THE IMPACT OF ENVIRONMENT AND MergERS
ON THE H I CONTENT OF GALAXIES IN
HYDRODYNAMIC SIMULATIONS

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The Impact of Environment and Mergers on The H I Content of Galaxies in Hydrodynamic Simulations

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Galaxy H I
Galaxy formation
Galaxy evolution
Galaxy ISM
N-body simulations
Galaxy mass function
Abstract

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We quantitatively examine the effects of merger and environment within a cosmological hydrodynamic simulation. We show that our simulation model broadly reproduces the observed scatter in H\textsubscript{i} at a given stellar mass as quantified by the HI mass function in bins of stellar mass, as well as the H\textsubscript{i} richness versus local galaxy density. The predicted H\textsubscript{i} fluctuations and environmental effects are roughly consistent with data, though some discrepancies are present at group scales. For satellite galaxies in $\gtrsim 10^{12}M_\odot$ halos, the H\textsubscript{i} richness distribution is bimodal and drops towards the largest halo masses. The depletion rate of H\textsubscript{i} once a galaxy enters a more massive halo is more rapid at higher halo mass, in contrast to the specific star formation rate which shows much less variation in the attenuation rate versus halo mass. This suggests that, up to halo mass scales probed here ($\lesssim 10^{14}M_\odot$), star formation is mainly attenuated by starvation, but H\textsubscript{i} is additionally removed by stripping once a hot gaseous halo is present. In low mass halos, the H\textsubscript{i} richness of satellites is independent of radius, while in high mass halos they become gas-poor towards the center, confirming the increasing strength of the stripping with halo mass. By tracking the progenitors of galaxies, we show that the gas fraction of satellite and central galaxies decreases from $z = 5 \rightarrow 0$, tracking each other until $z \sim 1$ after which the satellites’ H\textsubscript{i} content drops much more quickly, particularly for the highest halo masses. Mergers somewhat increase the H\textsubscript{i} richness and its scatter about the mean relation, but these variations are consistent with arising form inflow fluctuations, unlike in the case of star formation where mergers boost it above that expected from inflow fluctuations. In short, our simulations suggest that the H\textsubscript{i} content in galaxies is determined by their ability to accrete gas from their surroundings, with stripping effects playing a driving role once a hot gaseous halo is present.
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I, Mika Harisetry RAFIEFERANTSOA, understand the meaning of plagiarism and declare that all of the work in this document titled *The impact of environment and mergers on the H\textsubscript{I} content of galaxies in hydrodynamic simulations*, save for that which is properly acknowledged, is my own considering the valuable helps and directives from my supervisor during the edition as well as the outcome of scientific collaboration listed below, that it has not been submitted before for any degree or examination in any other University. I am conscious that the incorporation of material from other works or a paraphrase of such material without acknowledgement will be treated as plagiarism, subject to the custom and usage of the subject, according to the Regulations on Conduct of Examinations of the University of the Western Cape. The source of any observational data or other illustration is also indicated, as is the source, published or unpublished, of any material not resulting from my own analysis.

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Chapter 1

Introduction

The primary components of galaxies are stars and gas. The gas is comprised of hydrogen, helium and metals, but here we only focus on the hydrogen component. Thus, I refer to “gas” as the hydrogen component of the galaxy throughout this work. The amount of gas is a vital complement to that of stars as the fuel for new star formation. In galaxy studies, the formation of stars is quantified by the star formation rate (SFR), which gives the mass of stars formed per year. The specific star formation rate or sSFR is defined as the SFR relative to the stellar mass of the galaxy. The gas is also the repository for the nucleosynthetic by-products of stellar evolution. Therefore the gas content is a key probe of the life cycle of galaxies. Recently, much progress has been made in understanding the molecular gas content of galaxies throughout cosmic time (Tacconi et al. 2013) via observations of carbon monoxide (CO) lines and other dense gas tracers. In its molecular form, i.e. H$_2$, hydrogen in galaxies is predominantly cold ($\sim 10$K) and radiation is non-existent making it invisible. It is then necessary to use tracers to deduce its amount. Carbon monoxide (CO) turns out to be a good tracer; CO is easily excited at these low temperatures and it is thought to coexist with H$_2$ in the molecular clouds. It is thus possible to infer the amount of H$_2$ through observations of CO.

The other major gas component in galaxies is in neutral atomic form (H$\text{\textsc{i}}$). H$\text{\textsc{i}}$ produces an electromagnetic radiation spectral line at the frequency of $\sim 1.4$ GHz (equivalent to a wavelength of $\sim 21$cm). This radiation is due to the transition from a parallel spin disposition of the electron and proton of the hydrogen atom to an antiparallel spin disposition in which the interaction energy between the two particles is lower. The transition has a tiny rate of occurrence of $\sim 3 \times 10^{-15}\text{s}^{-1}$ (highly forbidden), but can still be observed in astronomical systems owing to the abundance of hydrogen.

In the nearby Universe, the past decade has seen major H$\text{\textsc{i}}$ surveys such as the
H1 Parkes All-Sky Survey (HIPASS; Meyer et al. 2004) and the Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovanelli et al. 2005), both able to probe galaxies down to H1 masses of $M_{\text{HI}} \approx 10^7 M_\odot$ in a uniform (albeit H1-selected) sample. The GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010) relaxed the H1 selection, and instead selected on stellar mass. While they did not probe as deeply in H1 mass (down to $M_s \approx 10^{10} M_\odot$), the lack of H1 selection allowed them to assess the biases associated with such a selection technique. It has been more difficult to study at higher redshifts owing to the current sensitivities of radio telescopes. With the upgraded Jansky Very Large Array, the CHILES survey is aiming to probe H1 evolution in 21cm emission out to sizeable lookback times, to $z \sim 0.45$ (Fernández et al. 2013). Currently, there are two major radio facilities that, as precursors to the SKA, will probe H1 to unprecedented levels both nearby and out to intermediate redshifts. The MeerKAT array in South Africa* and the Australian Square Kilometer Array Pathfinder both have major H1 surveys planned, namely the LADUMA† and DINGO‡ Surveys, which will probe H1 21cm emission in galaxies respectively out to $z \sim 1$ and $z \sim 0.4$.

1.1 Observations

To optimise these investments in observational resources, it is important to place observations of H1 within our modern framework for galaxy formation and evolution. Decades ago, Haynes & Giovanelli (1984) used 324 isolated galaxies and found a more constrained correlation of the optical diameter of a stellar disk with the H1 mass than with the morphological type. Even though H1 does not directly foster star formation (Kennicutt & Evans 2012), it has been shown that the mass of the stars and the atomic hydrogen (H1) mass are highly correlated (Cortese et al. 2011, Huang et al. 2012). Using HIPASS, Zwaan et al. (2005) measured the H1 mass function (HIMF, distribution of galaxies with respect to their H1 masses) down to H1 masses of $M_{\text{HI}} \approx 10^7 M_\odot$, although at low stellar masses the sample is likely biased towards high-H1 fraction galaxies. They also found dependences on environment, in the sense that dense regions tend to steepen the H1 mass function. An improvement in sensitivity was done by Moorman et al. (2014) using ALFALFA data, who found over 10,000 H1-selected galaxies down to $M_{\text{HI}} \sim 10^6 M_\odot$, finding a larger H1 cosmic density and a larger value of $M_{\text{H1},*}$, where $M_{\text{H1},*}$ is the characteristic mass from a Schechter function fit. The schechter function describes the space density of galaxies.

*http://www.ska.ac.za/meerkat/
†http://www.ast.uct.ac.za/laduma/Home.html
‡http://askap.org/dingo
1.1 Observations

Figure 1.1: $\text{H} \text{I}$ mass function of galaxies from HIPASS sample (Zwaan et al. 2005) Left: HIMF of the whole sample showing the different parameter fit of the Schechter function. Right: Evolution of the HIMF as function of local galaxy density.

