} - 3I_\nu \right) = k_\nu (S_\nu - I_\nu) , \quad (A.1)
\]
A.1. Basic equations

where \( I_\nu \equiv I(t, \vec{x}, \hat{n}, \nu) \) is the monochromatic specific intensity of the radiation field, \( \hat{n} \) is a unit vector along the direction of propagation of the ray, \( H(t) \equiv \dot{a}/a \) is the (time-dependent) Hubble constant, \( \bar{a} \equiv \frac{1+z_{em}}{1+z} \) is the ratio of cosmic scale factors between photon emission at frequency \( \nu \) and the present time \( t \), \( k_\nu \) denotes the opacity at frequency \( \nu \) and \( S_\nu \) is the source function of the medium.

If the scale of interest \( L \) is much smaller than the horizon, \( c/H \), (as it is always our case) and the medium properties are changing on a time scale shorter than the light crossing time \( L/c \), equation (A.1) reduces to the classical, static radiative transfer equation:

\[
\hat{n} \cdot \nabla I_\nu = k_\nu (S_\nu - I_\nu) .
\] (A.2)

This equation admits the following solution

\[
I_\nu(\hat{n}, \tau_\nu) = I_\nu(\hat{n}, 0) \cdot e^{-\tau_\nu} + \int_0^{\tau_\nu} S_\nu(\hat{n}, \tau_\nu') d\tau_\nu' ,
\] (A.3)

(where \( \tau_\nu \) is the optical depth along \( \hat{n} \)) and is in general adequate for cosmological simulations except on small distances from the sources (or, equivalently, for extremely bright sources). In this case, the approximations break down allowing the Ionization-fronts to expand faster than the speed of light. In sections 4.4.2 and 4.4.3 we discussed and applied an analytical correction to solve this unphysical behavior in the case of a single source in a homogeneous density field.

Using equation (A.3), the radiation field intensity can be specified at any point of the simulation box given the value of the optical depth to the sources. Given the radiation field, it is then possible to derive for each species \( i \) the photoionization rate:

\[
\Gamma_i(\vec{x}) = n_i \int_{4\pi} \int_\nu i \sigma_i(\nu) \frac{I_\nu(\vec{x}, \hat{n})}{h\nu} d\nu d\Omega
\] (A.4)

and the gas photoheating rate:

\[
G_i(\vec{x}) = n_i \int_{4\pi} \int_\nu i \sigma_i(\nu) \frac{I_\nu(\vec{x}, \hat{n})}{h\nu} h(\nu - \nu_i) d\nu d\Omega ,
\] (A.5)

where \( \nu_i \) and \( \sigma_i \) are the frequency threshold and the cross-section for the ionization of species \( i \), respectively, and \( n_i \) is the physical number density.

Finally, \( \Gamma_i \) and \( G_i \) are used to compute the chemistry evolution of the neutral fraction of hydrogen (\( y_1 \)), neutral helium (\( y_2 \)), singly ionized helium
(y_3), and the temperature (expressed in term of the total energy density \( E = (3/2)n_{tot}k_bT \)) according to the following rate equations:

\[
\frac{dy_1}{dt} = -y_1 \Gamma_1 - n_e y_1 q_1 C + n_e (1 - y_1) \alpha_1 C \quad (A.6)
\]

\[
\frac{dy_2}{dt} = -y_2 \Gamma_2 - n_e y_2 q_2 C + n_e y_3 [\alpha_2 + \xi] C \quad (A.7)
\]

\[
\frac{dy_3}{dt} = -y_3 \Gamma_3 - n_e y_3 q_3 C + n_e (1 - y_2 - y_3) \alpha_3 C \quad (A.8)
\]

\[
\frac{dE}{dt} + 2H \cdot E = n_H y_1 G_1 + n_{He} (y_2 G_2 + y_3 G_3) - \Lambda(y_i, T) \quad (A.9)
\]

Here \( \alpha_i, q_i \) and \( \xi \) are the (temperature-dependent) radiative recombination, collisional ionization, and dielectronic recombination coefficients, respectively; \( n_e = n_H (1 - y_1) + n_{He} (2 - 2y_2 - y_3) \) is the number density of electrons, \( C \) is the clumping factor, and \( \Lambda \) is the total cooling rate (including recombinations, collisional excitations, Compton, bremsstrahlung and Hubble cooling). Analytical fits for the ionization, recombination and cooling rates are taken from Hui & Gnedin 1998.

