Cover Page



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# INTRODUCTION

For more than a millennium, we have been aware of the existence of a celestial small cloud in the constellation of Andromeda (al-Sufi, 964), but it has been less than a century since we observed that the small cloud, which is commonly known to us as M31, is a spiral galaxy outside of our own Milky Way. In fact, almost everything we know about M31 and other galaxies has been learned during the last century, thanks to the advent of large telescopes and new technologies. During the last few decades, theoretical models have helped us to make sense of the rapidly increasing wealth of data and have caused a revolution in our understanding of the Universe. In particular, as a result of advancements in numerical techniques and computational recourses, cosmological simulations have become an indispensable tool for probing the main processes involved in galaxy formation and evolution.

This thesis is an attempt to add to our understanding of the Universe, by using cosmological simulations for studying the distribution and evolution of the neutral hydrogen around galaxies. In this work, I extensively use stateof-the-art cosmological hydrodynamical simulations of galaxy formation. To set the stage, I begin this chapter with a very brief overview of our current knowledge about how galaxies form and evolve. I continue by explaining the importance of studying the neutral hydrogen for understanding galaxies. Then, I discuss briefly how hydrodynamical and radiative transfer simulations work, before ending this introductory chapter with the outline of this thesis.

## **1.1** Current standard model for galaxy formation and evolution

The theory of galaxy formation is where the properties of the largest scales in the Universe meet the physics at tiny atomic scales. The huge dynamic range of the relevant scales spanned by the different physical entities (e.g., length, mass, time) that characterize galaxies, makes it a daunting task to model these complex systems. Despite the monstrous size of this problem, in principle, the formation and evolution of galaxies should be understandable in terms of the known physical laws. Using these physical laws to explain the observed trends among galaxies has been the main challenge of the theory of galaxy formation and evolution. As a result of the hard work of many great minds, we now have an understanding of how galaxies form and evolve, which can explain, with a good degree of accuracy, what we see in the Universe. However, as in other natural sciences, any progress in understanding galaxies reveals new puzzles to solve. As a result, there is (and there will be) a huge number of phenomena that we do not fully understand. In the following, I briefly review what I call the standard model of galaxy formation and evolution, which consists of ideas that glue together large sets of observed properties, and are commonly accepted by most experts who work in this field.

#### 1.1.1 Cosmology: the backbone of galaxy formation

Cosmology serves as the backbone of galaxy formation by describing the physical laws that govern the formation and evolution of structures on large scales. In this context, the  $\Lambda CDM$  paradigm has enjoyed great success by explaining a large number of observables, such as the temperature fluctuations in the radiation we receive from the early Universe (i.e., the Cosmic Microwave Background), the accelerated expansion of the Universe and the growth of structures. The constraints on the parameters of the  $\Lambda$ CDM concordance cosmological model have been improving rapidly in recent years, thanks to precise observational experiments like the Cosmic Background Explorer (COBE: Mather et al., 1990), the Wilkinson Microwave Anisotropy Probe (WMAP: Bennett et al., 2003; Spergel et al., 2003; Komatsu et al., 2011) and recently, the Planck satellite (Planck Collaboration et al., 2013). Based on the above mentioned measurements, and other experiments, we know that the vast majority of the energy density of the Universe is in the form of Dark Energy (i.e.,  $\Lambda$ ), which causes the accelerating expansion of the Universe. The rest consists mainly of cold dark matter (i.e., CDM) with tiny fractions of baryonic matter and radiation. The exact values of the above mentioned fractions define the dynamics of the Universe on large scales and the growth of small scale density fluctuations in the nearly homogeneous initial distribution of (Dark and baryonic) matter after the Big Bang.