![Image of Figure 1.1]

Figure 1.2: $\text{H} \text{I}$ mass function of galaxies from ALFALFA sample taken from Moorman et al. (2014).

![Image of Figure 1.2]

as a function of either $\text{H} \text{I}$ or stellar masses or luminosity. The function can be written as in equation 1.1 where in our case $x = M_{\text{H} \text{I}}/M_{\text{H} \text{I}, \ast}$ and $\Phi^*\,$ is a normalisation factor with units of number density.

$$\delta(x) dx = \Phi^* x^a \exp^{-x} dx \quad (1.1)$$

To compare, we present in figures 1.1 and 1.2 the results of the 2 surveys mentioned before. The characteristic mass of the Schechter fit is $\log M_{\text{H} \text{I}, \ast} = 9.80 \pm 0.02$ for HIPASS and $\log M_{\text{H} \text{I}, \ast} = 10.00 \pm 0.01$ for ALFALFA (void galaxies have lower characteristic mass of $\log M_{\text{H} \text{I}, \ast} = 9.86 \pm 0.02$). This means that the cut-off of the power law in the function shifts toward a slightly higher $\text{H} \text{I}$ mass.

Interestingly, the galaxy $\text{H} \text{I}$ mass and SFR together showed that the amount of gas in $\text{H} \text{I}$ is inadequate to yield the observed stellar mass of a given galaxy at
a sustained SFR at any observable redshift (Sancisi et al. 2008). To explain this
discrepancy, Hopkins et al. (2008) came up with two possibilities: first, there should
be gas replenishment at a rate slightly smaller than the requisite usage (in order
for gas fraction to slowly drop with time), or second, small galaxies are less able to
retain their gas. Mass loss from stellar evolution can help the imbalance between the
amount of infalling gas and the actual SFR (Leitner & Kravtsov 2011), although not
sufficiently in lower mass galaxies and not at epochs much earlier than today. The
idea of continued replenishment is also inferred from the evolution of the molecular
hydrogen content (e.g. Tacconi et al. 2013). Indeed, current theoretical models of
galaxy formation invoke continual gas infall as a driver for star formation (Kereš et al.
2005, Finlator & Davé 2008, Sancisi et al. 2008, Dekel et al. 2009, Davé et al. 2012,
Lilly et al. 2013). Hence, it appears that the gas content of galaxies, and particularly
the H\textsc{i} content, could provide a probe of gas accretion from the environment around
galaxies.

Environment is apparently a key factor in determining the H\textsc{i} content of galaxies.
Given the non uniformity of the galaxy distribution in the universe, “environment”
is used to define how galaxies are distributed in their immediate neighborhoods.
Environment can be dense, in the case of galaxies situated in the center of galaxy
cluster, less dense in galaxy groups and even lower density for isolated galaxies (these
might still have some small galaxy companions). Environment is also referred to the
halo mass where high halo mass corresponds to dense environment. Cortese et al.
(2011) found an anti-correlation of H\textsc{i} richness (i.e. H\textsc{i} mass per unit stellar mass)
relative to stellar mass, which is valid in moderate to low density environments but
highly clustered galaxies tend to be H\textsc{i} poor (Giovanelli & Haynes 1985, Solanes
et al. 2001). This is often thought to be related to why galaxies in very dense
environments also show low specific star formation rates. Pappalardo et al. (2012),
looking in the Virgo cluster, found that environment acts to lower the H\textsc{i} content
of galaxies, though the impact is stronger on the molecular content. Hughes et al.
(2013) also found that low H\textsc{i} objects are mostly found in clustered regions. Data
from ALFALFA α.40 (Haynes et al. 2011) showed that half of the optical sources
were observed in denser regions, but only less than a quarter of all of H\textsc{i} detected
sources are located in clusters or groups, and most H\textsc{i}-rich galaxies live outside of
group environments (Hess & Wilcots 2013).
1.2 Simulations

Theoretical work on studying H\textsubscript{i} is also progressing rapidly. Initially, much of the work utilised semi-analytic models (SAMs) based on prescriptively tying the H\textsubscript{i} content to the halo mass and merger history. SAMs are one of the two approaches used to solve the nonlinear physics encountered in the galaxy formation processes. SAMs are tailored from the observational evidence that is key in galaxy formation. To mention, the initial conditions are based on the WMAP cosmology results and the final conditions are derived from the properties of low redshift galaxies (such as our own and some nearby galaxies). Madau plot\textsuperscript{*} is used to get the star formation rate density against redshift, whereas Dickinson plot (Dickinson et al. 2003) is used to get the stellar mass density against redshift. The evolution of galaxies at redshift $z < 1$ is also well-studied. Using the previous information, many astrophysical processes are modeled and tuned to match the observational data. It is computationally inexpensive because it approximates the numerous phenomena in galaxy formation with simple physically-motivated equations. This makes it possible to model very large sample of galaxies. The method, however, loses some predictive power owing to the large numbers of free parameters typically of order $50$.

Obreschkow et al. (2009) used the De Lucia et al. (2012) SAM applied to the Millennium simulation, and found that with reasonable parameter choices they could broadly match observations of the H\textsubscript{i} mass functions for both early and late type galaxies. Lagos et al. (2011) improved on this by adding a prescription to separate H\textsubscript{i} and H\textsubscript{2} in the galform SAM (Bower et al. 2006) with several different recipes for H\textsubscript{2}, finding substantial differences between such recipes. They also found rapid evolution in H\textsubscript{i} properties out to $z = 2$. Similar models by Popping et al. (2014) showed that such differences between H\textsubscript{2} recipes are most important in small galaxies. Lagos et al. (2014) further examined the origin of H\textsubscript{i} in big elliptical galaxies, finding that most of the neutral gas in the elliptical galaxies is produced by radiative cooling from their hot halos. While the large number of free parameters in SAMs makes a unique physical interpretation of the results difficult, nonetheless there is clearly interesting progress being made from SAMs, which are especially useful for making predictions for large upcoming surveys.

Cosmological hydrodynamic simulations have also begun to make predictions for the H\textsubscript{i} content of galaxies. Detailed explanations about hydrodynamic simulations and the different general assumptions which are used in the models are given in chapter 2, but the following are the key points which differ from SAMs. This method

\textsuperscript{*}http://ned.ipac.caltech.edu/level5/Illingworth/Ill5.html
adopts a more *ab initio* principle. It solves the equations of gravity and hydrodynamics directly in the simulation time-step by time-step. Additionally explained in section 2.1, the formation of stars is due to the conversion of cold clouds on a characteristic timescale, say \( t_s \). Following this process and considering that some fraction \( \beta \) of the newly formed stars become supernovae, the local density of stars \( \rho_s \) can be written as a function of the local cold cloud density \( \rho_c \) as shown in equation 1.2.

\[
\frac{d\rho_s}{dt} = \frac{\rho_c}{t_s} - \beta \frac{\rho_c}{t_s}
\]  

(1.2)

Owing to the more direct approach, this method is computationally expensive compared to SAMs. Further computations are necessary with hydrodynamic simulations. For instance, to compute the H\(_\text{i}\) mass fraction from the “gas particle” *, one would need to post process the output of the simulation and use certain prescriptions as described in section 2.2. The commonly used technique is to look for the boundary beyond which the hydrogen is ionised by the background radiation of the intergalactic medium and inside which the hydrogen is self-shielded (or neutral). Popping et al. (2009) presented a simple self-shielding prescription for calculating the H\(_\text{i}\) content of galaxies tuned to match observations of the total cosmic H\(_\text{i}\) content, and showed that such a model produces roughly the correct H\(_\text{i}\) mass function. Duffy et al. (2012) improved on this with a more sophisticated self-shielding model which they applied to the Overwhelmingly Large Simulations (OWLS; Schaye et al. 2010). They obtained good agreement with the observed H\(_\text{i}\) mass function down to \( M_{\text{HI}} \sim 10^{9.5} \, M_{\odot} \), but below this mass they predicted an excess, though this was not very significant since their mass resolution limit was only a factor of several below that; nonetheless, this disagreement mimicked a similar discord in the stellar mass function that is likely a result of their assumed prescription for galactic outflows (Davé et al. 2011b). Here, galactic outflow is the mechanism transporting gas and metals out of the galaxies to the intergalactic medium. Davé et al. (2013) presented a model with an improved recipe for galactic outflows that matched the stellar mass function quite well, and applying another improved self-shielding prescription, they were able to also match the H\(_\text{i}\) mass function and H\(_\text{i}\) richness as a function of stellar mass \( M_* \) quite well. This simulation, therefore, provides a plausible model to study how the H\(_\text{i}\) content of galaxies is impacted by other factors in greater detail.

