Atomic hydrogen in the local universe
Zwaan, Martin Alexander

IMPORTANT NOTE: You are advised to consult the publisher's version (publisher's PDF) if you wish to cite from it. Please check the document version below.

Document Version
Publisher's PDF, also known as Version of record

Publication date:
2000

Link to publication in University of Groningen/UMCG research database

Citation for published version (APA):
Introduction

Atomic hydrogen gas plays a vital role in galaxy evolution. In the widely accepted hierarchical galaxy formation scenario, overdense regions collapse in a hierarchical fashion and structures grow through continuous accretion of smaller mass halos consisting of a mixture of non-baryonic dark matter and gas. The primordial gas dissipates energy when it is confined within a dark halo, allowing it to collapse to become the HI reservoir which forms the fuel for the formation of stars. The density and angular momentum of the HI as it collapses determines much of the properties of the visible part of galaxies as we observe them at the present time. A full assessment of the HI content and distribution of HI in the universe is therefore essential for understanding galaxy evolution.

Most evolutionary studies make use of the optical wavelengths exclusively and therefore concentrate mainly on the stellar component of the galaxies. The obvious reason for this preference is that the HI is much more difficult to chart than the star light. In a typical spiral galaxy the energy output from normal stars is millions of times higher than that from HI in the 21cm line, while the total mass in stars is only four times that of the mass in neutral gas. As a result, 21cm emission line studies have been limited to the very local (z < 0.1) universe. Absorption line studies (21cm or Lyman α) can help a great deal, but these are limited to those regions of the universe that are coincidently aligned with the observer and a strong background source that provides the continuum emission against which the gas can be detected.

The physics of radio emission from HI is simple. The mechanism responsible for the 21cm line is the hyperfine splitting of the hydrogen atom. In most situations, the population of the hyperfine levels is fully determined by collisions of HI atoms. The lifetime of the upper level is much higher than the typical time between collisions and the energy difference between the levels is very small. As a result, the efficiency of 21cm emission of an HI cloud is almost independent of its temperature and density. The radiation escapes freely and the HI column density can be readily derived from the brightness of the emission without attenuation by dust, which blocks optical wavelengths.

The aim of this thesis is to present an inventory of the atomic hydrogen gas in the
local universe. Where is the H I? How is it distributed among different types of galaxies? Are there large quantities of H I locked up in dim galaxies that are easily overlooked in optical surveys? How does the amount of H I at the present epoch compare to that at earlier times? This introductory chapter briefly presents a background for the questions addressed in this thesis.

1.1 H I as a tracer of the local galaxy population

The 21 cm line has been used extensively as a kinematic tracer of the galactic potential of spiral galaxies. Indeed, one of the main motivations for the theoretical derivation of the 21 cm line (van de Hulst 1945) and subsequently measuring it (Ewen & Purcell 1951; Muller & Oort 1951), was to study the structure of the Milky Way Galaxy. Since then, the 21 cm line has been used to map the H I distribution and velocity field of many galaxies, leading to the recognition of dark matter and measurements of its distribution (Bosma 1978, van Albada 1985).

Besides providing this indicator of dark matter in galaxies, the 21 cm line serves as a useful tracer of the local galaxy population and provides a way to appraise the completeness of optical galaxy catalogs. Optical selection effects have long been known to introduce biases in these catalogs. Soon after Freeman (1970) found that most nearby spiral galaxies have nearly equal optical central surface brightness of 21.65 mag arcsec$^{-2}$, Disney (1976) realized that this observation could be the result of a selection effect. Disney showed that the brightness of the night sky and conventional selection techniques conspire to disclose only disk galaxies with central surface brightnesses close to Freeman’s value\(^1\). It was speculated that the true dynamic range of central surface brightness is much larger than previously thought, and that a class of galaxies with very low optical surface brightness (LSB galaxies) could have escaped inclusion in conventional galaxy catalogs. These galaxies might contain a significant fraction of the mass content of the universe.