As the Universe expands, the separation between small scale density fluctuations increases. At the same time, the deviation between the density of fluctuations and the mean density of the Universe also increases. In other words, over-dense regions attract more matter at the expense of draining under-dense regions. When the density fluctuation (i.e.,  $\Delta \rho$ ) is much smaller than the mean density of the Universe (i.e.,  $\Delta \rho / \rho \ll 1$ ), its physical size increases with the expansion of the Universe as the magnitude of  $\Delta \rho$  increases (i.e., the linear regime). There is, however, a turn-around when  $\Delta \rho / \rho \sim 1$ , after which the physical size of the fluctuation starts to decrease (i.e., the non-linear regime). The result of the latter stage is the formation of self-gravitating bound structures. Since the majority of matter is in the form of collisionless dark matter, collapsing structures (i.e., dark mater haloes) are regularized through violent relaxation. On large scales and low over-densities, the baryonic matter is bound to the dark matter, which is the dominant gravitational actor. In the non-linear regime, however, baryons reveal their collisional nature and become shock heated to very high temperatures through the efficient conversion of gravitational energy into the internal energy of the baryonic gas, as it collapses into the inner parts of the gravitational potential wells. At this stage, the fate of baryons in the collapsed structures is significantly affected by the laws of small-scale atomic physics and related complex and collective processes like radiative cooling and star formation. At the same time, the large-scale evolution of structures continues and brings more matter into the collapsed structures and merges them.

#### 1.1.2 Main physical processes that drive galaxy evolution

Despite the great success of the ACDM paradigm in explaining the invisible side of galaxy formation by accurately predicting the formation and growth of dark matter haloes (e.g., Zehavi et al., 2011; Heymans et al., 2013), the complex physical processes that control the evolution of gas and stars are far from understood. To first order, the baryonic content of collapsing dark matter haloes, which is initially shock heated to high temperatures, loses its energy through radiative cooling. The conservation of angular momentum dictates the cooling gas to form a rotating disk as it looses energy and falls deeper into the potential well of the dark matter halo. The density of baryonic gas increases until the radiative cooling becomes inefficient and the gaseous disk approaches a quasi-equilibrium state. The small scale instabilities in the gaseous disk, however, continue to grow into dense molecular clouds which evolve and collapse to form stars.

The advent of stars makes the lives of galaxies much more complicated. Stars are energetic sources of feedback and significantly affect the fate of their parent galaxies. They heat up the gas and ionize it with their radiation, and they produce heavy elements as they evolve. These processes change the evolution of the gas around stars by changing its cooling/heating. Stars also transport large quantities of kinetic energy and heavy elements into their surroundings by injecting winds into the interstellar medium (ISM). Massive stars, which evolve faster than stars with lower masses, end their lives dramatically in energetic explosions (i.e., Supernovae; SNe) that inject huge amounts of energy into the ISM of their host galaxies, affecting subsequent star formation and launching largescale galactic winds. In addition to energetic SNe explosions, radiation pressure from very luminous young stars removes gas from star-forming regions, and possibly makes a significant contribution to the launching of galactic winds.

The presence of very massive black holes, the end result of the death of very massive stars, causes more complications in our understanding of how galaxies evolve. Super-massive black holes, which are found at the centers of many (if not all) galaxies we see in the Universe, are very efficient in converting mass into energy. The huge amount of energy they inject into their host galaxies in different ways, changes their fate dramatically.

There is much solid observational evidence and there are strong theoretical arguments for the presence and importance of the above mentioned mechanisms in the formation and evolution of galaxies. Understanding how they work individually and together to control the lives of galaxies at different epochs has been an active area of research during the last few decades, an area of research which is still vibrantly active due to its complexity.

#### **1.2** Neutral hydrogen in galactic ecosystems

As mentioned above, galaxies are influenced on the one hand by the force of gravity, which forms haloes, brings fresh material into the already existing haloes and keeps baryonic and dark matter structures together, and on the other hand, by the feedback mechanisms that fight against the force of gravity and try to unbind structures. The interaction between these two fronts creates a complex ecosystem in and around galaxies, and imprints the history of galaxies in the distribution of baryons around them (i.e., the circumgalactic medium; CGM). In this context, understanding the distribution of neutral hydrogen (HI) is of particular importance. The main reason for this is that HI is the main fuel for the formation of molecular clouds, the birth places of stars, which makes studying the distribution of HI and its evolution crucial for our understanding of various aspects of star formation.