Besides environment, which is mentioned in the previous section, mergers also interplay with the gas content of galaxies. A merger is the interaction between two (but sometimes more) galaxies. A merger can be characterized based on the

*gas particle is the smallest possible mass of gas cloud treated as one particle in the simulation
1.2 Simulations

Figure 1.3: Colour-magnitude diagram from Schawinski et al. (2014). The grey contours represent the underlying galaxy population; population concentrated on the top-right is strongly dominated by red and dead elliptical galaxies, and the population concentrated on the lower-left is mostly constituted with the late type galaxies. The coloured contours represent galaxies with (optical) green valley colours; the indeterminate-type galaxies as green contours, early types as orange contours and late types as blue contours.

mass ratio of the colliding galaxies, where a major merger involves two galaxies with roughly the same mass and a minor merger is when one galaxy is much less massive than the other. This is further explained in chapter 2.

Another interesting characteristic of galaxies that can be related to the H\textsubscript{i} properties, as discussed in a coming chapter, is the relationship between the mass and the absolute magnitude of the galaxies: the so called galaxy color-magnitude diagram (e.g: Figure 1.3). In this diagram, the galaxies are separated in three groups: the red sequence group, the blue cloud and the green valley. The red sequence contains mainly the red and dead elliptical galaxies, the blue cloud mostly includes the spiral galaxies and finally, the green valley is an intermediate group of transition between the two others where there are very few galaxies. Due to scarcity of the galaxies located in the green valley, the diagram shows a bimodal distribution of red and blue galaxies. This is interesting because the diagram shows the distribution of galaxies depending on their cold gas content which is the main driver of star formation.
1.3 Outline

In this work, we build on the work of Davé et al. (2013) to study the impact of environment and halo mass on the H\textsubscript{i} content of galaxies and its evolution across cosmic time. The main simulations were run by Prof. Romeel Davé and I computed the H\textsubscript{i} mass of the galaxies. The analysis and plots were done by myself as well as the rest of the work in this thesis. Neal Katz and Benjamin D. Oppenheimer gave very interesting comments on the results. Daniel Anglés-Alcázar gave me IDL codes containing the algorithm for tracking a galaxy back in time which I was able to reproduce in Python. He also gave very useful grammatical and typographical corrections. All of the data from observations were given to me as they are presented on the plots either in a fits file format or in a simple ascii file. And finally, all of the works were supervised and advised by Prof. Romeel Davé. Table 1.3 shows the key points of the project timeline. All of these steps were done by myself, except otherwise stated.
Table 1.1: Project timeline

| Year | Semester | Tasks |
|------|----------|-------|
| 2013 | 2nd      | • Got familiar with galaxy sample from simulations, particularly how to extract H\textsubscript{i} mass, stellar mass, halo mass, star formation rate of galaxies.  
   • Looked at the distribution of galaxies in the simulation box by computing the 2 point correlation function; this was done in different ways: first, I computed the 2 point correlation function of the whole sample, and second I changed the lower mass threshold with respect to the stellar mass and the H\textsubscript{i} mass of the galaxies in the simulated sample. The 1-halo and 2-halo terms were also computed. These were done in the purpose of finding correlations between the H\textsubscript{i}/stellar mass with the distribution of the galaxies.  
   • Looked at the H\textsubscript{i} mass function of the resolved galaxies and compared it to different observational data and results from semi-analytical models. Different H\textsubscript{i} mass functions were done such as the H\textsubscript{i} mass function with respect to the stellar mass (bin of different stellar masses), and the bivariate H\textsubscript{i} mass function inspired by Lemonias et al. (2013).  
   • Looked at how the halo mass is affecting the H\textsubscript{i} content of the galaxies. Within each halo, I looked at how the H\textsubscript{i} content of satellite galaxies is affected by their distance to the central one.  
   → These previous properties of the galaxies were randomly looked at in order to know whether the predicted H\textsubscript{i} content of the galaxies are consistent with the observational data, which turned out to be acceptable within uncertainties. |
### Year | Semester | Tasks
---|---|---
2014 | 1<sup>st</sup> | • Prof. Romeel Davé proposed a plan in a form of paper abstract containing different steps to look at which gathered the broad contents of a publishable paper. It was mainly to look at the H<sub>1</sub> content of galaxies and its relation to the environment (which was initially quantified as the halo mass).
• A change of the algorithm computing the H<sub>1</sub> mass was done as described in section 2.2 and I recomputed all of the H<sub>1</sub> masses of the galaxies in the sample. This brought a very interesting improvement in the H<sub>1</sub> content of galaxies compared to the previous result presented in Davé et al. (2013) (note that I used the same sample of simulated galaxies in this thesis)
• The flow of the rest of the work has been done as it is presented in this thesis.
• Mergers effects on the H<sub>1</sub> content of galaxies were difficult to find. Many aspects were looked at but at the end “we” only agreed to show fig.4.6 and fig.4.5 and commented on them.

2014 | 2<sup>nd</sup> | • The second semester was mainly based on writing up the thesis and the paper in the respective formats and formatting all of the plots. Prof. Romeel Davé helped a lot with editing.
• After putting everything together, the thesis as well as the paper were given the same title (the title was slightly changed by Prof. Romeel Davé for improvement) and the introduction was done afterwards, after reading lots of literature.

This work is structured as follows. In chapter 2, we begin by reviewing our simulations, particularly the outflow model that is central to matching a variety of observations, as well as our methodology to calculate the H<sub>1</sub> content of galaxies (2.2) and our methodology for tracking galaxy back in time (2.3). Chapters 3 and 4 contain our results that we summarize and discuss implications in chapter 5.
Chapter 2

Methods

2.1 Simulations

The main simulation used here is the same as in Davé et al. (2013), which we briefly review. Using the enhanced version of GADGET-2 (Springel 2005, Oppenheimer & Davé 2008), we run a cosmological hydrodynamic simulation with $512^3$ gas particles and $512^3$ dark matter particles having masses of $4.5 \times 10^6 \, M_\odot$ and $2.3 \times 10^7 \, M_\odot$, respectively, enclosed in a periodic box of $32h^{-1}\text{Mpc}$ comoving on a side and a gravitational softening length of $\epsilon = 1.25h^{-1}\text{kpc}$. Softening length $\epsilon$ is a characteristic length such that the density distribution function of a single particle is $\tilde{\delta}(x) = W(x, 2.8\epsilon)$ where $W$ is:

$$W(r, h) = \frac{8}{\pi h^3} \begin{cases} 
1 - 6 \left( \frac{r}{h} \right)^2 + 6 \left( \frac{r}{h} \right)^3 & 0 \leq \frac{r}{h} \leq \frac{1}{2} \\
2 \left( 1 - \frac{r}{h} \right)^3 & \frac{1}{2} < \frac{r}{h} \leq 1 \\
0 & \frac{r}{h} > 1
\end{cases}$$

(2.1a)

(2.1b)

(2.1c)

This is used to avoid the divergence of the gravitational potential of a point mass at zero-lag which becomes $-Gm/\epsilon$ in a non-periodic case. $G$ is the gravitational constant and $m$ is the mass of the particle.