There are several ways to break the surface brightness selection bias. One approach has been the inspection of new photographic survey material to search for galaxies to much lower surface brightness limits. Candidates are followed up with optical or H I spectroscopy to determine distances. This technique was applied by Schombert et al. (1992) to the Second Palomar Sky Survey and by Impey et al. (1996) with the Automated Plate Measuring (APM) technique on UK Schmidt Telescope plates. The analysis of the latter survey by Sprayberry et al. (1997) showed that the space density of LSB galaxies might be comparable to that of normal “Freeman-galaxies". Deep CCD-surveys (Dalcanton et al. 1997, O’Neil, Bothun, & Cornell 1997) yield basically the same conclusion. Despite their selection for low optical surface brightness, the integrated luminosity and H I content for these galaxies is often high.

One of the most famous results of the surveys for LSB galaxies is the detection of Malin 1 (Bothun et al. 1987). With an extrapolated disk central surface brightness of 26.0 B–mag arcsec$^{-2}$, a disk scale length of $60 h^{-1}_{100}$ kpc and a total H I mass of $4 \times 10^{10} h^{-2}_{100} M_\odot$ (Pickering et al. 1997), this may be one of the most extreme galaxies known. Malin 1 seems to be a spectacular example of the class of galaxies known as “crouching giants", that were predicted by Disney: massive, intrinsically luminous galaxies that are hiding from detection. Note however that its total central surface brightness

\(^1\) A similar effect, known as the Fish-law (Fish 1964) is known to exist for elliptical galaxies. Disney (1976) showed that also this effect could be the result of a selection bias.
(disk plus bulge) is \( \approx 20.5 \) \( \text{B}-\text{mag arcsec}^{-2} \). This is not a galaxy that would be missed if it were located in the Virgo cluster instead of \( 240 h_{100}^{-1} \) Mpc behind it.

Much less conspicuous LSB galaxies do exist. Especially the less luminous dwarf galaxies might easily be missed in optical surveys that select on the basis of stellar content, star-forming regions, or material associated with stellar mass-loss. Among the dimmest galaxies are gas-rich systems that have gas masses well in excess of their stellar mass. Searching for galaxies in the 21cm line can therefore help to develop a fair view of the local galaxy population and might even turn up pristine "proto-galaxies", dark matter potential wells filled with neutral gas that have been unable to convert any of their innate gas into stars. The search for such a new class of galaxies was one of the motivations for this thesis.

### 1.2 The evolution of \( \Omega_{\text{gas}} \)

The cosmological neutral gas density of the universe is one of the fundamental observational parameters that describes the formation and evolution of stars in galaxies and charts the processes that convert gas into stars. Linked with other indicators that have recently received much attention, such as the cosmic star formation rate (Madau 1996), the luminosity density (Lilly et al. 1996) and the metal enrichment rate (Connolly et al. 1997), it gives strong constraints on galaxy evolution models.

At high \( z \), \( \text{Ly} \alpha \) absorption lines that are identified in the spectra of background quasars are used to trace the neutral gas content. Most of the observed lines correspond to low column densities and trace the mostly ionized fraction of the gas. The scanty high column density absorbers or damped \( \text{Ly} \alpha \) (DLA) systems contain by far most of the neutral gas (Turnshek 1997). Most observations point to DLAs at high \( z \) being gas-rich disks in the process of contracting to present-day spiral galaxies (Wolfe 1995). The absorption line structures of associated unsaturated metal lines and Lyman series lines in DLA systems are similar to those of sight lines through spiral galaxies at \( z = 0 \) (Prochaska & Wolfe 1997). The fact that the comoving \( \text{H} \alpha \) mass density at \( z = 3 \) is equal to the mass in stars at \( z = 0 \) (Wolfe 1995, Fukugita, Hogan & Peebles 1998) supports this idea.

The picture emerging from these DLA studies is that \( \Omega_{\text{HI}} \) was slightly rising at the time corresponding to \( z > 3.5 \), followed by a nonvariable period from \( z \approx 3.5 \) to \( z \approx 1 \) (Storrie-Lombardi & Wolfe 2000). The evolution of \( \Omega_{\text{HI}} \) in the period from \( z \approx 1 \) to \( z = 0 \) is not well determined. Rao & Turnshek's (1999) results indicate that \( \Omega_{\text{HI}} \) was constant to \( z \approx 0.5 \), after which it must decline rapidly to \( z = 0 \). This implies that most of the conversion from gas to stars occurred between \( z \approx 0.5 \) to \( z = 0 \). Lane's (2000) measurement based on \( \text{Mg} \) ii-selected absorption systems is in agreement with this, although a more gradual evolution is also consistent with her findings.

