The hix Galaxy Survey
– How H\text{I} eXtreme galaxies maintain their H\text{I} reservoir –

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Abstract

Galaxies are vast systems of stars, gas, dust and dark matter. Stars are formed from gas, with the atomic hydrogen (H\textsubscript{i}) in galaxies being the raw fuel for the formation of giant molecular gas clouds. These clouds are the birthplaces of stars. In order to continue this process in the future, galaxies need to replenish their gas reservoir. Simulations and theory suggest two main avenues through which galaxies can do that: they can accrete gas directly from the intergalactic medium (cosmological or smooth accretion) or gas-rich satellites can fall into the galaxy (gas-rich minor mergers, clumpy accretion).

Observations of galaxies in the local Universe have been searched for ongoing gas accretion such as gas-rich minor mergers, gas accreted from the intergalactic medium, high velocity clouds or gas that is being reaccreted after it was expelled by star formation (e.g. the Galactic Fountain model). While all these phenomena have been detected, the total amount of gas that has been found to accrete onto galaxies, is still about one order of magnitude less than required to balance the amount of gas that is converted into stars (Heald, 2015; Sánchez Almeida et al., 2014a; Sancisi et al., 2008).

This thesis investigates gas-rich galaxies and the origin of their large gas content. If they are gas-rich, because they recently accreted gas, they should be perfect laboratories to study the mechanisms of gas accretion. If they are gas-rich because they are inefficient at forming stars from their given H\textsubscript{i} reservoir, then the study of these galaxies helps to understand which mechanisms regulate the galactic gas cycle. A sample of H\textsubscript{i} eXtreme (HIX) galaxies has been selected from a compilation of the HIPASS catalogues (Meyer et al., 2004; Koribalski et al., 2004), which should only include single galaxy detections with good optical photometry from HOPCAT (Doyle et al., 2005). Based on these catalogues, Dénes et al. (2014) have calibrated scaling relations between the stellar luminosity and the absolute H\textsubscript{i} mass. Galaxies within the HIX sample are galaxies that contain at least 2.5 times more H\textsubscript{i} than expected from their stellar luminosity and have stellar masses log $M_*$ [M\textsubscript{☉}] > 9.7.

To understand why the HIX galaxies are so H\textsubscript{i}-rich, they are compared to a CONTROL sample, the larger galaxy population and galaxies simulated with the semi-analytic model DARK SAGE (Stevens et al., 2016). Furthermore, observations of their H\textsubscript{i} content and the gas-phase metallicity distribution are examined for signs of gas accretion. It is found that the star formation rates of HIX galaxies are normal for their stellar mass and comparable to the CONTROL sample. Due to their H\textsubscript{i}-richness, it immediately follows that HIX galaxies are less efficient at forming stars from their available H\textsubscript{i} than CONTROL galaxies. The
reason for that is the larger than average H\textsubscript{I} specific angular momentum, which is not
driven by a large rotation velocity but by large amounts of H\textsubscript{I} at large radii. Due to
its large specific angular momentum, this H\textsubscript{I} is prevented from migrating towards the
centre of the galaxy, where stars could be formed from it, and the gas disc is stabilised
against gravitational instabilities. Thus H\textsubscript{I}X galaxies effectively park gas at large radii.
The reasons why H\textsubscript{I}X galaxies have large H\textsubscript{I} specific angular momentum are explored with
the semi-analytic model DARK SAGE. By selecting a H\textsubscript{I}X- and a CONTROL-like galaxy
sample from the DARK SAGE simulated galaxy catalogue, the halo spin parameters of
these two sample has been compared. It was found that H\textsubscript{I}X galaxies tend to reside in
dark matter haloes with higher spins than CONTROL galaxies. Hence, H\textsubscript{I}X galaxies inherit
their elevated angular momentum properties from their dark matter haloes. Neither the
distribution of the gas-phase metallicity within the stellar disc of the H\textsubscript{I}X galaxies, nor
their H\textsubscript{I} kinematics and morphologies show signs of recent elevated gas accretion.

In summary, H\textsubscript{I}-rich galaxies like the H\textsubscript{I}X galaxies reside in dark matter haloes with
higher spins and are thus able to host larger amounts of H\textsubscript{I} at large radii than average
galaxies. This gas can not participate in star formation and thus they accumulate large
H\textsubscript{I} discs over time. There is no evidence that these galaxies accrete gas more actively
than the average galaxy population in the local Universe.
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\(^{1}\)http://www.numpy.org/
\(^{2}\)https://www.scipy.org/
\(^{3}\)http://matplotlib.org/
\(^{4}\)https://aplpy.github.io/
Declaration

The work presented in this thesis has been carried out in the Centre for Astrophysics & Supercomputing at Swinburne University of Technology between 2014 and 2017. This thesis contains no material that has been accepted for the award of any other degree or diploma. To the best of my knowledge, this thesis contains no material previously published or written by another author, except where due reference is made in the text of the thesis.

The content of the chapters listed below is based on papers that have appeared in or are under revision by refereed journals. Alterations have been made to the published papers in order to maintain argument continuity and consistency of spelling and style.

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TO MY PARENTS
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3.1 Properties for four HighMass galaxies ................................................. 78
Humans have always been fascinated by a beautiful night sky. When looking up to the sky on a clear and dark night, the bright band of the Milky Way spans across the sky (Figure 1.1), only to be covered up in part by the dust of the Milky Way disc. The Ancient Greeks defined constellations based on the positions of the stars. A well-know example is Orion, the hunter. The three prominent stars of his belt are also relevant to the stories...
surrounding the night sky in other cultures: many aboriginal peoples of Australia also see hunters or young men in the three bright stars of the belt (Norris, 2016). Many aboriginal cultures not only interpret the stars of the Milky Way but also the Milky Way’s dust lanes. The shape of the dust obscured central part of the Milky Way is for example interpreted as the “Emu in the Sky” (as highlighted by the blue shape in Figure 1.1, Norris, 2016).

While bright stars, such as the belt of Orion, are visible with bare eyes, Galilei (1610) was only able to show that the entire Milky Way band is made up of individual stars when the first telescope became available. Based on the work of Wright (1750), Kant (1755) suggested 150 years after Galileo’s pioneering work that the Milky Way and other “nebulae” like Andromeda are actually rotating systems of stars, and “island Universes”. It took another two centuries before Slipher (1917) and Hubble (1926) were able to confirm with observations that these nebulae are indeed galaxies outside of the Milky Way. In addition, Hubble (1926) introduced a classification scheme for galaxies, which distinguishes between spiral, elliptical and irregular galaxies. Together with his observation that the Universe was expanding (Hubble, 1929), this was the beginning of modern astronomy and cosmology.

Investigating the relative velocities of galaxies in the Coma cluster (and thus the gravitational potential of the cluster), Zwicky (1933) found that the observable part of the cluster would not provide enough mass to gravitationally bind the cluster. Rubin & Ford (1970) measured the rotation of galaxies to very large radii and found again that there is not enough observable matter to explain the large rotation velocities at large radii if assuming Keplerian rotation. These observations suggest that the Universe not only contains visible, observable matter, but also so-called dark matter. Based on observations of the large-scale structure of the Universe, it is concluded that dark matter is made of kinematically cold, heavy particles (Blumenthal et al., 1984). Their actual nature, however, is yet to be determined.

As mentioned above, Hubble (1926) was one of the first to measure that the Universe is expanding. Later, Perlmutter et al. (1997), Riess et al. (1998) and Perlmutter et al. (1999) showed that the Universe is actually experiencing an accelerated expansion. Their conclusion was made possible by observations of supernovae Type Ia. The acceleration of the expansion is thought to be driven by the so-called dark energy and can be described by a constant (Λ) in the equations of general relativity (Einstein, 1916).

The combinations of these observations define the Λ-cold-dark matter cosmology (ΛCDM), which is the basis of today’s standard model of the Universe. Measurements suggest that

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the mass/energy density in the Universe is distributed between baryonic matter (the observable part of the Universe, 4.6 per cent), dark matter (24 per cent) and dark energy (71.4 per cent) (Hinshaw et al., 2013).

Within this model, the history of the Universe began about 13.7 Gyr ago with the Big Bang (Lemaître, 1927; Penzias & Wilson, 1965). Right after the Big Bang the Universe was hot and dense, and then gradually cooled down and expanded. Expansion of the very early Universe (around $10^{-34}$ s after the Big Bang) had to be faster than the speed of light to explain why the cosmic microwave background (CMB) is relatively uniform over the entire sky. This faster-than-light expansion is called inflation (Guth, 1981; Schneider, 2006). A few minutes after the Big Bang, the Universe had already cooled to temperatures around $10^9$ K when nucleosynthesis of light elements such as Helium and Lithium became possible (Mo et al., 2010). The temperature was still too hot to form neutral atoms, so at this stage the Universe contained ionised atom nuclei (e.g. protons, Helium nuclei), neutrons, electrons, neutrinos and photons. With the Universe further expanding and thus cooling down, it reached temperatures of 4000 K after about 200,000 years. At this point in time, approximately half of the baryonic matter had recombined into neutral atoms. As more and more electrons were bound in atoms, photons became less and less likely to interact with the electrons and were able to move freely. Today these decoupled photons are observed as the CMB (Penzias & Wilson, 1965).

Smoot et al. (1992) first observed small perturbations in the temperature of the CMB in observations from the COBE satellite. Through accretion and merging, these small perturbations in temperature (and thus density) have grown over time and have eventually developed into galaxies within dark matter haloes. This hierarchical clustering scenario has first been suggested by Peebles (1965). The basis for modern galaxy formation and evolution theory has been set by White & Rees (1978): First, dark matter haloes formed through hierarchical clustering (i.e. in a bottom-up scenario). Then galaxies formed within those haloes through cooling and condensation of gas. The large-scale structure of the Universe that grew from the temperature fluctuations in the CMB, has been observed and mapped with data sets of large spectroscopic surveys of many galaxies (e.g. Peacock et al., 2001). Large, dark matter only, N-body simulations like Millennium are able to reproduce the observed large-scale structure assuming hierarchical clustering in a ΛCDM Universe (Springel et al., 2005). Figure 1.2 shows a visualisation of the dark and baryonic matter structure from the Illustris simulation (Vogelsberger et al., 2014). Note how the structure consists of dense clusters (large haloes), groups (intermediate haloes), single galaxies (small haloes), filaments, and almost empty voids.
Figure 1.2 Visualisation of the cosmic web from the Illustris simulation. While the left side shows the dark matter distribution in blue and purple tones, the right side shows the distribution of gas in red tones. Note how gas and dark matter trace each other. The bright points at intersections of filaments are galaxies or larger systems of galaxies such as groups and clusters of galaxies. **Image Credit:** Illustris Collaboration/ Illustris Simulation, http://www.illustris-project.org/media/.
1.1 Matter and momentum maketh galaxies

The appearance of galaxies is tightly related to the dark matter halo, in which they form and evolve. The mass and angular momentum are the defining properties of a galaxy (Fall & Efstathiou, 1980; Mo et al., 1998) and are inherited to first order from their dark matter host halo. The mass of dark matter haloes grows through hierarchical assembly, i.e. they accrete material and other dark matter haloes (White & Rees, 1978). Their angular momentum (or spin) is thought to be caused by tidally induced torques between over-densities in the early Universe (Hoyle, 1949; Peebles, 1969).

Galaxies within those dark matter haloes are vast systems of stars, interstellar medium (ISM), and hot halo gas (and dark matter). The ISM consists of atomic and molecular gas, dust and hot, ionised gas. The above mentioned classification scheme of galaxies by Hubble (1926) distinguished between elliptical, spiral, and irregular galaxies. While it is still in use today, it evolves as more and more components of galaxies were discovered and are now systematically described. The interplay between galaxy components is quantified by scaling relations connecting two or more properties of galaxies, such as stellar content, gas content or star formation activity. This thesis investigates galaxies that are outliers to one particular scaling relation (atomic gas to stellar content) and have more atomic gas than expected for their stellar content.

Besides dwarf and irregular galaxies, two main classes of massive galaxies are distinguished in the local Universe (bimodality of the local galaxy population, e.g. Kauffmann et al., 2003b). One population consists of gas-rich, disc-dominated and star forming galaxies, such as the spiral galaxy in the left image of Figure 1.3. In a colour – magnitude diagram, these galaxies make up the blue cloud or star formation main-sequence. The second population is made of gas-poor, bulge-dominated and quiescent galaxies. An example for this population is the elliptical galaxy in the right picture of Figure 1.3. These galaxies form the red cloud.

Angular momentum is known to strongly influence the morphology of galaxies: galaxies with a higher angular momentum are more disc-dominated galaxies than galaxies with a lower angular momentum, which tend to be more bulge-dominated (Fall, 1983; Romanowsky & Fall, 2012; Fall & Romanowsky, 2013; Obreschkow & Glazebrook, 2014; Cortese et al., 2016a). Obreschkow et al. (2016) and Maddox et al. (2015) furthermore find that the angular momentum impacts on the atomic hydrogen content (H1) of galaxies. So far most studies focused on the stellar angular momentum (e.g. by Fall, 1983; Romanowsky & Fall, 2012). With the rise of ever more powerful optical integral field spectrographs and the increase in numbers of interferometric observations of H1, it is now
possible to systematically measure the angular momentum of (different components of) galaxies and further quantify its influence on galaxy evolution.

### 1.2 Star formation and gas cycle in galaxies

The stars and gas within a galaxy are tightly connected through the gas and star formation cycle, in which atomic gas condenses to form molecular clouds. These (giant) molecular clouds (GMCs) are the birth places for stars. Over their lifetime stars return part of their gas to the interstellar medium through stellar winds and supernova explosions. This initially hot gas cools and settles into the atomic gas reservoir. The remainder of stars’ material is locked into the remnants of stars: white dwarfs, neutron stars and black holes.

Their short lifetime and the fact that observations of non-star-forming GMCs are rare, suggest that the star formation in GMCs starts as soon as the GMC is formed (Mo et al., 2010). The process of forming molecular gas from atomic gas is therefore crucial and could be a potential bottleneck in the gas cycle (Saintonge et al., 2011).

On the particle scale, the most important process to form $\text{H}_2$ is the combination of two hydrogen atoms, which are adsorbed on the surface of dust grains (e.g. Gould & Salpeter, 1963; Hollenbach & Salpeter, 1971; Mo et al., 2010). At the same time, $\text{H}_2$ is constantly destroyed by photodissociation until the $\text{H}_2$ cloud is dense and large enough to shield itself. On larger scales, the formation of molecular clouds is potentially driven by multiple
mechanisms together, all of which need to cool and collapse the gas. These processes include thermal instability, disc gravitational instability, turbulence, Parker instability, spiral arms, and galaxy interactions and mergers (Mo et al., 2010).

For this thesis the contribution of the disc gravitational instability is particularly interesting. In a collapsing cloud, self-gravity has to overcome the internal pressure for further compression. If the cloud is located in a rotating galaxy disc, the cloud itself has to rotate due to conservation of angular momentum. Thus centrifugal forces in addition to the internal pressure support the cloud against its self-gravity and collapse (Mo et al., 2010). Taking this additional centrifugal force into account, atomic gas only becomes unstable against gravitational collapse if its surface density ($\Sigma_{\text{Gas}}$) becomes larger than a critical surface density ($\Sigma_{\text{crit}}$) or the Toomre $Q$ parameter becomes smaller than 1 (Toomre, 1964):

$$Q \equiv \frac{\Sigma_{\text{crit}}}{\Sigma_{\text{Gas}}}.$$  \hspace{1cm} (1.1)

Generally, galaxy discs are thought to be marginally Toomre stable (Lagos et al., 2016; Wong et al., 2016). Hence, a high angular momentum stabilises the atomic gas against gravitational instability and thus against star formation. In the EAGLE simulation for example, stars form preferentially in low angular momentum gas (Lagos et al., 2016). This stability against star formation can be quantified with the global stability parameter $q$ (Obreschkow et al., 2016), which is proportional to a disc wide average of the local Toomre $Q$ parameter. This parameter can be easier understood and interpreted when considering two galaxies with a similar exponential disc (i.e. similar scale radii) but different $q$’s. In the galaxy with a larger $q$, atomic hydrogen begins to be Toomre-stable at smaller galactocentric radii than in the galaxy with a smaller $q$ (see figure 1 in Obreschkow et al., 2016).

When investigating the star formation process, the most basic relation is the Kennicutt-Schmidt law (Schmidt, 1959; Kennicutt, 1998). The KS-law describes a relation between the gas surface density ($\Sigma_{\text{Gas}}$) and star formation rate surface density ($\Sigma_{\text{SFR}}$):

$$\Sigma_{\text{SFR}} = A \times \Sigma_{\text{Gas}}^N,$$  \hspace{1cm} (1.2)

where $N$ is the slope of the KS-law and $A$ a constant. It implies that stars can be formed where gas is dense enough. Kennicutt (1998) have found a slope of about $\simeq 1.4$ to $1.5$, but measuring the exact value of $N$ is challenging due to systematic uncertainties (Kennicutt & Evans, 2012).

The question of which physical processes govern the KS-law is still under debate. Ken-
nicutt & Evans (2012) suggest two pictures: One picture agrees with the above scenario where global dynamical processes in the galaxy control star formation (Silk, 1997). An elevated angular momentum can thus stabilise the gaseous disc against gravitational instabilities and star formation (Forbes et al., 2014a; Krumholz & Burkhart, 2016). The second picture is a bottom-up approach, where star formation is dependent on the local conditions on smallest scales in GMCs. Leroy et al. (2008) have tested multiple star formation thresholds and prescriptions and find that there is no unique driver for star formation and suggest that processes on smallest scales define the formation of GMCs and subsequently stars. These processes include the ability to form H$_2$ or turbulence due to supernovae.

A second relation concerning star formation is the one between star formation rate and stellar mass (e.g. Brinchmann et al., 2004). When correlating these two quantities, a tight star formation main sequence and a red sequence of quiescent galaxies are observed (see also the discussion on galaxy bimodality in Section 1.1). The main sequence is observed out to larger redshifts ($z \sim 2.5$) with a similar shape and slope at all redshifts, but a different normalisation and zero point (Whitaker et al., 2012; Wuyts et al., 2011). The different zero point is attributed to the overall higher cosmological star formation density at the epoch of peak star formation ($z \sim 2 – 3$, Madau & Dickinson, 2014). Hydrodynamical simulations (EAGLE, Lagos et al., 2016) and observations (Saintonge et al., 2016) find that the availability of neutral (particularly atomic) gas is crucial to determine the location of a galaxy in the star formation rate – stellar mass plane. Galaxies with small gas – to – stellar mass ratios are located preferentially on the red cloud of quiescent galaxies while more gas-rich galaxies populate the main sequence of star forming galaxies.

When a galaxy forms stars, subsequent supernovae explosions eject gas from the galaxy disc and inject energy in the ISM. This process is called stellar feedback. In simulations, stellar feedback is essential to keep galaxies from forming too many stars (Naab & Ostriker, 2017; Bower et al., 2012). Based on the Illustris simulation, Genel et al. (2015) and Zjupa & Springel (2017) suggest that feedback can also tamper with the angular momentum of a galaxy in the sense that strong stellar winds increase angular momentum by removing low angular momentum gas from the disc. This is in agreement with cosmological zoom-in simulations by Übler et al. (2014), who find that galaxies simulated with strong stellar feedback have a higher angular momentum than galaxies with weak stellar feedback.

The H$_1$-rich galaxies under investigation in this thesis might be more H$_1$-rich than expected, as they might form stars less efficiently than more average galaxies. In that case, understanding these galaxies can reveal the underlying mechanisms and physical processes that regulate the galactic star formation and gas cycle.
1.3 Gas accretion onto galaxies

The hierarchical assembly of galaxies requires them to accrete material form their surroundings in order to grow and evolve. There are two main avenues suggested by theory and simulations through which galaxies can achieve this: accretion of gas from the cosmic web (smooth or cosmological accretion), and gas-rich mergers (clumpy accretion), i.e. accretion of stars and gas. Both processes will be described in the following sections.

1.3.1 Accretion in cosmological simulations

Accretion from the cosmic web is a natural result in cosmological, hydrodynamical simulations. Like dark matter, gas is gravitationally pulled towards matter over-densities, i.e. deeper gravitational potentials. In their simulations, Kereš et al. (2005) and Dekel & Birnboim (2006) have shown that cosmological accretion onto the galaxy and its halo can occur through a hot and a cold mode.

In the hot mode, gas accretes onto a halo uniformly from the intergalactic medium (IGM). At the virial radius of the halo, the infalling gas is decelerated, due to the higher local gas density (compared to the IGM). The kinetic energy is dissipated as heat and the infalling gas is shock heated to the virial temperature \( \approx 10^{5} \) K. Over time, the gas cools and can then be integrated into the galaxy. The cooling time, however, is longer than the free-fall time, which is the time a freely falling particle would take to travel from the virial radius to the centre of the galaxy. Thus, hot mode accretion is inefficient.

In the cold mode, gas is transported through cold, dense filaments that pierce the hot halo. A visualisation of these filaments is shown in Figure 1.4. This gas is never shock heated to the virial temperature, leading to a more efficient accretion mode than the hot mode.

The hot accretion mode is prevalent in massive haloes and, at lower redshifts, while cold mode accretion is more dominant in low-mass galaxies, lower mass haloes and at higher redshifts (van de Voort et al., 2011; Lu et al., 2011). Simulations suggest that most gas that fuels star formation is accreted via the cold mode (Brooks et al., 2009; van de Voort et al., 2011; Genel et al., 2010). For both the hot mode and filamentary accretion, a stable hot halo is necessary (Dekel & Birnboim, 2006). However, if the dark matter halo is not massive enough, no stable hot gas halo can be formed and gas can be accreted onto these galaxies directly from the IGM.

Stewart et al. (2011, 2013); Stewart et al. (2017) use cosmological zoom-in simulations to show that gas accreted through cold filamentary accretion forms a cold flow disc which
co-rotates with the galaxy disc. They suggest that these cold flow discs might be observed as extended H\textsc{i} or UV disc today. Since the accreted gas has a high angular momentum, the interaction between the galaxy disc and the cold flow disc increases the angular momentum of the galaxy disc (Stewart et al., 2013).

Besides these processes, observations (Di Teodoro & Fraternali, 2014; Sancisi et al., 2008) and simulations (van de Voort et al., 2011) find that mergers play a small role as well. However, they are not sufficient to replenish the gas reservoir of galaxies. In particular, gas-poor (dry), major mergers decrease the angular momentum of galaxies and do not increase the H\textsc{i} reservoir of the resulting galaxy (Lagos et al., 2016). These types of mergers usually create gas-poor, bulge-dominated galaxies. Gas-rich (wet), minor mergers on the other hand, are not only able to bring in fresh gas but can also increase a galaxy’s angular momentum (Lagos et al., 2016).

1.3.2 Observational evidence for cosmological accretion

To date there is no direct observation of a filament or accretion in action available in the local Universe. There are, however, observations that can be explained with cosmological accretion, which will be discussed in more detail in the following paragraphs.

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Figure 1.4 Artist’s Impression of filamentary gas accretion onto a galaxy around redshift 2.3. **Image Credit:** ESO/L. Calçada/ESA/AOES Medialab \(^3\).
Gas in a galaxy disc is enriched with metals by supernovae. Whilst some of these metals are ejected into the IGM via winds, the metallicity of gas accreted from the IGM is generally lower than the metallicity in the galaxy disc. Metallicity gradients (Moran et al., 2012) and metallicity inhomogeneities (Filho et al., 2013; Ceverino et al., 2016) can be interpreted as indications of recently accreted gas. However, Sánchez et al. (2014) attribute metallicity gradients rather to different evolutionary states of the galaxy disc, and metallicity inhomogeneities can also be caused by tidal interactions with other galaxies (López-Sánchez et al., 2015).

The substantial scatter of the stellar mass – metallicity relation is also attributed to accretion of metal-poor gas. Hughes et al. (2013), Bothwell et al. (2013) and Brown et al. (2018) have shown that galaxies with higher H\textsc{i}-mass fractions have lower metallicities at a given stellar mass than more gas-poor galaxies. This can be interpreted as the following: when a galaxy accretes pristine gas, its ISM is diluted and it moves towards the metal-poor edge of the scatter of the mass–metallicity relation. Once the accreted pristine gas is used for star formation and supernovae pollute the ISM again, the galaxy moves back onto the relation. Simulations by Davé et al. (2013) and Forbes et al. (2014a) agree with this interpretation. Additionally, van den Bergh (1962) and later Kudritzki et al. (2015), find that the integrated metal content of galaxies today is smaller than in closed box chemical evolution models (i.e. galaxies that do not interact with their surroundings and do not accrete). This implies that the ISM has been diluted by accreted, pristine gas in the past.

It has been proposed that warps in galaxy discs might be caused by gas accretion. Hydrodynamical, cosmological simulations by Roškar et al. (2010) suggest the following scenario: When the hot halo and inner disc angular momenta are misaligned, cold, infalling gas is torqued by the hot halo. The fresh cold gas creates a warp at the edge of the disc. Such warps of the H\textsc{i} disc are observed in many galaxies, one striking example is NGC 5055 of the Things survey (Walter et al., 2008; Schmidt et al., 2016). It should be noted that interactions with dwarf companions or surrounding sub-haloes can form warps as well (e.g. Weinberg & Blitz, 2006 and Józsa, 2007).

Based on observations of galaxy NGC 891, Oosterloo et al. (2007) and Fraternali et al. (2011) hypothesise that accretion from the hot halo can be facilitated through the “Galactic Fountain” mechanism. In this model, gas is expelled from the disc due to star formation and when falling back onto the galaxy disc, hot halo gas is able to condense onto the expelled gas. The condensed hot halo gas is dragged along into the galaxy disc and the net amount of gas in the galaxy disc is increased. In the case of NGC 891, the relevant observational sign is a thick H\textsc{i} disc, which is lagging in rotation velocity. However, these
Chapter 1. Introduction

observations might also be explained with tidal interaction with a nearby galaxy (de Blok et al. in preparation) and evidence for sufficient density of hot haloes is scarce (see e.g. Bogdan et al., 2015).

The HALOGAS survey (Heald et al., 2011) has previously searched for signs of accretion in deep H\textsc{i} observations of nearby galaxies (distance $< 11$ Mpc). Through detailed modelling of the H\textsc{i} kinematics, the HALOGAS team has found a few high velocity clouds, thick H\textsc{i} discs, and warps in their samples galaxies (Gentile et al., 2013; Zschaechner et al., 2011, 2012; de Blok et al., 2014a). In the Milky Way, high velocity clouds are thought to be contributing to gas accretion (Putman et al., 2012). The thick disc component, which is usually lagging in rotation velocity with respect to the thin disc, can be interpreted as a sign of the Galactic Fountain (Oosterloo et al., 2007; Fraternali et al., 2011). However, the total rate of detected H\textsc{i} accretion in any form in the HALOGAS observations is not sufficient to fuel star formation in the sample galaxies (Heald, 2015).

Gas that is cooling directly from the hot halo to join the galaxy disc, already takes on the structure of the galaxy disc before being accreted (Stevens et al., 2017). Thus, few structural traces of this accretion mode can be observed. Accretion of cold gas, be it through filaments or directly from the IGM, tends to be asymmetric. Hence, lopsided gaseous galaxy discs might indicate accretion. However, asymmetries can also be caused by tidal interactions or minor mergers.

Any direct observations of gas accretion onto local galaxies does not yield a large enough accretion rate to sustain star formation. Estimated accretion rates are usually approximately one order of magnitude smaller than current star formation rates (see e.g. Sancisi et al., 2008). This thesis therefore focuses on exceptionally gas-rich galaxies. If these galaxies are gas-rich because they have recently acquired a lot of gas, then observations of these galaxies might show signs of accretion and give insights on the actual accretion mechanism.

1.4 Components of galaxies and how to observe them

To understand these gas-rich galaxies, the observation of their gas content is essential. However, it is also vital to understand the star formation activity and the stellar content of the galaxy. The gaseous and stellar components of galaxies emit light through different mechanisms and at different wavelengths. Observing a galaxy at different wavelengths thus yields information on each of those components and how they are related with each other. Figure 1.5 shows as an example different components of the galaxy M 101, which will be used to discuss in more detail what can be learned from these observations and
1.4. Components of galaxies and how to observe them

how they can be obtained.

The atomic gas

Hydrogen is the most common element in the Universe and the atomic gas disc of a galaxy is dominated by it. H\textsc{i} is observed in the radio L-band at a wavelength of approximately 21 cm, which is equivalent to a frequency of $\approx 1.4$ GHz. This light is emitted through the hyperfine structure transition of the hydrogen atom. Usually the spin of the proton and the electron in a hydrogen atom are parallel. Randomly the spin of the electron can flip from this parallel alignment to a lower energy, anti-parallel alignment, which simultaneously emits a photon. The first galaxy for which atomic hydrogen was observed was the Milky Way (Ewen & Purcell, 1951; Muller & Oort, 1951). An example for the H\textsc{i} observations of M 101 is given in panel (a) of Figure 1.5 with data taken from the THINGS survey (Walter et al., 2008). As the spatial resolution of a telescope is defined by the ratio of wavelength to telescope aperture, observations at 21 cm need a very large aperture (of the order of kilometres) for resolutions as shown in panel (a) of Figure 1.5. Currently the largest operational single dish telescope is the Arecibo Observatory (Gordon, 1964) with a diameter of 305 m. Larger apertures can be achieved by combining multiple antennae in an interferometric array as done with the Australia Telescope Compact Array (ATCA) or the Very Large Array (VLA).

The H\textsc{i} disc of spiral galaxies can be observed more easily to larger radii than any other component of a galaxy. All panels in Figure 1.5 are of the same physical size and it is clearly visible that the H\textsc{i} disc is the only detected component that is larger than the cut-out. This does not mean that there are no stars at large radii, but the stellar density is very small at large radii. Therefore, stars are a lot harder to observe at the outskirts of galaxies. The fact that significant amounts of H\textsc{i} are located at large radii and that H\textsc{i} is light-weighted, makes the H\textsc{i} disc one of the first components that is affected by interactions with the environment. This can be seen in the H\textsc{i} maps of the ram-pressure affected galaxy NGC 4522 (panel (b) of Figure 1.7, data from Chung et al., 2009) and in the H\textsc{i} maps of the M 81 group (Yun et al., 1994). These H\textsc{i} observations reveal evidence of ongoing interactions between members of the M 81 group, which are not visible in the optical images.

All these characteristics of the H\textsc{i} make it the perfect tracer to look into processes that happen on the outskirts of the galaxy disc. These processes include gas accretion, interaction with other galaxies, and the impact of the environment.

Usually, the column density of H\textsc{i} does not exceed $10 M_\odot$ pc$^{-2}$, as higher column
Figure 1.5 Spiral galaxy M101 in different wavelengths. All images are 15 by 15 arcmin. Panel (a): HI data from the THINGS survey. Panel (b): CO data from the HERACLES survey. Panel (c): hot dust emission at 350 µm from the Herschel telescope. Panel (d): hot dust emission at 24 µm from the Spitzer telescope. Panel (e): old and low mass stars observed in the $K_s$-band of the 2MASS survey. Panel (f): younger stars in the SDSS $g$-band. Panel (g): the Hα recombination line as excited by star formation. Panel (h): far ultraviolet emission from young and massive star observed by the GALEX mission.
densities lead to H\textsc{i} being transformed into molecular hydrogen (Bigiel et al., 2008). At column densities below $\approx 3 \times 10^{19} \text{atoms cm}^{-2} = 0.25 \text{M}_\odot \text{pc}^{-2}$, atomic hydrogen is not dense enough to self-shield against meta-galactic ultraviolet emission, becomes optically thin and thus mostly ionised. The neutral to ionised fraction of hydrogen rapidly decreases as the H\textsc{i} column density decreases (Popping et al., 2009). The atomic hydrogen column density within filaments is of the order of $\approx 10^{16} \text{atoms cm}^{-2} = 8 \times 10^{-5} \text{M}_\odot \text{pc}^{-2}$.

