Introduction

The Universe is build up from planets, stars and galaxies. Those are the objects that we can see, even with the naked eye on a clear night. The galaxies however are still small building blocks, embedded in galaxy clusters and much larger structures. Numerical simulations of the growth of cosmic structures predict large scale structures, with galaxy filaments on scales up to \( \sim 100 \) Mpc. The most famous of these simulations is the Millennium Run (Springel et al. 2005), simulating the evolution of the universe from \( z = 127 \) to the current epoch. The similarity on large scales between the simulations and optical surveys like the Sloan Digital Sky Survey (York et al. 2000) and the Two-Degree Field Galaxy Redshift Survey (Colless et al. 2001) is striking. While on large scales the correspondence between observations and simulations is remarkable, on smaller scales there is still a long way to go as there are many processes we do not understand.

Observations at different wavelengths have shown us beautiful images of the Milky Way and thousands of other galaxies. We can image the distribution of stars and gas in detail and measure the kinematics and rotation curves of galaxies. However when it comes to galaxy formation, we are not sure how gas that fuels star formation is accreting onto galaxies. We do not really understand the feedback processes by which the recycling of material is regulated. To truly understand the evolution of galaxies, we have to understand the interaction between galaxies and the Intergalactic Medium (IGM) in which they reside. Furthermore we have to understand the evolutionary path of baryons in the IGM with cosmic time, since in the current epoch this is a difficult region to explore observationally.

1.1 Missing Baryons

The abundance of baryonic matter has been determined from Big-Bang Nucleosynthesis (BBN) (Kirkman et al. 2003) and observations of the cosmic microwave background radiation (CMB) (e.g. Spergel et al. (2007)). The total number of baryons should amount to \( \Omega_b = 4.6 \pm 0.2\% \) of the total mass/energy density \( \Omega_b + \Omega_{\text{DM}} + \Omega_{\text{DE}} \). At redshifts \( z > 2 \) the majority of the baryons are thought to reside in the diffuse intergalactic medium traced by the Ly\( \alpha \) forest (e.g. Rauch et al. (1997); Weinberg et al. (1997)). Together with the mass found in
galaxies, the gas traced by the Ly\(\alpha\) forest can account for the total baryon budget and confirm the CMB measurements.

In the current epoch at \(z \sim 0\) only a small fraction of all the baryons can be revealed by adding up all the mass (stars, neutral H and He, molecular H and X-ray emitting plasma in clusters of galaxies) (e.g. Persic & Salucci (1992); Fukugita et al. (1998); Fukugita & Peebles (2004)). At low redshift the gas that is traced by the Ly\(\alpha\) forest can account for one third of the baryons (Danforth & Shull 2008), but the majority of the baryons is missing. This is the so called "missing-baryon problem".

\[ \text{1.2 The Cosmic Web and the WHIM} \]

Now we believe that the missing baryons are hidden in extended gaseous web-like filaments. The IGM, which was smoothly distributed in the early universe, organised into a Cosmic Web of large-scale structures with the passage of time. This Cosmic Web of gas filaments extending between the massive galaxies is a conspicuous prediction of high resolution numerical models of structure formation (e.g. Davé et al. (1999), Cen & Ostriker (1999), Davé et al. (2001)).

This gas is shock heated during the continuous gravitational collapse of filaments during structure formation to temperatures between \(10^5\) and \(10^7\) K. Due to the broad temperature range it is also called the Warm Hot Intergalactic Medium (WHIM). At high redshift the baryon budget was dominated by the Ly\(\alpha\) forest, however this thinned rapidly and the denser warm-hot component of the IGM became more important. An example of the Cosmic web at \(z = 0\) is shown in Fig. 1.1 from Cen & Ostriker (2006) where the spatial distribution of warm-hot gas is shown at low redshift, showing the characteristic appearance of a "Cosmic Web".