We know that shortly after the Big Bang, the initially hot plasma cools down as the Universe expands and electrons and protons recombine. Hydrogen, which is the most abundant element in the Universe, becomes highly ionized again by  $z \sim 6$  due to the formation of the first stars and galaxies (i.e., the reionization). After reionization, the mean-free-path of ionizing photons (i.e., the distance photons can travel before being significantly absorbed) increases with time, as the average star formation activity of the Universe increases and the Universe becomes less dense. The relatively uniform distribution of sources of ionizing radiation on large scales creates a relatively uniform ultraviolet background radiation (i.e., the UVB) which is dominated by stellar photons at  $z \gtrsim 3$  and quasars at lower redshifts (e.g., Becker & Bolton, 2013). As a result, after reionization most hydrogen atoms are kept ionized by the UVB radiation they receive from all the ionizing sources they can see in the Universe.

The complexity of processes that set the ionization state of hydrogen depends on the HI column density. At low HI column densities (i.e.,  $N_{\rm HI} \leq 10^{17} \, {\rm cm}^{-2}$ , corresponding to the so-called Lyman- $\alpha$  forest), hydrogen is highly ionized by the UVB radiation and largely transparent to the ionizing radiation. For these systems, the HI column densities can therefore be accurately computed in the optically thin limit. At higher HI column densities (i.e.,  $N_{\rm HI} \gtrsim 10^{17} \, {\rm cm}^{-2}$ , corresponding to the so-called Lyman Limit and Damped Lyman- $\alpha$  systems), the gas becomes optically thick and self-shielded. As a result, the ionization state of hydrogen in these systems is more sensitive to various radiative transfer effects such as self-shielding, shadowing and the fluctuations of the UVB radiation on small scales.

Studying the distribution of HI is proven to be challenging. In the local Universe, the HI content of galaxies can be probed by observing 21-cm emission, but at higher redshifts this will not be possible until the advent of significantly more powerful telescopes, such as the Square Kilometer Array<sup>1</sup>. At  $z \leq 6$ , i.e., after reionization, the neutral gas can be probed through absorption signatures that are imprinted by the intervening HI systems on the spectra of bright background sources, such as quasars. The analysis of these absorption features provides an alternative probe of the distribution of matter at high redshifts, compared to studying the Universe through emission. The large distances that separate most absorbers from their background QSOs make it unlikely that there is a physical connection between them. This opens up a window to study an unbiased sample of matter that resides between us and the background QSOs.

Constraining the statistical properties of the HI distribution has been the focus of many observational studies during the last few decades (e.g., Tytler, 1987; Kim et al., 2002; Péroux et al., 2005; O'Meara et al., 2007; Noterdaeme et al., 2009; Prochaska et al., 2009; O'Meara et al., 2013). Thanks to a significant increase in the number of observed quasars and improved observational techniques, more recent studies have extended these observations to both lower and higher HI column densities and to higher redshifts. Therefore, it is important to study the properties of the HI distribution in cosmological simulations to better understand the observed trends and to put them in the context of the standard theory of galaxy formation and evolution, which is the focus of this thesis. Once simulations agree with observations, one can use them to predict what future observations reveal. These predictions can be used to validate the underlying models in the simulations and to examine the importance of different processes that are relevant to the formation and evolution of galaxies, or in case of disagreement, to point us to necessary improvements.

<sup>&</sup>lt;sup>1</sup>http://www.skatelescope.org/

#### 1.3 Simulations

Hydrodynamical simulations attempt to model complex baryonic interactions by combining various physically motivated and empirical ingredients. Modern state-of-the-art cosmological simulations of galaxy formation try to put together most of what we know about the astrophysical and cosmological processes that are shaping the Universe on different scales and they try to reproduce different observables.