**The molecular gas**

The molecular gas disc is also dominated by hydrogen (H\textsubscript{2}). As H\textsubscript{2} does not have an electromagnetic dipole, observations of cold H\textsubscript{2} are not possible. Generally the rotational transitions of carbon monoxide (CO) are observed as a proxy for molecular hydrogen. The molecular gas mass can then be determined from the CO luminosity (Solomon et al., 1997). This conversion is dependent on the CO to H\textsubscript{2} ratio, which differs with the metallicity of the gas. There are prescriptions to take this dependence into account (e.g. Accurso et al., 2017). CO is assumed to trace the bulk of the molecular gas, while the denser cores of GMCs can be observed through emission by molecules like HCN, HCO\textsuperscript{+}, and HNC (Bigiel et al., 2016). In panel (b) of Figure 1.5, observations of the CO J(1-0) transition in M 101 are shown with the data taken form the HERACLES survey (Leroy et al., 2009). The molecular gas is centrally concentrated, where density and pressure are high enough to form H\textsubscript{2} from H\textsc{i}. Centres of spiral galaxies are usually dominated by H\textsubscript{2} over H\textsc{i} (Bigiel et al., 2008).

**Dust**

Dust is heated by stars (especially young and hot stars) and absorbs optical (stellar) light. This energy is re-emitted as black body radiation in the infrared. When measuring the star formation activity in galaxies, it is therefore important to take emission from the dust into account. Examples for infrared dust emission at 350 and 24 $\mu$m are given in panels (c) (Kennicutt et al., 2011) and (d) (Dale et al., 2009) of Figure 1.5, respectively. These data have been obtained with cameras aboard the Herschel and Spitzer space crafts and are made available through the NASA/IPAC Extragalactic Database (NED\textsuperscript{4}). As the dust is heated by star formation processes, the spatial distributions of dust and star formation (Panels (g) and (h)) are similar.

**Stars and ionised Gas**

In the optical wavelengths, a galaxy’s light is dominated by the stars and recombination

\[4\text{http://ned.ipac.caltech.edu/}\]
Chapter 1. Introduction

(de-excitation) lines of the ionised gas. Older and less massive stars emit light in the red part of the optical spectrum. The spectrum of our Sun for example peaks at an effective temperature of 5777 K$^5$, which is equivalent to a peak emission at a wavelength of 502 nm (green). Younger and more massive stars (recently formed O and B stars) are bluer, extending through to the ultraviolet. These young stars trace ongoing and very recent star formation and excite or ionise the atoms in the ISM around them. The strongest and most commonly observed recombination lines are the hydrogen Balmer lines $H\alpha$ and $H\beta$ at 656.3 nm and 486.1 nm, respectively. Other emission lines are O[III] $\lambda$ 500.7 nm and N[II] $\lambda$ 658.3 nm. The ratio between the strength of these emission lines can also be used to measure the gas-phase oxygen abundance (metallicity, Pettini & Pagel, 2004). Examples for stellar emission at various wavelengths are given in panels (e) to (h) in Figure 1.5. Panel (e) shows the near-infrared $K_s$-band (Jarrett et al., 2003), which is dominated by the older stellar population. Younger stars are shown in the image of the emission in the $g$-band (Panel (f), York et al., 2000). The youngest and most massive stars dominate the emission in the far-ultraviolet image (Panel (h), Morrissey et al., 2007; Martin et al., 2005). These recently formed stars ionise the material around them and thus cause the emission in the $H\alpha$ line (Panel (g), Hoopes et al., 2001).

1.5 Atomic gas

Of all the galaxy components described in the previous section, the atomic gas is the focus of this thesis. The atomic gas disc is an essential part of the galactic gas cycle as it is the raw fuel for star formation (as discussed in the previous Sections). Atomic hydrogen is furthermore the part of the galaxy that can be observed at largest radii, often well beyond the observable stellar disc. The observation of $H_1$ is thus essential when investigating the star formation in galaxies, their interactions with the environment, and accretion processes at the edge of the observable galaxy disc.

In their seminal review, Haynes et al. (1984) outlined how the $H_1$ content of a galaxy can be quantified. They suggest that the absolute $H_1$ mass or $H_1$ mass to stellar light ratio should be used. This ratio is effectively an $H_1$ to stellar mass ratio. Comparing the measured $H_1$ content to other properties such as morphology, environment or optical luminosity (i.e. stellar content) the first scaling relations were established (Haynes et al., 1984; Roberts & Haynes, 1994; Solanes et al., 1996). With the rise of large surveys, these scaling relations have evolved. These large surveys include both blind and targeted surveys. The $H_1$ Parkes All Sky Survey (HIPASS, Barnes et al., 2001) and the Arecibo Legacy Fast

$^5$https://solarsystem.nasa.gov/planets/sun/facts, visited on 21/10/2017
1.5. Atomic gas

ALFA Survey (ALFALFA, Giovanelli et al., 2005) are blind surveys scanning large parts of the sky for H\textsubscript{I} sources. The GALEX Arecibo SDSS survey (GASS, Catinella et al., 2010) is a targeted survey, measuring the H\textsubscript{I} content of \approx 800 stellar mass selected galaxies. In the following sections an overview of how the H\textsubscript{I} is related to other components of the galaxy and its environment will be given.

1.5.1 H\textsubscript{I} and the star formation activity in the galaxy

As previously mentioned, the star formation activity in a galaxy is dependent on how much gas is available and its density (Kennicutt-Schmidt Law). H\textsubscript{I} is the raw fuel of (or reservoir for) star formation and molecular gas is the actual medium from which stars are formed. Of all scaling relations between H\textsubscript{I} content and other properties of galaxies, the H\textsubscript{I} to stellar mass ratio and the specific star formation rate (star formation rate to stellar mass ratio, as approximated by the NUV-r colour) form the tightest relation (Brown et al., 2015; Catinella et al., 2013).

When comparing the current star formation rate and H\textsubscript{I} content of galaxies, Schiminovich et al. (2010) find that local galaxies would on average consume their entire H\textsubscript{I} reservoir within \sim 2 - 3 Gyr for star formation. However, this depletion time scale can vary from 1 to 100 Gyr.

1.5.2 H\textsubscript{I} and the optical morphology of the galaxy

The ratio between H\textsubscript{I} and stellar mass in spiral galaxies is anywhere between 10 and 150 per cent (Catinella et al., 2010, 2013). Elliptical galaxies were long thought to contain no H\textsubscript{I} at all, however, recent targeted surveys like GASS and ATLAS\textsuperscript{3D} (Cappellari et al., 2011; Serra et al., 2012) have shown that they do contain H\textsubscript{I}. Their H\textsubscript{I} to stellar mass ratio and the H\textsubscript{I} column densities, however, are smaller than in spirals (Serra et al., 2012; Catinella et al., 2013). Usually the H\textsubscript{I} to stellar mass ratio in elliptical galaxies is less than 10 per cent and often below the GASS detection limit of 1.5 per cent. Serra et al. (2012) detected H\textsubscript{I} in about 40 per cent of the observed ATLAS\textsuperscript{3D} galaxies. In the catalogues of data release 3 of the GASS survey (Catinella et al., 2013), 95 per cent of galaxies with stellar mass surface densities $\log \mu_*$ < 8.5 are detected. Galaxies at these stellar surface densities are disc-dominated systems (Catinella et al., 2010; Kauffmann et al., 2006). Galaxies with higher stellar mass surface densities are bulge-dominated systems and H\textsubscript{I} is only detected in 57 per cent of the bulge-dominated GASS galaxies. The detection fraction for bulge-dominated galaxies is therefore only about two-thirds of the detection fraction of disc-dominated galaxies. The relation between H\textsubscript{I} content and stellar mass surface density
is also recovered by Brown et al. (2015).

1.5.3 H I and the stellar mass of the galaxy

The scaling relation between H I mass and stellar mass has been one of the first H I scaling relations to be studied. In H I blind (i.e. H I selected) surveys such as HIPASS and ALFALFA, this relation is well defined (see e.g. Huang et al., 2012 and Dènes et al., 2014). For low stellar masses, it is near linear and then saturates for higher stellar masses. However, being H I selected, these surveys mostly include H I-rich and star-forming galaxies. This is demonstrated in Figure 1.6, which shows the star formation rate vs. stellar mass plane (i.e. effectively a colour–magnitude diagram, see also Brown et al., 2015). The data used for this plot comes from the MPA-JHU SDSS catalogue (for more details see Section 2.2.5) and the ALFALFA 40 per cent catalogue (Haynes et al., 2011), which was cross-matched to the MPA-JHU catalogue.

In this plane, ALFALFA detections are mostly found in the blue cloud and hardly on the red sequence. When investigating the H I–stellar mass relation with a stellar mass selected sample such as for example GASS, galaxies with smaller H I masses than detectable with an H I selected survey are included. In particular at high stellar masses, any gas mass fraction between the high values from the H I blind surveys and the small detection limits of the deeper, targeted surveys become possible. The relation thus turns into a scatter plot. Brown et al. (2015) have investigated this relation with a volume limited sample and find it to be a secondary effect: Galaxies in the local Universe are distributed bimodally (low-mass spirals and massive ellipticals) and galaxies that have gas form stars (Kennicutt-Schmidt Law). Hence, this relation mirrors the fact that at lower stellar masses galaxies tend to be star-forming, gas-rich spirals and at higher stellar masses, quiescent, gas-poor ellipticals are prevalent.

1.5.4 H I and the environment of the galaxy

When investigating the environment of galaxies, three types of environment are generally considered, although the transition between these classifications is smooth: the field, galaxy groups and galaxy clusters.

The environment of a galaxy plays a crucial role in the evolution of the galaxy. The morphology-density relation by Dressler (1980) describes how galaxies in clusters are predominately bulge-dominated and galaxies in the field tend to be disc-dominated. A similar pattern is found in the star formation activity (Lewis et al., 2002) and gas content of galaxies (Haynes et al., 1984; Chung et al., 2009; Brown et al., 2017). In the following, the effects
1.5. Atomic gas

Figure 1.6 The star formation main sequence for a volume limited galaxy sample from the SDSS (dark contours at 25, 68 and 95 percentiles) and an H\textsc{i} selected sample from ALFALFA (colour scale in the background). Note how ALFALFA galaxies are mostly located on the star formation main sequence rather than the red cloud.

of environment onto the H\textsc{i} content of galaxies will be discussed in more detail.

**The field**

Galaxies in the field are isolated, neighbours are far away and the local density of galaxies is low. The dark matter halo mass of these systems are of the order of $10^{10}$ to $10^{11} \, M_\odot$. Properties of field galaxies are generally used as benchmarks for group and cluster galaxies, and to define scaling relations.

**Galaxy groups**

The group environment can start at pairs and go all the way to groups of hundreds of galaxies, which are gravitationally bound. Their dark matter halo masses range from $10^{11}$ to $10^{13} \, M_\odot$. The majority of galaxies live in groups (Crook et al., 2007), where the group environment acts as an incubator for the evolution of member galaxies (Kilborn et al.,
The appearance of galaxy groups can vary. Common classifications are for example compact and loose groups.

Compact groups such as the Hickson Compact Groups (HCG, Hickson, 1982) typically contain only a few but closely located galaxies. Verdes-Montenegro et al. (2001) studied a large sample of HCGs in H\textsc{i}. They find efficient gas stripping and propose an evolutionary sequence for HCGs in which H\textsc{i} is initially located within member galaxies but gets gradually removed through tidal interactions. One example for a small, compact group is the Grus Quartet (see left panel in Figure 1.7 for the central three group members). The galaxies in this group interact tidally, which can be observed through H\textsc{i} tails.

The best studied loose group is the Local group, with the Milky Way and M 31 as the largest members. Even though galaxies in loose groups are not located as closely together as in compact groups, there is still an effect of the group environment on the member galaxies: Kilborn et al. (2009) find that spiral galaxies in loose groups are less H\textsc{i}-rich than spiral galaxies in the field probably due to tidal stripping.

Large studies based on ALFALFA, investigating the H\textsc{i} content of galaxies in comparison to their environment, already find significant changes in gas fractions at the group stage (Odekon et al., 2016). The larger the group the stronger the effect (Hess & Wilcots, 2013): Fewer galaxies are detected in H\textsc{i} in larger groups and H\textsc{i} detected galaxies tend to be located further from the centre of the group.

### Galaxy clusters

Large clusters like the Virgo or the Coma cluster host hundreds to thousands of galaxies. Their dark matter halo mass is usually above $10^{13} M_\odot$. Membership in such a cluster significantly impacts and transforms a galaxy. The hot intracluster medium (hot gas in between the cluster galaxies) can remove a galaxy’s gas reservoir through ram pressure stripping (Gunn & Gott, 1972, for an example see NGC 4522 in the right panel of Figure 1.7, data taken from Chung et al., 2009). The morphology-density relation (Dressler, 1980; Lewis et al., 2002) reflects the impact of the gas removal: The fraction of quenched and early-type galaxies increases with the density of the environment. Furthermore, bulge-dominated galaxies in clusters are less likely to contain significant amounts of H\textsc{i} (Serra et al., 2012). Interestingly, Dénes et al. (2014) find that unusually H\textsc{i}-rich galaxies are preferentially located on the edge of dense environments.

The effect of environment on the H\textsc{i} content has already been studied by Haynes et al. (1984). However, only now samples of integrated H\textsc{i} data are large enough to show which environmental effect is acting under which circumstance.
1.6 Key science question of the thesis

This thesis investigates a sample of the most \textit{H}~\text{\textsc{i}}\textit{eXtreme} galaxies in the Southern Hemisphere: the \textit{hix} galaxies. The overarching question is why are these galaxies more \textit{H}~\text{\textsc{i}}\textit{-rich} than other galaxies?

Most observational evidence for gas accretion is hard to obtain. The \textit{hix} sample was selected to contain the most \textit{H}~\text{\textsc{i}}-rich galaxies in the Southern Hemisphere. If these galaxies are \textit{H}~\text{\textsc{i}}-rich because they accrete gas more actively or efficiently than other galaxies, then they are the perfect sample to study gas accretion. Resolved \textit{H}~\text{\textsc{i}} and gas-phase oxygen abundance observations of the \textit{hix} galaxies are investigated to obtain conclusions on their accretion activity. Based on the previous literature review, searching for the following features will inform of the accretion activity of \textit{hix} galaxies:

- An extended \textit{H}~\text{\textsc{i}} disc. \textit{Stewart et al.} (2017) suggests that recently accreted gas is located in a cold-flow disc that might be observable as an extended \textit{H}~\text{\textsc{i}} or UV disc in local galaxies.

- A warped \textit{H}~\text{\textsc{i}} disc. \textit{Roškar et al.} (2010) find in simulations that warped discs occur when a galaxy is accreting gas and the spin of the halo is not exactly aligned with the spin of the galaxy.
Chapter 1. Introduction

• A lopsided \( \text{H} \text{I} \) disc. As filaments are not distributed symmetrically around a galaxy, filamentary accretion would cause asymmetries in the gas disc.

• A thick disc component (de Blok et al., 2014b), which might point to an active Galactic Fountain (Oosterloo et al., 2007).

• Steep gas-phase oxygen abundance gradients (Moran et al., 2012) or inhomogeneities (Ceverino et al., 2016). As the intergalactic medium is more pristine than the interstellar medium, accreted gas dilutes the outskirts the interstellar medium.

If \( \text{HIX} \) galaxies are less efficient at forming stars than other galaxies, then the reason for the reduced efficiency needs to be determined. As mentioned above the kinematic properties of a galaxy might be one important factor in determining its star formation efficiency.

The angular momentum and possible signs of gas accretion in observations of the \( \text{HIX} \) and a sample of CONTROL galaxies will be used to investigate these two possible reasons for \( \text{H} \text{I} \)-richness. The results of these investigations will also help answer open questions of galaxy formation and evolution:

(i) How do \( \text{H} \text{I} \)-rich galaxies maintain their gas reservoir?

The current gas content of average local galaxies is not sufficient to sustain ongoing star formation for more than \( \sim 2 \) Gyr. Theoretical models have suggestions on how galaxies can accrete gas from their surroundings. The physical mechanisms behind gas accretion, however, are not yet clear and observations are scarce. \( \text{HIX} \) galaxies contain enough gas to sustain star formation for a longer period than average local galaxies. Understanding how \( \text{HIX} \) galaxies obtained and maintained their gas can inform of gas accretion in the local Universe.

(ii) What is the connection between galaxy dynamics and gas content?

As mentioned above, the relation between galaxy angular momentum and gas content has recently moved into the focus of research. Already half a century ago, the angular momentum (together with mass) was identified as one of the main drivers of galaxy evolution (Fall & Efstathiou, 1980). However, even today baryonic specific angular momentum measurements out to large radii are only available for about 20-30 galaxies (mostly by Obreschkow & Glazebrook, 2014 and Butler et al., 2017). With the rise of large surveys of resolved \( \text{H} \text{I} \) discs like WALLABY, this number will rise. Already today the analysis of the baryonic specific angular momentum of \( \text{H} \text{I} \) extreme galaxies like the \( \text{HIX} \) galaxies can
1.7 Thesis outline

inform, whether relations between H\textsc{I} and angular momentum hold in unusual galaxies and how the angular momentum impacts on the H\textsc{I}.

(iii) What drives the scatter of scaling relations? Why are some galaxies outliers to scaling relations?

Scaling relations between different components of a galaxy show an intrinsic scatter, which is not due to measurement uncertainties but due to underlying physics. For example, the scatter in the relation between metallicity and stellar mass is thought to be driven by stochastic accretion. Understanding outliers, like the H\textsc{IX} galaxies, to a scaling relation can inform of the physical drivers of the scaling relation.

1.7 Thesis outline

This thesis is structured as follows: \textbf{Chapter 2} gives a summary of the data used in this thesis and how they are analysed. This includes a detailed description of the sample selection, data collection from public data sets and dedicated observing programs and, how the data was then processed and analysed. Finally a semi-analytic galaxy simulation will be introduced.

\textbf{Global properties of the H\textsc{IX} galaxies}

\textbf{Chapter 3} focuses on integrated properties of the H\textsc{IX} galaxies such as stellar mass, gas to stellar mass ratio, star formation activity and morphology. They are then compared to the broader galaxy population, a CONTROL sample and other samples of H\textsc{I}-rich galaxies. The H\textsc{IX} galaxies are found to have very high H\textsc{I} to stellar mass ratios at a given stellar mass. Hence, the sample selection for the most extreme galaxies is confirmed. These galaxies appear similar to the CONTROL galaxies, when only considering their morphology and star formation rate at a given stellar mass. However, when including their H\textsc{I} content in the analysis, H\textsc{IX} galaxies turn out to be less efficient than CONTROL galaxies at forming stars from that reservoir.

\textbf{Resolved HI observations of the H\textsc{IX} galaxies}

The resolved H\textsc{I} observations of the H\textsc{IX} and CONTROL galaxies are analysed in \textbf{Chapter 4}. This includes measuring the size of the H\textsc{I} discs, modelling the 3D kinematics and measuring the specific angular momenta in the sample galaxies. The H\textsc{I} discs of H\textsc{IX} galaxies have sizes as expected for their mass, i.e. the average column density is similar to other galaxies. In terms of the 3D kinematics H\textsc{IX} galaxies tend to be more disturbed than
CONTROL galaxies. HIX galaxies also host more gas with higher specific angular momentum than CONTROL galaxies. This gas is supported against star formation and “parked” at larger radii due to the high specific angular momentum.

**Metallicity distribution of the HIX galaxies**

In the last science chapter (Chapter 5), optical integral field spectra of the HIX galaxies are analysed. The accretion of pristine gas can dilute the outskirts of galaxies or induce gas-phase metallicity inhomogeneities. The optical spectra are obtained with the WiFeS spectrograph and provide data of the gas-phase metallicity distribution within the optical discs of the HIX galaxies. Based on these data, the metallicity gradient can be measured to find metallicity inhomogeneities. The data suggest that HIX galaxies show similar metallicity patterns to average local spiral galaxies. Thus they did not recently accrete large amounts of metal-poor gas.

**Conclusion and summary**

In Chapter 6, the results of this thesis are summarised along with final conclusions and suggestions for future works.
2

Galaxy sample and data

This chapter is published in the following two papers:

“The HIX galaxy survey I: study of the most gas-rich galaxies from HIPASS”

and

“The HIX galaxy survey II: HI kinematics of HI eXtreme galaxies”

It is an overview of all data, methods and the semi-analytic model used throughout the thesis. Initially, the sample selection of HIX and control galaxies is explained. This is followed by an overview of publicly available data, an overview of observations carried out with the Australia Telescope Compact Array and the WIFES integral field spectrograph, and how these data were reduced and analysed. Finally the semi-analytic model DARK SAGE is introduced.
2.1 Introduction

As outlined in Section 1.4, different components of galaxies can be observed at different wavelengths. Over the last two decades, large surveys have mapped vast parts of the sky in many wavelengths ranging from the radio all the way through to gamma rays. Among these large surveys is HIPASS, the H\textsubscript{i} Parkes All Sky Survey (Barnes et al., 2001). This is a blind H\textsubscript{i} survey of 70 percent of the sky, mostly covering the Southern Hemisphere. More than 5000 sources were detected in this data set. The H\textsubscript{i} Jodrell All Sky Survey (HIJASS, Kilborn, 2002; Lang et al., 2003) complemented HIPASS to cover the entire sky. The second generation of H\textsubscript{i} blind surveys – the Arecibo Legacy Fast ALFA Survey (ALFALFA, Giovanelli et al., 2005; Haynes et al., 2011) – has detected tens of thousands of sources in the Northern Hemisphere. In the future, the Square Kilometre Array (SKA) and its pathfinder ASKAP and precursor MeerKAT will detect thousands of galaxies in H\textsubscript{i}. Duffy et al. (2012) estimate that ASKAP’s WALLABY\footnote{http://www.atnf.csiro.au/research/WALLABY/} and DINGO\footnote{https://dingo-survey.org/} surveys will provide H\textsubscript{i} observations of \( \sim 6 \times 10^5 \) and \( \sim 10^5 \) galaxies, respectively. Abdalla & Rawlings (2005) find that the SKA might be able to detect more than one billion galaxies in H\textsubscript{i}.

At optical wavelengths, the first large surveys such as the National Geographic Society Palomar Observatory Sky Survey (NGS-POSS, Minkowski & Abell, 1963) or the Southern Sky Atlas (ESO / SERC, Holmberg et al., 1974) have been recorded on photographic plates. Later, these photographic plates have been digitised in the Digitised Sky Survey (DSS\footnote{The Digitized Sky Survey was produced at the Space Telescope Science Institute under U.S. Government grant NAG W-2166. The images of these surveys are based on photographic data obtained using the Oschin Schmidt Telescope on Palomar Mountain and the UK Schmidt Telescope. The plates were processed into the present compressed digital form with the permission of these institutions.}) and SuperCOSMOS projects (Hambly et al., 2001a). With the Sloan Digital Sky Survey (SDSS, York et al., 2000), the age of optical all sky surveys recorded with CCDs started. While SDSS is focused on the Northern Hemisphere, new and upcoming surveys such as SkyMapper (Keller et al., 2007), the Dark Energy Survey (DES, Flaugher et al., 2015), the Kilo Degree Survey (KiDS, de Jong et al., 2013) or VST ATLAS (Shanks et al., 2015) will extend these efforts to the Southern Hemisphere.

In the Infrared, the two most recent all-sky surveys are the Two Micron All Sky Survey (2MASS, Skrutskie et al., 2006) and the survey by the Wide-field Infrared Survey Explorer (WISE, Wright et al., 2010). 2MASS was carried out with two similar ground-based telescopes, one located in California, USA and the other one in Chile providing images at wavelengths of 1.2, 1.7 and 2.15 \( \mu \text{m} \). With 2MASX, a dedicated catalogue of extended
objects in 2MASS is provided as well (Skrutskie et al., 2006). Since the atmosphere is opaque for the light at wavelengths longer than the 2MASS range, WISE is a space based mission providing images at wavelength of 3.4, 4.6, 12, and 22 μm.

The Galaxy Evolution Explorer (GALEX, Morrissey et al., 2007; Martin et al., 2005) is the first mission to create a near-all-sky survey at ultraviolet wavelengths of 151.6 and 226.7 nm.

Combining measurements of different galaxy components from these surveys can inform of the interplay between different parts of galaxies, such as H\textsc{i} and stars. A quantitative and particularly powerful tool to identify these relations are the previously mentioned scaling relations. This thesis examines galaxies that contain more H\textsc{i} than would be expected for their stellar content. To do so data available from public surveys such as 2MASS, WISE and GALEX are used. In addition, these galaxies are observed with the Australia Telescope Compact Array (ATCA) near Narrabri (Australia), which is a radio interferometer of six 22 m antennae, and the WiFeS on the ANU 2.3 m telescope in Siding Spring (Australia), which is an optical integral field spectrograph. Furthermore, the observed galaxies are compared to galaxies simulated with the semi-analytic model DARK SAGE (Stevens et al., 2016).

This Chapter describes the data used throughout the thesis and how these data are reduced, processed and analysed. It is structured as follows: In Section 2.2, an overview of the publicly available data that is used for sample selection and for analysis of the galaxy samples is given. Section 2.3 explains how the galaxy samples used in this thesis have been selected. Details on the observations with the ATCA and WiFeS and the consecutive data reduction are presented in Sections 2.5 and 2.7 respectively. Methods to analyse the ATCA and WiFeS data are detailed in Sections 2.6 and 2.8 respectively. In Section 2.9, the DARK SAGE semi-analytic model is introduced. Finally, an introduction to other galaxy surveys, which are used and mentioned thought this thesis is given.

Unless otherwise stated, throughout the thesis a flat ΛCDM cosmology with the following cosmological parameters is assumed: \( H_0 = 70.0 \text{ km Mpc}^{-1} \text{s}^{-1} \), \( \Omega_m = 0.3 \). All velocities are used in the optical convention (cz).

2.2 Public catalogue data

The following publicly available data are used for sample selection and to set the samples into the context of the broader galaxy population:
2.2.1 HIPASS and HOPCAT

The HIPASS (Barnes et al., 2001) is a blind \( \text{H}_\text{i} \) survey of the entire Southern Hemisphere. The technical details of HIPASS are: a spatial resolution of 15.5 arcmin, a spectral resolution of 18 km s\(^{-1}\), and a maximal recession velocity of 12,700 km s\(^{-1}\). The HIPASS survey data (Barnes et al., 2001; Meyer et al., 2004; Zwaan et al., 2004) are used to calculate the \( \text{H}_\text{i} \) mass for the initial sample selection. Later, the \( \text{H}_\text{i} \) flux from the HIPASS data cubes is remeasured to account for extended structures.

The HIPASS optical counterpart catalogue (HOPCAT, Doyle et al., 2005) provides \( B_j \), \( R \) and \( I \)-band magnitudes, optical position angles and optical semi-major to semi-minor axis ratios. HOPCAT magnitudes are measured from SuperCOSMOS images (Hambly et al., 2001b,a) using ellipses created by the SExtractor software (Bertin & Arnouts, 1996). The final HOPCAT magnitudes are the mag-auto magnitudes measured by SExtractor within the apertures as defined on the \( B_j \)-band images. In Figure 2.1, these HOPCAT magnitudes are included. HOPCAT also provides the Galactic extinction measures \( E(B-V) \) at the location of each galaxy as estimated by Schlegel et al. (1998). For the sample selection as described below in Section 2.3, the HOPCAT magnitudes are corrected for:

- Galactic foreground extinction following Schlegel et al. (1998),
- the fact that HOPCAT uses the \( B_j \)-band apertures in all three bands (Dénes et al., 2014), and
- internal dust absorption depending on their inclination (Driver et al., 2008).

2.2.2 2MASS

The catalogue of extended sources in the Two Micron All Sky Survey (2MASX, Skrutskie et al., 2006) provides magnitudes in the \( J \), \( H \) and \( K_s \)-band, precise coordinates of the centre of the stellar disc, and radii of the stellar disc. The 2MASS data for the HIPASS parent sample are retrieved from the VizieR catalogue access tool\(^4\), which also took care of reliable cross-matching. Radial stellar mass profiles are measured as well on 2MASS \( K_s \)-band images (for more details see Section 2.6.2). The images were obtained from the SkyView archive\(^5\) and have a pixel scale of 2.0 arcsec and an effective wavelength of 2.159 \( \mu \text{m} \)\(^6\).

\(^4\)https://vizier.u-strasbg.fr/viz-bin/VizieR
\(^5\)https://skyview.gsfc.nasa.gov/current/cgi/basicform.pl
\(^6\)https://www.ipac.caltech.edu/2mass/releases/allsky/doc/sec6_4a.html
2.2. Public catalogue data

2.2.3 Optical images and photometry

Optical imagery used in this work is obtained from the SuperCOSMOS web page\(^7\) (Hambly et al., 2001b,a). These images have been observed in the \(B_J\)-band and were also used to create the HOPCAT catalogue. In addition to the optical catalogue data from HOPCAT, the ESO-LV catalogue (Lauberts & Valentijn, 1989) provides isophotal diameters and diameters at 90 per cent light, position angles and major to minor axis ratios in a band similar to the Johnson \(B\)-band (Holmberg et al., 1974). The homogenised, central wavelengths provided by NED are 467.7 nm and 440.2 nm for the SuperCOSMOS and ESO-LV images, respectively.

2.2.4 \textit{GALEX} and \textit{WISE}

Near- and far ultraviolet (\textit{NUV}, \textit{FUV}) photometry has been measured from the Galaxy Evolution Explorer imaging (\textit{GALEX}, Martin et al., 2005; Morrissey et al., 2007). \textit{NUV} images are available for all except one hix (ESO208-G026) and four control galaxies (NGC 685, NGC 3001 and NGC 3261, ESO123-G023). Only NGC 289 has data obtained with the medium imaging survey (MIS), all other galaxies have only been observed with the all-sky imaging survey (AIS), which is shallower than MIS (sensitive to 20.5 vs. 23.5 mag). The \textit{NUV} bandwidth ranges from 177.1 to 283.1 nm with an effective wavelength of 227.1 nm. The spatial resolution of \textit{NUV} images is 5.3 arcsec. \textit{NUV} science and sky background images are obtained from the Barbara A. Mikulski Archive for Space Telescopes (MAST\(^8\)). The sky background images are subtracted from the science images. Then \textit{NUV} counts are measured from the resulting intensity maps and converted into magnitudes using \textit{GALEX}’s flux calculator\(^9\).

The \textit{WISE} mission (Wright et al., 2010) provides imaging in the four mid-infrared \textit{WISE} bands: W1 (3.4 \(\mu m\)), W2 (4.6 \(\mu m\)), W3 (12 \(\mu m\)), W4 (22 \(\mu m\)). The published magnitudes in the AllWISE catalogue have been measured in a way which has been optimised for point sources. Hence, photometry for extended sources like the hix and control galaxies need to be remeasured. The flux of galaxies in each band is measured from images obtained from the ICORE co-adder\(^10\) (Masci & Fowler, 2008) and converted into magnitudes following the prescription in the \textit{WISE} data handbook (Cutri et al., 2013). The local sky background is estimated from dedicated background apertures and background images, which are also provided by ICORE and subtracted as prescribed in the

\(^{10}\)http://irsa.ipac.caltech.edu/applications/ICORE/
WISE data handbook. WISE W3 magnitudes for 90 randomly selected galaxies from the HIPASS parent sample have been provided by Vaishali Parkash via private communication. There is an article and a catalogue of WISE photometry of \(~2400\) HIPASS galaxies in preparation (Parkash et al., submitted; Jarrett et al., submitted)\(^\text{11}\).

The WISE and GALEX photometry is measured in elliptical apertures, where the semi major axis is of the size of the ESO-LV 25 mag arcsec\(^{-2}\) isophotal radius and the position angle and axis ratio is taken from HOPCAT. In the case of IC 4857, where the HOPCAT aperture is not matching the galaxy disc, the axis ratio and position angle from ESO-LV is used. Stars are masked out by hand. The measured NUV and W3-band magnitudes with their derived errors are given in Table 2.1. In Figure 2.1, magnitude measurements on all four WISE and the NUV GALEX band are included.

Figure 2.1 Overview of available photometry for the galaxies in this project. Absolute magnitudes at different wavelengths are given for every galaxy (colour-coded lines). On the x-axis both the wavelength and the name of the filter bands are noted.