The number of particles with the size of the box were chosen based on the desire to make high resolution simulations be able to produce considerable sample of galaxies, and to probe low mass galaxies in balance with the computational power. In the case of the parameters chosen for our simulations, the run took several months to finish. A $\Lambda$CDM cosmology consistent with the Wilkinson Microwave Anisotropy Probe results in Hinshaw et al. (2009) was chosen, namely $\Omega_m = 0.28$, $\Omega_\Lambda = 0.72$, $H_0 = 70 \, \text{km} \, \text{s}^{-1} \, \text{Mpc}^{-1}$, $\sigma_8 = 0.82$, $\Omega_b = 0.046$, and $n_s = 0.96$; these parameters are
not far from that favoured by the nine-year WMAP data (Hinshaw et al. 2013) and Planck (Planck Collaboration et al. 2013). GADGET-2 employs entropy-conserving smoothed particle hydrodynamics (SPH), which has some deficiencies related to handling surface instabilities but this makes little difference for the bulk properties of galaxies (Huang et al. 2014, in prep.). We include radiative cooling from primordial (Katz et al. 1996) and metal (Sutherland & Dopita 1993) species, and track the metallicity in four elements based on enrichment from Type II supernovae, Type Ia supernovae, and stellar mass loss from asymptotic giant branch stars. We will only cursorily be concerned with the metals in this work, and hence we refer the reader to Oppenheimer (2008) for more details on this aspect. We assume a Chabrier (2003) initial mass function throughout.

The primary distinguishing aspect of our code is the use of a highly constrained heuristic model for galactic outflows. The model we follow is presented in Davé et al. (2013), which utilises outflows scalings expected for momentum-driven winds in sizeable galaxies (velocity dispersion $\sigma > 75$ km s$^{-1}$), and energy-driven scalings in dwarf galaxies. In particular, we assume that the mass loading factor (i.e. the mass outflow rate in units of the star formation rate) is $\eta = 150$ km s$^{-1}/\sigma$ for galaxies with velocity dispersion $\sigma > 75$ km s$^{-1}$, and $\eta = 75 \times 150/\sigma^2$ for $\sigma < 75$ km s$^{-1}$.

Previous results have generally favoured the momentum scalings for all galaxies for matching everything from intergalactic medium (IGM) enrichment (Oppenheimer & Davé 2006, Oppenheimer et al. 2012) to circumgalactic gas properties (Ford et al. 2013) to galaxy mass-metallicity relations (Finlator & Davé 2008, Davé et al. 2011a) and stellar mass functions (Davé et al. 2011b). However, these prior simulations generally did not well resolve the dwarf regime but our current run does, and hence we found slight improvements in the dwarf regime by including a steeper scaling of $\eta(\sigma)$ here. Note that we always assume the velocity boost or initial velocity of ejection of particle $v_w \propto \sigma$ for all galaxies, consistent with observations (Martin et al. 2005, Weiner et al. 2009). Interestingly, these scalings are quite similar to those produced in the fully self-consistent outflow simulations of Hopkins et al. (2013), the Feedback in Realistic Environments (FIRE) suite of zoom simulations. The highly simplified physical explanation is that at low masses, supernova energy is sufficient to unbind a sizeable fraction of the gas (Dekel & Silk 1986), but at high masses, additional contributions from momentum input are necessary (Murray et al. 2010, Hopkins et al. 2012).

To implement outflows, we kinetically eject particles from the inter-stellar medium (ISM) in order to mimic unfettered escape through ISM chimneys. The mass ejection
2.1 Simulations

The wind rate is given by

\[ \dot{M}_{\text{wind}} = \eta \times \text{SFR}, \]

where the SFR is computed using a two-phase sub-grid ISM model. The formation of stars is due to the collapse of the cores of the molecular clouds which is much smaller than our simulation can resolve given the limited computer capabilities. It is then crucial to develop models that are able to describe the phenomenological processes taking place at a scale much lower than the simulation resolution, namely “sub-grid” models. In the model used here (Springel & Hernquist 2003), a fluid particle is considered as a combination of cold dense clouds in which the stars form and an ambient hot gas. In the two-phase particle, the cold clouds evolve under gravity, add inertia and contribute in the exchange of energy with the ambient gas which follow the equations of hydrodynamics, and these are computed using differential equations done on a particle-by-particle basis. The cold clouds are transformed into stars on a characteristic timescale and a fraction of these stars will quickly explode as supernovae and become hot gas (quantified by the 2\textsuperscript{nd} term of the right hand side of equation 1.2), rich with metals, feeding the ambient phase of the fluid. The description of the two-phase sub-grid model is fully described in Springel & Hernquist (2003).

If a gas particle has some probability to form into a star, it has \( \eta \) times that probability to be ejected in an outflow. We then eject it in a direction perpendicular to the plane formed by its instantaneous velocity \( \vec{v} \) and acceleration \( \vec{a} \) (direction parallel to \( \vec{v} \times \vec{a} \)) with a velocity \( v_w \) set by the velocity dispersion of the galaxy as estimated from an on-the-fly friends of friends galaxy finder; see Oppenheimer (2008) for details. After this, we turn off hydrodynamic forces on the particle until it reaches a density 10\% of the star-forming density threshold, i.e. \( 0.013 \, \text{cm}^{-3} \), or else a timescale corresponding to \( 1.95 \times 10^{10}/(v_w \, \text{km s}^{-1}) \) years has elapsed.

This simulation also includes a heuristic model to quench star formation in massive galaxies tuned to reproduce the exponential truncation of the stellar mass function. Star formation in a given galaxy is stopped depending on the quenching probability \( P_Q \) given in equation (2.3) which is a function of the velocity dispersion \( \sigma \) of the galaxy:

\[ P_Q = 1 - \frac{1}{2} \text{erfc} \left( \frac{\log \sigma - \log \sigma_{\text{med}}}{\log \sigma_{\text{spread}}} \right) \]

We use \( \sigma_{\text{med}} = 110 \, \text{km s}^{-1} \) as the velocity dispersion where a galaxy has 50\% chance to have its star formation turned off, and \( \sigma_{\text{spread}} = 32 \, \text{km s}^{-1} \) to describe some scatter between \( \sigma \) and the detailed physics of quenching. Note that this model does not attempt to directly model the physics of quenching, it is only a way to reproduce...
the observed mass function at the high mass end, and has virtually no effect below the knee of the mass function. When a galaxy is chosen to stop its star formation, any particle eligible for star formation first has its quenching probability assessed, and if it is selected for quenching then it is heated to 50 times the galaxy’s virial temperature which unbinds it from the galaxy. As discussed in Davé et al. (2013) and as we will demonstrate later, this quenching model does not substantially impact the H I content of galaxies.

To examine dependences on our feedback assumptions, we will use another model without quenching, namely the “vzw” or momentum-driven wind galactic outflows model. This model, fully described in Davé et al. (2011b), has 2 main differences with the model we use in this work. First, the vzw model does not include the quenching prescription as in our hybrid energy momentum-driven winds ezw model (the fiducial model in this work). Second, the mass loading factor $\eta$ is inversely proportional to the velocity dispersion $\sigma$ regardless of the size of the system. Hence, we would only expect a difference at the low $\sigma$ end ($\sigma < 75 \text{ km s}^{-1}$) owing to the ezw model adopting steeper outflow scaling ($\eta \propto \sigma^{-2}$) at that range. For massive galaxies, we will use the comparison between the two models to distinguish the effect of the star formation quenching prescription, which only operates at high $\sigma$ where the two models have the same mass loading factor $\eta$ dependency.