In this context, the vital importance of radiation and radiative transfer (RT) processes for galaxy evolution in general, and for producing the HI distribution in particular, is evident. However, RT is often ignored or poorly approximated in the simulations. The main reason for this is the high dimensionality of the underlying calculation which makes RT an enormous computational challenge for cosmological simulations. Thanks to increasingly more powerful computers, and in the light of new algorithms, the accurate treatment of radiative effects is now becoming possible.

Since in this thesis we extensively use hydrodynamical simulations and RT, we will briefly discuss how they work.

#### 1.3.1 Cosmological hydrodynamical simulations

Cosmological simulations calculate the evolution of the Universe by starting from an approximately uniform density of matter with small fluctuations on different scales. These fluctuations are set by the observed statistical properties of the fluctuations in the early stages of the Universe (i.e., the CMB). To be able to trace the evolution of the Universe numerically, different techniques are adopted to discretize the continuous distribution of matter into a finite number of resolution elements (e.g., particles). In addition, to keep the numerical calculations tractable, one needs to adopt a finite volume which is assumed to be a representative sample of the whole Universe. Periodic boundary conditions can then be used which assume that the distribution of matter on scales beyond the extent of the simulation box is statistically similar to that inside it.

The gravitational interactions between all particles in the simulation are followed directly while the large-scale cosmological expansion of the Universe is accounted for by a change of coordinate system. Different techniques are used to accelerate the computation of the gravitational field without losing accuracy significantly. For instance, calculating the gravitational interaction between two groups of particles that are far away from each other (compared to the typical distances between the particles in each group) is possible even if we neglect the small scale distribution of the group members and replace the whole group with a single gravitationally interacting element (see for an example the TreePM algorithm explained in Bagla, 2002).

Calculating the hydrodynamical forces, which are short-range forces compared to gravity, is simpler due to their local nature. In other words, only neighboring resolution elements interact hydrodynamically. One of the most successful methods to simulate the evolution of the gas fluid is the smoothed particle hydrodynamic (SPH) technique which was introduced by Gingold & Monaghan (1977) and Lucy (1977). In the SPH prescription, the fluid is discretized into individual particles that are smoothed. This means that the relevant properties of the fluid that are represented by each particle are distributed smoothly in space around the particle. Then, the value of each relevant quantity (in most cases only density), for any given position, is calculated by adding the contribution of all SPH particles that are close enough to have significant contributions. Then, the evolution of the fluid is calculated based on the known physical laws that affect the fluid, like the laws of mass, momentum and energy conservation.

By combining the gravitational and hydrodynamical forces, it is possible to start from small initial fluctuations and trace the evolution of dark matter and baryonic gas as the Universe evolves. As the formation of structure proceeds, the baryonic content of collapsing structures, which is initially shock heated, cools down due to radiative cooling. The radiative cooling is calculated in the simulations by including several important atomic processes. These processes are mainly sensitive to the density, temperature, the abundances of different elements (i.e., metallicity) and the properties of the radiation field. Because of the high-dimensionality of the equations that control the cooling, their net effect is included in the simulations using fitting functions and tables. Due to cooling, the density of baryons increases which further complicates the simulation of the evolution of baryons.

The limited spatial resolution of cosmological simulations, which is usually of the order of a kilo-parsec, is not enough to resolve the complex and multiphase structure of the ISM. Because of this, an effective equation of state is often adopted to model the collective hydrodynamical properties of the ISM gas. This effective equation of state can also be used to prevent artificial fragmentation of dense gas on scales close to the resolution limit (Schaye & Dalla Vecchia, 2008). As the gas density increases, the dense ISM should be converted into stars. Since it is not possible to simulate the complex process of star formation at kpc resolution, simplified algorithms are used to convert gas into stars. These star formation prescriptions are often tuned to match the observed relation between the gas (column) density and star formation rate in real galaxies, on kpc scales (i.e., the Kenicutt-Schmidt relation; Kennicutt, 1998).