\(^{11}\)For some information see: http://ict.icrar.org/store/staff/iwong/SWG3_2017/Parkash.pdf (visited on 05 June 2017)
2.2. Public catalogue data

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Table 2.1 A summary of the multiwavelength photometry used to calculate basic properties of the HIX (above the horizontal line) and CONTROL galaxies (below the horizontal line)

2.2.5 SDSS catalogues

SDSS (York et al., 2000) has surveyed about one third of the sky in the northern hemisphere. Based on the seventh data release (SDSS DR7, Abazajian et al., 2009), a catalogue of galaxies has been compiled: the MPA-JHU catalogue\(^{12}\). This catalogue provides derived measurements of stellar mass (Kauffmann et al., 2003a; Salim et al., 2007), star formation rates (Brinchmann et al., 2004) and metallicities (Tremonti et al., 2004). Additionally, the tables include some original SDSS data such as emission line fluxes. Star formation rates and stellar masses are used in Chapter 3 to provide a star formation main sequence and emission line fluxes and stellar masses are used in Chapter 5 to provide a mass–metallicity relation.

2.3 Sample selection

2.3.1 The HIX sample

The sample of \( \text{H} \text{I} \) eXtreme (HIX) galaxies is selected from a parent sample of 1796 galaxies. This parent sample has been compiled by Dénes et al. (2014) from a subset of the HIPASS catalogue and the HIPASS bright galaxy catalogue (Meyer et al., 2004; Koribalski et al., 2004) including only \( \text{H} \text{I} \) detections with reliable, single optical counterparts in the HIPASS catalogue of optical counterparts (HOPCAT, Doyle et al., 2005). Dénes et al. (2014) have used this parent sample to obtain scaling relations between the optical and the \( \text{H} \text{I} \) content of galaxies. Their scaling relation between the HOPCAT \( R \)-band luminosity and the HIPASS \( \text{H} \text{I} \) mass is used in this thesis to compare the average \( \text{H} \text{I} \) mass at a galaxy’s \( R \)-band luminosity to the \( \text{H} \text{I} \) mass as measured for this galaxy from the integrated 21 cm emission line in HIPASS. Haynes et al. (1984) defined an \( \text{H} \text{I} \)-deficiency factor as the difference between an average \( \text{H} \text{I} \) content and the actually measured \( \text{H} \text{I} \) content. Here, the deficiency parameter is defined as the difference between the \( \text{H} \text{I} \) mass as estimated from the Dénes et al. (2014) scaling relation, and the measured \( \text{H} \text{I} \) mass:

\[
\text{def} = \log M_{\text{HI,estimated}}[M_\odot] - \log M_{\text{HI,measured}}[M_\odot].
\]  

A smaller deficiency parameter indicates more “excess” gas being contained by the galaxy relative to its stellar content.

The detailed selection criteria for the HIX sample are:

\(^{12}\text{http://wwwmpa.mpa-garching.mpg.de/SDSS/DR7/}\)
(i) A HiPASS measurement of at least 2.5 times more H\textsc{i} than expected from the scaling relation, i.e. a deficiency factor of -0.4. Haynes et al. (1984) use a deficiency factor of ±0.3 to define outliers, which is of the order of the $1\sigma$ scatter of the Dénes et al. (2014) scaling relation. Hence, Dénes et al. (2014) and Dénes et al. (2016) used a deficiency factor of ±0.6 to define outliers. However, in the case of this study this conservative limit would have yielded a too small a sample. Therefore, the deficiency factor limit was selected to be -0.4. This is equivalent to a galaxy lying at least 1.4σ above the scaling relation. Figure 2.2 shows the scaling relation by Dénes et al. (2014) between the $R$-band absolute magnitude and the HiPASS H\textsc{i} mass, which was used here. At the time of sample selection, this was the scaling relation with the smallest scatter. In the published version of the scaling relations, the relation between $B_j$-band absolute magnitude and H\textsc{i} mass showed a smaller scatter ($\sigma_{Bj} = 0.26$ vs. $\sigma_R = 0.29$). If using the $B_j$-band deficiency factor, 58 per cent of the hix galaxies still have deficiency factor smaller than -0.4 and 92 per cent have a deficiency factor smaller than -0.35 (i.e. at least 2.2 times more H\textsc{i} than expected). ESO208-G026 has a $B_j$-band deficiency factor of -0.26 and as such only hosts 1.8 times as much H\textsc{i} as expected from the $B_j$-band luminosity.

(ii) Absolute $K_s$-band magnitude $M_K < −22.0$ mag, restricting the sample to massive galaxies. This is equivalent to a $K_s$-band luminosity cut at log $L_K [L_\odot] = 42.8$ or, if applying the stellar mass prescription in Section 2.4, a stellar mass cut of log $M_\star [M_\odot] = 9.7$. This lower stellar mass limit was applied for two reasons: (a) Some of the lower mass galaxies are very small in size and their H\textsc{i} observations would lack the necessary resolution for e.g. kinematic modelling and other intended investigations; (b) Mechanisms leading to H\textsc{i}-richness can be very different in dwarf and in massive spiral galaxies. Thus, the stellar mass cut intents to create a homogeneous sample.

(iii) Declination $< −30$ deg for observability with the ATCA.

Furthermore, galaxies near the galactic plane are excluded due to the high density of foreground stars, which complicate photometric measurements.

SuperCOSMOS B-band images (Hambly et al., 2001a,b) and NED have been searched for neighbouring galaxies within the size of the HiPASS spatial resolution element of 15.5 arcmin (Barnes et al., 2001). Where no galaxies of similar angular size and brightness have been found, H\textsc{i}-excess due to source confusion can be excluded and the galaxy can be included in the hix sample. Some galaxies, however, are accompanied by small dwarf
After this process, the hix sample consists of 14 galaxies, one of which has been transferred to the control sample due to poor Hopcat photometry (see Section 2.3.3). The criteria about observability with ATCA and sufficient distance to the Galactic Plane reduce the sample selection. A sample selection purely based on $\text{H}_\text{i}$ deficiency would yield in a sample of 119 galaxies, adding the stellar mass restriction (including the appearance in 2MASX) would result in a sample of 88 galaxies. Of the 1796 galaxies in the parent sample, 52 per cent (939 galaxies) are located south of -30 deg.

The parent sample for the hix galaxies is a subset of Hipass. It is therefore already an $\text{H}_\text{i}$ selected sample which is biased towards $\text{H}_\text{i}$-rich systems. Selecting the outliers from this parent sample leads to the hix galaxies being the most extreme galaxies with regards to their (relative) $\text{H}_\text{i}$ mass in the local Universe.

![Figure 2.2 The sample selection: The blue diamonds represent the hix sample, the red circles the control sample. The grey shade in the background represents the distribution of the Hipass parent sample. The black solid line gives the Dénes et al. (2014) scaling relation and the black dashed line marks, where the measured $\text{H}_\text{i}$ mass is 2.5 times larger or smaller than the expected $\text{H}_\text{i}$ mass.](image-url)
2.3. Sample selection

2.3.2 The CONTROL sample

A CONTROL sample has been compiled to compare the hix sample to a sample of average HIPASS galaxies. The CONTROL galaxies were drawn from the same parent sample and the selection criteria (ii) and (iii) were the same as used to define the hix sample. However, criterion (i) was changed to:

(i) a measured HIPASS H\text{I} mass between 1.6 times less and more than what is expected from the Dénes et al. (2014) scaling relation in order to capture galaxies well within the scatter (0.3\,dex). This is equivalent to galaxies being located within $\pm0.7\sigma$ of the scaling relation.

The ATCA Online Archive13 (ATOA) was searched for observations of galaxies that follow the CONTROL sample selection criteria. This lead to 13 CONTROL galaxies that have been observed for at least one synthesis in any 1.5\,km array configuration of ATCA. In Figure 2.2 these galaxies are drawn as red circles and lie well within the scatter of the scaling relation.

It is to be noted that the CONTROL sample is selected to be normal for an H\text{I} selected sample as e.g. HIPASS. This implies that the CONTROL sample is potentially still H\text{I}-rich compared to a stellar mass selected sample.

2.3.3 Changes to the samples

Initially, galaxy IC 4857 has been selected as a hix galaxy and has subsequently been observed with the ATCA and WiFeS. Further analysis has, however, shown that the HOPCAT aperture does not cover the entire galaxy in the magnitude measurement (see Figure 2.3). Thus, the HOPCAT R-band magnitude is underestimated and the H\text{I}-richness overestimated. The 6dFGS catalogue (Jones et al., 2004, 2009) also published R-band magnitudes measured from the same photographic plate data. When using their published R-band magnitude ($\text{mag}_R = 12.88$\,mag), then a deficiency parameter of -0.0 is obtained. Therefore, IC 4857 has been reclassified as a CONTROL galaxy. The HOPCAT photometry of all other sample galaxies has been checked as well, but no further issues were recovered. For each galaxy a Figure such as Figure 2.3 is provided in Appendix A.

HIX galaxy ESO327-G039 has been observed with the ATCA but a bright foreground star has made infrared, optical and ultraviolet photometry impossible. Thus ESO327-G039 is excluded from the analysis in Chapters 3, 4 and 5.

13\url{http://atoa.atnf.csiro.au/}
Chapter 2. Galaxy sample and data

Figure 2.3 The SuperCOSMOS $B_J$-band image of IC 4857 in red scales overlaid with the HOPCAT aperture in blue. Position angle, inclination, central position and size of the aperture are taken from HOPCAT. As can be seen, the HOPCAT aperture is misplaced and omits large parts of the galaxy.

CONTROL galaxies NGC 4672, IC 4366 and ESO462-G016 are included in the analysis of global parameters like total gas mass and star formation activity (Chapter 3). However, their resolved H$_I$ data did not reach data quality goals and they were thus omitted from the analysis of the resolved H$_I$ disc (Chapter 4).

2.3.4 Using different scaling relations for sample selection

Dénes et al. (2014) have defined multiple scaling relations, all of which can potentially be used for the HIX sample selection. Relations between the H$_I$ mass and the $K$, $H$, $J$, $I$, $R$ and $B_J$-band are available. The primary sample selection is based on the relation between the $R$-band luminosity and H$_I$ mass. Figure 2.4 shows a comparison between the deficiency factors obtained by using scaling relations from different bands.

The sample selection requires a $R$-band deficiency parameter of -0.4 or smaller. While this threshold is not observed in all bands, a clear separation between the HIX (blue diamonds) and the CONTROL (red dots) is seen in all bands. One exception is the now-CONTROL galaxy IC 4857, where the deficiency parameters in $K_s$, $H$ and $J$-band are close to 0.0 (i.e. average HIPASS galaxies), but in $I$, $R$ and $B_J$-band well below -0.4. Especially, in the lower three plots of the first column in Figure 2.4, this galaxy appears as the clear outlier. No other galaxy in HIX or CONTROL sample shows a similar behaviour.
2.3. Sample selection

Figure 2.4 Comparison of different deficiency parameters based on the different scaling relations by Denes et al. (2014). Small grey points are the HIPASS parent sample, red circles the CONTROL and blue diamonds the HIX sample. Each graph compares the deficiency parameters based on the photometry from two of the $K_s$, $H$, $J$, $I$, $R$ and $B_J$-band.
2.4 Basic galaxy properties

**H I mass (M\(_{\text{HI}}\))**

The H\(_1\) mass is calculated from the integrated 21 cm emission signal by:

\[
M_{\text{HI}}[\text{M}_\odot] = \frac{2.356 \cdot 10^5}{1 + z} \cdot (D[\text{Mpc}])^2 \cdot F_{\text{HI}}[\text{Jy km s}^{-1}],
\]

with \(z\) being the galaxy’s redshift, \(D\) the distance to the galaxy in Mpc and \(F_{\text{HI}}\) the integrated flux density in units of Jy km s\(^{-1}\). The error estimation closely follows the error estimation of \(F_{\text{HI}}\) as suggested by Koribalski et al. (2004):

\[
S/N = \frac{S_{\text{peak}}}{\sqrt{\text{rms}^2 + (0.05 \cdot S_{\text{peak}})^2}},
\]

\[
\Delta F_{\text{HI}} = \frac{4}{S/N} \cdot \sqrt{S_{\text{peak}} \cdot F_{\text{HI}} \cdot dv},
\]

where \(S_{\text{peak}}\) is the peak intensity in the spectrum, \(\text{rms}\) the root mean square of the data cube and \(dv\) the velocity resolution. Using Gaussian error propagation the error of \(F_{\text{HI}}\) is then propagated and combined with the error of the distance to obtain the error of the H\(_1\) mass. \(F_{\text{HI}}\) is measured from spectra using the MIRIAD (Sault et al., 1995) task MBSPECT and assuming a first order polynomial baseline.

**Stellar mass (\(M_\star\))**

To find the most useful mass to light ratio or log \(M_\star [\text{M}_\odot]\) calibration, multiple log \(M_\star [\text{M}_\odot]\) prescription were compared (see Figure 2.5).

Since most recent and most reliable data for extended galaxies in the Southern Hemisphere are not available in the optical but in the infrared spectrum, prescriptions based on infrared data were considered:

Prescriptions by Wen et al. (2013):

\[
\log M_\star[\text{M}_\odot] = -0.498 + 1.105 \times \log L_K[\text{L}_\odot],
\]

\[
\log M_\star[\text{M}_\odot] = -0.04 + 1.12 \times \log L_{W1}[\text{L}_\odot],
\]

\[
x = \log \frac{L_{W4}[\text{L}_\odot]}{L_{W1}[\text{L}_\odot]},
\]

\[
\log M_\star[\text{M}_\odot] = \log \left( L_{W1}[\text{L}_\odot] \times 10^{1.091 - 0.323x - 0.177x^2} \right),
\]

where \(L_x\) is the luminosity in band \(x\).
2.4. Basic galaxy properties

Figure 2.5 Comparison of different log $M_\star [M_\odot]$ prescriptions.

Prescriptions by Cluver et al. (2014):

$$
\log M_\star [M_\odot] = \log \left( L_{W1}[L_\odot] \times 10^{-1.93(W1-W2)-0.04} \right),
$$

(2.9)

where $W1$ and $W2$ are the magnitudes in the WISE W1 and W2-band respectively.

Prescriptions by Jarrett et al. (2013):

$$
\log M_\star [M_\odot] = \log \left( L_{W1}[L_\odot] \times 10^{-2.100(W1-W2)-0.246} \right),
$$

(2.10)

$$
\log M_\star [M_\odot] = \log \left( L_{W1}[L_\odot] \times 10^{-0.093(W2-W3)-0.192} \right),
$$

(2.11)

with $W3$ the magnitude in the W3-band.

For Figure 2.5, 2MASX data, remeasured WISE photometry and SDSS MPA-JHU stellar masses were collected for a sample of H i-rich galaxies from ALFALFA (the HighMass sample (Huang et al., 2014), see Section 3.2 for more information). For these galaxies, the above log $M_\star [M_\odot]$ prescriptions were plotted against the SDSS MPA-JHU stellar masses, which are based on spectral energy distribution (SED) modelling. As can be seen in Figure 2.5, all prescriptions agree with the SED stellar masses within approximately
±0.3 dex. There are, however, systematic offsets between different prescriptions. Due to these systematic offsets, only one of them will be used. Since the 2MASX data is reliable and readily available not only for selected galaxies but also for the majority of the parent sample, the Wen et al. (2013) prescription in Equation 2.5 was chosen and will be used for any log \( M_\star \) [M\(_{\odot}\)] calculation unless stated otherwise.

1478 out of the 1796 galaxies in the parent sample have a cross match in the 2MASX catalogue (82 per cent). “Missing” galaxies are probably not extended enough to be included in the 2MASX and are excluded from analysis, where a stellar mass is required.

**Atomic (\( M_A \)) and baryonic masses (\( M_B \))**

Besides the stellar and the H\( \text{I} \) mass, the atomic gas mass \( M_A \) and the baryonic mass \( M_B \) will be considered as well. The atomic gas mass accounts for atomic Helium (He) and is therefore 35 per cent higher than the H\( \text{I} \) mass (e.g. Obreschkow et al., 2016):

\[
M_A = M_{\text{HI+He}} = 1.35 M_{\text{HI}}. \tag{2.12}
\]

The baryonic mass is the mass of all baryons in the galaxy. This would include atomic, molecular, and ionised gas, dust, and stars. The baryonic masses of the galaxies analysed in this thesis are dominated by their atomic gas and stellar mass. The baryonic mass is therefore approximated with:

\[
M_B = M_A + M_\star. \tag{2.13}
\]

The measurement of the H\( _2 \) mass of sample galaxies is beyond the scope of this thesis. However, Saintonge et al. (2011) suggest that H\( \text{I} \)-rich galaxies are not necessarily H\( _2 \)-rich. Furthermore, the ratio of H\( _2 \) to H\( \text{I} \) is small in the local universe and H\( _2 \) is generally centrally located. It is thus assumed that here log \( M_{H_2} \) [M\(_{\odot}\)] is negligible for the purpose of measuring the baryonic mass or the baryonic specific angular momentum.

**Star formation rates (SFR)**

Star formation rates (SFR) are calculated from the GALEX NUV luminosity in combination with the WISE W3-band luminosity to account for dust obscured star formation. The prescription in equation (1) and (2) in Saintonge et al. (2016) are used, assuming a
2.4. Basic galaxy properties

Chabrier (2003) initial mass function (IMF):

\[
\log SFR_{W3,S16} = \log(4.91 \times 10^{-10} \times L_{W3}[L_\odot]),
\]
\[
\log SFR_{NUV} = \log(0.94 \times 6.84 \times 10^{-20} \times L_{NUV}[\text{erg s}^{-1}]),
\]
\[
\log SFR_{tot} = \log(SFR_{W3,S16} + SFR_{NUV}).
\] (2.14) (2.15) (2.16)

Where GALEX photometry is not available, the SFR prescription by Cluver et al. (2014), which is based solely on the luminosity in the W3-band, is used:

\[
\log SFR_{tot} = \log SFR_{W3,C14} = (1.13 \times \log(L_{W3}[L_\odot]) - 10.24).
\] (2.17)

Their IMF is consistent with a Chabrier (2003) IMF and the comparison of SFRs estimated with the both methods does not reveal systematic offsets. The combined NUV+W3 SFRs by Saintonge et al. (2016) agree within ±0.15 dex with the W3 SFRs by Cluver et al. (2014). ESO075-G006 is the only galaxy within the HIX and the CONTROL sample that is not detected in the W3-band. Its SFR therefore includes no mid-IR component.
Table 2.2 The hix galaxy sample. Column (1): An ID for every galaxy. Column (2) and (3): RA and DEC taken from 2MASS. Column (4): The stellar mass calculated as described in Section 2.4. Column (5): The H\textsc{i} mass calculated following Equation 2.2 using the measured HIPASS flux and the distance as stated in Column (8). Column (6): The H\textsc{i} gas mass fraction is defined as $f_{\text{HI}} = \frac{M_{\text{HI}}}{M_{\star}}$. Column (7): The heliocentric, systemic velocity from HIPASS (Meyer et al., 2004). Velocities here and throughout the thesis are given in the optical convention ($cz$). Column (8): Luminosity distance calculated from the systemic velocity in column 7 converted to the Galactic Standard of Rest frame and assuming the standard cosmology. Column (9): The star formation rate measured as described in Section 2.4.
### Table 2.3 The control galaxy sample. Columns as in Table 2.2

<table>
<thead>
<tr>
<th>ID</th>
<th>RA</th>
<th>DEC</th>
<th>log $M_*$ [M$_\odot$]</th>
<th>log $M_{HI}$ [M$_\odot$]</th>
<th>log $M_{HI} / M_*$</th>
<th>$V_{sys}$ [km s$^{-1}$]</th>
<th>$D$ [Mpc]</th>
<th>log SFR [M$_\odot$ yr$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 0685</td>
<td>01:47:42.8</td>
<td>-52:45:42</td>
<td>9.81</td>
<td>9.53</td>
<td>-0.28</td>
<td>1362</td>
<td>18</td>
<td>-0.63</td>
</tr>
<tr>
<td>ESO121-G026</td>
<td>06:21:38.8</td>
<td>-59:44:24</td>
<td>10.4</td>
<td>9.95</td>
<td>-0.46</td>
<td>2268</td>
<td>30</td>
<td>0.12</td>
</tr>
<tr>
<td>ESO123-G023</td>
<td>07:44:38.9</td>
<td>-58:09:13</td>
<td>10.1</td>
<td>10.0</td>
<td>-0.06</td>
<td>2914</td>
<td>39</td>
<td>-0.54</td>
</tr>
<tr>
<td>NGC 3001</td>
<td>09:46:18.7</td>
<td>-30:26:15</td>
<td>10.8</td>
<td>10.0</td>
<td>-0.81</td>
<td>2464</td>
<td>32</td>
<td>0.39</td>
</tr>
<tr>
<td>ESO263-G015</td>
<td>10:12:19.9</td>
<td>-47:17:42</td>
<td>10.3</td>
<td>9.67</td>
<td>-0.67</td>
<td>2531</td>
<td>33</td>
<td>-0.27</td>
</tr>
<tr>
<td>NGC 3261</td>
<td>10:29:01.5</td>
<td>-44:39:24</td>
<td>10.8</td>
<td>10.1</td>
<td>-0.76</td>
<td>2564</td>
<td>34</td>
<td>0.26</td>
</tr>
<tr>
<td>NGC 4672</td>
<td>12:46:15.7</td>
<td>-41:42:21</td>
<td>10.7</td>
<td>10.3</td>
<td>-0.43</td>
<td>3273</td>
<td>45</td>
<td>0.30</td>
</tr>
<tr>
<td>NGC 5161</td>
<td>13:29:13.9</td>
<td>-33:10:26</td>
<td>10.5</td>
<td>10.1</td>
<td>-0.34</td>
<td>2390</td>
<td>32</td>
<td>0.14</td>
</tr>
<tr>
<td>ESO383-G005</td>
<td>13:29:23.6</td>
<td>-34:16:17</td>
<td>10.4</td>
<td>9.75</td>
<td>-0.67</td>
<td>3614</td>
<td>50</td>
<td>-0.18</td>
</tr>
<tr>
<td>IC 4366</td>
<td>14:05:11.5</td>
<td>-33:45:36</td>
<td>10.7</td>
<td>10.1</td>
<td>-0.61</td>
<td>4615</td>
<td>65</td>
<td>0.54</td>
</tr>
<tr>
<td>IC 4857</td>
<td>19:28:39.2</td>
<td>-58:46:04</td>
<td>10.4</td>
<td>10.0</td>
<td>-0.33</td>
<td>4679</td>
<td>67</td>
<td>0.37</td>
</tr>
<tr>
<td>ESO462-G016</td>
<td>20:23:39.0</td>
<td>-28:16:40</td>
<td>10.1</td>
<td>9.85</td>
<td>-0.23</td>
<td>3055</td>
<td>45</td>
<td>0.073</td>
</tr>
<tr>
<td>ESO287-G013</td>
<td>21:23:13.9</td>
<td>-45:46:23</td>
<td>10.5</td>
<td>10.2</td>
<td>-0.34</td>
<td>2697</td>
<td>39</td>
<td>0.18</td>
</tr>
<tr>
<td>ESO240-G011</td>
<td>23:37:49.9</td>
<td>-47:43:41</td>
<td>10.9</td>
<td>10.3</td>
<td>-0.55</td>
<td>2840</td>
<td>40</td>
<td>-0.0013</td>
</tr>
</tbody>
</table>
Gas-phase oxygen abundance \((12 + \log (O/H))\)

The gas-phase oxygen abundance is estimated with the O3N2 and N2 method using the \(H\alpha\), \(H\beta\), \(O[III]\) \(\lambda 500.7\) nm, and \(N[II]\) \(\lambda 658.3\) nm emission lines as described by Pettini & Pagel (2004):

\[
O3N2 = \log \frac{O[III] \lambda 500.7\text{nm}/H\beta}{N[II] \lambda 658.3\text{nm}/H\alpha},
\]  
(2.18)

\[
N2 = \log \frac{N[II] \lambda 658.3\text{nm}}{H\alpha},
\]  
(2.19)

\[
12 + \log(O/H)_{O3N2} = 8.73 - 0.32 \times O3N2,
\]  
(2.20)

\[
12 + \log(O/H)_{N2} = 8.90 + 0.57 \times N2,
\]  
(2.21)

\[
12 + \log(O/H)_{N2-poly} = -8.0069 + 2.74353 \times N2 - 0.093680 \times N2^2
\]  
(2.22)

### 2.5 Australian Telescope Compact Array data

#### 2.5.1 Observations

The \(H_1\) interferometric data of the HIX and CONTROL sample were obtained with the Australian Telescope Compact Array (ATCA). While the majority of the observations for the HIX galaxies were carried out as part of the large program C2705, the data of the CONTROL sample were collected from the Australian Telescope Online Archive (ATOA)\(^{14}\). Tables 2.4 and 2.5 summarise the ATCA observations of the HIX and the CONTROL galaxies respectively.

For all observations, the standard ATCA flux and bandpass calibrator PKS 1934-638 was observed either before or after the galaxy observations for approximately 10 min. Phase calibrators were chosen such that they are strong sources but also close to the galaxy. This way the phase calibrator can be visited regularly during the galaxy observations without too much time loss. Typically, the phase calibrator was observed for 5 min for every 50 min of galaxy observation.

The HIX galaxies were observed with three different array configurations: once with any 1.5 km (long baselines), any 750 m (intermediate baselines) and any EW configuration (short baselines). The combination of the three arrays will provide both sensitivity to low column density gas and small spatial scales. For the CONTROL sample a minimum of one

\(^{14}\)http://atoa.atnf.csiro.au/
1.5 km array configuration was required. These observations are not as sensitive to low column density gas as the HIX galaxy observations. Yet, they provide small enough spatial resolution for kinematic analysis. Depending on the shortest (longest) baseline which has been included in any interferometric observation, the largest (smallest) structure to be resolved can be calculated by:

\[ \theta = 1.22 \times \frac{\lambda}{\text{baseline}}, \]

where \( \theta \) is the resolution in units of rad, \( \lambda = 21 \text{ cm} \) the wavelength and \textit{baseline} the length of the baseline in question. The longest baselines are observed with the 1.5 km array configuration and are between 1285.7 and 1484.7 m. With these maximal baseline length the smallest scales that can be resolved by the observations are 41 and 36 arcsec. The largest scales that can be observed are determined by the shortest baselines of the used array configurations. If only 1.5 km array configurations are available these largest scales can be as small as 5.8 arcmin. For galaxies that were also observed with any 750 m or EW array configurations, these largest scales range from 11.5 to 28.8 arcmin.

For the observations of the HIX and the control sample three different correlator set-ups were used:

(i) The Compact Array Broadband Backend (CABB, Wilson et al., 2011) in CFB 1M-0.5k mode. This is the preferred set-up for the C 2705 observations. Spectral line observations with this mode cover a 8.5 MHz bandwidth with a channel width of 0.5 kHz. This is approximately equivalent to a velocity resolution of 0.1 km s\(^{-1}\).

(ii) CABB in CFB 64M-34k mode. This is the set up for the archival data of three control galaxies (NGC 5161, NGC 3001 and ESO121-G026). In this mode, the spectral line observations have a bandwidth of 64 MHz and a channel width of 32 kHz (equivalent to 6 km s\(^{-1}\)).

(iii) the predecessor correlator of CABB (observations before 2009). The pre-2009 correlator covered an 8 MHz bandwidth with a channel width of 16 or 8 kHz resulting in a 3 km s\(^{-1}\) velocity resolution.

Continuum observations centred at 2.1 GHz are obtained simultaneously with the spectral line observations but are not used in this thesis.
<table>
<thead>
<tr>
<th>ID</th>
<th>1.5km Array</th>
<th>750m Array</th>
<th>EW Array</th>
<th>$t_{OS}$ [h]</th>
<th>Phase Calibrator</th>
<th>$f_{\text{cen}}$ [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESO111-G014</td>
<td>2012-12-19</td>
<td>2013-01-20</td>
<td>2013-01-16</td>
<td>24.6</td>
<td>2355-534</td>
<td>1384</td>
</tr>
<tr>
<td>ESO243-G002</td>
<td>2015-06-15</td>
<td>. . .</td>
<td>2012-11-08</td>
<td>17.9</td>
<td>0022-423</td>
<td>1378</td>
</tr>
<tr>
<td>NGC 289</td>
<td>2002-07-06$^{(a)}$</td>
<td>2015-09-07</td>
<td>2015-08-28</td>
<td>27.7</td>
<td>0022-423 / 0042-357</td>
<td>1413</td>
</tr>
<tr>
<td>ESO208-G026</td>
<td>2014-11-17</td>
<td>2015-09-10</td>
<td>2015-08-29</td>
<td>29.5</td>
<td>0823-500</td>
<td>1406</td>
</tr>
<tr>
<td>ESO378-G003</td>
<td>2015-06-13</td>
<td>2015-09-09</td>
<td>2015-08-31</td>
<td>28.3</td>
<td>1144-379</td>
<td>1406</td>
</tr>
<tr>
<td>ESO381-G005</td>
<td>2015-06-14</td>
<td>2015-09-07</td>
<td>2015-08-31</td>
<td>28.4</td>
<td>1232-416</td>
<td>1394</td>
</tr>
<tr>
<td>ESO461-G010</td>
<td>2014-11-14</td>
<td>2015-02-23</td>
<td>. . .</td>
<td>13.6</td>
<td>1921-293</td>
<td>1389</td>
</tr>
<tr>
<td>ESO075-G006</td>
<td>2012-12-20</td>
<td>2013-01-19</td>
<td>2012-11-08</td>
<td>20.5</td>
<td>1934-638</td>
<td>1370</td>
</tr>
</tbody>
</table>

Table 2.4: The ATCA H\textsuperscript{I} observations of the h\textsuperscript{I}x sample. \textit{Column (1): Galaxy ID. Column (2), (3) and (4): Date of observation in any 1.5 km, 750m and EW array configuration. Column (5): On source observation time in hours. Column (6): Phase Calibrator PKS [ID number]. Column (7): Central frequency of band in MHz. Most h\textsuperscript{I}x galaxy observations have been obtained through project C2705. More observations are taken from the following project: $^{(a)}$ C 819.
### Table 2.5 The ATCA H\textsubscript{i} observations of the control sample.

Observations of IC 4857 have been observed with the HIX project on the ATCA (C 2705). Other control galaxy observations are taken from the following projects: (\textsuperscript{b}) C 473, (\textsuperscript{c}) C 2921, (\textsuperscript{d}) C 885, (\textsuperscript{e}) C 869, (\textsuperscript{f}) C 633 and (\textsuperscript{g}) C 801.

<table>
<thead>
<tr>
<th>ID</th>
<th>1.5km Array</th>
<th>750m Array</th>
<th>EW Array</th>
<th>t\textsubscript{OS} [h]</th>
<th>Phase Calibrator</th>
<th>f\textsubscript{Cen} [MHz]</th>
</tr>
</thead>
<tbody>
<tr>
<td>NGC 685</td>
<td>1995-10-29\textsuperscript{(b)}</td>
<td>1995-09-30\textsuperscript{(b)}</td>
<td>...</td>
<td>20.0</td>
<td>0407-658</td>
<td>1414</td>
</tr>
<tr>
<td>ESO121-G026</td>
<td>2014-05-13\textsuperscript{(c)}</td>
<td>...</td>
<td>...</td>
<td>10.9</td>
<td>0539-530</td>
<td>1396</td>
</tr>
<tr>
<td>ESO123-G023</td>
<td>2001-08-04\textsuperscript{(d)}</td>
<td>2000-05-10\textsuperscript{(d)}</td>
<td>...</td>
<td>20.0</td>
<td>0727-365</td>
<td>1407</td>
</tr>
<tr>
<td>NGC 3001</td>
<td>2014-05-12\textsuperscript{(e)}</td>
<td>...</td>
<td>...</td>
<td>11.1</td>
<td>0919-260</td>
<td>1396</td>
</tr>
<tr>
<td>ESO263-G015</td>
<td>2001-03-15\textsuperscript{(e)}</td>
<td>...</td>
<td>...</td>
<td>10.8</td>
<td>1039-47</td>
<td>1408</td>
</tr>
<tr>
<td>NGC 3261</td>
<td>1997-05-01\textsuperscript{(f)}</td>
<td>1997-06-09\textsuperscript{(f)}</td>
<td>1997-04-02\textsuperscript{(f)}</td>
<td>30.0</td>
<td>0823-500 / 1215-457</td>
<td>1407</td>
</tr>
<tr>
<td>NGC 5161</td>
<td>2014-05-14\textsuperscript{(c)}</td>
<td>...</td>
<td>...</td>
<td>10.5</td>
<td>1255-316</td>
<td>1396</td>
</tr>
<tr>
<td>ESO383-G005</td>
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<td>...</td>
<td>9.8</td>
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</tr>
<tr>
<td>IC 4857</td>
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<td>2015-09-05</td>
<td>2012-06-06</td>
<td>20.4</td>
<td>1934-638</td>
<td>1399</td>
</tr>
<tr>
<td>ESO287-G013</td>
<td>2001-10-28\textsuperscript{(d)}</td>
<td>2000-05-09\textsuperscript{(d)}</td>
<td>...</td>
<td>20.6</td>
<td>2106-413</td>
<td>1408</td>
</tr>
<tr>
<td>ESO240-G011</td>
<td>2001-07-28 / 29\textsuperscript{(d)}</td>
<td>2000-05-11\textsuperscript{(d)}</td>
<td>...</td>
<td>19.9</td>
<td>2326-477</td>
<td>1407</td>
</tr>
</tbody>
</table>
2.5.2 Data reduction

The methodology of the data reduction is similar for all correlator set-ups and two semi-automated MIRIAD (Sault et al., 1995) pipelines were used in all cases. The pipelines are written in PYTHON\textsuperscript{15}, making use of the PYTHON wrapper for MIRIAD (MIRPY\textsuperscript{16}). Firstly, radio frequency interference (RFI, e.g. signal from GPS Satellites) is flagged out. RFI is identified by eye and with the sum-threshold method (Offringa et al., 2010) as implemented in the MIRIAD task pgflag. Then a semi-automated pipeline conducts bandpass, flux, and phase calibration using the MIRIAD tasks gpcal and mfboot. The calibration is then applied to the galaxy data. In the final step of this pipeline, a first order polynomial baseline is subtracted from each galaxy observation. The results of this procedure are considered satisfactory, once the phase of the phase calibrator is tightly scattered around 0 across the observing period and the amplitudes of the phase and bandpass calibrators are in agreement with the ATCA calibrator data base\textsuperscript{17}.