Our analysis will only consider galaxies constituted with at least 64 star particles having a respective stellar mass of $1.45 \times 10^8 \text{ M}_\odot$. With this limit, the simulation produces 3,732 galaxies, among which 2,607 and 1,125 are central and satellite, respectively. In these simulations, a central galaxy is referred to be the most massive galaxy in a group or cluster, and the others are all satellites. At the low masses, it was shown in Davé et al. (2013) that galaxies are most H I rich, with gas content at least as much as their stellar mass. Given that a gas particle can spawn 2 star particles, our stellar mass limit corresponds to the mass of 32 gas particles, which should be substantial enough to resolve environmental processes. Spatially, even our smallest galaxies have a typical H I-weighted radius of $\sim 10 \text{ kpc}$, well above our spatial resolution which is given by the smoothing length $\epsilon = 1.25h^{-1}\text{kpc}$. For these reasons, we are confident that this simulation will be able to resolve the environmentally-driven phenomena we are concerned about in the rest of the work such as stripping, which mainly happens in the outskirts of the galaxies.
2.2 Computing the H\textsubscript{1} content

The galaxies are identified using Spline Kernel Interpolative Denmax* (SKID), as bound collections of stars and star-forming gas. SKID can be summarised by the following steps. The densities of the gas particles are calculated, and then only those above a minimum density corresponding to star-forming gas are kept. Additionally, those particles are separated depending on their temperature, and only the cold gas is taken into consideration. The remaining particles are “moved” following the initial density gradient, until they reach a potential well where they remain. Then, a friends-of-friends technique is used to group the particles. Finally, particles unbound to the group owing to high velocities are removed. The unbinding procedure is done by looking back at the initial position of the particles and checking whether the particles are bound or not. The unbinding process requires few basic steps. First, the potential energies of the particles in a given group are all calculated with additional contribution from their environment (neighbor particles). Second, SKID looks for the center of mass and center of mass velocity after which the least bound particle can be deduced. If the least bound particle is bound to the group, the unbinding procedure is finished, but if it is not, SKID takes it away from the group and looks for the center of mass and center of mass velocity again, until convergence. We associate each galaxy with a halo identified using a spherical overdensity algorithm, as described in e.g. Kereš et al. (2005). The coordinates of the galaxies and the halos are matched and the galaxy is attributed to the halo when it is located within the virial radius of the halo. As already mentioned, the central galaxy is taken to be the most massive galaxy in the halo, while all others are satellites. While SKID adequately captures the stellar and molecular mass, significant amounts of H\textsubscript{1} can be present outside of star-forming gas.

We compute the H\textsubscript{1} content of simulated galaxies following the methodology described in full detail in Davé et al. (2013); we review the main points here as well as modifications to the previous modeling. First, we associate all particles within a sphere of a radius given by the outermost particle in the SKID galaxy, and associate all H\textsubscript{1} to that galaxy. For close pairs of galaxies, the particles associated with 2 or more galaxies are attributed to the galaxy to which they are more bound gravitationally. Then for each gas particle, we calculate the neutral fraction based on the assumption that the given particle is a sphere with a kernel density profile given by the SPH kernel, and it is bathed in radiation from the metagalactic radiation field given by Haardt & Madau (2001). We

*http://www-hpcc.astro.washington.edu/tools/skid.html
then integrate the column density inwards from the particle surface until it reaches a threshold column density where the particle becomes sufficiently neutral. The mass fraction within this radius is then considered to be 90% neutral (since some mass in the outskirts of galaxies remains ionised), while the mass outside this radius has the optically-thin ionisation fraction. We refer to this as the “auto-shielding” approximation, and in Davé et al. (2013) they showed that it yields good agreement with full radiative transfer simulations of Faucher-Giguère et al. (2010).

Compared to Davé et al. (2013), we have changed the column density threshold within which we consider the gas to be fully neutral in the auto-shielding calculation. Davé et al. (2013) utilised $N_{\text{HI}} = 10^{17.2}$ cm$^{-2}$ which corresponds to an optical depth of unity to ionizing radiation. However, given that the ionisation level of optically-thin gas bathed in metagalactic flux is much smaller than unity, typically $10^{-5} - 10^{-6}$ (e.g. Davé et al. 2010), an optical depth of unity will still not produce a substantial $\text{H}i$ fraction. Instead, we need an optical depth that will result in an $\text{H}i$ fraction of 0.5. The choice of this value is somewhat arbitrary, but the idea is only to make the region inside this region be $\text{H}i$-dominated. If we assume that the ambient gas has an ionisation fraction of $10^{-5}$, we require that the optical depth be 10.8 instead of unity. The resulting column density threshold thus rises from $1.6 \times 10^{17}$ cm$^{-2}$ to $1.7 \times 10^{18}$ cm$^{-2}$. We therefore use this latter column density threshold to calculate the radius within which the gas is assumed to be fully neutral. In §3.1 we will compare our results to that using the old threshold value. If such a radius does not exist (typically for particles with density $n \lesssim 10^{-2}$ cm$^{-3}$), then the particle is fully optically thin and its ionisation fraction is calculated assuming ionisation balance with the metagalactic flux.

Next, we must also determine how much of this shielded gas is molecular. For this, we employ the $\text{H}_2$ formation model of Krumholz & Gnedin (2011), which we compute for each particle. They solve the radiative transfer coupled with the formation and dissociation balance of the molecular hydrogen in a steady state of a molecular cloud. The resulting $\text{H}_2$ fraction is given by

$$f_{\text{H}_2} \simeq 1 - \left(\frac{3}{4}\right) \frac{s}{1 + 0.25 \times s}$$

(2.4)

where $s$ is a term dependent on the formation rate of the molecular hydrogen from dust grains (which depends on metallicity), the dust cross section per H nucleus and the ambient intensity of the ultra-violet radiation field. Note that in Davé et al. (2013) the default model was the observationally-constrained pressure law of Leroy et al. (2008). We use Krumholz & Gnedin (2011) here because we want to study the
2.3 Tracking progenitors

In this work, we will be interested in tracking the evolution of H\textsc{i} in individual galaxies back in cosmic time. We do this by associating a given galaxy at \( z = 0 \) to its most massive progenitor at all of our previous 134 snapshots back to \( z = 30 \). We define the most massive progenitor as the galaxy at an earlier snapshot containing the largest number of star particles in common with the galaxy at \( z = 0 \). We apply this to the SKID galaxies and, therefore, obtain for each galaxy a progenitor history back to the redshift where it first appeared considerably sizeable. The number of particles for a group is chosen to be the resolution limit, to make sure every resolved galaxy with more than 64 stars or \( M_* \geq 1.45 \times 10^8 \, M_\odot \) is included. We note that this choice does not affect the progenitor history of every galaxy.

From this, we can identify mergers by a simple prescription, following Gabor \& Davé (2012). Mergers can be either major or minor depending on the difference of mass between the two colliding galaxies. The merger is major when both galaxies are of about the same mass, otherwise it is minor. The merger can then be distinguished by the mass ratio \( r \) of the two merging galaxies. For an assumed major merger ratio \( r \), we search the stellar mass growth history for jumps in excess of \( 1/(1 + r) \). The minimum value of \( r \) at which continual infall and merger can be distinguished depends on the redshift and timestep between 2 successive snapshots, but it is generally quite far below a value of 1 : 3 (the minimum ratio we used in our analysis), that is our outputs are frequent enough (every 100 – 300 Myr) such that no galaxy would ever grow by 33% just from \textit{in situ} star formation between snapshots. However, there are occasionally complications with this approach. First, a star particle might, at a given snapshot, be attributed to no group. Second, two groups brought close along their path (without merging) would be regarded as one group by SKID, but would later “unmerge”. For the first problem, we examine back in time until the star belongs to
a galaxy, and then attribute that star to the descendent of that galaxy. To address the second problem, we check which galaxies at the previous snapshot are composed of two separate galaxies. We track those merging units until every star in both galaxies is assigned to a single galaxy. From then on, we assign the stars located in the smaller group to that single galaxy. We have found that this robustly identifies merger events despite the dynamical nature of the merger encounter.
Chapter 3

HI and environment at $z=0$

3.1 HI mass function

The most basic statistical property of HI galaxies is the HI mass function (HIMF). Davé et al. (2013) showed that the simulation we use here, together with their prescription to compute the HI content, yields an HI mass function that is in good agreement with observations down to the lowest resolvable masses ($\sim 10^8 M_\odot$). This is a non-trivial success that has been difficult to achieve in simulations. Recent SAMs (e.g. Obreschkow et al. 2009) have done better but still show an excess at $M_{\rm HI} \sim 10^9 M_\odot$. In this section we test our HIMF in more detail, in particular separating it into bins of stellar mass to compare with recent data from Lemonias et al. (2013).