### A.2 Computational method

The computational volume used by StART can be composed by a single Cartesian, uniform grid or a multi-grid (evolving) structure divided into cells of different size. StART can use the output of any AMR (Adaptive Mesh Refinement) hydro-code, providing that the grids are regular and nested. This allows a fast algorithm for the ray-tracing inside a multi-grid structure based on a tree-search. However, StART is also able to convert a not-nested grid into a nested structure, allowing the code to work with a great variety of AMR codes. The evolution of each grid of the multi-mesh structure is followed with a independent time-step (\( \Delta t_g \)). When a grid is evolved, the value of the corresponding simulation time is stored (\( t_g \)).

The algorithm consists of an iterative method divided into three parts for each simulation step (and for each grid/cell of the computational volume): i) finding the ionization and photo-heating rates, ii) choosing the time-step, and iii) solving the chemistry equation for the evolution of the medium properties. The first part of the algorithm is the most time-consuming (and important) part of the method and is described in detail in the following section.
A.2. Computational method

A.2.1 Finding the ionization and photo-heating rates

The ionization and photo-heating rates are computed for each “evolving” grid and corresponding cells down to the lowest (or the selected) refinement level. An “evolving” grid is defined, at a given simulation step \(i\), as a grid that satisfies one of these two conditions: i) its “next” evolving time (derived from the \(t_g^i\) and \(\Delta t_g^i\) at the previous simulation step) \(t_g^{i-1} + \Delta t_g^{i-1}\) is less than or equal to the present simulation time \((t_s^i)\); ii) it has not been touched (yet) by the Ionization-front (directly traced during the simulation) of the source(s). This allows to save a large amount of computational time, concentrating the efforts only on the grids where the Ionization-fronts are changing rapidly the medium.

The calculation of \(\Gamma_i\) and \(G_i\) for each cell is performed with an iterative procedure until convergence is reached. For each iteration step, a packet of rays is propagated from selected points within the cell to the source(s). These points are chosen with a Monte Carlo procedure based on a rejection-method algorithm that insures an uniform solid-angle distribution (as seen by the source) within the cell. For each ray, the HI, HeI and HeII column densities within the cell (\(\Delta N_i\)) and from the cell edges to the source (\(N_i\)) are computed with a fast ray-casting algorithm (Amantides & Woo 1987). The column densities are then used to calculate the frequency-dependent optical depths \(\Delta \tau_j(\nu) = \sigma_j(\nu)\Delta N_i\) and \(\tau_i(\nu) = \sigma_i(\nu)N_i\). Given the optical depths, we derive the probability that a photon with frequency \(\nu\) is absorbed by the species \(i\) within the cell:

\[
P_i(\nu) = \frac{1 - \exp[-\sum_{j=1}^{3} \Delta \tau_j(\nu)\{1 - \exp[-\Delta \tau_j(\nu)]\}]}{\sum_{j=1}^{3} \{1 - \exp[-\Delta \tau_j(\nu)]\}}.
\]  

(A.10)

The optical depths and the spectral energy distribution of the source(s) are sampled into \(N_\nu\) (logarithmically-spaced) frequency bins. The probability distributions \(P_i\) are used to compute the photoionization rate for each ray of the packet and for each source:

\[
\Gamma'_i = \sum_{\nu=1}^{N_\nu} P_i(\nu)\hat{N}_{\gamma}(\nu)\exp[-\tau_i(\nu)]
\]

(A.11)

where \(\hat{N}_{\gamma}(\nu)\) denotes the number of ionizing photons per unit time emitted by the source in the frequency bin \(\nu\). Finally, the value of \(\Gamma_i\) is obtained by averaging \(\Gamma'_i\) over the rays in the packet, the cell volume and the fraction of
A.2. Computational method

the solid angle covered by the cell (directly calculated with a new algorithm we developed). Several packets of rays are generated until the value of \( \Gamma_i \) converges. The procedure is repeated for each source and the single values of \( \Gamma_i \) are added. The photoionization rates \( G_i \) are obtained in a similar way, starting from

\[
G'_i = \sum_{i_v=1}^{N_v} P_i(\nu_{i_v}) h(\nu_{i_v} - \nu_i) \dot{N}_\gamma(\nu_{i_v}) \exp[-\tau_i(\nu_{i_v})] .
\]

(A.12)

In order to avoid redundant calculations of the column densities \( N_i \) from the cell edges to the sources for each ray packet, we first evaluate \( N_i \) on the cell vertices “visible” from each source. If the difference between these values is less than a given (small) threshold, we do not use the full ray-casting algorithm. Instead, we use the \( N_i \) values at the vertices to interpolate (linearly) the needed values on the cell faces. Typically, the cells that need the full ray-casting algorithm are few percent of the total volume and correspond to the Ionization-front regions (where the column-density varies rapidly). For the remaining cells, interpolating the column-densities is a good approximation and allows to substantially speed-up the computation.