The resolution elements (e.g., SPH particles) that satisfy the adopted star formation criteria are converted into stellar particles with typical masses of  $10^5 - 10^6 \, M_{\odot}$ . In other words, each stellar particle in cosmological simulations represent groups of stars which are comparable to observed stellar clusters. The subsequent evolution of this population of stars, which are assumed to be formed at the same time, is followed by assuming an initial mass function (IMF) and using stellar population synthesis models that trace the stellar evolution. As the simulation continues, the stars that are assumed to be embedded in each stellar particle, age and produce metals. The fraction of the stars that are massive

enough to explode as SNe, end their lives in dramatic explosions and heat up the gas which also launches high velocity flows that create large-scale galactic winds. All these processes, together with other complicated phenomena, are poorly understood and their detailed simulation requires much higher resolution than what is affordable in current cosmological simulations. Therefore, they are included in the simulations through approximate rules, similar to the formation of stars explained above, which are commonly known as sub-grid models. The sub-grid models in cosmological simulations try to incorporate our physical knowledge or observed empirical relations into simulations. Due to the large uncertainties, they are often tuned to produce the desired observables, such as the average star formation activity of the Universe or the stellar mass function at different epochs. Because of the complexity of how different subgrid models work individually and in combination, implementing them reliably in the simulations and understanding how they regulate galaxies is an active area of research.

By combining all the above mentioned ingredients (i.e., gravity, hydrodynamics and subgrid models), it is possible to start from initial conditions that are set by cosmological observations, and to simulate the formation and evolution of galaxies and the cosmic distribution of gas.

#### 1.3.2 Radiative transfer

In addition to hydrodynamical and gravitational interactions, radiation plays an important role in shaping the cosmos as we see it. The interaction between light and matter has important consequences for the evolution of structures across a range of different scales. While the radiation pressure close to stars, and perhaps on galactic scales, changes the dynamics of the gas, the UVB radiation, which is the superposition of radiation from large numbers of sources distributed on large scales, affects the cooling/heating of the baryons significantly. In addition, it is impossible to interpret the observations without understanding the relation between the measured intensity of radiation and different phenomena that produce/affect photons.

Although it is essential to include the impact of radiation accurately in cosmological simulations, it is tremendously challenging to follow the production of photons and their propagation as they interact with matter (i.e., radiative transfer). First of all, the details of the RT depend on frequency, which can change as photons travel through space. In addition, photons can travel to large distances which makes them important over a wide range of scales. Because radiation can propagate far from the locations where photons are generated, radiation is more similar to gravity than hydrodynamical interactions. However, unlike gravity, for calculating the radiation field it is important to know what is between the sources of radiation and the point at which the radiation field is calculated. The time-dependency of the radiation field adds further complexity to RT calculations.



**Figure 1.1:** Different steps in the photon transport with TRAPHIC : 1- Emission (top panels): Photons are emitted isotropically from source particles to their SPH neighbors and then travel down-stream based on their propagation directions. 2- Transport (middle panels): photon packets are distributed among the neighboring particles that are within the transmission cone. If there is no neighboring particle inside the emission/transmission cones, virtual particles are created to transport photons along their propagation directions (not shown). 3- Merging (bottom panels): if two or more of the photon packets that a particle receives have close enough propagation directions, they are merged into a single photon packet with appropriately averaged direction.

#### **1.3.3 Radiative transfer with TRAPHIC**

Because of the reasons mentioned above, RT is sensitive to a large number of variables which makes it computationally expensive. Various techniques have been developed to reduce the computational cost of the RT, mainly by adopting different simplifying assumptions. Among different methods, TRAPHIC (TRAnsport of PHotons In Cones; Pawlik & Schaye, 2008, 2011) is a unique RT method with several important advantages, as is explained below, for radiation transport in cosmological simulations that use the SPH prescription. Since we use SPH simulations in this work, TRAPHIC is a natural choice to compute the RT. In the following we briefly review how photon transfer is done with TRAPHIC (see also Figure 1.1).