Figure 3.1 shows the HIMF for our resolved simulated galaxies (blue line), down to our adopted galaxy resolution limit of $M_{\rm HI} = 1.4 \times 10^8 M_\odot$ (vertical dashed line) at redshift $z = 0$. Since our $N_{\rm HI}$ self-shielding threshold is altered from that assumed in Davé et al. (2013), we compare our HIMF (blue line) to theirs shown as the green line. Overall, this change is consistent with a $\sim 30\%$ shift towards lower $M_{\rm HI}$ (i.e. leftwards) versus the Davé et al. (2013) HIMF, since it results in a lower fraction of each gas particle being neutral. Consequently, this produces a larger change in amplitude at the high-mass end. The new HIMF is in better agreement with the observed HIMF from the ALFALFA survey (dashed line; Haynes et al. 2011). As mentioned in the caption of figure 3.1, the error bars show the cosmic variance in each $M_{\rm HI}$ bin. To compute this, I divided the simulation box into eight octants and compute the HIMF for each octant; the width of the error bars is then given by the scatter of these eight HIMFs.

We now break out our HIMF in bins of 0.5 dex in stellar mass $M_*$, shown as the coloured lines from $M_* = 10^8 M_\odot - 10^{12} M_\odot$. This shows how the HIMF is comprised
Figure 3.1: H\textsc{i} mass distribution at z=0 for the population of galaxies generated by the simulation described in section 2. \textit{Left panel:} We show our total HIMF as the blue line, the simulated HIMF of Davé et al. (2013) as the green line, and the HIMF of galaxies from the ALFALFA H\textsc{i} survey as the black dashed line. Contributions to our simulated HIMF from bins of 0.5 dex in stellar mass are indicated by the colored lines from black to yellow for the mass range $M_*=10^8 - 10^{12} M_\odot$ (the highest mass bin corresponds to $11 < \log_{10}(M_*) < 12$ due to the small number of galaxies in this mass range). \textit{Right panel:} Comparison between our simulated galaxy HIMF (red lines; error bars indicate the cosmic variance in each $M_{HI}$ bin) and the observational data of Lemonias et al. (2013) (green diamonds) for three different bins in stellar mass.
of galaxies of different masses. Since $M_{\text{HI}}$ correlates with $M_*$, there is a general trend that the HIMF shifts towards higher $M_{\text{HI}}$ at higher $M_*$. There is also a slight trend for an increased width of the HIMF as one moves towards higher $M_*$, reflective of the fact that low-$M_*$ galaxies have more uniformly high H$\text{I}$ richness, while more massive galaxies can have a wider range of H$\text{I}$ content. To quantify this wider range in $M_{\text{HI}}$ at higher $M_*$, we perform Gaussian fits to the HIMF for each stellar mass bin, shown in Figure 3.2 as the solid lines of different colors. We compute the mass range $\Delta \log M_{\text{HI}}$ centered at the mean value of the Gaussian fit that encloses 90% of the galaxies in each $M_*$ bin, which is indicated as the “w90” value in Figure 3.2 for each case. This steadily increases from 0.96 dex at the lowest $M_*$ bin to 1.76 dex at the highest $M_*$ bin, roughly following the relation $\Delta \log M_{\text{HI}} = \frac{1}{6} (\log M_*) - \frac{1}{3}$.

If there was perfect correlation between $M_{\text{HI}}$ and $M_*$, then the HIMFs broken out by $M_*$ would have no overlap. Hence the fact that the HIMF spreads over a larger range than the bin size in $M_{\text{HI}}$ is a measure of the scatter between $M_*$ and $M_{\text{HI}}$. This scatter is a key indicator of how the H$\text{I}$ content of galaxies varies with environmental influences. For instance, Moran et al. (2012) showed that galaxies with enhanced total $M_{\text{HI}}$ tend to have the excess H$\text{I}$ in their outskirts, accompanied by a metallicity drop, indicative of recent accretion. In such a context, the spread between $M_{\text{HI}}$ and $M_*$ tracks the frequency and amount of recent accretion (or lack thereof) that gives rise to variations in H$\text{I}$ without accompanying immediate variations in $M_*$. To test this aspect of our simulations, we can compare our results to the data from the GASS survey separated into stellar mass bins by Lemonias et al. (2013). The GASS survey is stellar mass-selected down to $M_* \approx 10^{10} M_\odot$, and hence provides a fair comparison to our stellar mass-selected simulated galaxy sample, at least down to their completeness limit.

The right panels of Figure 3.1 show the comparison to the data from Lemonias.
Figure 3.3: H\(i\) richness \(M_{\text{HI}}/M_*\) vs. \(M_*\) for our resolved sample of simulated galaxies at \(z=0\). Centrals are shown in red, satellites in blue, and data from GASS DR3 (Catinella et al. 2013) is shown as the stars. ALFALFA data are presented in black squares. Lines show the median fit, and points plotted at \(\log(M_{\text{HI}}/M_*) \approx 10^{-3}\), with some scatter for visibility, are galaxies with very small or no amount of \(\text{H}i\). The bottom panel shows the scatter in the \(\text{H}i\) richness about the mean value for the central galaxies.

et al. (2013), shown as the green points, in three bins of 0.25 dex in \(M_*\). In the two lower \(M_*\) bins, there is very good agreement between the simulations and the data. Owing to our small simulation volume, our galaxy population does not extend up to the largest \(M_{\text{HI}}\) galaxies. In the most massive \(M_*\) bin, the simulations are suggestive of an excess of low-\(M_{\text{HI}}\) galaxies. These galaxies are near the threshold where our quenching model begins to take effect, and may suggest that our quenching prescription requires refining. Given the ad hoc nature of our quenching prescription, it is not surprising that we do not match this data (it was tuned only to match the stellar mass function), but this comparison highlights that the \(\text{H}i\) content of massive galaxies provides quantitative constraints on how quenching from AGN or any other putative physical process must remove not just star-forming gas, but also \(\text{H}i\) (Lagos et al. 2014).

This comparison suggests that our simulations are generally reproducing the scatter in the relationship between \(M_{\text{HI}}\) and \(M_*\), at least down to \(M_* \approx 10^{10} M_\odot\). To
quantify this further, we show in Figure 3.3 the trend of H\textsc{i} richness ($M_{\text{HI}}/M_*$) as a function of $M_*$. We subdivide it by centrals (red) and satellites (blue), which we will discuss further in §3.2. This is identical to Figure 4 in Davé et al. (2013), except that we are now employing our new $N_{\text{HI}}$ self-shielding limit as described in §2.2. Furthermore, in the lower panel we now show the 1σ scatter around the median value for the central galaxies. We do not show the satellites’ scatter, as it is a sub-dominant contribution to the total at higher masses, and at low masses the distribution is poorly represented by a Gaussian. This shows explicitly that the scatter in H\textsc{i} richness increases to higher masses, similar to what was seen when breaking the HIMF into $M_*$ bins.

To compare, the simulations show very good agreement with the GASS data from their third data release (Catinella et al. 2013). We also show the results from the ALFALFA survey (black squares). These values are higher even in the region overlapping with GASS since this survey is H\textsc{i}-selected and hence picks out higher-$M_{\text{HI}}$ galaxies at any given mass. To compare to ALFALFA we would have to mimic the volume and selection function of that survey, which we leave for future work*. Hence, while the ALFALFA HIMF is appropriate to compare to our models (under the reasonable assumption that ALFALFA has appropriately accounted for its selection volume), the H\textsc{i} richness from that survey is biased high (Catinella et al. 2010).