A second pipeline combines all available observations of one galaxy from different array configurations in the Fourier transformation. For this step the MIRIAD task INVERT is used. The weighting of individual visibility data points is chosen such that the spatial resolution of the resulting data cube is suitable for kinematic modelling (see Section 2.6.1), i.e. the H\textsubscript{i} disc is resolved with four or more resolution elements. At the same time the aim is to use a weighting as close to natural as possible, since natural weighting provides the best sensitivity to diffuse and low column density gas. In the INVERT function the weighting is set by the robust parameter, where robust = 2.0 is equivalent to natural weighting and robust = −2.0 to uniform weighting. Aiming for as good sensitivity and as good spatial resolution as possible, results in the use of natural weighting for one galaxy (NGC 289), robust = 0 for two galaxies (ESO461-G010, ESO290-G0035) and robust = 0.5 for all other galaxies. The so obtained dirty data cube is then cleaned (CLEAN), restored (RESTOR) and primary beam corrected (LINMOS). Mosaicking is necessary, where data is compiled from different observing projects (NGC 289). In this case cleaning is carried out with MOSSID and no primary beam correction is necessary, as it is already included in the INVERT step.

Moment 0, 1 and 2 maps are created with the MIRIAD task MOMENT. A three sigma clipping is applied and velocities of the moment 1 must be within the cube’s parameter range. These two measures reduce the noise in the resulting maps. Moment 1 and 2 maps are then masked to regions where the column density in the moment 0 maps is larger than

\textsuperscript{15}www.python.org
\textsuperscript{16}https://pypi.python.org/pypi/mirpy
\textsuperscript{17}https://www.narrabri.atnf.csiro.au/calibrators/
0.4 and $0.8 \times 10^{20}$ cm$^{-2}$ for HIX and CONTROL sample respectively. In addition, moment 0 maps without the three sigma clipping are created.

The different column density limits are due to the fact that the HIX observations are in general more sensitive than the CONTROL galaxy observations because of:

- longer total on-source integration times for the HIX galaxies.
- higher system temperature for observations with the old correlator, which was used for most of the CONTROL sample observations. Observations using the new correlator CABB have lower system temperatures, as the digitisation level of CABB is superior to the previous correlator. This leads to a higher correlator efficiency and thus a lower system temperature (Wilson et al., 2011).

For the results in this thesis, the different limits do not pose a problem as:

(i) all extended features in HIX galaxies that are relevant in the analysis are also detected at column densities $> 0.8 \times 10^{20}$ cm$^{-2}$.

(ii) the H$\alpha$ radius is measured at $1 M_\odot$ pc$^{-2} = 1.2 \times 10^{20}$ cm$^{-2}$ (see Section 2.6.2).

It has to be emphasised again that the observations of the CONTROL galaxies are less sensitive to diffuse gas. The flux recovered by the ATCA observations is on average 98 per cent and 88 per cent of the HIPASS flux for the HIX and the control galaxies respectively. Within the errors, the H$\alpha$ masses as measured from the ATCA H$\alpha$ data cubes and the H$\alpha$ masses as measured from the integrated flux from the HIPASS catalogues agree for all HIX galaxies and for half of the CONTROL galaxies. In the appendices, a HIPASS spectrum is given, which has been re-measured from the HIPASS data cubes. Due to different baselines, the H$\alpha$ masses as measured from the ATCA H$\alpha$ data cubes and as re-measured from HIPASS data cubes only agree within the errors for 83 and 43 per cent of the HIX and the CONTROL galaxies, respectively. Especially for CONTROL galaxies, this means that possible extended structures of diffuse gas might be resolved out. Where this becomes relevant in the analysis a note has been added.

Table 2.6 summarises the characteristics of the final data cubes of each galaxy. The beam sizes (i.e. the resolution elements) are similar to the predictions from the length of the longest baseline in Equation 2.23. The noise (rms) as measured from emission-free channels in the data cubes ranges from 0.6 to 3.0 mJy beam$^{-1}$. The ATCA sensitivity calculator\textsuperscript{18} predicts a theoretical noise of 0.9 mJy beam$^{-1}$ for 30 h of on source integration in the CFB 1M-0.5k mode, which was used for the HIX observations. This theoretical

\textsuperscript{18} http://www.narrabri.atnf.csiro.au/myatca/interactive_senscalc.html
noise is slightly smaller than the rms of HIX data cubes, most likely due to slightly shorter exposure times.

The resulting ATCA data cubes are then further analysed with standard Miriad tasks, SAOIMAGE DS9, TiRiFiC (Józsa et al., 2007) and Python scripts. Details are given in Section 2.6.

<table>
<thead>
<tr>
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<th>$\theta_2$ [arcsec]</th>
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</table>

Table 2.6 Final data cubes for HIX (above horizontal line) and Control galaxies (below horizontal line). Column (1): Galaxy ID. Column (2): Beam major axis. Column (3): Beam minor axis. Column (4): RMS in the final data cube. The weighting is set by the robust parameter in Miriad’s invert task. A weighting of 2.0 indicates natural weighting and of -2.0 uniform weighting. For most cubes a weighting with robust=0.5 was chosen except for $^a$ and $^b$ where robust = 2.0 and 0.0 was chose respectively. $^c$ indicates that the cube of the galaxy has a velocity channel width of 6 instead of 4 km s$^{-1}$. 
2.6 H I data analysis

The ATCA H I data cubes provide a lot of information, including the distribution and kinematics of the H I. The following approach is used to obtain this information:

(i) A 3D kinematic model is fit to every galaxy. This provides the radial variation of rotation velocity ($V_{\text{rot}}$), inclination ($INCL$) and position angle ($PA$).

(ii) With this information elliptical, co-centric annuli can be constructed. Within those annuli, the average H I column density and the total H I or stellar mass can be measured. Thus, radial column density and mass profiles can be extracted.

(iii) Those profiles are used to determine the H I disc size and the specific angular momentum.

The details of this process will be discussed in the next sections.

2.6.1 TiRiFiC modelling

The TIlted RIng FIting Code TiRiFiC (Józsa et al., 2007) is used to analyse the kinematic properties of HIX and CONTROL galaxies. The tilted ring fitting method has first been introduced by Rogstad et al. (1974) and allows the fitting and measurement of rotation velocity, position angle, inclination and more properties in concentric annuli.
### Table 2.7 Results of the TiRiFiC modelling of HIX galaxies. The final models of galaxies marked with * are FLAT models, all other galaxies are modelled with WARP models. 

**Column (1):** The galaxy ID. **Column (2):** The rotation velocity in km s\(^{-1}\). The value I give here is the \(V_{\text{flat}}\) parameter from the fit of the Equation 2.24 rotation curve to the TiRiFiC rotation velocities. **Columns (3):** The systemic velocity in km s\(^{-1}\) as found by TiRiFiC. **Column (4):** the modelled velocity dispersion in km s\(^{-1}\). **Columns (5) and (7):** the median position angle and inclination angles. **Columns (6) and (8):** the difference between the largest and the smallest position angle and inclination values respectively. **Column (9):** the disc thickness modelled as a geometric parameter in TiRiFiC in kpc.

<table>
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<th>ID</th>
<th>(V_{\text{rot}}) [km s(^{-1})]</th>
<th>(V_{\text{sys}}) [km s(^{-1})]</th>
<th>(\sigma) [km s(^{-1})]</th>
<th>PA [deg]</th>
<th>(\Delta) PA [deg]</th>
<th>INCL [deg]</th>
<th>(\Delta) INCL [deg]</th>
<th>Z0 [kpc]</th>
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Chapter 2. Galaxy sample and data
### Table 2.8 Results of the TiRiFiC modelling for the control galaxies.

The final models of galaxies marked with * are FLAT models, all other galaxies are modelled with WARP models. Columns are as in Table 2.7.

<table>
<thead>
<tr>
<th>ID</th>
<th>$V_{\text{rot}}$ [km s$^{-1}$]</th>
<th>$V_{\text{sys}}$ [km s$^{-1}$]</th>
<th>$\sigma$ [km s$^{-1}$]</th>
<th>PA [deg]</th>
<th>$\Delta$ PA [deg]</th>
<th>INCL [deg]</th>
<th>$\Delta$ INCL [deg]</th>
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<td>3</td>
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<td>87.0</td>
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<td>0.28</td>
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</table>
In the case of the hix and CONTROL sample, the following two models are considered:

- a flat disc (FLAT). In this case only the surface brightness and the rotation curve are allowed to vary with radius. All other parameters like inclination, position angle, centre of rotation, velocity dispersion, thickness of the disc and systemic velocity do not vary with radius.

- a disc warped in inclination and position angle (WARP). In this model both the inclination and the position angle are varied with radius. Otherwise this model is identical to FLAT.

The inclination and position angle of the inner rings are in general kept constant regardless of the model to be fitted, as the optical discs of both the hix and the CONTROL sample do not appear warped upon visual inspection (see e.g. the approach to modelling NGC 4414 by de Blok et al., 2014b).

The width of the rings is of the order of the beam size and rings with smaller widths being introduced at small radii. The number of rings is chosen such that the outermost ring is the first one without emission.

To not over-interpret the data, other parameters like a vertical lag in rotation velocity, which might indicate an active Galactic Fountain (Oosterloo et al., 2007), are not fitted. The HALOGAS survey (Heald et al., 2011) has been one of the first surveys to systematically study H I kinematics, including a detailed search for active Galactic Fountains and other kinematic peculiarities. The sample galaxies of this thesis are located at distances between 18 Mpc and 148 Mpc, which is two to ten times further away than the HALOGAS galaxies. Therefore, one resolution element covers a larger fraction of the galaxy than was the case for HALOGAS galaxies. This implies that the data cubes of the hix galaxies have fewer independent data points to be fitted by TiRiFiC than the HALOGAS data cubes. The TiRiFiC modelling does include the geometrical “$Z_0$” parameter”, which is the thickness of the disc. In many cases, however, the thickness of the disc is not well enough resolved for a reliable fit.

A final TiRiFiC model was chosen for every galaxy in the CONTROL and hix sample by:

- visual inspection of channel maps and position–velocity diagrams of the input data cube and the output model cube.

- aiming for radially smooth variations (if any) of rotation velocity, inclination and position angle.
2.6. \textit{HI} data analysis

- minimising the free parameters that are fitted. That means, if a flat disc model and a warped disc model produce similarly small residuals the flat disc model will be used.

TiRiFiC then provides a model data cube (for example channel maps see Figure 2.6) and a table with the radial profiles of the fitted parameters (see Figure 2.7) as output.

![Channel Maps](image)

Figure 2.6 NGC 3001 channel maps: grey shaded background and blue contours present the data and the red contours the TiRiFiC model.

### 2.6.2 Radial profiles

**Mass and column density profiles**

The radial profiles of the \textit{HI} column density, \textit{H}i mass and stellar mass are measured using the radial profiles of inclination and position angle from TiRiFiC. In a first step the inclination and position angle are extrapolated between the TiRiFiC rings. Then,
Figure 2.7 NGC 3001 radial profiles of the TiRiFiC model. In the top panel the surface brightness \( \text{SBR} \) is shown as a function of radius, in the middle panel the rotation velocity and in the bottom panel the inclination and position angle. In each panel, the radial profiles for both half-discs are given, one half of the disc is marked with circles (disc 1, given are \( \text{SBR} 1 \), \( \text{VROT} 1 \), \( \text{INCL} 1 \) and \( \text{PA} 1 \)) and the other half with crosses (disc 2, given are \( \text{SBR} 2 \), \( \text{VROT} 2 \), \( \text{INCL} 2 \) and \( \text{PA} 2 \)). The solid line in the middle panel shows the fitted rotation curve using the functional form of Equation 2.24.
concentric, elliptical annuli are defined with a width of the order of the pixel size. The inclination and position angle of each annulus are taken from the extrapolated TiRiFiC profiles according to their radius. The mean H\textsc{i} column density and the summed H\textsc{i} or stellar mass is then measured within each elliptical annulus. H\textsc{i} mass and column density profiles are measured from the non-clipped moment 0 maps and stellar mass profiles from the 2MASS $K_s$-band images. The 2MASS luminosities in each annulus are converted to stellar masses using again equation 3 of Wen et al. (2013). Stellar masses are only determined in annuli, which are smaller than the aperture within which 2MASS measured the integrated $K_s$-band magnitude (i.e. $r < r_{\text{ext}}$ from 2MASX catalogue). Stars are masked out.

**Rotation curves**

TiRiFiC also provides rotation velocities for each fitted ring. These rotation velocities are fitted with a rotation curve of the functional form:

$$V_{\text{rot}}(r) = V_{\text{flat}} \cdot \left[ 1 - \exp \left( \frac{-r}{l_{\text{flat}}} \right) \right]$$

(Leroy et al., 2008 and references therein). $V_{\text{flat}}$ is the circular velocity in the flat part of the rotation curve and $l_{\text{flat}}$ describes the radius at which the rotation velocity flattens. In Figure 2.7 an example of the fitted rotation curve is shown as solid line in the middle panel.

**H\textsc{i} disc size**

The H\textsc{i} radius $R_{\text{HI}}$ is measured from the H\textsc{i} column density profiles. $R_{\text{HI}}$ is defined to be the radius at which the H\textsc{i} column density drops to 1 $M_\odot$ pc$^{-2}$. Before $R_{\text{HI}}$ is measured, H\textsc{i} column densities are de-projected by multiplying with the cosine of the inclination cos INCL. Therefore, in more edge-on galaxies the measurement of $R_{\text{HI}}$ is more sensitive to inclination variations than in more face on galaxies. The radius is determined by linearly extrapolating the two column density profile data points just above and just below 1 $M_\odot$ pc$^{-2}$. Following Wang et al. (2014, 2016), $R_{\text{HI}}$ is then corrected for beam smearing effects. This correction assumes a Gaussian beam and is implemented as follows:

$$R_{\text{HI},\text{corr}} = 0.5 \sqrt{(2 \times R_{\text{HI},0})^2 - B_{\text{maj}} \times B_{\text{min}}},$$

where $R_{\text{HI},\text{corr}}$ is the corrected radius, $R_{\text{HI},0}$ the measured radius, and $B_{\text{maj}}$ and $B_{\text{min}}$ the major and minor beam axis, respectively.
Table 2.9 Basic properties and H\textsubscript{i} measurements for the HIX galaxy sample. *Column (1):* Galaxy ID. *Column (2):* H\textsubscript{i} mass as measured from HIPASS data cubes. *Column (3):* H\textsubscript{i} mass as measured from ATCA data cubes in this work. *Column (4):* The H\textsubscript{i} radius as measured at the 1 M\textsubscript{⊙} pc\textsuperscript{-2} isophote in kpc. *Column (5):* The 2MASX K\textsubscript{s}-band half-light radius in kpc. *Column (6):* The baryonic specific angular momentum in units of [kpc km s\textsuperscript{-1}] calculated as detailed in Equation 2.26. *Column (7):* The halo spin parameter inferred from the baryonic specific angular momentum. For more details see Section 2.9.2. *Column (8):* The global stability parameter q calculated according to Equation 2.27.
<table>
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<th>log $M_{\text{HI, ATCA}}$</th>
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<td>9.8</td>
<td>38.4</td>
<td>5.7</td>
<td>4095.8</td>
<td>0.07</td>
<td>-0.86</td>
</tr>
</tbody>
</table>

Table 2.10 Basic properties and H I measurements for the control galaxy sample. Columns as in Table 2.9.
Specific angular momenta

The combination of the stellar or H\textsuperscript{i} mass profiles with the rotation curve allows the calculation of the stellar or H\textsuperscript{i} specific angular momentum of the disc following:

\[ j = \frac{\sum_i M_i \times V_{\text{rot},i} \times r_i}{\sum_i M_i} \]  

(Obreschkow & Glazebrook, 2014; Obreschkow et al., 2016), where \( M_i \) is the mass of ring \( r_i \) rotating at velocity \( V_{\text{rot},i} \). The baryonic specific angular momentum is the mass weighted average of the stellar and H\textsuperscript{i} specific angular momentum.

The angular momentum is a vector. If the velocity vectors of annuli are not aligned, as is the case for warps, then the amplitude of the total angular momentum is smaller than the sum of the angular momenta in each annuli (vector addition). This effect is not corrected for in the analysis, as the fitted inclination warps are of the order of 10 deg or less, which would translate into a 2 per cent decrease in angular momentum.

The specific baryonic angular momentum together with the velocity dispersion as fitted with TiRiFiC and the baryonic mass determine the global stability parameter \( q \) (Obreschkow et al., 2016):

\[ q = \frac{j_B \cdot \sigma}{G \cdot M_B} \]  

(G is the gravitational constant). Measurements of angular momenta and stability parameters of H\textsuperscript{i}X and CONTROL galaxies are summarised in Tables 2.9 and 2.10, respectively and are analysed in more depth in Chapter 4.

This way to estimate a “stellar” specific angular momentum assumes that the kinematics of the stellar disc behave as the kinematics of the H\textsuperscript{i} disc. In particular in the centres of galaxies, this is not always the case (Bershady et al., 2010; Cortese et al., 2016b, 2014).

Halo spin estimates

The (halo) spin parameter is a unit-less parameter that describes the angular momentum properties of dark matter haloes and is defined as:

\[ \lambda \equiv \frac{J |E|^{1/2}}{G M_{\text{vir}}^{5/2}} = \frac{j_{\text{halo}}}{\sqrt{2} R_{\text{vir}} V_{\text{vir}}} \]  

(Peebles, 1969; Bullock et al., 2001), where \( J \) is the halo’s total angular momentum, \( E \) its total energy, \( M_{\text{vir}} \) its virial mass, \( j_{\text{halo}} \) its specific angular momentum, \( V_{\text{vir}} \) its virial velocity, and \( R_{\text{vir}} \) its virial radius. Simulations show that the spin parameters of haloes follow an
approximately log-normal distribution with a peak around 0.03 and are independent of the halo mass or redshift (Barnes & Efstathiou, 1987; Bullock et al., 2001; Shaw et al., 2006). When attempting to estimate the dark matter halo spin parameter for real galaxies, some assumptions have to be made. For this thesis, equation (19) in Obreschkow & Glazebrook (2014) is used:

$$\lambda = \left( \frac{M_B}{10^{10} M_\odot} \right)^{-2/3} \times \frac{j_B}{10^3 \text{kpc km s}^{-1}} \times \frac{1}{1.96 \times f_j \times f_M^{-2/3}}, \quad (2.29)$$

where $M_B$ and $j_B$ are the baryonic mass and specific angular momentum. They suggest values for the ratio of cold-baryon mass (stars + H$1$+ H$_2$) to halo mass ($f_M = 0.05$) and for the ratio of the specific angular momentum of cold baryons to that of the halo ($f_j = 1$), based on the results of Stewart et al. (2013), McMillan (2011), Flynn et al. (2006), Kalberla & Dedes (2008), and Sanders et al. (1984). Note, however, that in practice, there is a large scatter in both quantities (Romanowsky & Fall, 2012; Obreschkow & Glazebrook, 2014; Stevens et al., 2016; Lagos et al., 2017). Therefore, the estimates of the dark matter halo spin parameter from observed data can only be rough approximations. It is furthermore not obvious whether the ratio of cold-baryon mass to halo mass in HIX galaxies is similar to more average galaxies, as HIX galaxies contain so much H$1$. If HIX galaxies not only contained more H$1$ than average for their stellar content but also for their dark-matter halo content, then $f_M$ would increase and thus $\lambda$ would increase.

### 2.7 WIDE FIELD spectrograph data

#### 2.7.1 Observations

The WIDE FIELD Spectrograph (WiFeS, Dopita et al., 2007) on the ANU 2.3 m telescope in Siding Spring, Australia has been used to obtain optical integral field spectra (IFS) of 10 out of 13 HIX galaxies and one control galaxy. WiFeS is an image slicing IFS, meaning that it consists of 25 slitlets, each 1 × 36 arcsec in size. Combining the length of the slitlets and their number, WiFeS has a 36 × 25 arcsec$^2$ field of view. This is smaller than the optical disc of the HIX sample galaxies. Therefore, the aim was to observe every galaxy with multiple pointings to cover the centre and the outer regions of the stellar disc. In the left panel of Figure 2.8, an example of multiple pointings towards ESO111-G014 is given.

The aim was to obtain 60 min (90 min) of on-source time per pointing for galaxies
Figure 2.8 Example of WiFeS data for ESO111-G014. **Left:** the red-scale image in the background shows the $B_j$-band optical image. The overlaid blue squares are of the size of the WiFeS aperture and are located, where the telescope was pointed at. **Right:** The colour map in the background shows the $NUV$ image, the overlaid blue squares indicate where “single” star forming regions were defined.

with average surface brightness brighter (fainter) than 22 mag arcsec$^{-2}$. The actual total on-source exposure times of each pointing vary from 15 to 90 min depending on the signal strength and data availability. The total on-source time per pointing is distributed into single exposures of 15 min. Stacking multiple short exposures helps to remove cosmic rays and small image errors. The night sky is a strong foreground for optical spectra. This includes, for example, de-excitation emission lines of atoms in the atmosphere and zodiacal light (Hicks et al., 1972). To be able to subtract that foreground, all science spectra are taken in the so-called nod-and-shuffle mode. In this mode, the telescope nods between the science target, i.e. the galaxy and an “empty” part of the sky. This way a spectrum of the sky and a sum of the sky spectrum and the galaxy is obtained. The separate sky spectrum is then subtracted from the intermingled sky and galaxy spectrum to obtain a pure galaxy spectrum. In the case of the hix sample, the galaxy has been observed for 5 min, then a blank sky region has been observed for 5 min and this pattern has been repeated three times resulting in one galaxy exposure with an on-source time of 15 min (and a pure sky exposure of the same length).

Incoming spectra are split by a dichroic at 560 nm into a red and a blue half. Thus a wide wavelength range can be covered in one shot. WiFeS has been setup with $R = 3000$ gratings in both the red and blue arm for all observations. At a wavelength of 660 nm, this
is equivalent to a wavelength step of 0.22 nm per pixel or a velocity step of 100 km s$^{-1}$.

Every night of observations has been completed with standard calibration images including bias, sky and dome flat field, wire imaging for centring the slitlets, and NeAr and CuAr arc lamp spectra for wavelength calibration. Two to three times a night a standard star has been observed for flux calibration. Dark current information is obtained from overscan regions, i.e. parts of the CCD that were not exposed. The observations have been conducted between August 2014 and April 2016 under photometric conditions. Details about the number of pointings and on-source exposure times for each WiFeS observations of the HIX galaxies are given in Table 2.11.
Table 2.11 The WiFeS observations of the hix sample and control galaxy IC 4857. *Column (1)* gives the ID of the galaxies. *Columns (2) to (7)* give the exposure times in minutes for single pointings. The name of the column describes where the pointing is located with respect to the galaxy centre. For a visualisation of pointing location see Figure 2.8 for ESO111-G014 and Appendix D for all other galaxies.

<table>
<thead>
<tr>
<th>ID</th>
<th>Central</th>
<th>South/ East</th>
<th>North/ West</th>
<th>Arm/ Dwarf</th>
<th>Outer South</th>
<th>Outer North</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESO111-G014</td>
<td>60</td>
<td>60</td>
<td>60</td>
<td>45</td>
<td>—</td>
<td>—</td>
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<tr>
<td>NGC 289</td>
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<td>—</td>
<td>—</td>
<td>—</td>
<td>45</td>
<td>60</td>
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<tr>
<td>ESO245-G010</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ESO417-G018</td>
<td>—</td>
<td>75</td>
<td>—</td>
<td>—</td>
<td>—</td>
<td>—</td>
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<tr>
<td>ESO208-G026</td>
<td>—</td>
<td>75</td>
<td>90</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ESO378-G003</td>
<td>45</td>
<td>60</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ESO381-G005</td>
<td>30</td>
<td>45</td>
<td>60</td>
<td>60</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ESO075-G006</td>
<td>30</td>
<td>90</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>ESO290-G035</td>
<td>30</td>
<td>60</td>
<td>60</td>
<td>—</td>
<td>—</td>
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</tr>
<tr>
<td>IC 4857</td>
<td>90</td>
<td>15</td>
<td>60</td>
<td>—</td>
<td>—</td>
<td>—</td>
</tr>
</tbody>
</table>
2.7. **Wide Field spectrograph data**

2.7.2 **Data reduction**

Childress et al. (2014) provide the fully automated pywifes pipeline for WiFeS data. This pipeline includes bad pixel repair, bias and dark current subtraction, flat fielding, wavelength calibration, sky subtraction, flux calibration and data cube creation. The resulting data cubes are 70 by 25 pixels (35 by 25 arcsec) in size and their wavelength range is set from 650.0 to 685.0 nm and 460.0 to 525.0 nm for the red and blue cubes respectively. Note that these measures imply a pixel size of 1 arcsec in one spatial direction and 0.5 arcsec in the other spatial direction.

Due to lack of guiding during the observations, single galaxy exposures are spatially offset to each other. To account for this, pywifes is run on each observed galaxy exposure individually. For each pointing, data cubes are median stacked after the full data reduction by pywifes. To align single data cubes of one pointing, the distributions of Hα emission in the data cubes are compared. For an example see Figure 2.9. The locations of bright centres of star forming regions are matched up in between the different exposures of one pointing. Once the pixel offset between the single data cubes per pointing are known, the cubes are median stacked.

![Image](image.png)

**Figure 2.9** The colour scale images in the four left panels show the plane with Hα emission in the four single data cubes of the southern pointing of ESO111-G014. The black circles mark the feature that was used to align the four data cubes. The right panel shows the plane with Hα emission in the final, stacked data cube.

After stacking, cubes are reshaped such that both spatial dimensions have pixel sizes of 1 arcsec. For this task the scipy (Jones et al., 2001) function `scipy.interpolate.griddata` was used. Data were linearly interpolated to the new pixel size of 1 × 1 arcsec.

Observations of this WiFeS project do not include any world coordinate system (WCS).
information in their file headers. This information is however necessary. To include this information in the file headers the following procedure was applied: In the stacked and reshaped cube, the brightest centre of star forming regions is matched to the corresponding star forming region in GALEX NUV and/or SuperCOSMOS $B_j$-band images. The pixel location of this anchor point is then used as reference pixel for the WCS coordinate definition and the coordinates for the star forming region in the images as values for this pixel. To complete the assignment of WCS coordinates to a data cube, information on the pixel size (set to 1 arcsec) and the rotation of the cube on the sky is necessary. This is implemented with a rotation matrix in the “CD_i,j” header keywords. The rotation angle is set to the same value that was given to the telescope at the time of observation. An example of the matching of star forming regions between the Hα plane of a data cube and a NUV image is shown in Figure 2.10.

Figure 2.10 The left panel shows one of the planes in the stacked data cube of the northern pointing in ESO111-G014 that contains Hα emission. The black squares indicate the defined star forming regions. In the right panel the GALEX near-ultraviolet image in this area of ESO111-G014 is shown. Here, the black square indicates the planned WiFeS pointing. The black cross in both panels indicate which point was used to assign coordinates to the WiFeS data cube.

This procedure results in two data cubes for each pointing: one containing the red half of the spectrum and the other one the blue half. More details about the analysis of the data are given below in Section 2.8.

### 2.8 Analysis of the optical spectra

This section describes the analysis of the WiFeS integral field spectra of HII galaxies. The aim is to investigate the spatially resolved gas-phase oxygen abundance in HII galaxies.
To increase the signal–to–noise ratio of spectra, the spaxels are binned such that the Hα and N[II] λ 658.3 nm emission lines are visible in the resulting spectrum. Ceverino et al. (2016) and Sánchez Almeida et al. (2014b) suggest that in extremely metal-poor dwarf galaxies, recently accreted pristine gas may trigger star formation. This star formation would take place in metal-poor star forming regions. To be able to investigate the metallicity of star forming regions rather than random bins, spaxels within star forming regions are stacked resulting in one or two spectra per star forming region. These star forming regions are defined by hand on those planes of the WiFeS data cubes that contain Hα emission. One example of the northern pointing of ESO111-G014 is given in the left panel of Figure 2.10. The colour-scale image in the background is one of the cube planes with Hα emission. The black squares encompass defined star forming regions. There are usually three to nine star forming regions per pointing. A spectrum from the cube is extracted for each of these regions by averaging along the spatial dimensions of all spaxels belonging to each region. This results in a single one-dimensional spectrum per star forming region. The one-dimensional spectra of five star forming regions in the centre of ESO245-G010 are shown in Figure 2.11.

In pointings towards the edges of stellar discs, the one-dimensional spectra of individual star forming regions do not pick up emission from the stellar continuum (see for example Figure 2.11, Spectrum 1). In those cases the background is modelled with a third order polynomial. For the fit of the polynomial, emission lines are masked out. Then the modelled background is subtracted and emission lines are fitted with Gaussians of the functional form:

\[
F(\lambda) = A \times e^{-\frac{(\lambda - \lambda_{\text{cen}})^2}{2 \times \sigma^2}}. \tag{2.30}
\]

Here \(F\) is the flux as a function of the wavelength \(\lambda\). \(A\) is the amplitude, \(\lambda_{\text{cen}}\) the central wavelength of the emission line, and \(\sigma\) the width of the emission line. As this is a Gaussian, the integrated flux of one emission lines follows as:

\[
F_{\text{tot}} = \sqrt{2\pi} \times \sigma^2 \times A. \tag{2.31}
\]

The redshift of the emission line can be calculated from the central wavelength \(\lambda_{\text{cen}}\). The recession velocity of the line is then:

\[
V = c \times \frac{\lambda_{\text{cen}} - \lambda_0}{\lambda_0}, \tag{2.32}
\]

where \(c\) is the speed of light and \(\lambda_0\) the rest frequency of the emission line.
Figure 2.11 Example of spectra in the centre of ESO245-G010. Dark blue lines show the stacked spectra for single star forming regions, light blue the fit to the background (a polynomial for spectrum 1 and a stellar population synthesis model for all other galaxies), and red the fit of the emission lines.
If stellar continuum is observed for a spectrum of a star forming region (see for example Figure 2.11, Spectra 0, 2, 3 and 4), then the full spectrum (i.e. the blue and the red half) is used to fit a stellar population synthesis model and gas emission lines with the pPXF method and complimentary *python* script by Cappellari & Emsellem (2004). pPXF fits the stellar population synthesis models from the Vazdekis et al. (2010) library and emission lines. From the location of stellar absorption features, the stellar recession velocity in this star forming region can be measured. The line strength is given for each modelled emission line individually (H\(_{\alpha}\), H\(\beta\), O[III] \(\lambda 500.7\) nm and N[II] \(\lambda 658.3\) nm) and one recession velocity for the entire gas component.