TRAPHIC is an explicitly photon-conserving RT method designed to transport radiation directly on the irregular distribution of SPH particles. This means that unlike many RT methods that use coarse grids to simplify the calculations, TRAPHIC exploits the full dynamic range that is available based on the underlying SPH simulation. Another challenge that RT methods face is the large number of sources in cosmological simulations. The computational cost of most RT methods is proportional to the number of radiation sources, which poses a big challenge for cosmological RT simulations. TRAPHIC solves this problem by tracing photon packets inside a discrete number of cones which renders the computational cost of the RT independent of the number of radiation sources. The two above mentioned advantages make TRAPHIC particularly well-suited for RT calculation in cosmological density fields with a large dynamic range in densities and large numbers of sources.

The photon transport in TRAPHIC proceeds in two steps: the isotropic emission of photon packets by source particles and their subsequent directed propagation on the irregular distribution of SPH particles. After sources emit photon packets isotropically to their neighbors, the photon packets travel along their propagation directions to neighboring SPH particles which are inside their transmission cones. Transmission cones are regular cones with solid angle  $4\pi/N_{TC}$  and are centered on the propagation direction. The parameter  $N_{TC}$  sets the angular resolution of the RT. The transmission cones are defined locally at the transmitting particle, and hence the angular resolution of the RT with TRAPHIC is independent of the distance from the source.

It can happen that transmission cones do not contain any neighboring SPH particles. In this case, additional particles (virtual particles, ViPs) are placed inside the transmission cones to accomplish the photon transport. The ViPs, which enable the particle-to-particle transport of photons along any direction independently of the spatially inhomogeneous distribution of the particles, do not affect the SPH simulation and are deleted after the photon packets have been transferred.

An important feature of the RT with TRAPHIC is the merging of photon packets, which guarantees the independence of the RT computational cost from the number of sources. Photon packets received by each SPH particle are binned based on their propagation directions in  $N_{\text{RC}}$  reception cones. Then, photon packets with identical frequencies that fall in the same reception cone are merged into a single photon packet with a new direction set by the luminosity-weighted sum of the directions of the original photon packets.

Photon packets are transported along their propagation direction until they reach the distance they are allowed to travel within the RT time step by the finite speed of light. At the end of each time step the ionization states of the particles are updated based on the number of absorbed ionizing photons.

By following the aforementioned steps, TRAPHIC calculates the radiation field in cosmological simulations and the ionization state of different species accurately (see Pawlik & Schaye, 2008, 2011). In this work, we mainly use TRAPHIC to calculate the ionization state of hydrogen by taking into account different sources of radiation.

#### 1.4 This thesis

Observational studies are moving rapidly beyond studying only the stellar components of galaxies, towards probing the important but complex processes that affect the distribution of gas in and around galaxies. Hydrodynamical cosmological simulations of galaxy formation are also improving rapidly by including better numerical techniques, more physically motivated and better-understood subgrid models and by using higher resolution. It is important, if not essential, to compare observations and simulations in order to improve our understanding of the observational results and to test/improve the simulations.

The neutral hydrogen distribution and its evolution is closely related to various aspects of star formation. This makes understanding and modeling the HI distribution critically important for studying galaxy evolution. The main focus of this thesis is therefore the study of the cosmic distribution of neutral hydrogen using hydrodynamical cosmological simulations. To do this, we combine hydrodynamical cosmological simulations based on the OverWhelmingly Large Simulations (OWLS; Schaye et al., 2010) with accurate radiative transfer, and account for different photoionizing processes.