Calculations suggest that in the current epoch baryons are almost equally distributed by mass amongst three components: (1) galactic concentrations, (2) a warm-hot intergalactic medium (WHIM) and (3) a diffuse intergalactic medium (seen as the Ly\(\alpha\) forest). This is shown in the left panel of Fig. 1.2 from Davé et al. (1999) where the evolution of the three components (condensed, shocked and diffuse) is shown as function of redshift. The right panel of Fig. 1.2 shows the distribution of gas particles at redshift \(z = 0\) as function of density and temperature. The plot is roughly split in three regions, where the Ly\(\alpha\) forest is in the bottom left with low temperatures and low overdensities. In the bottom right is a narrow tail, which represents the gas that is condensed in galaxies with low temperatures and high densities. The rest of the plot is essentially the WHIM, with temperatures ranging from \(\sim 10^5\) to \(\sim 10^7\) K.

The three components are each coupled to a decreasing range of baryonic overdensity \(\log(\rho/\bar{\rho}_\text{H}) > 3.5, 1 - 3.5, \text{and } < 1\) and are probed by QSO absorption lines with specific ranges of neutral column density: \(\log(N_{\text{H}}} > 18, 14 - 18, \text{and } < 14\).

The main driving force behind the heating of the WHIM is shock heating of gas accreting onto large scale structure (Davé et al. 2001). In addition to shock heating, feedback processes following star formation in galaxies and galactic super winds (GSWs) can heat gas to the
The spatial distribution of warm-hot gas with temperatures between $10^5$ and $10^7$ is shown in a 85 $h^{-1}$ Mpc box. The same WHIM temperature range. While GSWs are less dominant than gravitational heating caused by the collapse of large-scale density waves, they nevertheless make about a 20% contribution to the overall WHIM mass (Cen & Ostriker 2006).

Like the intergalactic medium, WHIM gas does cluster around dense regions that are sites of galaxy formation and the easiest place to detect emission from the WHIM gas is relatively close to galaxies. Nevertheless most of the warm-hot gas is not contained in these regions but in the less-dense filaments (Davé et al. 2001): Shock heating occurs mainly in filaments rather than in virialised structures, and hence this gas remains at low overdensity. Furthermore a substantial component of shock heated gas within halos cools to $T < 10^5$ K during the assembly of galaxies within a group.

The existence of the WHIM is tentatively confirmed by a number of observations using oxygen lines and other heavy elements (e.g. Tripp et al. (2000); Tripp & Savage (2000); Oegerle et al. (2000); Scharf et al. (2000); Tittley & Henriksen (2001); Savage et al. (2002); Nicastro et al. (2002); Mathur et al. (2003); Kaastra et al. (2003); Finoguenov et al. (2003); Sembach et al. (2004); Nicastro et al. (2005b); Savage et al. (2005); Lehner et al. (2007) and Tripp et al. (2008)). No observational studies have been attempted so far, using the neutral hydrogen line.
Chapter 1: Introduction

Figure 1.2: Left panel: The evolution of baryonic mass fraction with redshift in a ΛCDM model. At z = 0 the three components contribute approximately equally to the total mass budget. Right panel: The distribution of gas particles as function of temperature and overdensity; both figures are from Davé et al. (1999)

1.3 Accretion and feedback processes

As mentioned before, an important step in galactic evolution is how gas particles move from the IGM into the galaxies, to cool down into virialised objects. There are several descriptions of how gas accretion might work (see e.g. Kereš et al. (2005)). The mode of accretion depends on the depth of the potential well in which the intergalactic gas resides. In the conventional picture of galaxy formation the gas is shock heated to roughly the virial temperature of the galaxy potential well (T ∼ 10^6 K), before cooling and condensing. Kereš et al. (2005) have shown that in many cases gas does not reach these high temperatures; instead it acquires its gravitational energy at lower temperatures, typically T < 10^5 K. The process is bimodal where 'cold mode' accretion dominates for low-mass galaxies with baryonic masses M_b < 10^{10} M_⊙ and 'hot-mode' accretion dominates in high-mass systems. The two paths are demonstrated in Fig. 1.3 from Kereš et al. (2005), where the trajectories of simulated particles is followed in time. The "cold" lines are illustrated by solid lines, while the "hot" lines are indicated by the dashed lines.