In Figure 2.12, different metallicity estimators are compared for spectra in those star forming regions that can be modelled with pPXF. The following metallicity estimators are compared to the \(O3N2\) metallicity calculated (Equation 2.20) from pPXF modelled emission line fluxes (from top to bottom panel):

(i) polynomial N2 method (Equation 2.22) with the emission lines measured after subtraction of a polynomial background,

(ii) polynomial N2 method (Equation 2.22) with pPXF modelled emission line fluxes,

(iii) the N2 method (Equation 2.21) with the emission lines measured after subtraction of a polynomial background,

(iv) the \(O3N2\) method (Equation 2.20) with the emission lines measured after subtraction of a polynomial background and

(v) the N2 method (Equation 2.21) with pPXF modelled emission line fluxes.

As can be seen, the scatter in the middle panel is the smallest (method (iii)) and this method will be used whenever a pPXF model is not available. The metallicity and ionised gas kinematics are analysed in Chapter 5.

To de-project the on-sky distance \(r\), first the angle \(\theta\) between the galaxy semi-major axis and the line between galaxy centre and star forming region is determined. The de-projected radius \(r_{dpj}\) is then:

\[
r_{dpj} = \frac{r \times \sqrt{(b \cos \theta)^2 + (a \sin \theta)^2}}{b},
\]

where \(a\) and \(b\) are then semi-major and semi-minor axis respectively.

To measure the metallicity gradient, a line is fitted to the metallicities as a function of de-projected galactocentric radius. The slope of this line is the metallicity gradient.
Figure 2.12 Comparison of different methods to estimate the gas-phase metallicity: the x-axis in every plot is the O3N2 metallicity calculated (Equation 2.20) from pPXF modelled emission line fluxes. On the y-axis different other metallicity estimators are given (for more details see text). Red data points mark data in CONTROL and blue data points in HIX galaxies. The solid line is the one on one line, the dashed and dotted lines mark ±0.15 and 0.3 dex, respectively.
2.9 The DARK SAGE semi-analytic model

2.9.1 Introduction to the DARK SAGE semi-analytic model

To further deepen the understanding of the HIX galaxies, the observations are compared to simulations. Saintonge et al. (2017) have shown that simulations, which calibrate against gas mass functions and/or scaling relations provide the most accurate predictions of the gaseous content of galaxies. In addition, a strong focus of this thesis is the specific angular momentum of galaxies. The semi-analytic model DARK SAGE (Stevens et al., 2016) fits the HIX survey perfectly by focusing on the specific angular momentum of the model galaxies. Furthermore, in addition to other properties, the model is calibrated to the observed H\textsc{i} mass function (Zwaan et al., 2005) and to the mean H\textsc{i}-to-stellar mass fraction of galaxies as a function of stellar mass (Brown et al., 2015). DARK SAGE has the further advantage that its galaxy catalogues are easily accessible through the Theoretical Astrophysical Observatory (TAO\footnote{https://tao.asvo.org.au}, Bernyk et al., 2016).

Semi-analytic models use halo merger trees, typically produced from a cosmological N-body simulation, as input for a series of coupled differential equations that describe the evolution of galaxies (see reviews by Baugh, 2006; Somerville & Davé, 2015). At each time-step in DARK SAGE gas can cool onto a galaxy from its halo. The net specific angular momentum of the gas that cools is assumed to be the same as that of halo at that instant (related to $\lambda$ through Equation 2.28). This gas is distributed with an exponential profile into 30 disc annuli, each of which has a fixed specific angular momentum. The angular-momentum vector of this gas is then summed with that already in the galaxy to define the gas disc’s new plane, and both distributions are projected onto a new set of annuli in that plane. Frequent changes to the halo’s spin direction (or magnitude) and mergers can lead to a reduction in the galaxy’s specific angular momentum. The conversion of H\textsc{i} to H$_2$ is modelled with the prescription by Blitz & Rosolowsky (2004), in which the mid-plane pressure of the disc determines the H\textsc{i} to H$_2$ ratio. Stars are formed when H$_2$ is present (more important in low mass galaxies) or when the gas is Toomre-unstable (more relevant in high mass galaxies). This method produces an axis-symmetric (1D) model of galaxies. Hence, DARK SAGE can predict sizes and concentration but no morphology.

In DARK SAGE, there are no assumptions made about the relationship between the instantaneous spin of a (sub)halo and the galaxy it hosts (see Stevens et al. 2017 and references therein for a discussion on the importance of this). Instead, a galaxy’s specific angular momentum depends on the entire history of its halo’s spin evolution, along with
its merger history, and its own secular evolution.

2.9.2 The simulated galaxy catalogue

A box-type catalogue of simulated galaxies was obtained from TAO. The underlying dark matter-only simulation is the Millennium simulation (Springel et al., 2005) with the full box size of \((500 \text{ Mpc}/h)^3\) at a redshift of \(z = 0\). The Millennium simulation uses the cosmological parameters from \textit{WMAP-1} (Spergel et al., 2003). These parameters \((H_0 = 73.0 \text{ km Mpc}^{-1} \text{s}^{-1}, \Omega_m = 0.25)\) are different to the standard cosmology used in this thesis. Note, however, that \(H_0 = 70 \text{ km Mpc}^{-1} \text{s}^{-1}\) is applied where relevant to the simulation data in order to be consistent with the presentation of observational data. The dark matter haloes are populated using the 2016 version of the \textit{Dark Sage} semi-analytic model (Stevens et al., 2016). Because \textit{Dark Sage} evolves galaxy discs in annuli of constant specific angular momentum, the model can make predictions on structural and kinematic properties of the simulated galaxies.

In addition to the galaxy parameters that \textit{Dark Sage} computes, TAO can also fit the spectral energy distribution (SED) of a galaxy and thus calculate its brightness in given filters. In this case, Bruzual & Charlot (2003) SEDs with a Chabrier (2003) initial mass function were chosen. The final catalogue of simulated galaxies includes masses and angular momenta for each of stars, \textsc{Hi} and molecular gas, as well as bulge-to-total mass ratios, \textsc{Hi} and stellar disc sizes, absolute R-band magnitudes, and dark matter halo spin parameters.

In Figure 2.13, colours provided by the TAO SED models are used to look at the NUV-r colour distribution. As can be seen, galaxies with lower stellar masses tend to have bluer colours than more massive galaxies. Furthermore, a bimodality in the colour distribution can be identified. This is in good agreement with e.g. work by Kauffmann et al. (2003b). It is, however, to be noted that \textit{Dark Sage} is particularly aimed at reproducing disc-dominated galaxies rather than bulge-dominated galaxies.

2.9.3 Selecting \textsc{Dark Sage HIX} and CONTROL galaxies

The \textsc{HIX} and \textsc{CONTROL} sample were selected using the \(R\)-band – \textsc{Hi} mass scaling relation by Dénès et al. (2014). This relation is also used to select simulated \textsc{HIX} and \textsc{CONTROL} galaxies from the \textit{Dark Sage} catalogue. Furthermore, a stellar mass cut of \(9.7 \leq \log M_{\textsc{Hi}}[\text{M}_\odot] \leq 11.2\) and a bulge to total mass ratio cut \(B/T < 0.3\) is applied to select only massive, disc-dominated galaxies. The selection of disc galaxies mimics the Hipass bias towards disc-dominated, \textsc{Hi}-rich galaxies.
2.10. Other surveys: GASS and COLD GASS

This results in a catalogue of 288,385 disc galaxies of which 18,416 (6 per cent) are HIX and 154,730 (53 per cent) CONTROL sample-like. In Chapters 3 and 4, it will be discussed how similar these samples are to the observed samples.

2.10 Other surveys: GASS and COLD GASS

The GALEX Arecibo SDSS survey (GASS, Catinella et al., 2010, 2013) and the CO Legacy Survey for GASS (COLD GASS, Saintonge et al., 2011) collected data for a stellar mass selected sample in the local Universe. This sample was randomly selected from SDSS within a redshift range of $0.025 \leq z \leq 0.05$ to sample the stellar mass range above $\log M_* [M_\odot] > 10.0$. The data sets include integrated H\textsc{i} measurements for $\sim 800$ galaxies from Arecibo, integrated CO measurements for $\sim 350$ galaxies from the IRAM 30 m single dish and optical long-slit spectra for 174 star forming galaxies (Moran et al., 2012). These data are publicly available. The catalogues of integrated properties are used in Chapter 3.
to compare to a stellar mass rather than H\textsc{i} selected galaxy sample. In Chapter 5, the optical long-slit spectra are used to measure metallicity gradients along the slit direction, i.e. the major axis. These metallicity gradients are compared to the metallicity gradients of H\textsc{ix} galaxies.
This chapter is published in the paper

“The HIX galaxy survey I: study of the most gas-rich galaxies from HIPASS”


The focus of this chapter lies on setting the HIX sample in context with the broader galaxy population. This includes comparing the HIX sample to other HI rich galaxy samples, to the local galaxy population in general, and to simulated galaxies from the semi-analytic model Dark Sage. The analysis of the star formation activity and stellar morphology of the HIX galaxies is here of particular interest.
Chapter 3. The HIX galaxies in context

3.1 Introduction

This thesis examines outliers towards the very H\textsubscript{i}-rich end of one of the Dénes et al. (2014) scaling relations – the one between \textit{R}-band luminosity and H\textsubscript{i} mass – and aims to investigate why these galaxies host a more massive H\textsubscript{i} disc than average. Two scenarios are considered: these galaxies are either more efficient at accreting gas from their environment, or they are less efficient at converting available gas into stars (see also Huang et al., 2014). A combination of the two scenarios is also possible.

Over the last three decades large, systematic surveys of the atomic hydrogen (H\textsubscript{i}) content of galaxies have allowed the study of the relation between star formation, stellar and H\textsubscript{i} content of galaxies. Scaling relations have shown that the H\textsubscript{i} content of gas-rich galaxies in the local Universe is correlated with the galaxies’ stellar content (Haynes et al., 1984; Catinella et al., 2010; Dénes et al., 2014; Brown et al., 2015). In this Chapter, the global properties of the HIX galaxies will be examined, compared to other gas rich samples and set in context with the wider galaxy population. To do so, scaling relations will be used. A particular focus lies on the star formation activity and morphology of the HIX galaxies. This will help to understand the star formation efficiency of the HIX galaxies.

Different surveys are used to calibrate scaling relations. They include blind HI surveys such as Hipass and ALFALFA, which are biased towards H\textsubscript{i}-rich galaxies, but also stellar mass or volume limited surveys such as GASS (Catinella et al., 2010, 2013). The latest results from these surveys indicate that in general early-type or bulge-dominated galaxies have smaller H\textsubscript{i} to stellar mass fractions than late-type or disc-dominated galaxies (Catinella et al., 2013; Serra et al., 2014; Brown et al., 2015). The available cold gas determines the star formation activity in galaxies (Kennicutt, 1998; Brown et al., 2015; Saintonge et al., 2016). Since galaxies in the local Universe can broadly be divided into a low-mass, disc-dominated, and star forming population and a massive, bulge-dominated, quiescent population, a relation between H\textsubscript{i} to stellar mass fraction and stellar mass is also observed (Brown et al., 2015).

In terms of absolute H\textsubscript{i} mass, (spiral) galaxies with a higher stellar mass or brighter optical disc also tend to have a higher H\textsubscript{i} mass (Dénes et al., 2014; Maddox et al., 2015). In the H\textsubscript{i} selected sample of HIPASS, this is a well defined and linear relation, which has been used to select the sample of H\textsubscript{i}-rich galaxies. When adding galaxies with higher stellar masses and lower H\textsubscript{i} mass fraction (which were detected more likely in ALFALFA than in HIPASS), this relation “saturates” at high stellar masses. Data suggest that this saturation effect or upper envelope is defined by the angular momentum of haloes (Maddox et al., 2015), but also the fact that the galaxy population at high stellar masses is dominated by
3.2. Other H I-rich galaxy surveys

gas-poor, bulge-dominated galaxies plays a role.

This Chapter is structured as follows: in Section 3.2, the HIX sample selection is compared to the selection of other “H I-rich” surveys. A short overview of the optical morphology of HIX and CONTROL galaxies is given in Section 3.3. In Section 3.4, the location of HIX galaxies on the log $M_{\text{HI}} / M_\star$ vs. log $M_\star [M_\odot]$ relation is investigated. Sections 3.5 and 3.6 examine the star formation rates and efficiencies of HIX galaxies, respectively. The findings are then discussed in Section 3.7.

3.2 Other H I-rich galaxy surveys and their sample selections

The HIX survey is the first survey of H I-rich galaxies in the Southern Hemisphere and selects galaxies to have a high H I mass for their stellar content. There are five other surveys and studies of H I-rich galaxies, which were selected based on data from GASS, SDSS and ALFALFA and are thus all located in the Northern Hemisphere. Their sample selection is mostly based on a large H I to stellar mass fraction for either their stellar content or their star formation activity and morphology. In more detail, the other surveys and their sample selection criteria are:

HHighMass

HHighMass galaxies are selected from the 40% ALFALFA $\alpha.40$ catalogue (Huang et al., 2014). The two main selection criteria for HHighMass are:

(i) an H I mass log $M_{\text{HI}} [M_\odot] > 10.0$ and

(ii) a high H I to stellar mass fraction (log $M_{\text{HI}} / M_\star$). This is defined to be the case if a galaxy lies more than 1 $\sigma$ above the running average of the ALFALFA parent sample in the log $M_{\text{HI}} / M_\star$ vs. log $M_\star [M_\odot]$ plane. Considering Huang et al. (2014), this can be quantified as

$$\log M_{\text{HI}} / M_\star > 6.8 - \frac{2}{3} \times \log M_\star [M_\odot].$$

(3.1)

This leads to a relatively large sample of galaxies. So the HHighMass team has randomly selected a sample of 34 galaxies. Hence, HHighMass is a sample of galaxies that host a high H I mass fraction for their stellar content. As will be discussed in the next sections, this makes HHighMass similar to HIX galaxies.

The specific angular momentum and halo spin properties of HIX galaxies will be compared to four HHighMass galaxies, for which resolved H I maps and accurately measured
Table 3.1 Properties for four H\textit{i}ghMass galaxies. Properties marked with * are taken from Hallenbeck et al. (2014, 2016). All other properties are calculated as described in the text.

<table>
<thead>
<tr>
<th></th>
<th>UGC 9037</th>
<th>UGC 12506</th>
<th>UGC 6168</th>
<th>UGC 7899</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\lambda^*$</td>
<td>0.07</td>
<td>0.15</td>
<td>0.09</td>
<td>0.08</td>
</tr>
<tr>
<td>$\log M_{\text{HI}} [M_\odot]^*$</td>
<td>10.33</td>
<td>10.53</td>
<td>10.35</td>
<td>10.42</td>
</tr>
<tr>
<td>$\log M_\star [M_\odot]$</td>
<td>10.45</td>
<td>10.79</td>
<td>10.43</td>
<td>10.82</td>
</tr>
<tr>
<td>$\log M_B [M_\odot]$</td>
<td>10.75</td>
<td>11.03</td>
<td>10.76</td>
<td>11.01</td>
</tr>
<tr>
<td>$j_B$ [kpc km s$^{-1}$]</td>
<td>3239</td>
<td>10583</td>
<td>4169</td>
<td>5438</td>
</tr>
<tr>
<td>$\log q$</td>
<td>-0.84</td>
<td>-0.60</td>
<td>-0.73</td>
<td>-0.86</td>
</tr>
</tbody>
</table>

H\textit{i} monsters

Similarly to H\textit{i}ghMass, H\textit{i} monsters (Lee et al., 2014) were selected from ALFALFA. These are galaxies from the March 2008 ALFALFA catalogues (Haynes et al., 2011), which have H\textit{i} masses larger than log $M_{\text{HI}} [M_\odot] > 10.5$, and a set of low surface brightness galaxies with H\textit{i} masses larger than log $M_{\text{HI}} [M_\odot] > 10.0$. In principle this should result in an overlap between H\textit{i}ghMass and H\textit{i} monsters. However, only AGC 005543 is a member of both samples.

The sample by Lemonias et al. (2014)

The Lemonias et al. (2014) sample has been selected from the second data release of the GASS survey (Catinella et al., 2012). H\textit{i}-rich galaxies in this study are those 5 percent of galaxies with the largest log $M_{\text{HI}} / M_\star$ for their stellar mass in GASS. The explicit selection criterion is:

$$
\log M_{\text{HI}} / M_\star > 0.02 - 0.75 \times (\log M_\star [M_\odot] - 10.) \quad (3.2)
$$

$$
> 7.52 - \frac{3}{4} \times \log M_\star [M_\odot] \quad (3.3)
$$

This selection criterion is slightly less strict than the H\textit{i}ghMass criterion in the stellar mass range of 10.0 < log $M_{\text{HI}} [M_\odot] < 11.5$, which is the stellar mass range of the Lemonias
et al. (2014) parent sample. This might be due to the fact that the HighMass criterion is defined on an H I mass selected sample and the Lemonias et al. (2014) criterion on a stellar mass selected sample (despite volume corrections in the HighMass case). Many of the sample galaxies host an active galactic nuclei.

The sample by Gerеб et al. (2016)

The sample of Gerеб et al. (2016) and Gerеб et al. (2018) is also selected from the GASS survey and most H I observations come from ALFALFA. In contrast to Lemonias et al. (2014), Gerеб et al. select their sample galaxies to be H I-rich for their star formation and morphology. The relevant scaling relation in this case is the gas-fraction plane as defined by Catinella et al. (2013):

\[
\log \frac{M_{\text{HI}}}{M_\star} = -0.240 \times \log \mu_\star - 0.250 \times (NUV - r) + 2.083. \quad (3.4)
\]

As these galaxies are gas rich for their star formation and morphology rather than their stellar mass, they are different to the HIX galaxies.

BLUEDISK

As in the Gerеб et al. (2016) sample, the BLUEDISK galaxies were selected to be outliers to the gas-fraction plane (Wang et al., 2013). However, at the time of sample selection, actual H I measurements were not available. Therefore, the approach was to calculate the H I mass fraction with the gas-fraction plane of Catinella et al. (2010). If the estimated \( \log \frac{M_{\text{HI}}}{M_\star} \) was larger than -1.0, then a correction term depending on the (g-i) colour gradient and on the stellar mass was applied. If this correction term was larger than 0.6, then the galaxy was classified as “H I excess”. Once the sample galaxies were observed in H I, they were re-classified depending on whether they were located above or below the Catinella et al. (2010) gas-fraction plane. This sample selection has two effects:

(i) Again, the H I-rich galaxies of the BLUEDISK sample are not selected to be H I-rich for their stellar mass but for their star formation activity and morphology, which would make them different to the HIX galaxies.

(ii) As the BLUEDISK H I-rich and control sample have been re-classified after observations, many of the H I-rich galaxies are located well within the scatter of the scaling relation and some control galaxies are H I-deficient for their star formation activity and morphology.
Chapter 3. The HIX galaxies in context

HIGHz

The HIGHz sample is a selection of the most H1-rich galaxies around a redshift of \( z \approx 0.2 \) and includes some of the highest redshift detection of a single galaxy in H1 (Catinella & Cortese, 2015). The observations of these galaxies appear to be the first to show massive, H1-rich galaxies beyond the local Universe. HIGHz galaxies have high H1 mass fractions for their stellar masses and may be high redshift analogues to the most H1 massive galaxies in the local Universe (Catinella & Cortese, 2015), such as hix galaxies.

When setting the hix galaxies into the context of the general galaxy population in the local Universe, the hix sample will be compared to other samples of H1-rich galaxies. The HighMass sample will have the most similar galaxies to the hix ones as all other samples either select galaxies with high H1 mass fractions for their star formation activity rather than stellar content, or include galaxy types in their analysis, which are not prevalent in the hix sample (e.g. galaxies with active galactic nuclei or low surface brightness galaxies). Furthermore, the hix and HighMass sample selection will be compared in Section 3.4.

For a fair comparison, SFRs and stellar masses were calculated the same way for HighMass, H1 monsters and Lemonias et al. (2014) sample galaxies as for the hix galaxies, i.e. W3 and NUV photometry was remeasured in a consistent way and 2MASX photometry was obtained. For the HIGHz and BLUEDISK galaxies those values were taken from the respective publications. For all samples, distances and H1 masses were adopted from the respective publications.

3.3 Optical morphology

In Figures 3.1 and 3.2, small postage stamp images of the hix and the control sample are shown, respectively. Both samples consist of fairly regular spiral galaxies, which is in agreement with the RC3 catalogue (de Vaucouleurs et al., 1991). This catalogue classifies all galaxies as spirals except for ESO055-G013 and ESO208-G026, which are classified as S0.

The two samples also do not differ in a WISE colour-colour diagram (Figure 3.3, adapted from figure 12 in Wright et al., 2010), which also classifies all galaxies as spirals. Furthermore, the effective 2MASS Ks-band surface brightness covers a similar range for the hix and the control galaxies. This implies a similar stellar surface brightness within the effective radius (see Figure 3.4).

It has been found that many low surface brightness (LSB) galaxies are rich in H1. Some of the most H1 massive galaxies known are LSB galaxies, like for example Malin 1.
3.3. Optical morphology

Figure 3.1 Panel of SuperCOSMOS $B_j$-band postage stamp images of all HIX galaxies. All images are 3 arcmin by 3 arcmin in size except for the image of NGC289, which is 6 arcmin by 6 arcmin in size. The scale bar in the bottom right corner indicates 25 kpc at the distance of the galaxy.
Figure 3.2 Panel of SuperCOSMOS $B_J$-band postage stamp images of all control galaxies. All images are 3 arcmin by 3 arcmin in size except for the image of NGC 3261, which is 6 arcmin by 6 arcmin in size and the images of NGC 685, NGC 3001, NGC 5161, ESO240-G011, which are 4.5 arcmin by 4.5 arcmin. The scale bar in the bottom right corner indicates 25 kpc at the distance of the galaxy. Galaxies with a red name written on the image are not included in the analysis of resolved H$\text{I}$ maps.
3.4. \textit{HI} mass and stellar mass

The relation between gas fraction (defined as $M_{\text{HI}}/M_{\star}$) and stellar mass ($M_{\star}$) is well known for HI-selected samples and used here to test the HIX selection criteria and compare the HIX galaxies to the CONTROL and parent sample as well as other samples as discussed in Section 3.2.

Figure 3.5 shows this relation. In the top panel, most HIX galaxies (blue diamonds) are located above the $1\sigma$ scatter of the parent sample, while the CONTROL galaxies (red circles) populate the HIPASS scatter (green shaded region). The HIX galaxy that is located within the green shaded area is ESO208-G026. It has been selected to be an HI eXtreme galaxy according to the $R$-band scaling relation of Dénes et al. (2014). On the gas mass fraction vs. stellar mass relation, however, it lies within the scatter of the HIPASS parent sample and thus, its HI-richness on that scale is not as obvious as for the other HIX galaxies. In the analysis of spatially resolved HI data of ESO208-G026 in Chapter 4, it will be determined whether this galaxy is a true HIX galaxy, a more “normal” HIPASS

Figure 3.3 The \textit{WISE} colour-colour magnitude diagram as introduced by Wright et al. (2010). (Bothun et al., 1987). Following Monnier Ragaigne et al. (2003), LSB galaxies can be identified through a faint ($> 18$ mag arcsec$^{-2}$) $K_s$-band surface brightness in the central 5 arcsec as given by the 2MASX catalogue. Yet, none of the HIX or CONTROL galaxies are classified as LSB galaxy according to this criterion.

Following Monnier Ragaigne et al. (2003), LSB galaxies can be identified through a faint ($> 18$ mag arcsec$^{-2}$) $K_s$-band surface brightness in the central 5 arcsec as given by the 2MASX catalogue. Yet, none of the HIX or CONTROL galaxies are classified as LSB galaxy according to this criterion.
Chapter 3. The HIX galaxies in context

Figure 3.4 The average stellar surface brightness within one effective radius as a function of $\text{H}_\text{I}$ mass. The central surface brightness of HIX galaxies is not fainter than the central surface brightness of CONTROL and HIPASS galaxies.

galaxy or something in between.

The top panel of Figure 3.5 also shows the running average of the GASS sample for comparison (yellow dashed line, data release 3, Catinella et al., 2010, 2012, 2013). Non-detections are included as upper limits. GASS is a stellar mass selected sample and as such not biased towards H$\text{I}$-rich systems as it is the case for HIPASS. The running average of the GASS sample is therefore lower than for the HIPASS parent sample and even the CONTROL sample appears H$\text{I}$-rich compared to GASS. This further emphasises that the HIX galaxies are among the most H$\text{I}$-rich galaxies in the local Universe.

The HIX sample is further compared to the previously introduced surveys of H$\text{I}$-rich galaxies (see Section 3.2): HighMass, the sample by Lemonias et al. (2014), H$\text{I}$monsters, HIGHZ, and BLUEDISK. In being H$\text{I}$ massive and spiral galaxies, the HighMass (and H$\text{I}$monsters) sample galaxies appear to be the most similar to the HIX sample. As neither of the HIX galaxies is an LSB galaxy and most of the H$\text{I}$monsters have larger stellar masses than the HIX galaxies, there is little overlap between these studies. Where both samples overlap, they host comparably massive H$\text{I}$ reservoirs at a given stellar mass. The
3.4. HI mass and stellar mass

Figure 3.5 The HI gas mass fraction as a function of the stellar mass. In all panels: (blue) diamonds present the HIX sample and (red) circles the control sample. Their symbols with error bars indicate the median errors of the samples. Top panel: The green, solid line presents the running average of the HIPASS parent sample along with the 1σ scatter as the green shaded region. The yellow, dashed line and shaded area represents the running average and 1σ scatter of the GASS sample. Open symbols present other surveys of (HI-rich) galaxies as labelled in the legend. Middle panel: Small points present HIPASS galaxies colour-coded according to their deficiency factor. Bottom panel: The grey-shading in the background shows the distribution of DARK SAGE disc galaxies (logarithmic scaling), the dashed lines present running average for DARK SAGE galaxies of different deficiency factors (with 16 to 84 percentile range shaded) and the solid green line the HIPASS running average.
Lemonias et al. (2014) and HIGHz galaxies mostly have higher stellar masses than HIX galaxies. Bluedisk galaxies are located within the scatter of the HIpass parent sample and are more similar to the control than the HIX galaxies (see also their description in Section 3.2). Galaxies from the THINGS survey (Walter et al., 2008) have also been included in this plot, since they are the only other “large” sample of galaxies for which the specific angular momentum has been measured (see also Section 4.5). THINGS is not a sample of particularly H1-rich galaxies but a survey of nearby galaxies in general. Thus, these galaxies are also less H1-rich than the HIX galaxies.

In the middle panel of Figure 3.5, the data of HIX (diamonds), control (circles) and HIpass parent sample (small dots) are shown again. This time, the symbols are colour coded according to the deficiency factor. In addition, the HIpass running average (green, solid line) and the HighMass sample selection threshold (the dominant criterion at stellar masses log $M_\star [M_\odot] > 9.5$, light blue, dashed line) are shown. The HIpass galaxies which host more H1 than expected from the Dénes et al. (2014) scaling relations (bluer colours), also have a high H1 mass fraction for their stellar mass. Similarly, HIpass galaxies with less H1 than expected from the Dénes et al. (2014) scaling relations (redder colours), have a low H1 mass fraction for their stellar mass. Therefore, the HIX and HighMass sample selection criteria will find similarly H1-rich galaxies. There are a few exceptions to this trend, most notably IC 4857 (but see Section 2.3.3). Another difference between HIX and HighMass is that HighMass also includes galaxies with very large stellar masses (compared to the HIX stellar masses). This might be because H1-rich galaxies with large stellar masses are rare. ALFALFA probes a larger volume than HIpass, thus HighMass is more likely to find these galaxies than HIX.

The bottom panel of Figure 3.5 shows the distribution of disc galaxies modelled with the semi-analytic model Dark Sage, as well as the running average for Dark Sage galaxies in different deficiency factor bins (dashed lines, colour coded according to the central deficiency factor of the bin). The running average of the HIpass parent sample is shown by the green line. The running average of simulated HIX galaxies coincides with the location of observed HIX galaxies. Control galaxies are located in a similar region as the running averages of control-like Dark Sage galaxies.

3.5 HIX galaxies on the star formation main sequence

In order to further characterise the sample of HIX galaxies, their star formation activity is investigated and compared to the control sample. The star formation main sequence, which shows the star formation rate ($SFR$) as a function of stellar mass ($M_\star$) is shown in
Figure 3.6 The star formation rate as a function of stellar mass (the star formation main sequence). Panels and symbols as in Figure 3.5. The grey shaded area in the background of the top panel represents the galaxies from the MPA-JHU catalogue of SDSS galaxies. H1-rich galaxies tend to be located on the star formation main sequence.
Chapter 3. The HIX galaxies in context

Figure 3.6. At a given stellar mass, both the HIX and the control sample form stars at a similar rate, i.e. the average specific star formation rates \((sSFR = SFR / M_\star)\) of HIX (\(\log sSFR [\text{yr}^{-1}] = -10.3\pm0.2\)) and control sample (\(\log sSFR [\text{yr}^{-1}] = -10.4\pm0.2\)) are comparable. As can be seen in the top panel of Figure 3.6, galaxies from the HighMass, Lemonias et al. (2014), and H I monsters samples are also located on the star formation main sequence. The HIGHz galaxies are located above the star formation main sequence. As Catinella & Cortese (2015) point out, these galaxies are selected to be very blue and actively star forming. Locating these galaxies on the \(sSFR - \log M_{\text{HI}} / M_\star\) relation shows that HIGHz galaxies form stars as is expected for their H I content.

In the middle panel of Figure 3.6, the star formation rates for the 90 randomly selected galaxies from the HIPASS parent sample with WISE photometry (Parkash et al., submitted; Jarrett et al. submitted) are shown (dots) together with the HIX (diamonds) and control galaxies (large circles). All data points are colour coded according to the deficiency parameter. There is no clear trend as to H I-rich galaxies being more or less actively star forming for their stellar mass than average HIPASS galaxies.

The bottom panel again shows the data from the DARK SAGE model in four bins of the deficiency parameter. The running averages of H I-rich and average galaxies \((-0.4 < \text{def}_R < 0.4)\) in DARK SAGE are very similar and appear to fall on a common main sequence of star formation. This main sequence is, however, at slightly higher values than for the observed data. This might be due to the fact that in simulations, star formation can be measured more directly and is not obscured by dust. Observations may miss star formation, which is obscured by dust or too faint to be observable, whereas simulations might include assumptions that do not mirror reality.

In summary, HIX galaxies form stars as actively as control galaxies for their stellar mass. In other words, both samples have similar specific star formation rates.

3.6 The star formation efficiency of HIX galaxies

In this section, the star formation efficiency \((SFE = SFR / M_{\text{HI}})\) or H I depletion time scale \((t_{\text{depl}} = SFE^{-1})\) of HIX galaxies are investigated. As found in the previous section, HIX galaxies form stars at similar rates than control galaxies. HIX galaxies are, however, more H I-rich than the control sample. Hence, their star formation rate per H I mass are systematically lower, as can be seen in Figure 3.7, which shows the relation between the star formation efficiency and stellar mass for the HIX and control samples.

When comparing to the other H I-rich samples in the top panel, HighMass, H I monsters and the Lemonias et al. (2014) sample occupy a similar parameter space to the HIX galax-
3.6. The star formation efficiency of HIX galaxies

Figure 3.7 The star formation efficiency as a function of stellar mass. Panels and symbols are as in Figure 3.5. In the middle panel, the black, dotted line is the average SFE for log $M_\star [M_\odot] > 10$ galaxies found by Schiminovich et al. (2010) and the grey, dotted lines are model predictions by Wong et al. (2016). H I-rich galaxies in the local Universe tend to be less efficient at forming stars than CONTROL galaxies.
ies, while HIGHz galaxies have higher SFEs.