To interpret these results, it is crucial to obtain a reliable \( z = 0 \) anchor point. Just as the optical morphologies of galaxies, their luminosities, and stellar populations at \( z = 0 \) are fundamental to the study of galaxy evolution, the complete census of \( \text{H} \alpha \) and its distribution among and within galaxies at present defines the relation between star formation and the raw material from which stars are made.

Determining the current neutral gas content requires a different observational technique than at high \( z \). The small cross-section of DLA absorbers, combined with cosmological expansion, make DLAs very rare along any QSO sightline through the local universe. DLA survey results for the low-\( z \) regime must be given in \( \Delta z = 0.5 \) bins, which are sig-
nificant fractions of a Hubble time. Furthermore, the effects of dust (Pei, Fall & Hauser 1999), and the fact that the Ly$\alpha$ line is not observable from the ground at $z < 1.65$ complicate the measurement at the present epoch. Furthermore, the historical requirement for QSO catalogs that objects be “quasi-stellar” means that only quasars away from foreground galaxies have been selected to search for absorption lines, and it is therefore not surprising to find that at low redshift optical identification of galaxies responsible for DLA absorption is often problematic (cf., Rao & Turnshek 1999).

At $z = 0$, 21cm emission from galaxies and possible intergalactic clouds is the logical indicator for the cosmological mass density of H $\perp$. One of the principle results of this thesis is the measurement of an accurate and unbiased value for $\Omega_{\text{HI}}(z = 0)$ from a radio survey. The first steps toward 21cm line measurements of $\Omega_{\text{HI}}$ as a function of redshift are shown in Chapter 8, where preliminary results on the gas content of galaxies in a cluster at $z = 0.2$ are presented.

1.3 The H $\perp$ mass function

Quantifying the space density of H $\perp$-holding objects is normally done with a tool known as the H $\perp$ mass function (HiMF). This function is defined analogously to the commonly discussed optical luminosity function and defines the number of galaxies per cubic Mpc as a function of H $\perp$ mass $M_{\text{HI}}$. A reliable measurement of the HiMF contains considerable information: 1) construction of the HiMF yields an alternative view of the local galaxy population based on gas-richness rather than optical brightness; 2) integration over the HiMF readily yields a measurement of $\Omega_{\text{HI}}$; 3) the HiMF indicates which types of galaxies currently form the main reservoirs of fuel for star formation; 4) models of galaxy formation require a detailed measurement of the HiMF to test the predictions (e.g., Somerville & Primack 1999; Cole et al. 2000).

A first order computation of the HiMF can be made by using measured H $\perp$ fluxes of a sample of optically selected galaxies with well-understood selection criteria. For example, Hoffman et al. (1989) conducted a series of pointed observations with the Arecibo telescope of known galaxies in the Virgo cluster. They constructed a preliminary HiMF and concluded that there is no excess of gas rich dwarf galaxies. Briggs (1990) made the first computation of the HiMF for optically selected galaxies and further concluded that there was unlikely to be a significant $z = 0$ population of intergalactic H $\perp$ clouds of large mass. Briggs & Rao (1993) reappraised the Hoffman et al. Virgo data, supplemented with the Fisher & Tully (1981b) catalog of H $\perp$ observations of spiral galaxies, and were able to construct the HiMF over the range $10^7$ to $10^{10}$ M$_\odot$. They also concluded that there is no evidence for a sharp rise in the number of gas rich dwarf galaxies toward low masses, and that in clusters the HiMF might even go down.