For clarification to the readers, figure 3.4 is shown to give more insight on the galaxy distribution. The left panel presents the distribution of the sample in terms of H\textsc{i} mass separated into central (red) and satellite galaxies (blue), the central panel shows the distribution in terms of stellar mass and the right panel the distribution in terms of the H\textsc{i} richness.

In summary, our simulated HIMF agrees very well with ALFALFA observations, particularly with our more physically-motivated criterion for the column density where auto-self-shielding becomes important. Binning the HIMF into $M_*$ bins, for non-quenched galaxies, our simulation agrees well with observations from the GASS survey, suggesting that the scatter in $M_{\text{HI}}$ versus $M_*$ also agrees with observations. For quenched galaxies (or galaxies on the verge of quenching), we likely require a more sophisticated quenching prescription to match the data at the low-$M_{\text{HI}}$ end, and this will provide a new and interesting constraint to test our ongoing improvements to our quenching model (e.g. Gabor & Davé 2014). The general agreement in the scatter between $M_{\text{HI}}$ and $M_*$ is interesting and a first for cosmologically-based H\textsc{i}

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*We note that this has caused some confusion in the literature. For instance the Illustris simulation (Vogelsberger et al. 2014) agrees well with the ALFALFA H\textsc{i} richness data, but this is using all their galaxies without mimicking the ALFALFA selection.
Figure 3.4: Histograms showing the distribution of the full sample of simulated galaxies in terms of H\textsc{i} mass (left panel), stellar mass (middle panel), H\textsc{i} richness (right panel). The galaxies with $\log(M_{H\textsc{i}}/M_\ast) < -3$ are clamped at $\log(M_{H\textsc{i}}/M_\ast) = -3$. As already mentioned before, the choice of “-3” is not based on any physics except that a galaxy with $M_{H\textsc{i}} < 10^3 M_\ast$ can be considered as H\textsc{i} poor galaxy. It is for this reason that we see a peak at -3 in the right panel.

3.2 Satellite galaxies

Once a galaxy falls into another galaxy’s halo, a number of physical processes can act to remove or deplete its gas. These include tidal stripping, ram pressure stripping (e.g. Gunn & Gott 1972, van Gorkom et al. 2003), viscous stripping (e.g. Marcolini et al. 2003), induced star formation from encounters with other galaxies (harrassment; Moore et al. 1996), and strangulation (or starvation) of inflow to sustain star formation. Hence the behaviour of satellites within a halo is expected to differ from that of the central galaxy. These various physical processes are expected to leave different signatures on the H\textsc{i} content, based on how much ambient gas is within the central galaxy’s halo. For instance, tidal stripping is independent of the halo gas, being driven primarily by encounters with other galaxies. Ram pressure stripping scales as $\propto \rho v^2$, where $\rho$ is the ambient gas density and $v$ is the relative velocity of the satellite, and hence is effective in high velocity dispersion halos with significant halo gas. Induced star formation relies on the presence of other satellites to stimulate a starburst. Starvation often relies on the presence of a hot gaseous halo that is unable to cool sufficiently quickly onto a galaxy. The H\textsc{i} gas, generally being more loosely bound and hence more easily susceptible to stripping and heating than
the molecular gas and stars, provides a unique and interesting testbed to study the importance of these environmental processes over a wide range of halo masses. In this section we focus on the properties of centrals and satellites as a function of halo mass.

Figure 3.5 shows the $\text{H}_i$ mass (upper panel) and $\text{H}_i$ richness (lower panel) as a function of halo mass for galaxies in our simulations. Central galaxies are shown in red, while satellites are in blue. In the bottom of both panels, points are galaxies that have very low amount of $\text{H}_i$. The choice of $2 \times 10^6 \text{ M}_\odot$ and $2 \times 10^{-4}$, for upper and lower panels respectively, are arbitrary: our sample of galaxies are clipped at these values for convenience and does not affect in anyway the trend of the medians (those galaxies are included in the calculation of the medians). We also add a little scatter around these values to show the density of galaxies having such low amount of $\text{H}_i$ and $\text{H}_i$ richness respectively. The magenta and blue lines show the running median values for centrals and satellites. Histograms on upper panel show the distribution of all resolved galaxies and histograms on the bottom panel indicate the projected distribution of galaxies with $M_{\text{halo}} > 10^{12} \text{ M}_\odot$. The amplitudes of the histograms in each panel are arbitrary, as these are purely for comparing the abundance of centrals versus satellites.

The top panel shows that the $\text{H}_i$ mass of centrals increases steadily with halo mass, though there is marked transition at $M_{\text{halo}} \gtrsim 10^{12} \text{ M}_\odot$ above which the relationship is less steep. This trend mimics the drop in sSFR around this halo mass (e.g. Davé et al. 2011b), which arises owing to a combination of the increased presence of a hot gaseous halo along with quenching feedback. Meanwhile, the $\text{H}_i$ mass in satellites is roughly independent of halo mass, rising with centrals at low masses but plateauing in more massive halos. The histogram along the bottom shows that satellites strongly increase in relative abundance at larger halo masses, as expected from halo occupation distribution statistics (e.g. Berlind et al. 2003).

For $\text{H}_i$ richness (bottom panel), the centrals and satellites at a given halo mass track each other quite well at low masses, with the satellites having slightly higher $\text{H}_i$ richness owing to their typically lower $M_\star$. Hence at $M_{\text{halo}} \lesssim 10^{12} \text{ M}_\odot$, it seems that satellites’ $\text{H}_i$ content is essentially unaffected by being within the halo of another larger galaxy.

The situation is dramatically different for $M_{\text{halo}} \gtrsim 10^{12} \text{ M}_\odot$. Here, the median satellites $\text{H}_i$ richness drops dramatically, and even though their masses are lower (and hence by the overall correlation should have higher $\text{H}_i$ richness), their $\text{H}_i$ richness is significantly below that of centrals. Looking more closely, this drop is driven by a rapidly growing population of satellites with essentially no $\text{H}_i$, whereas the satellites
Figure 3.5: H\textsc{i} mass (top) and H\textsc{i} richness (bottom) of simulated galaxies as a function of halo mass at z=0. Centrals are shown in red, satellites in blue, and the magenta and blue lines correspond to their running median values. Histograms in the upper panel show the distribution of halo masses for all resolved central (red) and satellite (blue) galaxies. Histograms in the lower panel show the distribution of H\textsc{i} richness for centrals (red) and satellites (blue) with $M_{\text{halo}} > 10^{12} \, M_\odot$. The galaxies seen at the bottom of each panel are galaxies with $M_{\text{HI}} \leq 2 \times 10^6 \, M_\odot$ (upper) and $M_{\text{HI}}/M_\ast \leq 2 \times 10^{-4}$ (lower). Scatter is added around these values to better show the number of galaxies at these low values.
3.2 Satellite galaxies

Figure 3.6: H\textsc{i} richness of satellite galaxies with respect to their stellar mass at $z=0$. The galaxies are color coded by their respective halo mass as shown in the figure. The lines represent the median values for each halo mass bin. The dots at the bottom of the figure are H\textsc{i} deficient galaxies.

that have H\textsc{i} tend to lie slightly above the centrals following the trend at lower halo masses. The blue histogram along the right axis shows this bimodality for galaxies with $M_{\text{halo}} > 10^{12} \, M_{\odot}$. The strong bimodality, analogously to that in a galaxy color-magnitude diagram, indicates that the H\textsc{i} in satellites is fairly rapidly removed once it enters into a massive halo.