For further insights, a model by Wong et al. (2016) is included and shown as grey dashed line in the middle panel. This simple model calculates the SFE of local galaxies under the assumption that galaxies are marginally stable discs. This model thus suggests that the SFE is dependent on the kinematic properties of the galaxy disc. Since the model is calibrated on SINGG galaxies (Meurer et al., 2006), which is an H\textsc{i} selected sample, it is suitable to compare to the hix and control galaxies. Based on a rotation velocity, the model generates a rotation curve using a given functional form. Using empirical relations such as the Tully-Fisher relation and the surface brightness – luminosity relationship, the stellar surface density is calculated. Assuming a marginally stable disc with two components (stars and gas) the gas surface density is deduced. The relative contributions by H\textsc{i} and H\textsc{2} in the model galaxies are disentangled using two different prescriptions, one of them is dependent on the stellar surface mass density (D) and the other one on the hydrostatic pressure (P). While the hydrostatic pressure model is the preferred model by Wong et al. (2016), the stellar surface mass density model better describes the SFEs of the control sample. The hix galaxies form stars less efficiently than suggested by both models. Nevertheless, this model provides a first hint that the low SFEs and thus H\textsc{i}-richness of hix galaxies can be attributed to kinematic properties.

As in the previous sections (Sections 3.4 and 3.5), a comparison is made to a stellar mass selected sample. All hix and control galaxies form stars less efficiently than the average value found by Schiminovich et al. (2010) for the GASS sample. It has to be noted though that the scatter of their data is three orders of magnitudes and they included both disc and bulge dominated galaxies. The depletion times of all hix and control galaxies are larger than $t_{\text{depl}} < 56$ Gyr (equivalent $SFE = 10^{-10.75}$.yr$^{-1}$). For larger depletion times, Schiminovich et al. (2010) consider a galaxy passive for their H\textsc{i} reservoir. One example for these passive galaxies is GASS 3505 ($t_{\text{depl}} \sim 79$ Gyr, Geréb et al., 2016), which is an H\textsc{i}-rich galaxy for its sSFR and morphology.

CONTROL galaxies ESO123-G023 and ESO240-G011 are less efficient than the rest of the control sample and many hix galaxies. This indicates that the scatter of the HIPASS parent sample might be larger as is the case for the Schiminovich et al. (2010) analysis. A sample of 90 random HIPASS galaxies with WISE photometry by Parkash et al. (submitted) and Jarrett et al. (submitted) are again shown in the middle panel of Figure 3.7. These HIPASS galaxies are shown together with the hix and control galaxies (as in Figure 3.6), with their data points colour coded by their deficiency factor. These galaxies indeed show a larger scatter than the control galaxies. Nevertheless, there is
a trend that H I-rich or HIX galaxies are less efficient in forming stars than CONTROL or more average HIPASS galaxies.

In the bottom panel, the HIX and CONTROL galaxies are shown together with the DARK SAGE model data. Similar to the star formation main sequence, there is a systematic offset between the model and the observed galaxies. However, the overall trend is similar: HIX-like galaxies are less efficient at forming stars than CONTROL-like galaxies.

3.7 Discussion and conclusion: HIX galaxies in context

The HIX galaxies have been selected to have a high H I mass in comparison to their R-band luminosity. This also implies a high H I mass fraction at a given stellar mass.

Comparing the HIX sample to other H I-rich samples shows that it is most similar to the HighMass sample. A closer comparison of the two samples reveals that both approaches select the most extreme galaxies in terms of absolute H I mass and H I to stellar mass ratio. HighMass galaxies, which would not be included by the HIX selection criterion, tend to have large stellar masses. This is likely due to the fact that these massive galaxies are not detected by HIPASS but only by ALFALFA with its larger survey volume. While especially the HighMass and the HIX sample are very similar, different sets of auxiliary data and approaches make these surveys of H I-rich galaxies highly complementary.

When looking at the star formation main sequence, HIX galaxies are located in similar regions to the CONTROL sample. Hence, their star formation rates are as expected for their stellar masses, i.e. specific star formation rates are similar in HIX and CONTROL galaxies. However, a comparison of the star formation efficiency of the HIX and CONTROL sample suggests that HIX galaxies form stars systematically less efficiently than the CONTROL sample (and the parent sample as a whole). So, the massive H I reservoirs of HIX galaxies might be explained by a less efficient star formation than in CONTROL or more average HIPASS galaxies. In fact, HIX galaxies form stars so inefficiently that at the current rate their available gas reservoir would last for another 11 to 12 Gyr, which is almost the age of the Universe.

Saintonge et al. (2016) have found that the position of a galaxy on the star formation main sequence is to first order described by how much cold gas (as traced by H I) is detected in the galaxy but also how much of the cold gas is available for star formation. The fact that the HIX galaxies are located on, and not well above, the star formation main sequence, despite their large cold gas reservoirs, might indicate that not their entire cold gas reservoir is available for star formation. Unlike H I excess galaxies such as GASS 3505 (Geréb et al., 2016), which have very low SFRs, HIX galaxies must, however, still have
access to some parts of their gas reservoir for star formation.

HX galaxies and the HIPASS parent sample were compared to simulated disc galaxies from the semi-analytic model DARK SAGE. Deficiency parameters can be defined the same way for simulated galaxies as for observed galaxies. Simulated and observed galaxies behave similarly on the log $M_{HI} / M_\ast$ vs. log $M_\ast [M_\odot]$ relation. The star formation rates in simulated and observed galaxies do not agree quantitatively. However, the star formation rates and efficiencies show the same overall trend: HIX-like galaxies are located on the star formation main-sequence but given their large H I reservoirs they form stars less efficient than CONTROL-like galaxies. Hence, in terms of H I content and star formation activity DARK SAGE galaxies behave similar to observed galaxies. Some characteristics of observed galaxies are not accessible to observers such as their dark matter halo characteristics. In simulations this information is readily accessible. As the simulated galaxies show a similar behaviour to observed galaxies the simulations can be used in the next Chapter to infer information on the dark matter halo of the observed HIX galaxies.

As far as the analysis in this Chapter goes, the stellar mass range, the optical morphology, and the sSFR of HIX galaxies are similar to these properties of the CONTROL galaxies. Brown et al. (2015) have identified the H I mass fraction as a primary driver for sSFR as well as a residual relation with morphology and stellar mass. If the CONTROL and the HIX sample match in these properties, the difference in H I content arises from other causes, such as potential gas accretion or the inefficiency to form stars from the H I. Since these are the effects this thesis is examining, the CONTROL sample was well selected.

The comparison of the resolved H I properties of the HIX and the CONTROL sample in the next Chapter will investigate why HIX galaxies are not forming more stars from their available H I reservoir. In addition, it will be examined whether the H I-richness in HIX galaxies can be attributed to recent gas accretion.
Analysis of H\textsubscript{i} kinematics of HIX and control galaxies

This chapter is published in the paper

“The HIX galaxy survey II: HI kinematics of HI eXtreme galaxies”


The main topic of this Chapter is the resolved H\textsubscript{i} data of the HIX and the control sample. After comparing the size of H\textsubscript{i} and stellar discs of the two samples, it is investigated how many galaxies have flat or warped discs and how often galaxies of either sample have H\textsubscript{i} tails or arms. Finally, the TiRiFiC kinematic models are used to measure the baryonic specific angular momentum of the sample galaxies and compare the results to semi-analytic model galaxies from the Dark Sage simulations.
4.1 Introduction

Galaxies need to replenish their gas reservoir in order to remain active starformers in the future (Sancisi et al., 2008, Sánchez Almeida et al., 2014a and references therein). Gas-rich mergers and smooth accretion from the circumgalactic medium are suggested as avenues for gas replenishment (White & Rees, 1978). Observations of local galaxies do not find evidence for enough gas rich mergers to sustain star formation (Di Teodoro & Fraternali, 2014; Sancisi et al., 2008; Sánchez Almeida et al., 2014a). Thus smooth accretion should be the dominant channel of gas accretion. This might be the re-accretion of gas previously ejected by feedback mechanisms together with halo gas dragged along (à la the “Galactic Fountain”, see e.g. Oosterloo et al., 2007; Fraternali et al., 2011) or the cosmological accretion of pristine gas. Cosmological simulations suggest accretion occurs through the cooling of hot halo gas or through the delivery of cold gas through filaments (Birnboim & Dekel, 2003; Kereš et al., 2005; Dekel & Birnboim, 2006; van de Voort et al., 2011). If no stable hot halo is formed around the galaxy, then gas might just condense from the intergalactic medium. In the local Universe, observations of gas-phase metallicity gradients and inhomogeneities (Moran et al., 2012), warps (Roskar et al., 2010) and lopsided discs (Bournaud et al., 2005) may be interpreted as observations of cosmological accretion but may also result from tidal interactions with other galaxies.

The HALOGAS survey (Heald et al., 2011) has previously searched for signs of accretion in deep H I observations of nearby galaxies (distance < 11 Mpc). Through detailed modelling of the H I kinematics, the HALOGAS team has found a few high velocity clouds, thick H I discs, and warps in their sample galaxies (Gentile et al., 2013; Zschaechner et al., 2011, 2012; de Blok et al., 2014a). In the Milky Way, high velocity clouds are thought to contribute to gas accretion (Putman et al., 2012). The thick disc component, which is usually lagging in rotation velocity with respect to the thin disc, can interpreted as a sign of the Galactic Fountain (Oosterloo et al., 2007; Fraternali et al., 2011). However, the total rate of inferred H I accretion – be it through the Galactic Fountain mechanism or high velocity clouds – in the HALOGAS observations is not sufficient to fuel star formation in their sample galaxies (Heald, 2015).

The original motivation for the HIX galaxy survey was to study H I-rich galaxies to try and observe accretion. One possible avenue for HIX galaxies to become H I-rich could be that they are very actively accreting gas. However, as shown in Chapter 3, HIX galaxies are also less efficient at forming stars than a CONTROL sample. So the gas-rich galaxies of the HIX survey are not necessarily gas-rich due to recent or very active gas accretion but could also be inefficient at using their available gas for star formation. Simple models
4.2. Masses and sizes

As detailed in the previous Chapter, the HiX galaxy sample was selected to contain more H\textsc{i} than expected from their stellar luminosity using scaling relations by Dénes et al. (2014). This translates into HiX galaxies containing a high H\textsc{i} to stellar mass fraction for their stellar mass. The stellar discs of the HiX galaxies are similar to those of the control sample in terms of star formation activity and morphology. Now, a stellar mass–size relation will be investigated. The relation between stellar mass and the $K_s$-band effective radius is shown in Figure 4.1. As stellar masses are calculated from $K_s$-band luminosities, radii in the $K_s$-band can be treated as a proxy for stellar radii, so the $K_s$-band effective radius is a proxy for the half-mass radius. For the galaxies in the Hipass parent sample that are identified with a 2MASX counterpart, a correlation between $M_*$ and $R_*$ is seen. The running average of these Hipass galaxies is in good agreement with the corresponding scaling relation for GAMA galaxies (Lange et al., 2015). Here the GAMA relation, which was calibrated for disc-dominated galaxies, is used. Both the HiX and the control sample follow this relation and are located in similar regions of the stellar mass–size plane. Thus in terms of average stellar surface density and physical size, the stellar discs of HiX galaxies are similar to the stellar discs of the control sample. It has to be noted though that the 2MASX observations are relatively shallow and would only pick up the older stellar population. So, if HiX galaxies had extended, low surface brightness discs of young stars,
this would not be reflected in this measurement.

Figure 4.1 furthermore shows the 68 and 95 per cent contours for Dark SAGE galaxies. For the simulated data, only the radius that encompasses half the stellar disc mass can be computed. This disregards any mass that is in the bulge. While the distribution of the simulated HIX-like galaxies is not too far away from the distribution of the observed galaxies, simulated CONTROL-like galaxies are consistently smaller than for the observed control galaxies. This in one part is due to the fact that the bulge is simply not included in the measurement and in part due to the way stars are formed in the model: Most stars are formed in disc instabilities. Unstable gas is transported to the centre. So the less gas a galaxy has, the more stars it has formed, the more stars are in the centre, i.e. the bulge, which does not contribute to the size. Hence the difference.
4.2. Masses and sizes

Figure 4.2 shows the relation between the H\textsubscript{i} disc size and H\textsubscript{i} mass for the hix and the control sample. \( R_{HI} \) is the radius where the H\textsubscript{i} column density reaches 1 M\(_\odot\) pc\(^{-2}\). For details on the measurement technique see Section 2.6 (page 51). Both samples follow the Wang et al. (2016) relation, which was fitted to \( \approx 400 \) galaxies and is in good agreement with the previous relation by Broeils & Rhee (1997). hix and control galaxies are located within the 3\( \sigma \) scatter of the Wang et al. (2016) relation. Therefore, all hix and control galaxies have average H\textsubscript{i} column densities and their H\textsubscript{i} discs behave as average H\textsubscript{i} discs in the local Universe. The running averages and the 16 to 84 percentile ranges of DARK SAGE galaxies are also shown in Figure 4.2. The modelled galaxies also follow the Wang et al. (2016) relation.

Figure 4.2 The relation between H\textsubscript{i} disc size and mass. Blue diamonds present the hix sample and red circles the control sample. The grey dashed line is the relation found by Wang et al. (2016), where the grey shaded area covers the \( \pm 3 \sigma \) scatter of 0.18 dex. Light blue and orange dashed lines present DARK SAGE simulated galaxies and the shaded areas their respective 16 to 84 percentile ranges. H\textsubscript{i} masses and sizes of the hix galaxies are consistent with the literature relation.

This is further emphasised when comparing the median H\textsubscript{i} column density profiles of hix and control samples as presented in Figure 4.3. For these profiles the galactocentric radii have been normalised to \( R_{HI} \). The solid lines show the median profiles and the shaded
areas present the 16 to 84 percentile range. The shape of the profiles agree well, and the 16 to 84 percentile regions overlap. Hence, not only the average column densities within $R_{\text{HI}}$ are similar between HIX and CONTROL galaxies, but also the shape of the radial column density distribution. Note, however, that galactocentric radii are normalised to $R_{\text{HI}}$. If the galactocentric radii were given in units of kpc rather than $R_{\text{HI}}$, then the the shape of the radial column density profile would be more stretched to larger radii in HIX than in CONTROL galaxies. It has to be noted though that at small radii the median HIX H\textsc{i} column density profile is consistently smaller than the CONTROL profile. With the small sample numbers investigated in this thesis, this effect is not significant. It will however be important to return to this observation once ASKAP, MeerKAT and the SKA provide larger samples.

![Figure 4.3](image.png)

**Figure 4.3** The median radial H\textsc{i} column density profile for the HIX and CONTROL galaxies as blue and red solid lines respectively. The blue and red shaded regions cover the 16 to 84 percentile ranges. The median column density profiles are similar for HIX and CONTROL galaxies.

Both the H\textsc{i} and the stellar discs of the HIX and CONTROL samples fall on the same respective mass–size relations. However, the HIX galaxies have more massive H\textsc{i} discs than the CONTROL sample. Comparing the $D_{\text{HI}}$ and the $K_s$-band effective diameter in
Figure 4.4, the H\textsc{i}–to–stellar disc size ratio is larger in most HIX than in control galaxies. Exceptions are two HIX galaxies, for which the data points are located within the scatter of the control sample data. These two galaxies are ESO461-G010 and ESO290-G035.

Figure 4.4 The relation between $D_{\text{HI}}$ and the $K_s$-band effective diameter. Blue diamonds present the HIX sample and red circles the control sample. Grey lines denote different ratios between the two sizes. At a given $K_s$-band effective diameter, HIX galaxies tend to have larger H\textsc{i} disc sizes than the control sample.

ESO461-G010 and ESO290-G035 are the two only HIX galaxies with TiRiFiC inclination angles above 80 deg. The column density is de-projected with a factor of $\cos(INCL)$ (with $INCL$ the inclination). For larger inclination angles (e.g. above 80 deg), a small error in $INCL$ can cause a larger error in the de-projection than at lower inclinations. This might affect the measurements. A change of +5 and -5 deg in $INCL$ for ESO290-G035 results in a change of +3 and -3 per cent in $R_{HI}$. For ESO461-G010 a change of +5 and -5 deg in $INCL$ results in a change of -21 and -24 per cent, respectively. There are also four control galaxies with such high inclinations, these galaxies are however at smaller distances, thus better resolved and less prone to errors in determining the inclination.

The two galaxies with the largest H\textsc{i} to stellar diameter ratios and H\textsc{i} diameters above 150 kpc are NGC 289 and ESO075-G006. The “smaller” of the two galaxies is
Chapter 4. Analysis of HI kinematics of HIX and CONTROL galaxies

NGC 289. This galaxy has been studied extensively before. Walsh et al. (1997) have classified NGC 289 as a low surface brightness galaxy with a high surface brightness inner disc. Latest photometry shows a central surface brightness in $r$-band of $\sim 17$ mag arcsec$^{-2}$ (Li et al., 2011), i.e. the central disc is a high surface brightness disc\textsuperscript{1}. In addition, NGC 289 has been found to host an extended UV disc (XUV disc) and has star forming regions beyond the optical disc (Meurer, 2017). There is a potential dwarf galaxy, PGC 708504, which is not detected by 2MASS and is not detected as a separate HI source in the ATCA data. In that respect NGC 289 is remarkably similar to ESO075-G006, which also has a nearby dwarf companion without a distinct HI detection. The GALEX NUV image of ESO075-G006 has a much shorter exposure time than the one of NGC 289 (207 s compared to 1696 sec) and optical imaging is of lower quality. Hence, a XUV disc or an extend low surface brightness stellar disc can not be excluded in ESO075-G006. Given the large HI column densities above 1 M$_\odot$ pc$^{-2}$ well outside the detected stellar disc of ESO075-G006, star formation in an XUV disc is a possibility in this galaxy. If this is the case, then galaxies with very large HI to stellar disc sizes might be galaxies with a high surface brightness inner disc, an extended low surface brightness outer disc, and an extended UV disc.

Interestingly, the HI disc of ESO208-G026 is approximately 7.5 times larger than the stellar disc, despite the fact that this galaxy is located less than 1 $\sigma$ above the running average of HIPASS in Figure 3.5. In the HI mass–size plane, this galaxy lies right on the Wang et al. (2016) relation. In the stellar mass–size plane, this galaxy is located approximately 1 $\sigma$ below the running average of HIPASS. ESO208-G026 has been classified as an S0 galaxy by the RC.3 catalogue (de Vaucouleurs et al., 1991) and upon inspection of optical images, a bright bulge and a very faint disc can be seen (see Figure 3.1). This might explain why the half-light radius is small. There is a second S0 galaxy in the HIX sample: ESO055-G013. This galaxy has a gas mass fraction more than 1 $\sigma$ above the HIPASS running average. In terms of stellar and HI radii it still behaves similar to ESO208-G026.

4.3 The Tully-Fisher relation

The Tully–Fisher relation (Tully & Fisher, 1977) connects the rotation velocity of a galaxy, which is a proxy for the dark matter halo mass, to the mass of the galaxy. It is one of the most basic relations for spiral galaxies and highlights the tight relation between the dark matter halo and the galaxy contained in that halo. It implies that a dark matter halo at a

\textsuperscript{1} for detailed photometric profiles see https://cgs.obs.carnegiescience.edu/CGS/object_html_pages/NGC289.html
4.3. The Tully-Fisher relation

given halo mass (approximated by the rotation velocity of the galaxy) will host a galaxy of a certain mass. Figure 4.5 shows the baryonic Tully–Fisher relation, where the galaxy mass is measured by the baryonic mass. Most HIX and CONTROL galaxies agree with the fitted relation (and its errors) by Lelli et al. (2016). The outliers with higher baryonic masses than expected from the relation are HIX galaxies ESO243-G002, ESO378-G003, and ESO381-G005. Their H I morphology is lopsided, in particular ESO378-G003 and ESO381-G005 show very prominent arms and tails. Hence, the elevated baryonic mass might be due to a recent minor merger. The CONTROL galaxy with the large rotation velocity is NGC 3261. This galaxy has a very low inclination, so small errors in the inclination fit lead to large errors in the rotation velocity.

![Figure 4.5](image_url)

Figure 4.5 The baryonic Tully-Fisher relation. Blue diamonds present the HIX sample and red circles the CONTROL sample. The grey line denote the fitted relation by Lelli et al. (2016) and the grey shaded area, the error of the fit. Most HIX and CONTROL galaxies agree with the relation within the errors.
Chapter 4. Analysis of HI kinematics of HIX and CONTROL galaxies

4.4 Warps, tails and asymmetries of HI discs

In this section, the grade of lopsidedness in the HI discs of the CONTROL and HIX galaxies is compared. The moment 0 maps of both samples are visually inspected and the results from the TiRiFiC modelling are used.

4.4.1 Visual inspection of moment 0 maps

Figures 4.6 and 4.7 show the HI moment 0 maps overlaid on the optical images of the HIX and CONTROL galaxies respectively.

It is important to note that all HIX galaxies have been observed with three different array configurations (1.5 km, 750m, and EW configurations), while half of the CONTROL galaxies have only been observed with any 1.5 km array configuration of the ATCA. This implies that diffuse, low column density structures might not always be detected in CONTROL galaxies. If only using 1.5 km array configuration observations of HIX galaxies ESO378-G003 and ESO381-G005, one would detect the arm to the south of ESO378-G003 but not the cloud north of that galaxy or the arm to the west of ESO381-G005. As soon as 1.5 km and 750 m array configurations are combined, these features can be detected. Hence, if similar arms, clouds and tails were present in CONTROL galaxies, they should at least be detectable in those CONTROL galaxies that were observed with a combination of 1.5 km and 750 m array configurations. These are NGC 685, ESO123-G023, NGC 3261, IC 4857, ESO287-G013, ESO240-G011 (marked with orange beams and galaxy IDs in Figure 4.7). With the exception of ESO123-G023, these galaxies are remarkably regular. The two edge-on galaxies in this subset of control galaxies with deeper observations (ESO287-G013, ESO240-G011) show no signs of warps, while all edge-on HIX galaxies show clear warps (ESO290-G039 and ESO461-G010). More face-on galaxies (NGC 685, NGC 3261, IC 4857) show no signs of tails or arms. The most irregular galaxy is ESO123-G023, with diffuse gas on the outskirts. The remaining CONTROL galaxies also appear as symmetric discs, while all HIX galaxies show some degree of lopsidedness or asymmetry.

4.4.2 Disturbance of HI discs based on TiRiFiC results

TiRiFiC (Józsa et al., 2007) is used to fit tilted ring models to the HI data cubes of HIX and CONTROL galaxies. These models are either flat discs (FLAT), where only the surface brightness and the rotation velocity are allowed to vary with radius or models of warped discs (WARP). In addition to radial variation of surface brightness and rotation velocity, WARP models also allow for warps (i.e. radial variations) in inclination and position.
4.4. Warps, tails and asymmetries of H I discs

Figure 4.6 Panel of H I moment 0 maps overlaid on SuperCOSMOS $B_J$-band images of all HIX galaxies. All images are 3.5 arcmin by 3.5 arcmin in size except for the image of NGC 289, which is 11 arcmin by 11 arcmin in size and those of ESO378-G003, ESO381-G005 and ESO208-G026, which are 7 arcmin by 7 arcmin. The scale bar in the bottom right corner indicates 25 kpc at the distance of the galaxy. North is up and east is left. The ellipse in the bottom left indicates the beam size.
Figure 4.7 Panel of H\textsc{i} moment 0 maps overlaid on SuperCOSMOS $B_J$-band postage stamp images of all CONTROL galaxies. Images are 3.5 arcmin by 3.5 arcmin for 5 galaxies. For the remaining 6 galaxies NGC 685, NGC 3001, NGC 3261, NGC 5161, ESO287-G013, and ESO240-G011 the images are 7 arcmin by 7 arcmin. The scale bar in the bottom right corner indicates 25 kpc at the distance of the galaxy. North is up and east is left. The ellipse in the bottom left indicates the beam size. Red colours of beam and galaxy ID indicate observations in three array configurations, orange colours two array configurations, and yellow colours one array configuration.
4.4. Warps, tails and asymmetries of H\textsc{i} discs

angle. For more details see Section 2.6.1 (page 51).

One out of twelve H\textsc{i}x (8 per cent) and four out of eleven CONTROL galaxies (36 per cent) are well fitted with a FLAT disc model. The remaining galaxies are fitted with a WARP model. Hence, a higher percentage of CONTROL than H\textsc{i}x galaxies can be described as flat discs.

If a disc is fitted as a warped disc, the range of the inclination is of the same magnitude in both the H\textsc{i}x and the CONTROL galaxies (see Figure 4.8). The span of the position angles in one fit tends to be larger in H\textsc{i}x than CONTROL galaxies (see Figure 4.9). This trend is mostly driven by H\textsc{i}x galaxies ESO208-G026, ESO378-G003 and ESO381-G005. These galaxies host prominent arm features (see Figure 4.6), which TiRiFiC describes with a large warp in position angle. These three galaxies will be discussed in more detail below.

![Figure 4.8](image)

Figure 4.8 A summary of the radial variations of the inclination in all H\textsc{i}x (blue shades) and CONTROL galaxies (red shades). For each galaxy, the minimal inclination as measured by TiRiFiC is subtracted from the TiRiFiC radial inclination profile and plotted against the radius normalised by $R_{HI}$.

The thickness of the disc is also modelled in TiRiFiC. In general, H\textsc{i}x galaxy models have thicker discs than CONTROL galaxies. However, when comparing the ratio between disc thickness and disc size, both samples are again more similar, with the ratio being
around 5 to 10 per cent in most cases. Outliers with larger ratios are HIX galaxies ESO243-G002, ESO055-G013 and ESO075-G006. Following the Galactic Fountain model, thick discs might indicate gas accretion in these galaxies. However, in most cases, the disc thickness is smaller than the beam size. According to Kamphuis et al. (2015), TiRiFiC tends to overestimate the disc thickness if it smaller than the beam. Hence, this result might be at least in part driven by resolution issues.

As mentioned above, galaxies ESO208-G026, ESO378-G003 and ESO381-G005 are fitted with the strongest warps. Upon visual inspection, these galaxies also show the most interesting H I morphologies with H I tails, arms and clouds. Images in the top panel of Figure 4.10 show the moment 0 maps of these galaxies. To further quantify the contribution of these peculiar morphologies to their H I richness, flat disc model data cubes for all galaxies are generated (not fitted) with TiRiFiC. These cubes are generated using the following parameters:

- the previously fitted TiRiFiC column density profile,
- the fitted rotation curve (functional form as in Equation 2.24),
• radially constant position angle and inclination (the median of the warped profiles),

• velocity dispersion, systemic velocity and kinematic centre as found previously with the fully fitted TiRiFiC model.

For galaxies with a FLAT TiRiFiC fit, these generated cubes are the same as the fitted model cube. For galaxies with a warped TiRiFiC fit, these generated data cubes are “rectified” versions of the fitted model cube.

Figure 4.10 Examples of HI moment 0 maps for HiX (top row, from left to right: ESO208-G026, ESO378-G003 and ESO381-G005) and control galaxies (bottom row, from left to right: ESO123-G023, NGC3261 and ESO287-G013). The colour scale indicates HI column densities of the measured data, with darkest colours starting $8 \times 10^{19} \text{ cm}^{-2}$. The overlaid black contours indicate structures in residual moment 0 maps at a column density level of $8 \times 10^{19} \text{ cm}^{-2}$. Red crosses mark locations of nearby dwarfs or potential stellar debris from minor mergers. The images are 3.6 arcmin in size, except for the image of ESO378-G003, which is 6 arcmin in size.
In the next step, the generated cube is subtracted from the observed data cube. If the moment 0 map of this residual cube shows structure, the H I mass is measured. This is the case for 42 and 36 per cent of the HIX and the control galaxies, respectively. Hence, within Poisson errors, residual structures are found in the same percentage of HIX galaxies as control galaxies. Figure 4.10 shows examples for HIX (top row) and control galaxies (bottom row) with residual structures (black contours).

For those galaxies with residual structure, the average fraction of residual H I to total H I mass is 20 and 10 per cent for HIX and control galaxies, respectively. Hence, HIX galaxies host on average two times more H I that does not agree with a flat, regularly rotating disc than control galaxies. Judging from the moment 0 maps, this additional gas is likely due to gas-rich minor mergers or dwarf companions on the verge of falling into the central galaxy. However, according to this measurement, the irregular H I can not fully account for the more than 2.5 times higher than expected H I mass in HIX galaxies. Consequently, irregular gas is not the sole driver of H I excess in HIX galaxies. In addition, some of the irregular gas in control galaxies might be missed due to the less sensitive observations. Using fully automated tilted-ring fitting pipelines such as FAT (Kamphuis et al., 2015) or 3D Barolo (Di Teodoro & Fraternali, 2015) with large data sets such as WALLABY might allow in the future to use this method to search for galaxies with irregularly rotating gas, i.e. gas that is potentially accreted.

The reason for the irregularity of the HIX galaxies in Figure 4.10 can only be speculated about: ESO208-G026 is located in a relatively sparse environment. It would therefore be more likely for the arm to be caused by a gas-rich minor merger than by tidal interaction. However, the stellar disc of ESO208-G026 appears regular and does not show any signs of an in-falling dwarf galaxy.

ESO378-G003 is part of the NGC 3783 group (Kilborn et al., 2006) and the elliptical galaxy NGC 3706 is located 22 arcmin = 255 kpc away (projected distance). In this group, Kilborn et al. (2006) have furthermore found an isolated H I cloud (GEMS N3783_2) without apparent optical counterpart (see their figure 6 for a resolved map). They concluded the cloud to be a remnant of tidal interaction. This tidal interaction could have potentially disturbed the H I distribution of ESO378-G003 as well.

In ESO381-G005 the arm feature is aligned with wide spiral arms and points towards a dwarf companion (PGC 629239) towards the south, which is also detected in H I. Additionally, the inspection of optical images reveals three more sources aligned within the arm that are not foreground stars (PGC 630365, USNO A2 0525-15319577 and USNO A2 0525-15322378), but look more like potential debris. Their position on the H I column density
4.5. Global stability parameter $q$

map is marked with black crosses in Figure 4.10. This might indicate a recent minor merger. However, in order for the minor merger to increase the H\textsc{i} content of a galaxy from \textsc{control} sample levels to \textsc{hix} sample levels, it would have had to bring in almost $10^{10} \, M_\odot$ without changing the stellar disc a lot. This appears very unlikely to be the only cause why ESO381-G005 is a \textsc{hix} galaxy.

In summary, both the \textsc{hix} and \textsc{control} galaxies show warped discs. \textsc{hix} galaxies tend to be fitted with stronger warps and are more likely than the \textsc{control} galaxies to have tails or ill-defined outskirts. As mentioned before, the differences in sensitivity of the observations might increase the difference in H\textsc{i} morphology between \textsc{hix} and \textsc{control} galaxies (the beam and galaxy ID colours in Figures 4.6 and 4.7 indicate the sensitivity of the observations). Homogeneous, large surveys of the resolved H\textsc{i} content of galaxies, such as the WALLABY survey, will help to shed more light onto this problem. Even in the most irregular \textsc{hix} galaxies, the amount of H\textsc{i} in arms and tails appears not to be sufficient to explain why these galaxies host more than 2.5 times more H\textsc{i} than expected.

4.5 Global stability parameter $q$

So far, the analysis has shown that the most striking difference between \textsc{hix} and \textsc{control} samples is the difference in the H\textsc{i} disc mass and subsequently size. It has been suggested that the galaxy size is determined by the angular momentum of the galaxy (Fall & Efstathiou, 1980; Dalcanton et al., 1997; Mo et al., 1998). More recently, Maddox et al. (2015) and Obreschkow et al. (2016) have suggested based on \textsc{alfalfa} (Giovanelli et al., 2005) and \textsc{things} data (Walter et al., 2008) that the H\textsc{i} mass (and thus size), and atomic–to–baryonic mass fraction is regulated by the angular momentum properties of the galaxy. Furthermore, the model of star formation efficiency by Wong et al. (2016) is able to reproduce the star formation efficiencies in the \textsc{hix} and \textsc{control} sample galaxies and is also based on the idea that star formation efficiency is regulated by galaxy kinematics. Huang et al. (2014) and Hallenbeck et al. (2014) suggest that the H\textsc{i}-rich galaxies in the HighMass sample are H\textsc{i}-rich due to to an increased specific angular momentum. A higher specific angular momentum affects the disc in two ways:

(i) Gas is stabilised against gravitational collapse and subsequent star formation.

(ii) H\textsc{i} is kept at larger galactocentric radii, where the total disc density is too low to form molecular hydrogen and stars.