To achieve a better performance it is also possible to choose a column-density threshold (or, equivalently, an optical depth threshold at the ionization limit) above which StAR T skips the calculation of the \( \Gamma_i \) and \( G_i \) values. This is computationally convenient, e.g., in the early stages of the expansion of an Ionization-front in a neutral and dense medium, when most of the volume is still optically thick to the source radiation.

In the case of the recombination radiation, we generate a set of rays propagating from the cell center. The photoionization and photo-heating rate are calculated similarly to the previous case, where now the value of \( \dot{N}_\gamma(\nu_{i_v}) \) is given by emissivity of recombination radiation generated by the gas within each crossed cell. Recombinations in a cell contribute to its own ionization. The photoionization and photo-heating rate obtained in this way are added to the \( \Gamma_i \) and \( G_i \) generated by point sources. As source of recombination radiation we include: i) HI, HeI and HeII free-bound continuum (from Osterbrock 1989), ii) HeII Balmer (from Ercolano & Storey 2006) and two-photon continuum (from Nussbaumer & Schmutz 1984), and iii) HeII Ly-alpha line. We neglect the HeI Balmer continuum and emission lines given their (relatively) small contribution to the total emissivity.
A.3. Validating tests

A.2.2 Choosing the time-step

As mentioned above, each grid in the computational volume has an individual time-step $\Delta t_g$. This is obtained by taking a fixed fraction $f$ of the minimum ionization timescale $(dy_i/dt)^{-1}$ from the rate equations, with the newly calculated $\Gamma_i$ for each cell of the grid. The $\Delta t_g$ of the “evolving” grids (see previous section) is fixed to the shortest time-step in the computational volume. The grid time $t_g$ is updated if necessary.

A.2.3 Evolving the medium properties

In the last part of the computational algorithm, we solve the rate equation and we evolve the medium properties with the newly calculated $\Gamma_i$ and $G_i$. Only the grids with $t_g$ equal or less than the simulation time $t_s$ are evolved.

In the case that $t_g < t_s$ we readjust the grid time-step to have $t_g = t_s$, i.e. all the evolved grids are synchronized to the same time. For the integration of the rate (stiff) equations, we use the Radau IIA method (Hairer & Wanner 1996), an implicit Runge-Kutta scheme of order 5. This allows this part of the code to be computationally stable and reasonably fast for the required accuracy.

A.2.4 Simulation output

The output of the simulation consists in a multi-mesh structure, at a given time-step or simulation time, with the gas and grid properties. The output files are written in the widely-used HDF5 format. All the gas properties are synchronized (i.e., the grids are evolved to the same time) before output. The grids and cells at a given refinement level $l_i$ that contain further refinements are updated coarsening the corresponding $l > l_i$ levels. Optionally, the outputs can be produced in a Chombo\(^1\)-like format that can be directly visualized with the most recent and performing visualization tools (e.g., Visit\(^2\)). Every output can be also used to restart the code.

A.3 Validating tests

In this section we present the validating tests of the code based on the radiative transfer code comparison project (Iliev et al. 2006; I06 thereafter).

\(^1\)http://seesar.lbl.gov/ANAG/chombo
\(^2\)https://wci.llnl.gov/codes/visit/
A.3. Validating tests

These tests have been designed to compare all the important aspects of several radiative-transfer codes present in the literature. In general, a direct comparison between the results of several different algorithms is the only possibility to test the code, since analytical solutions exist only in a very few particular cases (see Test 1 below). The tests include the correct tracking of both slow and fast Ionization-fronts in homogeneous and inhomogeneous density fields, spectrum hardening and the solution of the temperature state. The original tests in I06 are performed for a single, uniform grid and pure hydrogen medium. In order to compare our results with the other RT codes, we use the same single grid (pure-hydrogen) configuration and we present at the end of this section (Test 4) a validating test for the multi-grid case.