While these were interesting exercises, they do not solve the surface brightness selection bias. H $\perp$ clouds that are totally devoid of stars are missed completely if a sample of optically selected galaxies is used to calculate the HiMF. A complete and unbiased view of neutral gas in the local universe can only be obtained using blind 21cm surveys. The computation of the HiMF is a logical step in the analysis of 21cm line surveys, leading to a value for $\Omega_{\text{HI}}$. This thesis reports the first HiMF that fully recovers the known galaxy population. This HiMF is valid over three orders of magnitude in H $\perp$ mass. In the following paragraph I give a brief overview of recent work on H $\perp$ surveys.
1.4 Extragalactic H I surveys

H I surveys are time-consuming. Blind surveys in the 21 cm line take hundreds of hours of observing time to yield only few dozen galaxies, while optical surveys systematically produce catalogs of thousands of galaxies. For illustration, the first published blind H I survey in the field (Shostak 1977) took many days of observing time with the NRAO 300 ft telescope and yielded only one detection which later turned out to be a high velocity cloud gravitationally bound to the Milky Way galaxy. In order to increase the detection efficiency many surveys were pointed toward known overdensities: groups and clusters of galaxies. Surveys in the M81, Sculptor, CVn I and NGC 1023 groups (Lo & Sargent 1979; Haynes & Roberts 1979; Fisher & Tully 1981a; Kraan-Korteweg et al. 1999) yielded several new LSB systems but no H I clouds. Clusters that were surveyed in H I are Hydra (McMahon 1993), Hercules (Dickey 1997), and Centaurus and Fornax (Barnes 1997). No surprises were found there with respect to the H I MF: a similar shape is found in these clusters and in the field.

Empty regions of sky have also been the subject of H I surveys. It is interesting to investigate if the morphology-density relation (Dressler 1980) persists down to the lowest density regions and whether very LSB or dark galaxies might be filling the voids. Krumm & Brosch (1984) performed drift-scan surveys in the Perseus and Hercules voids. Although they covered an enormous volume (∼ 4500 l/100 Mpc³), their H I mass sensitivity would have allowed them to detect only the most massive of galaxies with $M_H > 10^{10} M_\odot$.

Szomoru et al. (1996) observed selected fields in the Boötes void and found no differences in the properties of void galaxies and field galaxies. No new population of gas rich dwarfs or LSB galaxies was found, although the survey volumes were small and the detection limits not very restrictive.

A fair calculation of the H I MF for H I selected galaxies requires a blind H I survey of the field, with no preference to known over- or underdensities. Henning (1995) conducted a series of pointings on lines of constant declination over a redshift range of 7200 km s⁻¹. A total number of 39 significant detections were recorded, of which 50% were previously unknown. While Henning's H I MF seems to be indicative of an increasing number of dwarf galaxies, the overall function lies below the lower limit to the H I MF set by counting the optically selected population. Two large surveys in the 21 cm line have been conducted recently, both with the Arecibo telescope. The results from one of these surveys, named AHIS (Arecibo H I Strip Survey) forms the basis for Chapters 2, 3 and 4 of this thesis. The other survey, similar in size, is described in Spitzak (1996) and Schneider, Spitzak & Rosenberg (1998). The Arecibo Dual-Beam Survey (Rosenberg & Schneider 2000) covers a larger area on the sky, but is less sensitive to low column density gas than the AHIS. Unfortunately, systematic optical follow-up on this survey does not yet exist. Eventually, the HIPASS survey (Staveley-Smith et al. 1996) with the Parkes Telescope, which covers the entire southern sky out to 12,700 km s⁻¹, will yield a sample of thousands of H I selected galaxies.

1.5 The faint tail of the H I MF

The faint tails of the H I MF and the optical luminosity function deserve special attention. The slope of the faint-end is determined by the shape of the distribution function of primordial density fluctuations, a complex interplay of various astrophysical processes during galaxy formation and evolution, and dynamical evolution dependent on the local
galaxy density. The slope of the faint end of the luminosity function is still uncertain; published values range from $\alpha = -2.0$ to $\alpha = -0.7$ (Compare Lin et al. 1996 and Loveday 1997), where $\alpha$ is defined as $N(L)dL \propto L^{-\alpha}dL$.