As a result, a galaxy with a higher specific angular momentum can support a larger H\textsc{i} disc. This stability can be quantified as the global stability parameter $q$ (Obreschkow et al.,
Chapter 4. Analysis of HI kinematics of HIX and CONTROL galaxies

2016, see also Section 2.6.2), which is proportional to a disc wide average of the local Toomre $Q$ parameter (Toomre, 1964). A more descriptive way to understand and interpret this parameter used when considering the radial variation of the Toomre $Q$ parameter in two galaxies with a similar exponential discs (i.e. similar scale radii) but different $q$'s. In the galaxy with the larger $q$, HI begins to be Toomre-stable at smaller radii than in the galaxy with a smaller $q$ (see figure 1 in Obreschkow et al., 2016).

Figure 4.11 shows the atomic–to–baryonic mass fraction as a function of $q$. Most of the HIX and the CONTROL sample follow this model within the scatter of the analytical model of Obreschkow et al. (2016). This means that galaxies from both samples host as much HI as they can support against star formation. For comparison, the THINGS galaxies (data taken from Obreschkow & Glazebrook, 2014) and HighMass galaxies (Hallenbeck et al., 2014, 2016) are depicted as well (see Section 3.2 for more details on the data). Both samples follow the above described model as well.

Most HIX galaxies have systematically larger global stability $q$ values than the CONTROL galaxies. This is due to a larger baryonic specific angular momentum, which is driven by a larger HI specific angular momentum. Rotation velocities are of similar magnitude in HIX and CONTROL galaxies (see Table 2.9 and Section 4.3). So the large HI specific angular momenta in HIX galaxies are mostly due to large masses of high angular momentum gas located at large galactocentric radii.

The question now is: why do HIX galaxies have higher HI specific angular momenta than CONTROL galaxies? In the cases of galaxies ESO378-G003, ESO381-G003, and ESO208-G026, which were discussed in the previous section, the gas might have been recently accreted or dislocated in some interaction. Other galaxies might be living in high-spin haloes, which gives them an intrinsically high specific angular momentum. To test this hypothesis, the observed galaxies are compared to simulated galaxies from the semi-analytic model DARK SAGE in the next section.

4.6 HIX galaxies in DARK SAGE

Previously, galaxies simulated with the DARK SAGE semi-analytic model have been included on various scaling relations, such as the log $M_{\text{HI}} / M_\star$ vs. log $M_\star [\text{M}_\odot]$ plane (Figure 3.5), the $SFE$ vs. log $M_\star [\text{M}_\odot]$ plane (Figure 3.7) and the HI mass–size relation (Figure 4.2). Overall, HIX-like galaxies from the DARK SAGE catalogue behave similar to the observed sample of HIX galaxies. The same is true for CONTROL galaxies. This similarity is now used to investigate the dark matter halo spin of the simulated galaxies. In Figure 4.12 the dark matter halo spin distribution of the entire DARK SAGE disc sample,
4.6. HIX galaxies in DARK SAGE

Figure 4.11 The atomic to baryonic gas ratio as a function of the global stability parameter. In addition to the data of the HIX (blue diamonds) and CONTROL sample (red circles), data of THINGS galaxies (orange pentagons, Obreschkow & Glazebrook, 2014) and HighMass galaxies (light blue squares) are shown. The grey line and shaded area indicate the predicted relation and its predicted scatter by Obreschkow et al. (2016). The orange and light-blue contours encompass 68 and 95 percent of the CONTROL-like and HIX-like galaxies from DARK SAGE, respectively. Observed galaxies, simulated galaxies and the analytical model of Obreschkow et al. (2016) are in good agreement.

The estimates for the halo spin of the observed HIX and CONTROL galaxies show a similar trend: the median estimated halo spin (dashed line) is larger for HIX than CONTROL galaxies and the 1σ scatter of the two samples do not overlap. The galaxy with the largest spin parameter (λ = 0.11) is CONTROL galaxy ESO123-G023. This galaxy is also the CONTROL galaxy with the most irregular H I disc. As can be seen in Figure 4.7 and in the bottom, left image in Figure 4.10, it has diffuse edges. In the H I mass fraction...
Figure 4.12 Distributions of the halo spin parameter for the DARK SAGE model galaxies (which come directly from Millennium data). The entire disc sample is shown in the green dashed histogram, HIX–like galaxies in the light blue and CONTROL–like in the orange histogram. Estimates for the halo spin of single HIX and CONTROL galaxies are shown in blue diamonds and red circles (the vertical position is arbitrary) and the sample medians are marked with the vertical blue and red dashed line, respectively. The $1\sigma$ range of the HIX and CONTROL galaxies is shaded in the respective colours. For comparison, the spin parameters for four HighMass galaxies as taken from Hallenbeck et al. (2014, 2016) are given as light blue squares (vertical position arbitrary). HIX galaxies tend to live in haloes with larger spins.

vs. stellar mass plot (Figure 3.5), ESO123-G023 is located almost $1\sigma$ above the HI\textsc{pass} running average. In fact, it is the CONTROL galaxy with the highest H I mass fraction.

The CONTROL galaxy with the next highest spin parameter is ESO263-G015 with $\lambda = 0.076$. The spin parameters of 10 out of 12 HIX galaxies are between the spin parameters of these two CONTROL galaxies. Only HIX galaxies ESO111-G014 and ESO243-G002 have $\lambda < 0.076$. ESO245-G010 and ESO417-G018 have $\lambda = 0.077$ and have thus spin parameters only slightly above the bulk of the CONTROL galaxies.

The four HighMass galaxies that are shown in Figure 4.12, are those HighMass galaxies with published resolved H I maps. For the fifth HighMass galaxy with a published resolved
4.7 Discussion

H I map no spin parameter has been published. The HighMass galaxies show mostly spin parameters of the same order as the HIX galaxies, except for galaxy UGC 12506 (Hallenbeck et al., 2014), which lives in a very high-spin halo. This implies that HighMass galaxies are similar to HIX galaxies.

In summary, model galaxies from DARK SAGE behave similar to the observed HIX and CONTROL galaxies. When looking at the halo spin parameters of the modelled galaxies, HIX-like galaxies tend to reside in higher spin haloes than CONTROL-like galaxies. The estimates of the halo spin parameter in the observed HIX and CONTROL galaxies show a similar trend.

4.7 Discussion

HIX galaxies are more likely to host warped discs, and arms and tails than CONTROL galaxies. While almost all HIX galaxies (except for one, 8 per cent) are modelled with a warped disc, about one quarter of CONTROL galaxies can be described with a simple flat disc. Some diffuse gas in the CONTROL galaxies, however, might be missed due to less sensitive observations. This might lead to fewer warps being fitted to the data of CONTROL galaxies. Still, the majority of both the HIX and the CONTROL galaxies show warps. The cause of these warps is not yet fully understood. They can for example be created in hydrodynamical, cosmological simulations when the angular momenta of the inner disc and of the surrounding halo, or of accreted gas are misaligned (Roškar et al., 2010). Hence, the detection of warps in both samples can indicate ongoing or recent gas accretion. Warps can also be formed by minor mergers (Sancisi et al., 2008). Many of the HIX and CONTROL sample galaxies have dwarf galaxies nearby, some of which are also detected in H I. Gas-rich, minor mergers can not only cause warps, but can also contribute to the H I content of the galaxy. Furthermore, the extended HIX H I discs reach far into the halo. There they might be more susceptible to interactions with sub-haloes or torques by a misaligned outer halo and less supported by the stellar disc. These effects can lead to warps as well (Józsa, 2007).

There is one HIX galaxy that shows clear signs of interaction both in its stellar and H I disc (ESO245-G010), and three HIX galaxies that have some kind of H I arms or clouds attached to their disc (ESO208-G026, ESO378-G003 and ESO381-G005). These features might be due to the accretion of gas rich dwarf companions (ESO245-G010 and ESO381-G005) or tidal interaction with another galaxy (ESO378-G003 with NGC 3706). It is found, however, that the H I mass of those features is not large enough to fully explain the high H I masses of HIX galaxies. It should be noted that the kinematic properties of the
discs of these galaxies still agree with a model of a marginally stable disc.

There is no CONTROL galaxy with any signs of interaction in the stellar disc, but one galaxy hosts irregularly shaped gas at large radii (ESO123-G023). Three CONTROL galaxies are accompanied by dwarf galaxies that are detected in my H\textsc{i} data cubes (ESO287-G013, IC 4857 and NGC 3261). In summary, HIX galaxies tend to be more lopsided than CONTROL galaxies, however, the mass of irregular H\textsc{i} is not high enough to fully explain their H\textsc{i} extreme content.

The only information on a galaxy’s merger history that the DARK SAGE catalogue provides is the time of the last major merger. The distribution of those times is not different between the HIX-like and the CONTROL-like model galaxies. Hence, if mergers play a role in creating a difference between HIX and CONTROL galaxies, it must be minor-mergers.

The environments of the HIX and CONTROL galaxies are very diverse. Some galaxies are located just a few Mpc (projected) away from centres of clusters: HIX galaxy ESO243-G002 resides 2.2 Mpc away from ABELL 2836 and CONTROL galaxy ESO383-G005 galaxy is located 1 Mpc away from ABELL 3563. Other galaxies are very isolated. The nearest neighbour within ±500 km s$^{-1}$ in recession velocity for example of ESO208-G026 according to NED is ESO208-G031 at a projected distance of 1.7 Mpc. This would make ESO208-G026 similar to the isolated galaxies discussed by Pisano et al. (2002). Thus some features of HIX galaxies might be attributed to their environment (such as the tail and cloud of ESO378-G003) but a more detailed study utilising a more complete catalogue than NED will be necessary to fully understand the impact of environment on H\textsc{i}-rich galaxies.

Resolved H\textsc{i} maps have been published for five HighMass galaxies (Hallenbeck et al., 2014, 2016). None of these galaxies show any signs of arms, tails or diffuse and irregular edges to their column density limits of > 8.4 × 10$^{20}$ cm$^{-2}$. This limit, however, is about 10 to 20 times higher than the column density limits obtained in this work and thus too high to detect arms as hosted by ESO208-G026, ESO378-G003 and ESO381-G005.

When considered independently, H\textsc{i} and stellar discs of both samples follow the same mass–size relations (Figs. 4.1 and 4.2). Hence, the average H\textsc{i} and stellar column densities are similar to average galaxies in the local Universe in both samples. However, the ratio of H\textsc{i} to stellar radius is larger in HIX than in CONTROL galaxies. The same is true for the absolute values of $R_{HI}$ in units of kpc. HIX galaxies host H\textsc{i} at larger galactocentric radii than CONTROL galaxies. This gas has a larger specific angular momentum and can therefore not flow to the central parts of the galaxy. Due to the low overall density (no detected stellar disc component) at these large galactocentric radii, this gas is furthermore
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unable to collapse and form stars. One exception might be NGC 289, where star formation at large radii is detected in the form of an extended UV disc (Meurer, 2017).

The high specific angular momentum of this H I gas at large radii heavily contributes to the total specific baryonic angular momentum, which is higher in HIX than in CONTROL galaxies. Making use of the analytic Obreschkow et al. (2016) model (Figure 4.11), evidence points to the specific baryonic angular momentum as a primary regulator of H I disc size and mass in HIX galaxies. This is also in agreement with the results of hydrodynamical simulations (Lagos et al., 2017).

In HIX galaxies, the high H I specific angular momentum is the sole driver of an elevated baryonic specific angular momentum. The measurements of stellar specific angular momenta are of similar size in the HIX and CONTROL sample. This allows parameters like the specific star formation rate (see Figure 3.6) or the average stellar surface density (see Figure 4.1) to be similar between the two samples. Note that the proxy for the stellar specific angular momentum is measured assuming that the stars have the same kinematics as the H I.

From the observations presented here it is not possible to determine how these galaxies acquired significant amounts of H I at large radii or why their specific baryonic angular momentum is elevated. In Section 4.6, the semi-analytic galaxy model DARK SAGE built on the dark matter Millennium simulation was used to investigate the dark matter halo properties of HIX CONTROL-like model galaxies. HIX-like galaxies in this simulated galaxy catalogue tend to exist in dark matter haloes with a larger halo spin than CONTROL-like galaxies. The estimated dark matter spins for observed HIX galaxies show a similar trend: The bulk of the HIX galaxies is within haloes that have higher spin parameters than the bulk of the CONTROL galaxies. However, the galaxy with the highest spin parameter in the samples is a CONTROL galaxy and some HIX galaxies have spin parameters of the same order as CONTROL galaxies.

A plausible explanation for those HIX galaxies with high dark matter halo spins might be that their high baryonic angular momentum is simply inherited from their high spin halo. The relation between dark matter halo spin and galaxy disc angular momentum is subject to a lot of variation (Übler et al., 2014; Bett et al., 2010). There is, however, a scatter in the ratio of halo to baryonic specific angular momentum, which can be modified by the specific history of a galaxy. Simulations suggest some mechanisms that can lead to an increased specific angular momentum (and thus an extended H I disc).

Based on the cosmological, hydrodynamical Illustris simulation, Genel et al. (2015) and Zjupa & Springel (2017) suggest that feedback can affect the specific angular momentum
in the sense that strong stellar winds increase and radio-mode AGN feedback decreases the angular momentum of galaxies. This is in agreement with cosmological zoom-in simulations by Übler et al. (2014), who find that galaxies simulated with strong stellar feedback have higher angular momenta than galaxies with weak stellar feedback. According to these works, stellar winds increase the angular momentum because they preferentially expel low angular momentum gas into the halo. There the gas can gain angular momentum and is then re-accreted onto the galaxy with increased angular momentum. Radio-mode AGN on the other hand decrease angular momentum because this type of feedback prevents the accretion of high angular momentum gas in Illustris galaxies. Hence, HIX galaxies might have undergone stronger star bursts in the past that removed more low-angular-momentum gas in galactic winds. Thus the overall specific angular momentum was increased.

Stewart et al. (2011, 2013); Stewart et al. (2017) hypothesise, based on cosmological zoom-in simulations, that gas accreted through cold filamentary accretion increases the angular momentum of the galaxy disc. In particular Stewart et al. (2013) find that gas accreted in the cold mode forms a so-called “cold flow disc”, which co-rotates with the galaxy disc. They suggest that these cold flow discs might be observed as extended H\textsc{i} or UV disc today. In their picture, HIX galaxies might be galaxies, which accreted gas that was never shock heated. Furthermore, the specific angular momentum can be increased in minor and gas-rich mergers (Lagos et al., 2018).

The HIX galaxies with a relatively low halo spin are ESO111-G014, ESO243-G002, ESO245-G010 and ESO417-G018. These galaxies might have increased their galaxy angular momentum over time through some of the above mentioned mechanisms. HIX galaxies with a relatively low halo spin might also be galaxies in transition. ESO245-G010 for example shows clear signs of a recent merger. Large gas masses at large radii might move further towards the centre of the galaxy and be used for star formation, once the disc settles.

With the given data, it appears that HIX galaxies are more likely to host arms, tails and low column density gas at their outskirts. This result might however be driven by the differences in sensitivity between the observations of the HIX and the control galaxies. The low column density gas in HIX is partly due to tidal interactions or minor mergers, which may contribute to the H\textsc{i}-richness of the HIX galaxies. However, considering the observations of the high specific angular momenta, H\textsc{i} discs of HIX galaxies are scaled-up versions of average H\textsc{i} disc.

Warren et al. (2007) and Warren et al. (2006) investigated a sample of dwarf galaxies with large H\textsc{i} mass to light ratios, which initially appears analogous to the HIX sample
selection at lower stellar masses. They found that these galaxies are actually star poor rather than H$\text{I}$-rich by showing that their sample agrees with the baryonic Tully-Fisher relation but not a stellar Tully-Fisher relation. This has been checked for the HIX sample as well and it was found that the HIX galaxies lie within the scatter of the Lelli et al. (2016) baryonic Tully-Fisher relation and agree with the stellar Tully-Fisher relation of the CONTROL galaxies. Hence, HIX galaxies are truly H$\text{I}$-rich rather than star-poor.

4.8 Summary and conclusions: H$\text{I}$ kinematics of HIX galaxies

In this Chapter, the spatially resolved H$\text{I}$ distribution and kinematics of the HIX and the CONTROL galaxies were analysed. The findings can be summarised in the following three points:

(i) The stellar and H$\text{I}$ discs of the HIX and CONTROL samples follow the same respective mass–size relations. This means that the stellar discs of the HIX galaxies behave like average stellar discs, and the H$\text{I}$ discs of HIX galaxies are consistent with average H$\text{I}$ discs in the local Universe. Only the relation between H$\text{I}$ and stellar disc within HIX galaxies makes them outliers to the Dénes et al. (2014) scaling relations.

(ii) The H$\text{I}$ discs of galaxies in the HIX sample are more likely to be warped and irregular than in the CONTROL sample. Yet, the majority of CONTROL galaxies are also warped and host irregularly shaped gas at the edge of their discs. Warps and irregular features can be a sign of gas-rich minor mergers and cold gas accretion in the HIX and the CONTROL sample. The analysis suggests that the mass of detected irregular gas in HIX galaxies is not sufficient to explain their excess in H$\text{I}$.

(iii) HIX galaxies have a higher H$\text{I}$ and thus baryonic specific angular momentum than CONTROL galaxies. This implies that HIX galaxies host as much H$\text{I}$ as they can support with their baryonic specific angular momentum (Obreschkow et al., 2016). A comparison to the DARK SAGE semi-analytic model (Stevens et al., 2016) suggests that the majority of the HIX galaxies have an elevated baryonic specific angular momentum because they tend to reside in higher spin haloes than the majority of the CONTROL galaxies. Those HIX galaxies that do not reside in intrinsically high spin haloes might have increased their specific angular momentum over their life time through strong stellar feedback that expels low angular momentum gas or through the accretion of high angular momentum gas. They might also be galaxies in transition, like the interacting galaxy ESO245-G010, which are likely to use some of their gas in the future.
These results indicate that most HIX galaxies will continue to be HIX galaxies in the future unless they are heavily disturbed by e.g. interactions with other galaxies. The next Chapter will be dedicated to the analysis of optical spectra obtained for the HIX sample. These data will be used to look for indications of the accretion of metal-poor gas (e.g. inhomogeneities or gradients in the gas-phase metallicity distribution).
Analysis of Optical Spectra of HIX galaxies

In this chapter, the optical integral field unit spectra from the WiFeS spectrograph are presented for a sub-sample of ten HIX galaxies and one control galaxy.
5.1 Introduction

The original aim of this thesis was to search for gas accretion from the IGM in HIX galaxies. The findings in the previous Chapter indicate that HIX galaxies rather maintain their H\textsc{i} reservoir than replenishing it more actively than other galaxies. This Chapter focuses on the accretion of metal-poor gas on the HIX galaxies. One line of argument that points to the fact that galaxies accrete gas from the intergalactic medium (IGM) is the comparison of chemical evolution models of galaxies to observations of the gas-phase metallicity in galaxies. When assuming a closed box model, where the ISM of galaxies is not diluted by pristine gas from the IGM, metallicities of modelled galaxies are overestimated with respect to observed metallicities (van den Bergh, 1962; Kudritzki et al., 2015). Hence, galaxies need to accrete relatively metal-poor gas from the IGM to dilute their ISM.

An important probe into the chemical evolution of galaxies is the mass-metallicity relation. This relation connects the stellar mass of a galaxy to the central gas-phase metallicity (Tremonti et al., 2004). The significant scatter of this relation is attributed to the H\textsc{i} content of galaxies (Hughes et al., 2013; Bothwell et al., 2013; Lagos et al., 2016). It has been suggested that the scatter of the mass-metallicity relation might also be driven by the star formation rate of galaxies (Mannucci et al., 2010). However, more and more evidence points to H\textsc{i} being the primary driver and SFR being a secondary effect due to the dependence of star formation on gas (e.g. Lagos et al., 2016, Brown et al., 2018).

The N-body, smoothed particle hydrodynamical simulations of Davé et al. (2013) assume that galaxies are systems in equilibrium between gas accretion, star formation and outflows. This assumption leads to gas rich galaxies being more metal poor at a given stellar mass than gas poor galaxies, in agreement with observations. Their explanation is the following: accretion of pristine gas is a stochastic process. When gas is accreted, it increases the gas content of the galaxy, dilutes the ISM and triggers star formation. Thus the galaxy moves from the centre of the mass-metallicity relation to a more metal-poor position for its stellar mass. With the triggered star formation, the galaxy now grows in stellar mass and its ISM is gradually enriched again. Thus, it moves back to the equilibrium line of the mass-metallicity relation. Forbes et al. (2014b) use a simple model, which does not force galaxies to return to the equilibrium position of the mass–metallicity relation. They still find that after a phase of elevated gas accretion, their simulated galaxies naturally return to equilibrium and thus find similar explanations for the mass–metallicity relation as Davé et al. (2013).

Often, the observed mass–metallicity relation is defined using just the central metallicities of galaxies. For example the Tremonti et al. (2004) relation is based on SDSS spectra,
which have been observed with a 3 arcsec fibre. Hence, only the metallicity of the central
3 arcsec are included in their relation.

However, the metallicity of the disc and outskirts of the galaxy also provides vital
information on the chemical evolution. Recently a number of large samples of galaxies
have been observed with long-slit or integral field spectra, examples are the SAMI survey
(Croom et al., 2012; Fogarty et al., 2012), the CALIFA survey (Sánchez et al., 2012), the
MaNGA survey (Bundy et al., 2015) or follow-up of some GASS/ COLD GASS galaxies
(Moran et al., 2012). Using these data, a metallicity gradient (i.e. how much the gas-phase
metallicity changes with radius) can be measured. The gas-phase metallicity in regular
spiral galaxies decreases towards the edges of the disc. In the CALIFA survey, Sánchez
et al. (2014) find a universal metallicity gradient in the sense that the steepness of the
gradient is not dependent on the stellar mass. They suggest that this result indicates a
similar chemical evolution in all disc galaxies. Hence, the metallicity at a given radius is
set by how evolved the galaxy is at that radius rather than global, basic properties of the
galaxy. As galaxies form from the inside – out, the outskirts of a galaxy would be less
evolved and thus more metal-poor. These findings are confirmed by Ho et al. (2015) and
Kudritzki et al. (2015), who are able to reproduce the uniform metallicity gradients with
a simple chemical evolution model including in- and outflows. These models indicate that
the metallicity is dependent on the local stellar to gas mass ratio.

Moran et al. (2012) have measured the radial metallicity gradient in massive galaxies
from the GASS survey and find steepest declining metallicity gradients in galaxies at
their lower stellar mass limit of log $M_\star [M_\odot]> 10$. They furthermore find that about
10 per cent of their sample have a sharp downturn in metallicity at large radii. This
decline is correlated with the H$\textsc{i}$ content of these galaxies and is interpreted as a sign for
a phase of active gas inflow and disc-building.

Conversely, results from the MaNGA survey suggest a metallicity gradient that varies
with stellar mass (Belfiore et al., 2017). They suggest that flat gradients in low mass
galaxies show that strong feedback, gas mixing, and wind recycling must also be important
in low mass galaxies.

One scenario that might explain the H$\textsc{i}$-richness of HIX galaxies, is very effective or
active gas accretion, which recently increased the H$\textsc{i}$ content of HIX galaxies. This might
either be a temporarily high accretion rate of gas from the IGM or a recent gas-rich merger.
To probe these scenarios, the H$\alpha$ and stellar kinematics are compared to the H$\textsc{i}$ kinematics.
Any misalignments in the rotation of these components can point towards recent mergers
(Corsini, 2014). Furthermore, the central gas-phase metallicity of HIX galaxies is examined
using the mass–metallicity relation and the steepness of the gas-phase metallicity gradient in HIX galaxies is compared to the literature. Both measures can also inform of recent inflow of pristine gas.

This Chapter is structured as follows: in Sections 5.2, 5.3 and 5.4, results from the analysis of the WiFeS data are presented. These results are discussed and summarised in Section 5.5. In this Chapter, integral field spectra from the WiFeS spectrograph are used. Observations and analysis of these data are detailed in Sections 2.7 and 2.8 (on pages 61 and 2.8, respectively).

5.2 Comparison of stellar, Hα and H I velocities

Figures 5.1 and 5.2 show position-velocity diagrams of the kinematics of H I, Hα and stars in ten HIX galaxies and one control galaxy. For these diagrams, the H I data cubes were sliced along the central positions of the WiFeS pointing. Overlaid on these slices, the measured Hα and stellar velocities of single star forming regions are shown.

Overall, there is agreement between H I, stellar, and Hα recession velocities. No galaxy shows any signs of counter-rotation between any of the components. However, there are a few differences between the optical (stars and Hα) and H I position-velocity diagrams: The measurements of the Hα velocity in IC 4857 trace the H I position-velocity measurements, but show a lot of scatter around the H I measurements.

5.3 HIX galaxies on the mass–metallicity relation

For the HIX and control galaxies that have been observed with WiFeS, the mass–metallicity relation is shown in Figure 5.3. As indicated in the introduction (Section 5.1), simulations suggest galaxies that have recently accreted a lot of gas should lie at low metallicities for their stellar mass. For comparison the relation for galaxies in the MPA-JHU SDSS DR7 catalogue is shown as colour scale in the background (similar redshift range as HIX galaxies, for more details on this catalogue see Section 2.2.5). The contours enclose 65, 95 and 99 per cent of SDSS galaxies.

Since the SDSS metallicities have only been measured within a 3 arcsec aperture, only the metallicities of the most central star forming region in the WiFeS data are shown. The majority of the metallicities are measured within 3 to 13 arcsec of the centre of the galaxy, in apertures of about 10 arcsec in size. Hence, these measurements can still be considered to represent the central gas-phase metallicity. Most of these data points are located within the 65 per cent contour, i.e. with the “1 σ” scatter of the relation. Exceptions are ESO290-
5.3. **HIX galaxies on the mass-metallicity relation**

Figure 5.1 Position-Velocity diagrams for H\(\alpha\) (red circles), stars (yellow stars where available) and the H\(\text{I}\) (grey scale and light-blue contours). For the H\(\text{I}\) position-velocity diagrams, the H\(\text{I}\) data cubes were sliced along the centres of the WiFeS pointings. The WiFeS data points for stars (yellow stars) and H\(\alpha\) measurements (red circles) have a position error-bar of 10 arcsec. This is approximately the size of the star forming regions, over which these measurements are averaged. The error-bars for the H\(\alpha\) velocity include errors in wavelength calibration, spectral resolution and fitting errors. They are usually smaller than the symbols.
Figure 5.2 Position-Velocity diagrams continued. The galaxies between the double line are ESO245-G010 and ESO417-G018, for which only part of the disc was observed. Below the two lines is IC 4857, the only control galaxy with WiFeS observations.
Figure 5.3 The mass-metallicity relation for the HIX galaxies: shown the is gas-phase metallicity (estimated with the O3N2 parameter following Pettini & Pagel (2004)) as a function of stellar mass. The grey scale in the background describes the distribution of SDSS galaxies, the red circle indicates the CONTROL galaxy IC 4857 and HIX galaxies are marked with blue diamonds (note that one HIX galaxy is located “behind” the CONTROL galaxy). The contours enclose 65, 95 and 99 per cent of SDSS galaxies.

G025 and ESO417-G018. ESO290-G010 is located within the 2σ contour (95 per cent) and ESO417-G018 is located well outside the 3σ contour (99 per cent). The most “central” metallicity of ESO417-G018 can only be measured at a distance of 35 arcsec (11 kpc) from the centre, because no pointing closer to the centre was observed. As galaxies in the local Universe have a declining metallicity gradient, the long distance to the galaxy centre may be the reason why this measurement is located below the SDSS relation. Overall, the central gas-phase metallicities of observed HIX and CONTROL galaxies agree with the average local galaxy population.

5.4 Gas-phase metallicity distribution

In this section, the spatially resolved metallicity distribution and the corresponding gradient in HIX and CONTROL galaxies are considered. In addition to establishing in the
previous Section that the central metallicity of HIX and CONTROL galaxies has not recently been diluted by metal-poor gas accretion, this will inform about metal-content of a larger part of the observable stellar disc.

Based on IFU data from the CALIFA survey, Sánchez et al. (2014) have found that the metallicity in local star forming galaxies declines by on average \(0.1 \pm 0.09 \text{dex} \frac{1}{r_{\text{eff}}}\), where \(r_{\text{eff}}\) is the effective radius. This gradient does not vary with stellar mass or morphology. Ho et al. (2015) uses a smaller sample of galaxies than Sánchez et al. (2014) but find similar results, when measuring the gradient in units of \(\text{dex} \frac{1}{r_{25}}\) (with \(r_{25}\) the 25 mag arcsec\(^{-2}\) isophotal radius). When measuring the gradient in units of \(\text{dex} \frac{1}{kpc}\), they find that galaxies above \(\log M_\star [M_\odot] > 9.6\) again show a near universal gradient, while lower mass galaxies tend to have steeper gradients. Both the effective radius and the 25 mag arcsec\(^{-2}\) isophotal radius vary with wavelength. For a fair and consistent comparison, the metallicity gradients in HIX galaxies are measured in units of \(\text{dex} \frac{1}{kpc}\).

In Figure 5.4, metallicity gradients as a function of stellar mass are shown. The grey line is the average Ho et al. (2015) gradient at stellar masses \(\log M_\star [M_\odot] > 9.6\) and the grey shaded area their 1\(\sigma\) scatter. The overlaid data points show the measurements for the HIX (diamonds) and the CONTROL galaxies (larger circle). All HIX galaxies have decreasing metallicity profiles and half of the HIX galaxies agree with the Ho et al. (2015) scatter within the error bars. Galaxies for which the gradient does not agree with the Ho et al. (2015) scatter tend to be galaxies with larger stellar masses. Moran et al. (2012) reported a tendency that more massive galaxies have flatter metallicity gradients. This trend can also be seen in Figure 5.4, where the GASS galaxies are included as small dots (for more details on the data see Section 2.10). The HIX galaxies with flatter metallicity gradients than the average Ho et al. (2015) gradient follow the trend of the GASS galaxies.

The discrepancy between the Moran et al. (2012) and Ho et al. (2015) results might be due to the fact that the GASS sample of long-slit spectra also includes bulge-dominated galaxies, which show a tendency to have flatter metallicity profiles than more disc-dominated systems (Moran et al., 2012; Sánchez et al., 2014). However, the RC.3 morphology of HIX galaxies with relatively flat metallicity gradients ranges from Sa to Sc type spirals.

Moran et al. (2012) suggest that large, abrupt drops (of about 0.25 dex) in metallicity at the outskirts of the optical disc in massive galaxies can be caused by the inflow and distribution of pristine gas from the outskirts of the gaseous disc throughout the entire galaxy disc. Similarly, Sánchez Almeida et al. (2014b) find in a sample of dwarf galaxies, star forming regions with very low metallicities compared to other star forming regions within the same dwarf galaxy. They and Ceverino et al. (2016) argue that these metal-poor
5.5 Discussion and conclusion: optical spectra of HIX galaxies

In this Chapter, the analysis of optical spectra of one CONTROL and ten HIX galaxies is presented. In a first step, measurements of the Hα, stellar (where available) and H I recession velocities in the HIX and CONTROL galaxies were compared. Generally, the kinematics of all three components are similar. Counter-rotation, in particular between stellar and gaseous component, can be interpreted as a sign of recent accretion of large star forming regions are induced by pristine gas accretion. There are neither metallicity drops at the outskirts nor particularly metal-poor star forming regions observed in the HIX and CONTROL galaxies (for the detailed data see Appendix D).

Figure 5.4 The metallicity gradient in dex kpc$^{-1}$ as a function of stellar mass. The grey line indicates the average gradient for galaxies with log $M_\ast$ [M$_\odot$] $>$ 9.6 (Ho et al., 2015) and the grey shaded area the 1 $\sigma$ scatter. Diamonds present the metallicity gradient measured in HIX galaxies, the circle the gradient of the CONTROL galaxy and the small dots galaxies from the GASS survey. All symbols are colour-coded by the H I mass fraction of the galaxy. Overall, HIX and CONTROL galaxies behave similar to the galaxies in the Ho et al. (2015) and GASS sample.
amounts of gas (Corsini, 2014). This is not the case for HIX galaxies. The co-rotation of ionised and atomic gas further supports the scenario that none of the HIX galaxies went through a recent major merger to increase its H\textsubscript{I} content.