A.3.1 Test 1: isothermal HII region expansion

This test represents the classical problem of the expansion of a HII region in an uniform (pure-hydrogen) medium around a single ionizing source. We assume that a steady, monochromatic ($h\nu = 13.6$ eV) source emitting $\dot{N}_\gamma$ ionizing photons per unit time turns on in an initially-neutral, uniform-density, static medium with hydrogen number density $n_H$. The temperature is fixed at $T = 10^4$ K. Under these conditions, and assuming that the front is sharp (i.e. that it is infinitely-thin, with the gas inside fully-ionized and the gas outside fully-neutral), there is a well-known analytical solution for the evolution of the I-front radius, $r_I$, and velocity, $v_I$, given by

$$r_I = r_S \left[1 - \exp\left(-t/t_{rec}\right)\right]^{1/3}, \quad (A.13)$$

$$v_I = \frac{r_S \exp\left(-t/t_{rec}\right)}{3t_{rec} \left[1 - \exp\left(-t/t_{rec}\right)\right]^{2/3}}, \quad (A.14)$$

where

$$r_S = \left[\frac{3\dot{N}_\gamma}{4\pi \alpha_B(T)n_H^2}\right]^{1/3}, \quad (A.15)$$

is the Strömgren radius, i.e. the radius at which recombinations balance ionizations and the HII region expansion stops. Here $\alpha_B(T)$ is the Case B recombination coefficient and

$$t_{rec} = \left[\alpha_B(T)n_H\right]^{-1}, \quad (A.16)$$

is the recombination time. The HII region initially expands quickly and then slows down as the evolution time approaches the recombination time, $t \sim t_{rec}$. At a few recombination times I-front stops and, in absence of gas motions, remains static thereafter.
A.3. Validating tests

Figure A.1 Test 1: image slices of the HI fraction at time $t = 500$ Myr in the plane $y = 0$ (left panel) and $z = 0$ (right panel).

The numerical parameters we used for this test are as follows: computational box dimension $L = 6.6$ kpc (the source is at the corner of the box), gas number density $n_H = 10^{-3}$ cm$^{-3}$, initial ionization fraction (given by collisional equilibrium) $x = 1.2 \times 10^{-3}$, and ionization rate $\dot{N}_\gamma = 5 \times 10^{48}$ photons s$^{-1}$. For these parameters the recombination time is $t_{rec} = 3.86 \times 10^{15}$ s = 122.4 Myr. Assuming a recombination rate $\alpha_B(T) = 2.59 \times 10^{-13}$ cm$^3$ s$^{-1}$ at $T = 10^4$ K, then $r_S = 5.4$ kpc.

In Figure (A.1) we show the images of the HI fraction in the plane $y=0$ and $z=0$ at time $t = 500$ Myr, when the equilibrium Strömgren sphere is reached. The HII region is nicely spherical in both the planes, demonstrating that our algorithm produces an uniform coverage of the solid angle around the source. In Figure (A.2) we plot the spherically averaged radial profiles of the ionized ($x$) and neutral fraction ($1-x$) at times $t = 30$ and 500 Myr. The thickness of the transition between the HII and HI regions is in agreement with both analytical and numerical expectations from other codes (see Figures 6 and 8 in I06). Finally, in Figure (A.3), we show the time evolution of the I-front position (defined as the point of 50% ionization). The code tracks the I-front correctly, with the position never varying by more than few percent from the analytical solution.
A.3. Validating tests

Figure A.2 Test 1: spherically averaged ionized (x) and neutral (1-x) fraction profiles at times $t = 30$ Myr (left panel) and $t = 500$ Myr (right panel).

Figure A.3 Test 1: time-evolution of the I-front position $r_I$ with respect to the Strömgren radius $r_S$ (bottom panel) and the analytical solution (top panel). See text for details.
A.3. Validating tests

Figure A.4 Test 2: image slices of the HI fraction at coordinate $z = 0$ and times $t = 10$ Myr (left panel) and $t = 100$ Myr (right panel).

Figure A.5 Test 2: spherically averaged ionized ($x$) and neutral (1-$x$) fraction profiles at times $t = 10$ Myr (left panel) and $t = 100$ Myr (right panel).

A.3.2 Test 2: HII region expansion with temperature evolution

In this test we assume the same parameters of Test 1, but the ionizing source is assumed to have a $10^5$ blackbody spectrum and we allow the gas temperature to evolve. Initially, the gas is fully neutral with a temperature $T=100$
A.3. Validating tests

Figure A.6 Test 2: image slices of the gas temperature at coordinate $z = 0$ and times $t = 10$ Myr (left panel) and $t = 100$ Myr (right panel).