In the case of 'hot-mode' accretion the gas starts in the diffuse phase and moves steadily to the shock-heated phase. Once it reaches the virial temperature, it cools down very rapidly and condenses to reach the galactic phase. In 'cold-mode' accretion the gas starts in the diffuse phase and moves directly to the galactic phase along narrow filaments, without being shock heated to high temperatures.

On the other hand there are also processes that move gas and material from the galaxies into the IGM. In dense environments such as galaxy groups, gas is removed from galaxies through tidal and ram pressure stripping (e.g. Kantharia et al. (2005)) or during the accretion of gas-rich dwarfs onto large galaxies (e.g. Mayer et al. (2007)). Another process involves
The 21-cm line of neutral hydrogen

Figure 1.3: Hot mode (dashed lines) and cold mode (solid lines) for gas particles in a simulation. In hot mode accretion gas is shock heated to high temperatures and than rapidly cools down to condense in galaxies. In cold mode accretion the gas goes straight from the diffuse phase to the condensed phase; figure from Kereš et al. (2005)

galactic winds which eject material at galactic escape velocities (e.g. Heckman et al. (2001)). All these processes which remove material from the galaxies, also enrich the IGM with metals.

The best way to observe cold accretion in the local universe is through H\textsc{i} emission, an overview of recent detections is given by Sancisi et al. (2008). Detecting hot mode accretion is more difficult in H\textsc{i}, as the hot gas is highly ionised and the timescales on which the hot gas is cooling down to become condensed are relatively very short.

1.4 The 21-cm line of neutral hydrogen

In this thesis we will try to learn more about gas in the extended environment of galaxies and the IGM using the H\textsc{i} emission line.

Hydrogen is the lightest and most abundant element in the Universe, that contributes \( \sim 76\% \) to all the baryonic matter in the Universe. Although diffuse ionised hydrogen is difficult to observe, neutral atomic hydrogen is extensively used by radio astronomers, to in-
vestigate the kinematics of galaxies.

The 21-cm or H\textsc{i} line refers to the spectral line, that is emitted when a neutral hydrogen atom changes its energy state. The radiation causing the hydrogen line comes from the transition between the two hyperfine levels of the hydrogen 1s ground state. This transition occurs at a frequency of 1420.40575177 MHz, or approximately a wavelength of 21.1 cm.

The existence of the neutral-hydrogen line was predicted by van de Hulst in 1944 and observed for the first time by Ewen & Purcell (1951) and confirmed by Muller & Oort (1951) and Christiansen & Hindman (1952). Initially the 21-cm line was used to make H\textsc{i} maps of the galaxy, but was soon extended to the first extragalactic observations by Kerr & Hindman (1953), who observed the Magellanic Clouds.

Over the past decades, H\textsc{i} observations have developed very rapidly resulting in many radio telescopes and many thousands of detections all over the sky, both via pointed observations and blind surveys.

In general the H\textsc{i} radius of a galaxy is more extended than the optical radius. The neutral hydrogen line cannot only provide information about the kinematics within a galaxy, like rotation, but it can also trace merger and accretion events. As the sensitivity of radio observations has improved over the years, more evidence is found for tidal remnants and very extended H\textsc{i} emission in galaxies.