Using strong emission lines, gas-phase metallicities have been measured throughout the detected stellar discs of HIX and CONTROL galaxies. These measurements were used to place the HIX and CONTROL galaxies on the mass–metallicity relation and to compare the metallicity gradient of HIX and CONTROL galaxies to gradients in other galaxies as measured for GASS galaxies and as reported by Ho et al. (2015) and Sánchez et al. (2014).

On the mass–metallicity relation, HIX galaxies follow the ridge of the distribution of star forming SDSS galaxies within the HIX redshift range. Observations and hydrodynamical simulations have indicated that H\textsubscript{I}-rich galaxies should have lower metallicities at a given stellar mass than more H\textsubscript{I}-poor galaxies (Hughes et al., 2013; Lagos et al., 2016). This would imply that more metal-poor galaxies with a higher H\textsubscript{I} content would have recently accreted at a higher rate than average (i.e. a maximum in a stochastic accretion history). However, the measurements of the central gas-phase metallicity for the HIX galaxies are not lower than expected from the SDSS relation. The analysis presented in Chapter 4 suggested that HIX galaxies are H\textsubscript{I}-rich because they are able to stabilise their H\textsubscript{I} disc against star formation due to a higher baryonic specific angular momentum. The fact that these galaxies lie on the mass–metallicity relation further supports the scenario in which HIX galaxies do not accrete more gas than other galaxies but convert accreted gas less efficiently into stars.

The same picture is drawn by the radial distribution of the gas-phase metallicity. The gas-phase metallicity gradients in local star forming galaxies are thought to mirror the inside-out growth of galaxies: the inner parts of galaxies are generally more evolved and thus the ISM is more metal-rich there than at the galaxy outskirts (Sánchez et al., 2014). The metallicity is dependent on the local rather than global stellar mass to gas mass ratio (Kudritzki et al., 2015; Ho et al., 2015). Large metallicity drops on the outskirts, however, might indicate that metal-poor gas is flowing inwards and is redistributed throughout the stellar disc (Moran et al., 2012).

All measured gradients are negative, i.e. all HIX galaxies and the CONTROL galaxy are more metal-poor in the outskirts than in the centres, again in agreement with the scenario, where no major merger occurred recently. About one half of the gradients agree with the scatter of the Ho et al. (2015) gradient for massive galaxies within their error-bars. The other half agrees with metallicity gradients for GASS galaxies (Moran et al., 2012), which flatten for larger stellar masses. This further underpins the picture in which HIX galaxies
have not recently accreted a lot of pristine gas and their stellar discs have evolved similarly to other less Hi-rich galaxies in the local Universe. The simple chemical evolution model of Ho et al. (2015) and Kudritzki et al. (2015) is able to reproduce measured metallicity gradients. This model suggests that the local metallicity is mostly dependent on the local stellar to total gas mass ratio. At the galactocentric radii where gas-phase metallicities can be measured, the Hi column densities in HIX galaxies are similar to the Hi column densities of CONTROL galaxies. It is only at larger radii, that the Hi column densities in CONTROL galaxies are smaller than in HIX galaxies. The stellar surface densities are similar in HIX and CONTROL galaxies. Thus, a lot of the Hi in HIX galaxies does not have an influence on the metallicity gradient.

Galaxies with flatter gradients than suggested by Ho et al. (2015) are ESO290-G035, ESO075-G006, ESO111-G014, ESO417-G018 and ESO245-G010. Metallicity gradients can be flattened by minor-mergers (e.g. López-Sánchez et al., 2015) and also show a tendency to be flatter in Sa, S0, and generally more bulge-dominated galaxies than in disc-dominated systems (Sánchez et al., 2014; Moran et al., 2012). Belfiore et al. (2017) hypothesise that flatter metallicity gradients are produced by efficient mixing and feedback. Thus flatter metallicity gradients might indicate an active Galactic Fountain. There is only one galaxy with a relatively thick Hi disc and a flatter gradient than expected by Ho et al. (2015): ESO075-G006. Other galaxies either have thick discs or flattened metallicity gradients with respect to the Ho et al. (2015) average. It is thus not clear whether a Galactic Fountain is at work in the majority of the HIX galaxies or not.

For ESO417-G018, only pointings towards the northern part of the disc and a spiral arm to the south of the disc are available. There is no data available for the centre of the galaxy. For ESO245-G010, only data for the central part of the galaxy disc are available. The metallicity gradient of these two galaxies might therefore be underestimated due to a small range of radii at which the metallicity was measured.

ESO290-G035 is a Sa galaxy with a very pronounced warp in the Hi disc, and lives within a relatively dense environment with the next neighbours (PGC 130807, ESO290-IG037) at a projected distance of ~ 350 kpc. The scenarios to explain the warp and shallow metallicity gradient in ESO290-G035 might thus be tidal interaction with these neighbours, but the shallow metallicity gradient might also be due to its morphology.

ESO075-G006 is a very isolated Sb galaxy. The next neighbour is located at a projected distance of 3.6 Mpc and its Hi disc does not show any tails that might indicate a recent minor merger. There is a nearer companion PGC 277784 (Paturel et al., 2003), which was classified as an interaction partner (Arp & Madore, 1987). However, neither is the redshift
of this companion known, nor was it detected in H\textsubscript{1}. So it is not possible to tell whether the flattened metallicity gradient is indeed induced by tidal interaction or a minor merger.

ESO111-G014 is a Sc galaxy, for which the H\textsubscript{1} disc does not show any signs of tidal interaction or recent mergers. Together with ESO075-G006, these galaxies have the highest stellar masses in the WiFeS sample. These galaxies might thus follow the observed trend in GASS galaxies, which show flatter gradients at higher stellar masses.

In summary, the distribution of gas-phase metallicity within the stellar disc of HIX galaxies is similar to other local star forming galaxies (as presented e.g. in (Ho et al., 2015) or Moran et al. (2012)). Using the metallicity as an indicator for galaxy evolution (Sánchez et al., 2014) and recent gas inflows (Moran et al., 2012; Sánchez Almeida et al., 2014b), this implies that the stellar discs of HIX galaxies evolved similar to the stellar discs of other local, star forming galaxies and HIX galaxies have not experienced any massive inflows of pristine gas recently. Furthermore, the kinematics of ionised gas, stars and H\textsubscript{1} are in good agreement. Together with the findings in previous Chapter, these results confirm that HIX galaxies have accumulated their massive H\textsubscript{1} reservoirs due to their larger baryonic specific angular momentum rather than any recent accretion or merger event.
Gas accretion onto local galaxies is an elusive phenomenon, which is hard to observe. Nevertheless, gas accretion is vital to replenish the gas reservoir of galaxies for their continued active star formation in the future. If galaxies are H\textsuperscript{i}-rich, they might have recently accreted a lot of gas or are generally more efficient at accreting gas than more H\textsuperscript{i}-poor galaxies. This thesis project was therefore driven by the idea to search for signs of gas accretion onto H\textsuperscript{i}-rich galaxies. Throughout the investigation of these H\textsuperscript{i}-rich galaxies, however, it was found that the extremely H\textsuperscript{i}-rich galaxies of the hIX sample are less efficient at forming stars from their gas reservoir rather than being more efficient at replenishing their gas reservoir than galaxies with a more average H\textsuperscript{i} content. The results and detailed outcomes of this analysis are summarised in this Chapter.

6.1 Summary of the results of this thesis

This thesis focuses on H\textsuperscript{i}-rich galaxies, which were selected such that they are located at least 1.4$\sigma$ above the H\textsuperscript{i} mass – to – optical luminosity scaling relations by Dénès et al. (2014). To understand the reason for their H\textsuperscript{i}-richness, these H\textsuperscript{i} eXtreme (hIX) galaxies were compared to the general galaxy population, a control sample (galaxies within $\pm0.7\sigma$ of the Dénès et al. (2014) relation), and galaxies simulated with the semi-analytic model Dark Sage.

Observational results

To further examine the sample selection and to understand the star formation activity in hIX galaxies, the hIX galaxies were compared to the local galaxy population with the help of scaling relations (see Chapter 3). In the log $M_{\text{HI}}/M_*$ vs. log $M_*$ [M$_{\odot}$] plane, the hIX galaxies are located more than 1$\sigma$ above the running average of the H\textsuperscript{i} mass

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fractions of the Hipass parent sample. This means that the selection of galaxies with large H\textsubscript{i} masses for their stellar luminosity also selects galaxies with large H\textsubscript{i} to stellar mass fractions for their stellar mass.

In terms of star formation activity, HiX galaxies are located on the star formation main sequence, i.e. they are average star forming galaxies and their specific star formation rates ($sSFR \equiv SFR/M_\star$) are comparable to the $sSFR$’s of the CONTROL sample. As the HiX galaxies have larger H\textsubscript{i} masses than the CONTROL galaxies, this result immediately implies that the star formation efficiencies ($SFE \equiv SFR/M_{\text{H}i}$) are systematically lower than in the CONTROL galaxies. Hence, HiX galaxies do not form stars as actively as they could, given their large H\textsubscript{i} reservoir.

To understand the reason for the inefficient star formation, the resolved H\textsubscript{i} disc of the HiX and CONTROL sample were examined (see Chapter 4): In a first step, the physical sizes of the H\textsubscript{i} discs were measured and compared to the physical sizes of the stellar disc. To understand whether the average column densities of H\textsubscript{i} and stars within the discs are as expected, H\textsubscript{i} and stellar mass–size relations were considered. This analysis showed that the stellar discs of HiX and CONTROL galaxies are consistent with the stellar mass–size relation for disc galaxies from GAMA (Lange et al., 2015) and the H\textsubscript{i} disc sizes of both samples lie on the H\textsubscript{i} mass–size relation (Broeils & Rhee, 1997; Wang et al., 2014, 2016). Since the H\textsubscript{i} masses of HiX galaxies are larger for their stellar content than in CONTROL galaxies, this results immediately implies that the ratio of stellar to H\textsubscript{i} disc sizes is larger in HiX than in CONTROL galaxies. Hence, HiX galaxies host larger amounts of H\textsubscript{i} at larger radii than CONTROL galaxies.

In a second step, the kinematic properties of the HiX and CONTROL galaxies were investigated. Both samples are mostly located within the scatter of the baryonic mass Tully-Fisher relation of Lelli et al. (2016). In addition, HiX and CONTROL galaxies form together a stellar mass Tully-Fisher relation. Under the assumption that the rotation velocity is a measurement for the virial mass of the halo (Klypin et al., 2011), this implies that both the baryonic and the stellar mass in HiX galaxies are as large as expected for their halo mass. From the Tully-Fisher relation it also becomes apparent that the rotation velocities in both samples are comparable.

The angular momentum of a disc has long been recognised to define the size of galaxy discs (Fall & Efstathiou, 1980; Dalcanton et al., 1997; Mo et al., 1998). Making use of the H\textsubscript{i} distribution and kinematics together with the stellar distribution, allowed for the calculation of the H\textsubscript{i}, stellar and baryonic specific angular momentum. While the stellar specific angular momentum is similar in HiX and CONTROL galaxies, the H\textsubscript{i} specific
angular momentum is larger in HIX than in CONTROL galaxies. The baryonic specific angular momentum is the mass-weighted average of H1 and stellar angular momentum and is thus also larger in HIX than in CONTROL galaxies. Since the rotation velocities in both samples are of similar magnitude, it is the large mass of H1 at large radii in HIX galaxies that leads to this situation. The larger baryonic specific angular momentum allows HIX galaxies to stabilise their large H1 discs against star formation and collapse, which is in agreement with the analytic model by Obreschkow et al. (2016). Estimating the dark matter halo spin parameter from the baryonic specific angular momentum and the baryonic mass shows that most HIX galaxies tend to exist in dark matter haloes with larger spins than most CONTROL galaxies.

In Chapter 5, the gas-phase metallicity of HIX galaxies was investigated. Since gas which has been recently accreted from the intergalactic medium has a lower metallicity than gas within a galaxy disc, this analysis can help to find out whether HIX galaxies recently accreted a lot of gas. The central gas-phase oxygen abundances of HIX galaxies are consistent with the mass–metallicity relation of SDSS galaxies at similar redshifts. In addition, the metallicity gradients are as steep in HIX galaxies as in other local spiral galaxies (Sánchez et al., 2014; Ho et al., 2015). The conclusion is that the ISM within the stellar disc of HIX galaxies has not been more diluted by accretion of pristine gas than in other local spiral galaxies.

There is tentative evidence that the H1 discs of HIX galaxies are more warped and asymmetric than the H1 discs of the CONTROL sample and that they host more clumpy or unsettled gas than CONTROL galaxies. This result, however, is potentially influenced by the fact that the observations of HIX galaxies are more sensitive to diffuse gas than the observations of CONTROL galaxies. If this result holds, then one possible explanation for more lopsided H1 discs in HIX than in CONTROL galaxies is that HIX galaxies have acquired some of their gas through recent minor mergers. The unsettled and clumpy gas in HIX galaxies is, however, not enough to fully explain the H1 excess. Another possible scenario for the increased number of warps is that the H1 discs of HIX galaxies reach further out into the halo and are thus more easily affected by subhaloes and the large-scale environment of the halo. That means that the H1 discs of HIX galaxies are more easily disturbed by tidal interactions.

Information from the Dark Sage semi-analytic simulation

One result of the analysis of resolved H1 observations is that HIX galaxies reside in dark matter haloes with a larger spin than CONTROL galaxies. Properties of the dark matter
halo of observed galaxies, however, can only be indirectly measured. In simulations, the properties of dark matter haloes are more easily accessible. Hence, these observational results were compared to data of galaxies simulated with the semi-analytic model DARK SAGE (Stevens et al., 2016), which was built on the Millennium dark matter only simulation (Springel et al., 2005). This simulation is well suited to analyse the relation between H\textsc{i}, angular momentum and halo spin as it is explicitly calibrated to reproduce the H\textsc{i} mass function and focuses on the angular momentum evolution of local disc galaxies. The theoretical astronomical observatory TAO was used to produce the catalogues of simulated galaxies, which not only includes simulation results such as H\textsc{i} mass but also simulated photometry in optical bands. The optical photometry of the simulated galaxies is based on spectral energy distribution fitting and was used to classify the simulated galaxies in HIX-like and CONTROL-like galaxies using the Dénes et al. (2014) scaling relation.

To test whether the simulated HIX and CONTROL galaxies behave like the observed sample, the simulated galaxies were placed on the same relations that had been used to characterise the observed HIX galaxies: the log $M_{\text{H\textsc{i}}}/M_\star$ vs. log $M_\star$ [$M_\odot$] plane, the SFE vs. log $M_\star$ [$M_\odot$] plane, and the H\textsc{i} mass–size relation. On all three relations, simulated and observed HIX galaxies behave similarly. Investigating the simulated HIX galaxies in more detail showed that they indeed reside in higher spin haloes than simulated CONTROL galaxies. This is in good agreement with the estimate of the halo spin of the observed HIX galaxies.

\subsection*{6.2 The big picture}

The picture emerging from observational and simulated results

For this thesis, a sample of galaxies, which host at least 2.5 times more H\textsc{i} than expected for their stellar luminosities, has been selected from HIPASS. This sample of H\textsc{i} eXtreme (HIX) galaxies is accompanied by a sample of CONTROL galaxies, which represent average HIPASS galaxies. These samples have been compared with each other and to the local galaxy population. HIX galaxies are found to form stars at average levels for their stellar mass. However, since they host a large amount of H\textsc{i} for their stellar mass, they are less efficient at forming stars from their H\textsc{i} reservoir than than the CONTROL sample. The gas-phase metallicity distribution within the stellar discs of the HIX galaxies has also been examined. It does not show any distinctive features but behaves as in other spiral galaxies. This indicates that HIX galaxies have not recently accreted a large amount of pristine gas from the intergalactic medium. In some cases, recent gas-rich minor mergers may add to the H\textsc{i}-richness of HIX galaxies. However, the mass of irregular H\textsc{i} is not high...
6.2. The big picture

enough to fully explain why they are hix galaxies.

The analysis of spatially resolved H\textsc{i} data of the hix and control galaxies together with a comparison of the observations to results from the semi-analytic model DARK SAGE, suggests the following scenario: hix galaxies tend to reside in dark matter haloes with larger halo spin parameters than control galaxies. This leads to a higher specific angular momentum of the hix galaxy discs. Thus, hix galaxies can support a larger H\textsc{i} disc against star formation and collapse than control galaxies. A large amount of H\textsc{i} is located at large radii, where it is unavailable for star formation. Unless hix galaxies are heavily disturbed by e.g. a major merger, the hix galaxies will continue to be hix galaxies in the future.

Answers to key science questions

The key science questions and motivation for this thesis were (see Section 1.6):

(i) How do H\textsc{i}-rich galaxies maintain their H\textsc{i} reservoir? Did H\textsc{i}-rich galaxies recently accrete a lot of gas?

(ii) What is the connection between galaxy dynamics and gas content?

(iii) What drives the scatter of scaling relations? Why are some galaxies more gas rich than others?

Throughout the analysis, no evidence has been found to support the scenario that hix galaxies recently accreted a lot of gas or that they generally accrete gas more efficiently than other galaxies. Instead, they maintain their large H\textsc{i} content because they are less efficient at forming stars than control galaxies. The lowered star formation efficiency is a result of the higher baryonic specific angular momentum of hix galaxies. Due to this high specific angular momentum, some of the gas is effectively taken out of the star-formation–gas cycle. This implies that just because a galaxy is H\textsc{i}-rich, it does not mean that all gas is available for star formation. The radial distribution and kinematic properties of the gas are also determining parameters. Consequently, there is a tight connection between the H\textsc{i} content and the kinematic properties of galaxies. In fact, this relation is so tight that all outliers to the Dénes et al. (2014) relation above a stellar mass of log $M_* [\text{M}_\odot] > 9.7$ studied in this thesis are outliers due to their kinematic properties.

The results of this thesis confirm findings from hydrodynamical simulations (Lagos et al., 2017), simple analytical models (Obreschkow et al., 2016), observations of integrated properties of galaxies (Maddox et al., 2015), and observations of small samples (Hallenbeck et al., 2014, 2016) that the angular momentum properties of (disc-dominated) galaxies...
shape and define their H\textsubscript{I} content. This thesis expands on these results by examining one of the largest samples of galaxies to date, for which the H\textsubscript{I} specific angular momentum was measured from resolved H\textsubscript{I} maps rather than integrated properties. This is particularly important in HIX galaxies, where the H\textsubscript{I} is distributed out to large galactocentric radii and the H\textsubscript{I} content can not be inferred from their optical properties. Furthermore, this analysis includes two well defined samples: H\textsubscript{I}-rich galaxies (HIX) and galaxies with an average H\textsubscript{I} content for an H\textsubscript{I} selected sample (CONTROL). These results are therefore highly suitable to be compared to simulations. This sample selection is in particular able to produce HIX-like and CONTROL-like samples from a catalogue of galaxies simulated with the semi-analytic model DARK SAGE. The properties of the simulated galaxies are in good agreement with the observations.

6.3 Outlook and future works

This thesis has provided a detailed look into important aspects of the properties of HIX galaxies. Based on work presented here, there arise further questions that warrant a detailed investigation:

**Environmental studies on the HIX galaxies**

Dénès et al. (2014) have suggested that many H\textsubscript{I}-rich galaxies tend to be located on the edges of large structures, such as groups and clusters. Simulations furthermore indicate that the environment can affect the angular momentum of galaxies (Welker et al., 2014). As has been shown here, the H\textsubscript{I} discs of some of the HIX galaxies are affected by their environment. Galaxies like ESO378-G003 have H\textsubscript{I} tails likely due to tidal interactions with fellow group members, whereas other HIX galaxies like ESO208-G026 have no neighbouring galaxies for \( \sim 1.7 \) Mpc. What are the environmental effects that act on HIX galaxies?

**Angular momentum studies of H\textsubscript{I}-poor galaxies**

This thesis has shown that their high specific angular momentum is the main driver for the large H\textsubscript{I} discs in HIX galaxies. There are several mechanisms that can strip galaxies of their H\textsubscript{I} discs such as ram pressure stripping, tidal stripping or strangulation. However, these mechanisms require a dense environment such as groups or clusters to act on galaxies. If an H\textsubscript{I}-poor galaxy is located in the field, why does it contain less H\textsubscript{I} than expected? Could the angular momentum also define their H\textsubscript{I} content as predicted by the Obreschkow et al. (2016) model?
6.3. Outlook and future works

Continue the search for gas accretion in local galaxies

Gas accretion onto local galaxies remains an elusive phenomenon. As has been shown in this thesis, H\text{\textsc{i}}-rich galaxies do not appear to be the “right” laboratories to examine gas accretion. Other galaxies that might be more suitable to find signs of gas accretion, could be galaxies with strong metallicity inhomogeneities or steep metallicity gradients, such as the extremely metal-poor galaxies studied by Filho et al. (2013) and Sánchez Almeida et al. (2014b). To find those galaxies large surveys of resolved optical spectra of galaxies out to large radii are necessary. These data may already be available in galaxies observed with CALIFA or SAMI but also the growing observation archive of the MUSE spectrograph might be useful. It would then be interesting to investigate the H\text{\textsc{i}} content of these galaxies to search for infalling, radial gas motions.

The future with the ASKAP, MeerKAT and the SKA

The pathfinder and the precursor of the SKA, ASKAP and MeerKAT, are starting to deliver data (e.g. Serra et al., 2015 or Carignan et al., 2013). Over the coming years, the Wallaby survey will detect more than 600000 galaxies and provide resolved, homogeneously sampled H\text{\textsc{i}} images for \(\sim 5000\) galaxies (Duffy et al., 2012). Based on this data set, systematic studies of H\text{\textsc{i}} morphology, kinematics and specific angular momenta will be possible. The CHILES (Fernández et al., 2013), LADUMA\textsuperscript{1}, and DINGO\textsuperscript{2} surveys will probe the H\text{\textsc{i}} content to higher redshifts than ever before. The first galaxies detected in these surveys will be the most H\text{\textsc{i}}-rich galaxies of their epoch but the observations of their H\text{\textsc{i}} disc will be unresolved. So, if H\text{\textsc{i}}-rich galaxies such as the hix galaxies are understood in the local Universe, that knowledge can be transferred to future discoveries of high redshift H\text{\textsc{i}} discs.

The work presented here has again shown how important a multiwavelength approach is in understanding galaxy evolution. In synergy with the SKA and its pathfinder and precursor, the Southern Hemisphere will be explored with new, optical and infrared imaging (e.g. SkyMapper, Keller et al., 2007), a multi-object, optical, spectroscopic survey (Taipan\textsuperscript{3}), and a potential optical integral field spectroscopic survey (HECTOR, Bland-Hawthorn, 2015). Together these surveys will, among other science objectives, further investigate the connection between H\text{\textsc{i}}, stars and star formation.

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The figures in this chapter show two images for each galaxy in the HIX and CONTROL sample:

The left panel shows the SuperCOSMOS $B_j$-band image overlaid with the Hopcat aperture that was used by Doyle et al. (2005) for photometry measurements. The right panel shows the 2MASS $K_s$-band image overlaid with the 2MASX aperture that was used to measure photometry in the $K_s$-band.
Figure A.1 ESO111-G014

Figure A.2 ESO243-G002
Figure A.3 NGC289

Figure A.4 ESO245-G010
Appendix A. Infrared and optical photometry

Figure A.5 ESO417-G018

Figure A.6 ESO055-G013
Figure A.7 ESO208-G026

Figure A.8 ESO378-G003
Appendix A. Infrared and optical photometry

Figure A.9 ESO381-G005

Figure A.10 ESO461-G010
Figure A.11 ESO075-G006

Figure A.12 ESO290-G035
Figure A.13 NGC685

Figure A.14 ESO121-G026
Figure A.15 ESO123-G023

Figure A.16 NGC3001
Figure A.17 ESO263-G015

Figure A.18 NGC3261
Figure A.19 NGC5161

Figure A.20 ESO383-G005
Figure A.21 IC4857

Figure A.22 ESO287-G013
Figure A.23 ESO240-G011
This and the following Chapter includes the H\textsubscript{i} data of the HIX and the CONTROL sample, respectively, that has been used in this thesis. For each galaxy, there are two figures with 6 panels each. The first of the two figures shows on the left side the moment 0, 1 and 2 map (from top to bottom) of the observed ATCA data cube. On the right side the moment 0, 1 and 2 maps (again from top to bottom) of the model data cube as produced by TiRiFiC. In addition, the top, right panel shows the moment 0 map of the residual data cube with black contours.

The second figure shows:

- Top left panel: spectra as measured from the data cube (black, solid line), from the HIPASS data cube (grey, solid line) and from the residual between the input data cube and the TiRiFiC model cube (grey dashed line).

- Middle and bottom left panel: position velocity diagrams along the minor and the major axis, respectively. Blue contours and grey scale background present the data cube and red contours the TiRiFiC model cube.

- Top right panel: the radial profile of the H\textsubscript{i} column density as measured from elliptical annuli. The vertical solid grey line marks the H\textsubscript{i} radius R\textsubscript{HI} and the dashed grey line the stellar radius R\textsubscript{K,20magarcsec^{-2}}.

- Middle right panel: the rotation velocity measured by TiRiFiC (black dots connected by a black dashed line) and a fit to that rotation curve (grey solid line) of the functional form:

\[
v_{\text{rot}}(r) = v_{\text{flat}} \cdot \left[1 - \exp \left(\frac{-r}{R_{\text{flat}}}\right)\right]
\]  

(B.1)

- Bottom right panel: the radial variation of the inclination (black dots and dashed
line, left y-axis) and the position angle (grey dots and dashed line, right y-axis) as modelled by TiRiFiC.
Figure B.1 ESO111-G014: panel of observed (left) and modelled (right) data cubes.
Figure B.2 ESO111-G014: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.3 ESO243-G002: panel of observed (left) and modelled (right) data cubes.
Figure B.4 ESO243-G002: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.5 NGC289: panel of observed (left) and modelled (right) data cubes.
Figure B.6 NGC289: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.7 ESO245-G010: panel of observed (left) and modelled (right) data cubes.
Appendix B. H\textsc{i} data of the HIX sample

Figure B.8 ESO245-G010: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.9 ESO417-G018: panel of observed (left) and modelled (right) data cubes.
Figure B.10 ESO417-G018: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.11 ESO055-G013: panel of observed (left) and modelled (right) data cubes.
Appendix B. \( \text{H I} \) data of the HIX sample

Figure B.12 ESO055-G013: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.13 ESO208-G026: panel of observed (left) and modelled (right) data cubes.
Figure B.14 ESO208-G026: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.15 ESO378-G003: panel of observed (left) and modelled (right) data cubes.
Figure B.16 ESO378-G003: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.17 ESO381-G005: panel of observed (left) and modelled (right) data cubes.
Figure B.18 ESO381-G005: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.19 ESO461-G010: panel of observed (left) and modelled (right) data cubes.
Figure B.20 ESO461-G010: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.21 ESO075-G006: panel of observed (left) and modelled (right) data cubes.
Figure B.22 ESO075-G006: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure B.23 ESO290-G035: panel of observed (left) and modelled (right) data cubes.
Figure B.24 ESO290-G035: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
H: data of the CONTROL sample
Figure C.1 NGC685: panel of observed (left) and modelled (right) data cubes.
Figure C.2 NGC685: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.3 ESO121-G026: panel of observed (left) and modelled (right) data cubes.
Figure C.4 ESO121-G026: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Appendix C. \textit{H}1 data of the \textit{CONTROL} sample

Figure C.5 ESO123-G023: panel of observed (left) and modelled (right) data cubes.
Figure C.6 ESO123-G023: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.7 NGC3001: panel of observed (left) and modelled (right) data cubes.
Figure C.8 NGC3001: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.9 ESO263-G015: panel of observed (left) and modelled (right) data cubes.
Figure C.10 ESO263-G015: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.11 NGC3261: panel of observed (left) and modelled (right) data cubes.
Figure C.12 NGC3261: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Appendix C. $H\text{I}$ data of the CONTROL sample

Figure C.13 NGC5161: panel of observed (left) and modelled (right) data cubes.
Figure C.14 NGC5161: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Appendix C. $H_1$ data of the CONTROL sample

Figure C.15 ESO383-G005: panel of observed (left) and modelled (right) data cubes.
Figure C.16 ESO383-G005: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.17 IC4857: panel of observed (left) and modelled (right) data cubes.
Figure C.18 IC4857: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.19 ESO287-G013: panel of observed (left) and modelled (right) data cubes.
Figure C.20 ESO287-G013: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Figure C.21 ESO240-G011: panel of observed (left) and modelled (right) data cubes.
Figure C.22 ESO240-G011: panel of spectra (top left), position–velocity diagrams (middle and bottom left) and radial profiles of column density (top right), rotation velocity (middle right) and position angle and inclination (bottom right).
Data products from optical spectra

This Appendix provides data products based on the WiFeS optical spectra:

- In the top left panel, the pointings (blue boxes) are overlaid on SuperCOSMOS $B_J$-band images (red scale).

- Top right panel: The regions of the single star forming regions (blue boxes) are overlaid on GALEX NUV images (colour scale). Galaxy ESO208-G026 was not observed in NUV and thus the SuperCOSMOS $B_J$-band image is shown.

- Middle left panel: Here, the $H\alpha$ moment 0 map is shown overlaid with measurements of $H\alpha$ recession velocities as measured for each star forming region.

- Middle right panel: This panel shows again the SuperCOSMOS $B_J$-band image overlaid with the metallicity measurements in each star forming region.

- Bottom right panel: The left y-axis and red diamonds present the radial profile of metallicity measurements. The solid red line marks the linear fit to the metallicity profile, the slope of which is the metallicity gradient. The right y-axis and blue circles connected with the dashed blue line show the radial $H\alpha$ profile. The grey, dotted line marks the ESO-LV 25 mag arcsec$^{-2}$ isophotal radius.

D.1 HIX galaxies with full data set
Figure D.1 ESO111-G014
Figure D.2 NGC289
Appendix D. Data products from optical spectra

Figure D.3 ESO055-G013
Figure D.4 ESO208-G026
Appendix D. Data products from optical spectra

Figure D.5 ESO378-G003
D.1. HIX galaxies with full data set

Figure D.6 ESO381-G005
Appendix D. Data products from optical spectra

Figure D.7 ESO075-G006
Figure D.8 ESO290-G035
D.2  HIX galaxies with partial data set
Figure D.9 ESO245-G010
Figure D.10 ESO417-G018
D.3  CONTROL galaxy
Figure D.11 IC4857
The Figures in this Chapter show the optical spectra of every star forming region that was used in this work. The dark-blue, solid line shows the spectrum, the light-blue line the background model and the red line the fit to the emission lines.

E.1 HIX galaxies with full data set
Figure E.1 ESO111-G014 arm
Figure E.2 ESO111-G014 centre
Figure E.3 ESO111-G014 centre
Figure E.4 ESO111-G014 north
Figure E.5 ESO111-G014 south
Figure E.6 NGC289 centre
Appendix E. Optical spectra

Figure E.7 NGC289 centre
Figure E.8 NGC289 inner north
Figure E.9 NGC289 inner north
Figure E.10 NGC289 inner south
Figure E.11 NGC289 outer north
Figure E.12 NGC289 outer south
Appendix E. Optical spectra

Figure E.13 ESO055-G013 centre
Figure E.14 ESO055-G013 centre
Figure E.15 ESO208-G026 east
Figure E.16 ESO208-G026 west
Figure E.17 ESO208-G026 west
Figure E.18 ESO378-G003 centre
Figure E.19 ESO378-G003 centre
Figure E.20 ESO378-G003 north
Figure E.21 ESO378-G003 south
Figure E.22 ESO381-G005 arm
Figure E.23 ESO381-G005 centre
E.1. HIX galaxies with full data set

Figure E.24 ESO381-G005 centre
Appendix E. Optical spectra

Figure E.25 ESO381-G005 north
Figure E.26 ESO381-G005 south
Figure E.27 ESO075-G006 centre
Figure E.28 ESO075-G006 north
Figure E.29 ESO075-G006 south
Figure E.30 ESO290-G035 centre
Figure E.31 ESO290-G035 north
Figure E.32 ESO290-G035 south
E.2 HIX galaxies with partial data set
Figure E.33 ESO245-G010 centre
Figure E.34 ESO245-G010 centre
Figure E.35 ESO417-G018 arm
Figure E.36 ESO417-G018 south
E.3  

CONTROL galaxy
Figure E.37 IC4857 centre
Figure E.38 IC4857 north
Figure E.39 IC4857 north
Figure E.40 IC4857 south