Figure A.7 Test 2: spherically averaged temperature profiles at times $t = 10$ Myr (left panel) and $t = 100$ Myr (right panel).

K. For this test, there are no analytical solutions and we will compare our results with the results of the other codes in I06.

In Figure (A.4), we show the images of the neutral hydrogen fraction (on the $z = 0$ plane) at times $t = 10$ and $t = 100$ Myr. The spherically averaged HI profiles, for the same time-snapshots, are presented in Figure
A.3. Validating tests

Figure A.8 Test 3: image slices of the HI fraction at coordinate z=0.5 (box units) and time $t = 0.05$ Myr.

The overall size of the HII region and the internal structure agree very well with the results of the other codes in I06. The temperature images and the spherically averaged profiles at times $t = 10$ and $t = 100$ Myr are presented in Figures (A.6) and (A.7). Since our code is able to follow a large number of frequency bins with high angular resolution, we can obtain a large pre-heated region without spatial anisotropies (cfr. the results of a Monte Carlo method like CRASH in I06). The resulting temperature structure agrees very well with most of the other codes.

A.3.3 Test 3: Multiple sources in a cosmological density field

In this test, we follow the propagation of the Ionization-fronts from multiple sources in a static cosmological density field. The initial conditions for the density and source spatial distribution/luminosities are provided by I06. In particular, we use a time-slice at $z = 9$ from a hydro-simulation with a box size of $0.5 h^{-1}$ comoving Mpc and $128^3$ cells. The initial temperature is fixed
A.3. Validating tests

Figure A.9 Test 3: image slices of the gas temperature at coordinate $z=0.5$ (box units) and time $t=0.05$ Myr.

to $T=100$ K everywhere. The ionizing sources correspond to the 16 most massive halos in the box, with a luminosity proportional to the halo mass (see I06 for details). In this test, we use a low threshold for the maximum optical depth for the ray-tracing algorithm (see section A.2.1) in order to speed-up the computation. This results in a limited gas pre-heating ahead of the Ionization-fronts.

In Figure (A.8), we present slices of neutral hydrogen fraction cut through the simulation box at coordinate $z=0.5$ (box units) and time $t=0.05$. Comparing our results with the three codes that performed this test in I06 ($C^2$-Ray, CRASH and FTTE), we find a general agreement (although all the codes produce somewhat different morphologies). In particular, our result is very similar to the one obtained with FTTE (that does not allow gas pre-heating in the code). We see a similar behavior and a general agreement also for the temperature maps presented in Figure (A.9). In Figure (A.10), we show a three-dimensional contour-plot of the HI fraction at later times ($t=0.1$), when most of the HII bubbles start to percolate creating a structure with complex topology.
A.3. Validating tests

A.3.4 Test 4: Multi-grid structure

In this final test (not present in the original set of I06), we show and test the multi-grid capability of StART. In particular we use the same initial condition of Test 1 changing the original grid with three nested, concentric grids with $64^3$ cells, corresponding to two levels of refinement (with a factor two and four increased resolution with respect to the base mesh). With this configuration, the center of the box has a resolution equivalent to a $256^3$ cell grid. We limit the number of levels and the resolution of the base grid for illustrative purposes. The source position is $(x = 0, y = 0, z = 0.5)$.
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Figure A.11 Test 4: (Ionization-front expansion in a multi-grid structure) HI fraction image slice at time \( t = 200 \) Myr and coordinate \( z = 0.5 \) (box units). The multi-grid structure in the plane \( z = 0.5 \) is overlaid.

In box units. In Figure (A.11), we show the image of HI fraction and the computational meshes corresponding to the slice at coordinate \( z = 0.5 \) and time \( t = 200 \) Myr. As we can see from the image, the front is tracked very well despite of the different grids (and resolution), with no spurious effect introduced by the multi-grid structure.
A.4 Summary and conclusions

We presented a new radiative transfer code, called StART, based on an adaptive (in space and time), photon-conserving, ray-tracing scheme particularly suited to be coupled with the multi-mesh structures of cosmological AMR hydro-simulation. We described the main algorithm and characteristics of the code.

Among several new features, the code has an adaptive scheme for the solid-angle sampling of the computational volume based on a new cell-by-cell (and grid-by-grid) approach (section A.2). This algorithm allows us to obtain the same resolution and accuracy for every cell in a multi-mesh simulation box without over-sampling the low-resolution grids. In other words, our method scales (roughly linearly) with the total number of cells in the box, rather than with the angular resolution of the highest refined cells. This allows, together with an adaptive time-stepping scheme, a substantial increase in the computational speed and code performance without loss of accuracy.