### 1.5 Extended H\textsc{i} halos around galaxies

Recent deep H\textsc{i} observations show that many galaxies have a huge gaseous halo, which is much more extended than seen before. Oosterloo et al. (2007) made observations of NGC 891 to a brightness sensitivity of $1.6 \times 10^{18} \text{ cm}^{-2}$ and revealed that almost 30% of the H\textsc{i} is in the halo. This is not the only case; deep studies of neutral hydrogen in several nearby spiral galaxies show that about 15% of the H\textsc{i} is located in the halo. Several examples are NGC 891 (Swaters et al. 1997), NGC 2403 (Fraternali et al. 2001), NGC 4559 (Barbieri et al. 2005), M31 (Westmeier et al. 2005), NGC 253 (Boomsma et al. 2005) and NGC 6946 (Boomsma et al. 2008).

The origin of this extended halo is a matter of debate, but feedback processes seem to play a major role. The galactic fountain mechanism (Shapiro & Field 1976) is a process that has received most attention. Stellar winds and supernova explosions push gas from the galaxy into the halo, this gas is mostly hot and ionised. This gas moves through the halo as it falls back to the galaxy, meanwhile it cools down and becomes neutral again (Bregman 1980).

Although there is observational evidence that favours this mechanism (Boomsma et al. 2008), the sample of observations is too small to prove that this is the mechanism causing the extended neutral halos. The fountain mechanism does also have complications, as Fraternali & Binney (2006) have shown that the kinematics of the neutral halo gas cannot be explained by galactic fountains alone. Accretion of gas from the intergalactic medium or interaction with a preexisting halo must play a major role.

Understanding the distribution of neutral hydrogen in the halo and extended environment of galaxies is important for several reasons. The halos are the regions where feedback processes happen that can exchange material within the galaxy. Eventually these circulation
<table>
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Table 1.1: Comparison of Blind H_i Surveys: (a): mJy beam⁻¹ at 18 km s⁻¹, (b): cm⁻² over 18 km s⁻¹, (c): Zwaan et al. (1997), (d): Rosenberg & Schneider (2000), (e): Braun et al. (2003), (f): Kraan-Korteweg et al. (1999), (g): Barnes et al. (2001), (h): Henning et al. (2000), (i): Minchin et al. (2003), (j): Lang et al. (2003), (k): Davies et al. (2004), (l): Minchin et al. (2007), (m): Giovanelli et al. (2007)

processes determine the life cycle of galaxies. Furthermore, halos are the interface between galaxies and the intergalactic medium (IGM).

1.6 H_i surveys

To study the distribution of neutral hydrogen on large scales and in many galaxies, blind surveys are needed, mapping a significant piece of the sky. In the last decades several blind H_i surveys have been carried out, to identify galaxies that contain H_i emission. Properties of several well known H_i surveys are listed in table 1.1, of which the ones that received most attention are probably HIPASS (Barnes et al. 2001) and ALFALFA (Giovanelli et al. 2005). Most H_i surveys have been undertaken with single dish telescopes. The disadvantage of single dish observations is that although they have excellent sensitivity to detect galaxies, they cannot resolve detailed structures. A big challenge for blind surveys is to observe a very large region, but still achieve sensitivities to map the faint extended environment of galaxies. Most conventional (interferometric) H_i observations are limited to a brightness sensitivity of a few time 10¹⁹ cm⁻². Due to their larger beam size, single dish telescopes can reach significantly lower column densities.

1.7 H_i edge

Deep, high resolution observations of galaxies indicate that in the outer disks the H_i column density decreases slowly with radius until a sharp edge occurs at N_Hi ~ 2 × 10¹⁹ cm⁻² (e.g. Corbelli et al. (1989), and more recently Portas et al. (2009)) These H_i edges are caused as the ratio of neutral to ionised hydrogen drops due to ionising radiation.

A sharp decline in H_i can occur over a narrow H_i -H_ii transition zone where the column
density gets sufficiently low so that the gas becomes optically thin to the extragalactic ionizing flux. That H\textsc{i} edges might result from extragalactic photoionization was first proposed by Silk & Sunyaev (1976).