The hierarchical clustering scenario is presently the most widely accepted model for galaxy formation (e.g. Kaufmann 1996). It explains the formation of galaxies by many generations of mergers of dark matter dominated smaller masses. Observational support comes from a increasing merger fraction of field and cluster galaxies with increasing redshift (Lavery et al. 1996, van Dokkum et al. 1999). Numerical models based on the hierarchical scenario generally predict steep slopes of the mass function since large numbers of low mass halos might survive to the present day if the merging and accreting is not fully efficient (Klypin et al. 1999; Moore et al. 1999). On galaxy and galaxy group scales, the predicted halos outnumber optically identified satellites by a factor of 10. If no stars have been found associated with the halos, their baryonic content must consist of primordial gas. Whether the cloud densities are sufficiently high to shield the gas from ionization by the extragalactic uv background determines if most of the baryonic content is neutral or not.

Blitz et al. (1999) have argued that high velocity clouds (HVCs) are either remnants from the formation of the LG or as representatives from an intergalactic population of dark matter dominated mini-halos in which hydrogen has collected and remained stable on cosmological time scales. This scenario gives an appealing solution for the missing satellite problem as it both predicts the right number of dark matter halos (between 500 and 2000) and also shows how the dynamical evolution of the Local Group with infalling gas can reproduce the distribution of the HVCs on the sky.

$\text{H}^\text{I}$ surveys in galaxy groups provide the way to settle the issue of missing satellites. If the flatness of the $\text{H}^\text{I}$ mass function persists down to the lowest masses, current hierarchical clustering models may have to be re-evaluated as this requires severe suppression of the primordial density fluctuation spectrum on small scales (Kamionkowski & Liddle 1999). Self-interacting dark matter (e.g., Spergel & Steinhardt 1999) and other dark-matter flavors (fluid dark matter, repulsive dark matter) have been suggested as possible explanations for a less efficient formation of small mass halos.

It should be noted that the faint tail of the $\text{H}^\text{I}$MF might also have ramifications for the determination of $\Omega_\text{H}$. There might be substantial amounts of $\text{H}^\text{I}$ hiding in very small masses if the faint tail rises to $\alpha = -2$ or steeper. This would have important implications on the interpretation of the evolution of $\Omega_\text{H}$. In this thesis we report two surveys of nearby groups and galaxy halos where extragalactic analogs of the HVCs should be detected if they are massive enough to make up the missing satellites.

1.6 Brief thesis outline

The Chapters 2, 3, and 4 of this thesis are devoted to the results of the Arecibo $\text{H}^\text{I}$ Strip Survey, the most sensitive blind $\text{H}^\text{I}$ survey of the extragalactic sky to date. Chapter 2 presents the 21 cm and optical follow-up on the 66 detections that were made in this survey. The sample is divided into two subgroups: previously identified galaxies and newly discovered galaxies. It is tested whether the new galaxies have properties that set apart from their optically selected counterparts.

A detailed analysis of the survey sensitivity and possible influence of large scale structure is given in Chapter 3. The $\text{H}^\text{I}$MF and the cosmological mass density of $\text{H}^\text{I}$ are calcu-
lated and compared to previous determinations. Chapter 4 presents the optical luminosity function and surface brightness distribution of H I selected galaxies. It is tested whether the space density of LSB galaxies is in agreement with previous determinations based on deep CCD surveys. We also calculate the contribution that LSB galaxies make to the local cosmic baryon density and total mass density.

In Chapter 5 a connection is made between QSO absorption line statistics and H I measurements in the local universe. The tool that is used is the column density distribution function, \( f(N_{\text{HI}}) \), which describes the change of finding a certain column density \( N_{\text{HI}} \) along a normalized path length. A \( z = 0 \) measurement of \( f(N_{\text{HI}}) \) is calculated from 21cm observations of nearby galaxies.

The next two chapters concentrate on the lowest H I masses. In Chapter 6 we calculate whether the model in which Galactic high velocity clouds (HVCs) are actually distributed throughout the Local Group is in agreement with the results of blind H I surveys. In Chapter 7 a targeted survey for H I clouds in five galaxy groups is discussed.

In Chapter 8 we make a short excursion to higher redshift to present the first results of a program of deep H I imaging of galaxy cluster Abell 2218 at \( z = 0.2 \).

Finally, a summary of the main conclusions and a brief outlook are presented in Chapter 9.

References

Krumm, N., & Brosch, N. 1984, AJ, 89, 1461
Lane, W. M. 2000, Ph.D Thesis, University of Groningen
van de Hulst, H. C. 1945, Ned. Tijd. Natuurk., 11, 210