The code is able to trace the Ionization-fronts from multiple sources as well as the diffuse ionizing radiation produced by hydrogen and helium recombinations. The time-evolution of six different species (HI, HII, HeI, HeII, HeIII, e) and the gas temperature is followed with a time-dependent non-equilibrium chemistry solver based on an implicit Runge-Kutta scheme of order 5.

StART is able to use the output of most of the existing AMR codes, both with nested and non-nested grids. The output of the code is produced in HDF5 format and, optionally, in a Chombo-like format that can be directly visualized with the most recent and high-performance visualization tools (e.g., Visit).

In the last part of the appendix, we have shown a set of validating tests based on the code comparison project (I06). The results are in very good agreement with most of the others radiative transfer codes. Finally, we extended one of the original test in I06 to a multi-grid structure in order to test and validate our new method.

Presently, the code can be easily parallelized on shared-memory machines. As a next improvement, we are developing a new algorithm for the code parallelization on distributed-memory machines and for a direct coupling with hydro-codes.
Bibliography

Baldwin, J. A. 1974, Ph.D. Thesis
BIBLIOGRAPHY


116
BIBLIOGRAPHY


117

119
Sargent, W. L. W. 1980, PhyS, 21, 753
Shapiro, P. R., & Giroux, M. L. 1987, ApJL, 321, L107
Stenflo, J. O. 1980, Astron. Astrophys., 84, 68
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Publications

Refereed Publications

• *Mapping Neutral Hydrogen during Reionization with the Ly\(\alpha\) Emission from Quasar Ionization Fronts.*

• *Plausible Fluorescent Ly\(\alpha\) Emitters around the z = 3.1 QSO0428-388.*

• *Fluorescent Ly\(\alpha\) Emission from the high-z Intergalactic Medium.*

To be submitted

• *START: a New Cosmological Radiative Transfer Code for Adaptive Mesh Refinement Simulations*

Conference Proceedings

• *Fluorescent Ly\(\alpha\) Emission from the Intergalactic Medium at z=3: Theoretical Model and Observations.*
  Cantalupo, S., Porciani, C., Lilly, S. J., & Miniati, F. 2006,
  http://www.astro.rug.nl/~bernard60/index.php, p. 72.1
Acknowledgments

During my long journey through my PhD studies, from my first step at ETH to the present, I met many people that helped me to discover a new world and to become what I am now.

First, I would like to thank the two persons that gave me the possibility to cross the Alps and to write this thesis: Cristiano Porciani and Simon Lilly. Cristiano introduced me into this exciting field of study, the Intergalactic Medium and the Radiative Transfer. He helped me to discover that no choice could have been better. I was lucky to have also a supervisor like Simon. From him I learnt a lot, not only in the observational side of my PhD, but also in how to develop a critical spirit, how to address my creativity and enthusiasm in producing solid scientific results.

An important part in the success of this PhD thesis is due to the serenity, the happiness and positive energy given to me in the last two years and an-half by an extraordinary person called Nadine. Thank you for your patience, your smiles, your joy in sharing with me every single moment of my life.

Many people I met at ETH deserve also thanks. I would like to thank all my colleagues at the Institute of Astronomy, with whom I enjoyed nice (scientifically and not) discussions and the necessary breaks from every-day working life. In particular, I would like to mention Francesco Miniati (with whom I had a fruitful collaboration during my thesis), Claudia Scarlata, Mark Sargent, Annalisa Pillepich, Anna Cibinel, Oliver Hahn, the colleagues that shared (for the longest period) the office with me: Pascal Oesch, Robert Feldmann, Tristen Hayfeld. A special thank to the players of the “Toeggli” team: Pawel Kampczyk, Thomas Bschorr, Martin Bernet, the already mentioned Pascal, Robert, Oliver, Tristen, and others. At the moment, we are certainly the best players of “Toeggli” in the HIT building (!). Anyway, I hope you can make progresses in the next years.

I also would like to thank the friends that shared with me several climbs on the wonderful swiss Alps, sometimes even harder than completing this thesis: the “un-dopable” cyclists Claudio, Andrea and Amsicora (also called, “Lepre”, “Muca” and “Canguro”).

Finally, the last thanks are for my family. Thank you for your continuous support and for having given to me the possibility of finding my way.