The neutral hydrogen column density can decrease form $\sim 10^{19}$ to $\sim 10^{18}$ cm\textsuperscript{2} over a fairly small decrease of the total column density (e.g. Corbelli et al. (2001)). Examples of similar breaks have been found in the distribution of $N_{\text{HI}}$ of absorbers from the Ly\textalpha forest to Damped Ly\textalpha Systems (DLS) (Petitjean et al. (1993); Storrie-Lombardi et al. (1996); Storrie-Lombardi & Wolfe (2000)).

Dove & Shull (1994) have tried to explore the possibility that the apparent H\textsc{i} edges are caused by photoionization, but that the true edges are not being observed. This is demonstrated in Fig. 1.4 from Dove & Shull (1994) where the H\textsc{i} column density is plotted as function of radius. The dots in the plot represent real observed H\textsc{i} columns from NGC 3198 observed by van Gorkom. The solid line on the top represents the column density of total hydrogen, while the other lines represent the column density of neutral hydrogen obtained from a model with different photo-ionising fluxes.

In the central part of the galaxy the neutral column density is essentially identical to the total column density. The gas is completely dominated by self shielding in these very dense environments and the neutral fraction is unity. Towards the outer regions of the galaxy the effect of self shielding decreases as the density becomes lower and ionising radiation can penetrate. At a certain point the gas becomes optically thin; the very rapid decline in neutral fraction then stops and decreases more slowly as the neutral fraction is determined by the balance between photo-ionization and radiative recombination.
Figure 1.5: H\textsc{i} distribution function of M31 and its environment derived from different observations, the solid line is from Braun & Thilker (2004), the dashed line from Braun et al. (2003) and the dotted line is from Thilker et al. (2004). The filled circles with errorbars are the low red-shift QSO absorption line data as tabulated by Bandiera & Corbelli (2001).

The consequence of this effect is a plateau in the H\textsc{i} column density distribution of galaxies between column densities of $10^{17}$ and $10^{19}$ cm$^{-2}$ which is shown in Fig. 1.5 from Braun & Thilker (2004) where the H\textsc{i} distribution function of H\textsc{i} around M31 is plotted, together with data from QSO absorption lines tabulated by Bandiera & Corbelli (2001).

1.7.1 Flux sensitivity and brightness sensitivity

When reading this thesis, one should always be careful when sensitivities are mentioned, whether this is flux sensitivity or brightness sensitivity. Brightness sensitivity is directly linked to the beam size, that defines the angular resolution of the observation and thus the scale of structures that can be detected. The quoted sensitivities or fluxes in this thesis are not just numbers to consider in isolation; in each case they should be considered in combination with the beam size, to understand the physical implications.

Whether emission can be detected in a certain observation does not only depend on the integrated strength of the signal, but to a high degree it also depends on the angular extent.

When brightnesses are mentioned, the units are usually [Jy beam$^{-1}$] over a certain velocity interval. A point source filling just a fraction of the beam cannot be distinguished from a more extended source as long as the object is unresolved. To be able to make a distinction between
a compact and diffuse source, the H\textsubscript{i} column density is often used, where the flux density is divided by the beam area and scaled to units of [atoms cm\textsuperscript{-2}].

As we are looking for diffuse emission, we make use of the detectability of sources in observations at different angular resolution, this is illustrated schematically in Fig. 1.6. A bright compact source is represented on the left side by five vertical blocks, while an extended diffuse source is represented by five horizontal blocks. Each block represents a flux unit, so both sources intrinsically have the same amount of integrated flux. Two beam shapes are shown, a very compact beam (dark) and an extended beam (light). On the left side the source is unresolved in both beams and they both collect all the flux. On the right side however, the small beam can only observe a small fraction of the source at a time, while the large beam collects significantly more flux. Suppose the noise level for both beam types is 1 block beam\textsuperscript{-1} in arbitrary units. The right source is barely visible at the 1 or 2\textsigma level in the compact beam, while in the large beam it has a convincing 5\textsigma detection.