In **Chapter 2**, we include the radiative transfer effects of the metagalactic UVB radiation and diffuse recombination radiation for hydrogen ionization at redshifts z = 5 - 0. We focus on studying HI column densities  $N_{\rm HI} > 10^{16} \,{\rm cm}^{-2}$ , where RT effects can be important. By modeling more than 12 billion years of evolution of the HI distribution, we show that the predicted HI column density distribution is in excellent agreement with observations and evolves only weakly from z = 5 to z = 0. We find that the UVB is the dominant source of HI ionization at  $z \gtrsim 1$ , but that collisional ionization becomes more important at lower redshift, which affects the self-shielding significantly. Based on our simulations, we present fitting functions that can be used to accurately calculate the neutral

hydrogen fractions without RT. Given the difficulty of RT simulations, these fitting functions are particularly useful for the next generation of high resolution cosmological simulations.

Stars typically form at very high column densities, where the gas is selfshielded against the external ionizing radiation. This makes local stellar radiation an important source of ionization at these column densities. However, simulating the effect of ionizing stellar radiation for the large numbers of sources that are typical of cosmological simulations, is extremely challenging. As a result, different studies have found different (and often inconclusive) results regarding the importance of local stellar radiation on the HI distribution. In Chapter 3, we tackle this problem by combining cosmological simulations with RT using TRAPHIC, which is designed to handle large numbers of sources efficiently. We simulate the ionizing radiation from stars together with the UVB and recombination radiation. We show that the local stellar radiation can significantly change the HI column density distribution at column densities relevant for the so-called Damped Ly $\alpha$  (DLA) and Lyman-Limit (LL) systems. We also show that the main source of disagreement between previous works is insufficient resolution, a problem we solve by using star-forming particles as ionizing sources. We also show that the absence of a fully resolved ISM in cosmological simulations is a bottle-neck for modelling the properties of strong DLAs (i.e.,  $N_{\rm HI} \ge 10^{21} \, {\rm cm}^{-2}$ ).

Strong HI absorbers, such as DLAs, are likely to be representative of the cold gas in, or close to, the ISM in high-redshift galaxies. Because of this, they provide a unique opportunity to define an absorption-selected galaxy sample and to study the ISM, particularly at the early stages of galaxy formation. However, because observational studies are limited by the small number of known strong HI absorbers and are missing low-mass galaxies in surveys for their counterparts in emission, it is very difficult to probe the relation between HI absorbers and their host galaxies observationally and we have to resort to cosmological simulations to help us understand the link between the two. In Chapter 4, we use the hydrodynamical cosmological simulations that we have shown to match the HI observations very well (see Chapter 2), to study the link between strong HI systems and galaxies at z = 3. We show that most strong HI absorbers are associated with low-mass galaxies too faint to be detected in current observations. We demonstrate, however, that our predictions are in good agreement with the existing observations. We show that there is a strong anti-correlation between the column density of strong HI absorbers and the impact parameters that connect them to their closest galaxies. We also investigate correlations between the column density of strong HI absorbers and different properties of their associated galaxies.

Similar to the neutral hydrogen, which provides fuel for star formation, the dust content of galaxies has a strong connection with their star formation activity. This makes studying the distribution and evolution of the dust also very important for understanding the evolution of galaxies. The low angular resolution of observations at long wavelengths makes identification and spectroscopy

of individual distant infrared galaxies a daunting task. Significant information about the evolution and statistical properties of these objects is encoded in the surface density of sources as a function of brightness (i.e., the source count). In **Chapter 5**, we present a model for the evolution of dusty galaxies, constrained by the 850*um* source counts and redshift distribution. We use a simple formal-

by the  $850\mu m$  source counts and redshift distribution. We use a simple formalism for the evolution of the luminosity function and the color distribution of infrared galaxies. Using a novel algorithm for calculating the source counts, we analyze how individual free parameters in the model are constrained by observational data. The model is shown to successfully reproduce the observed source count and redshift distributions at wavelengths  $70\mu m \leq \lambda \leq 1100\mu m$ , and to be in excellent agreement with the most recent *Herschel* and *SCUBA* 2 results.

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