In the case of very extended and diffuse emission, a very significant detection is possible at low angular resolution without any sign of emission at high angular resolution, if the differences in beam area are large enough.

\begin{figure}
\centering
\includegraphics[width=\textwidth]{figure16}
\caption{Schematic representation of flux sensitivity per beam. A compact and extended source is represented by five blocks. The large beam is much more sensitive to extended emission.}
\end{figure}
1.8 This thesis

Imaging the Cosmic web is essential to understand the distribution and kinematics of diffuse systems. This intergalactic regime provides a wealth of information about structure formation: e.g. tidal filaments and feedback processes such as galactic winds or AGN driven cavities. Furthermore, observations of the Cosmic Web can test our cosmological model and can demonstrate under what conditions “cold-mode” or “hot-mode” accretion dominates.

In this thesis we will investigate the IGM using the H\textsc{i} emission line, by both exploring deep observations and numerical simulations.

Due to the moderately high temperature in the intergalactic medium of above $10^4$ Kelvin, most of the gas in the Cosmic Web is highly ionised. The neutral hydrogen component covers column densities from $10^{14}$ to $10^{19}$ cm$^{-2}$, but most of the H\textsc{i} will be in the Lyman Limit regime at column densities between $10^{17}$ and $10^{19}$ cm$^{-2}$.

Although conventional imaging in the 21-cm emission line of neutral hydrogen has not typically reached column densities below about $10^{19}$ cm$^{-2}$, this is not a fundamental limitation. Long integrations with an (almost-)filled aperture can achieve much lower limits, permitting direct imaging of the Cosmic Web down to $10^{17}$ cm$^{-2}$. The first such diffuse filament was detected between M31 and M33 by Braun & Thilker (2004) as is shown in Fig. 1.7, where an extended filament with very low column densities connects the two galaxies. Multiple independent lines of evidence demonstrate that the surface area subtended by atomic hydrogen at column densities near $10^{17}$ cm$^{-2}$ significantly exceeds that seen at $10^{19}$ cm$^{-2}$ (e.g. Corbelli & Bandiera (2002); Braun & Thilker (2004)).

1.8.1 Simulated H\textsc{i}

No matter how good observations are, at some level they are limited by sensitivity and the angular resolution of the telescope. We have reconstructed the distribution of neutral hydrogen from a hydrodynamic simulation. The reconstructed H\textsc{i} maps give the distribution of neutral hydrogen on large scales and describe the complete column density range from the Ly\textalpha forest to that of galaxies. Simulations are a good tool to test different cosmological models and feedback processes. Furthermore they can be used to make predictions for future observations.

1.8.2 H\textsc{i} observations

In the search for H\textsc{i} emission in the IGM we use three H\textsc{i} surveys at different angular resolutions.

Using the Westerbork Synthesis Radio Telescope (WSRT) the galaxy filament connecting the Local Group with the Virgo Cluster has been observed. This product is called the Westerbork Virgo H\textsc{i} filament survey (WVFS). The region from 8 to 17 hours in Right Ascension and from $-1$ to 10 degrees in Declination has been observed in a sequence of drift scans. The auto-correlations have been separated from the cross-correlations and a total-power product has been created. By using the WSRT array in single-dish mode, very high brightness sensitivity could be achieved because of the 25 meter sized dishes.
Figure 1.7: Integrated $\text{H}_\text{i}$ emission of the extended environment of M31 (top-right) and M33 (bottom-left); a diffuse filament connects the two galaxies. The gray scale varies between $10^{17}$ and $10^{18}$ cm$^{-2}$ and contour levels are drawn at $\log(N_{\text{HI}}) = 17, 17.5, 18, ..., 20.5$; figure form Braun & Thilker (2004)

A second survey product utilizes a subset of the original $\text{H}_\text{i}$ Parkes All Sky Survey (HIPASS) that was re-processed. By improving the noise characteristics, the new data product is more sensitive to diffuse and extended emission. Although the flux sensitivity of the HIPASS data is better than the WVFS total power flux sensitivity, the brightness sensitivity is worse due to the approximately ten times smaller beam size for the Parkes telescope compared to the WSRT dishes.

The cross-correlation data of the WVFS is used to create a high resolution data product. The region that has been observed with the WSRT was chosen such that the telescope had to observe at very extreme hour angles. In this way the individual dishes of the interferometer form a filled aperture of 300 meters in projection in one dimension. The configuration of the dishes is illustrated in Fig. 1.8.

By using this configuration, a brightness sensitivity can be achieved that is typical for single dish observations, while having the benefits of an interferometer in making a good estimate of the bandpass. This final data product has the best flux sensitivity amongst the three surveys, but the worst brightness sensitivity due to the relative compact synthesised beam.
1.8.3 Science goals

Each of the three surveys covers the same region in the sky with excellent brightness sensitivity. In each of the three surveys we are looking for new H\textsc{i} detections, where detections without an optical counterpart are of primary interest. These H\textsc{i} detections without optical counterpart do not directly belong to galaxies, and thus could be the densest components of the Cosmic web. By comparing the results of the three individual surveys we can confirm detections, and test whether new detections are compact or diffuse.

Although neither of the surveys have the angular resolution to resolve the details and edges of individual galaxies, we can observe the extended environment and are sensitive to very diffuse emission.

The main questions we hope to answer are:

- Can we detect diffuse neutral hydrogen in the IGM?
- If so, what is the physical extent and what is the typical column density of these features?
- Do galaxies have an extended halo of diffuse H\textsc{i}, that typically has not been observed, i.e. is there a connection between galaxies and the IGM?
- What is the kinetic temperature of diffuse gas, i.e. can we observe hot-mode or cold-mode accretion?
- Can simulations be used to reconstruct the distribution of diffuse neutral hydrogen?

Observations of the IGM at low redshift, and detection of Cosmic Web features is essential to understand structure formation and feedback processes. Furthermore, it can also confirm the cosmological model that applies.

With the three H\textsc{i} surveys we can have an unbiased look at a significant piece of the sky to look for the denser parts of the IGM where traces of neutral hydrogen can be found.

Figure 1.8: Configuration of the WSRT dishes during the WVFS observing runs. Due to the extreme hour angles, a filled aperture is created in projection.
1.9 Thesis outline

Although the main theme in this thesis is to understand the distribution of neutral hydrogen using simulations and observations, there is also a short technical chapter. After this introductory chapter (Chapter 1), Chapter 2 will discuss the standing wave phenomenon in radio telescopes in general, but especially in the case of the Westerbork Synthesis Radio Telescope. To achieve the best image fidelity when doing observations, a good understanding of the behaviour of the telescope is crucial. We have modeled the frequency modulation in the primary beam of the WSRT.

In Chapter 3 a method is presented to reconstruct the neutral hydrogen component of a hydrodynamic simulation, containing dark matter, star and gas (SPH, Smoothed Particle Hydrodynamics) particles. H\text{I} maps are created in a low and high resolution grid, that show the distribution of neutral hydrogen on large scales. The reconstructed maps can be used to simulate mock observations of currently existing and future telescopes.

In Chapters 4 to 6, the three individual H\text{I} surveys are presented: the WVFS total-power data, the re-processed HIPASS data and the WVFS cross-correlation data. For each survey the observing strategy and data reduction are explained. A catalogue of detected objects is presented and in each chapter we concentrate on new H\text{I} detections.

The discussion in Chapters 4 to 6 is fairly short, as the three data products are compared in Chapter 7. The flux densities of the three different observations are compared and we look for confirmation of previous new detections and additional new detections by comparing the three data-sets. New H\text{I} detections are analysed in more detail and we search for common properties.

We present a short summary of all the work in Chapter 8, together with some notes for future work and observations.