We also present in Figure 3.6 the relation between H\textsc{i} richness and stellar mass of satellite galaxies with different halo mass bins differentiated by the colors: purple for $\log M_{\text{halo}} \sim 11$ and red for $\log M_{\text{halo}} \sim 14$. From the figure, we can see that starting from a certain range of halo mass, mainly $M_{\text{halo}} \sim 10^{12} \, M_{\odot}$ (as mentioned before), there is a clear evidence of the growing population of gas poor satellite galaxies. The H\textsc{i} poor satellite galaxies (shown by the dots in the bottom panel) are dominated by those located in more massive halos. Small satellites (low stellar mass) get their gas content easily stripped leading to the higher number of galaxies at the lower stellar mass end in the highest halo mass bins. Currently, observations are not capable of attaining such high sensitivities (and therefore of reaching low enough $M_{\text{HI}}$) in HI detection. For instance in Cortese et al. (2011), their gas fraction deduced from galaxies in the Virgo cluster is far higher than our simulated galaxies in the range of low stellar mass.

The often noted emergence of a hot gaseous halo around that mass scale (e.g. Kere\v{s} et al. 2005, Gabor & Davé 2012) hints at a connection between the presence
of a hot halo and the removal of H\textsubscript{i}, which favours a removal mechanism associated with gas stripping. However, there are also many more satellite galaxies in such massive halos that could tidally strip or harass satellites, so the connection is not completely certain. Nonetheless, as shown in Cunnama et al. (2014) from hydrodynamic simulations, H\textsubscript{i}-poor satellites generally feel a ram pressure force sufficient to remove its gas whereas H\textsubscript{i}-rich ones do not. This suggests a strong link between ram pressure stripping and satellite H\textsubscript{i} removal, which our results corroborate from a different perspective.

There are emerging observations of the relationships between H\textsubscript{i} content in centrals and satellites as a function of halo mass. In particular, Catinella et al. (2013) combined data from GASS with the Yang et al. (2007) SDSS halo catalog to separate their galaxies into satellites and centrals. In Figure 3.7, we compare $M_{\text{HI}}/M_*$ vs $M_{\text{halo}}$ for centrals and satellites to this data. To make a fairer comparison to the data, we restrict our sample to $M_* > 10^{10} M_\odot$ galaxies. In their sample, galaxies with $\log M_* \leq 10.5$ the H\textsubscript{i} mass has a fixed lower limit value of $\log M_{\text{HI}} = 8.7$ whereas for more massive galaxies, the H\textsubscript{i} limit is derived from $\log(M_{\text{HI}}/M_*) = -1.8$; we clipped our simulated values according to those limits and added a little random scatter of $\sim 0.3$. The red points are the central and the blue points the satellite galaxies from the simulation, whereas the magenta and the cyan crosses are respectively the central and the satellite galaxies from the observations. The black lines show the median value for all the simulated galaxies (central & satellite combined), while the stars show the medians of all the observational data with the grey error bars showing the 1\sigma spread of only the H\textsubscript{i} detected galaxies; this is dominated by the centrals at low masses and satellites at high masses.

The simulation is quite consistent with the observation across all halo masses, which suggests that the simulation properly tracks the H\textsubscript{i} richness in satellites in massive halos. This is a nontrivial success, as stripping processes in satellite evolution have generally been a difficulty for models, particularly for SAMs (e.g. Weimann et al. 2010). Nonetheless, there are some small discrepancies which may prove interesting. In the lower panel, we notice that the H\textsubscript{i} richness predicted in the simulation is somewhat above observations for halo masses around $M_{\text{halo}} \sim 10^{13} M_\odot$, being the same at the lowest halo mass range; the model is nonetheless consistent with the data. The decrease in gas fraction from the simulation seems to be lower than that from the observational data. In that range, the observational data show a constant H\textsubscript{i} richness regardless of the halo mass, driven by more numerous H\textsubscript{i} undetected galaxies in the GASS sample, while that of the simulations decreases with halo mass due to the growing population of H\textsubscript{i} poor galaxies (especially beyond $M_{\text{HI}} = 10^{12} M_\odot$).
3.2 Satellite galaxies

Figure 3.7: Comparison of simulated galaxies and GASS observations from Catinella et al. (2013) for galaxies with $M_* > 10^{10} M_\odot$. We show the H\textsc{i} mass (top) and H\textsc{i} richness (bottom) as a function of halo mass. Red points are central galaxies and blue points are satellites from the simulation. Magenta and cyan crosses correspond to centrals and satellites from the GASS data, respectively. Black solid lines are running medians for simulated galaxies while the stars show median values for the GASS data (grey error bars show the 1\sigma spread for the H\textsc{i} detected galaxies only). The dashed black lines are running medians for simulated galaxies using a model without quenching. Downward arrows indicate H\textsc{i} non-detected galaxies in the GASS data.
as explained in §3.2 and also shown in Figure 3.5. This may owe to the fact that this comparison is still approximate since we have not precisely matched the GASS selection, but if real, it may suggest that the predicted satellite H\textsc{i} content in this crucial poor group mass range is slightly discrepant with the data. At lower and higher halo masses, the simulation agrees very well with the observations.

The “vzw” model (dashed lines) is slightly lower than our model for both gas content and H\textsc{i} richness. This is consistent with the results from Dav\'e et al. (2013), who found that stronger outflows at low masses assumed in ezw yield greater H\textsc{i} in galaxies. In this case, the selection criterion (\(M_{\text{halo}} \gtrsim 10^{12} M_\odot\)) emphasizes galaxies that are mostly susceptible to be quenched. Despite the quenching in ezw, the H\textsc{i} content in this model is higher than in vzw, which likely comes from the lower mass loading factors in vzw at low masses that simply gets propagated to higher masses. Hence our quenching prescription does not seem to have a strong effect on the H\textsc{i} content of high-mass galaxies. Coincidentally, the vzw model actually matches this data somewhat better, though we will show later it does significantly worse in comparisons with environmental measures.

In summary, the halo mass is a strong determinant for the H\textsc{i} content of its galaxies. In \(M_{\text{halo}} \lesssim 10^{12} M_\odot\) halos, the H\textsc{i} mass in centrals rises with halo mass while the H\textsc{i} richness drops, and the H\textsc{i} richness of satellite galaxies is essentially unaffected by living within another halo. In more massive halos, the H\textsc{i} mass of centrals continues to rise but more slowly, and the median H\textsc{i} richness in satellites drops dramatically, driven by the bimodal appearance of substantial numbers of H\textsc{i}-poor satellites. This trend is likely driven primarily by gas stripping, as we discuss further below; our ad hoc quenching model has little impact on this. The predicted H\textsc{i} content of satellites in massive halos is in good agreement with observations when matching the data selection, which is a non-trivial success.

### 3.3 Timescales for H\textsc{i} loss in satellites

The bimodality of H\textsc{i} richness in satellites of high-mass halos indicates a fairly rapid loss of H\textsc{i} once a satellite falls into a \(M_{\text{halo}} \gtrsim 10^{12} M_\odot\) halo. In this section we trace galaxies back in time to determine the evolution of its H\textsc{i} once a galaxy becomes a satellite, in order to quantify the timescales for H\textsc{i} removal.

In Figure 3.8, we show the evolution of H\textsc{i} richness of satellite galaxies that fall into another halo. For each satellite, we define \(t = 0\) as the last snapshot that it is identified as a central galaxy, i.e. if a satellite galaxy “backsplashes” to become a central again, we do not include it here. Then, in later snapshots, we
3.3 Timescales for H\textsubscript{i} loss in satellites

Figure 3.8: Evolution of H\textsubscript{i} richness and sSFR for satellite galaxies after falling into halos with masses $10^{11} M_\odot \leq M_{\text{halo}} < 10^{12} M_\odot$ (red with circles), $10^{12} M_\odot \leq M_{\text{halo}} < 10^{13} M_\odot$ (green with squares) and $M_{\text{halo}} \geq 10^{13} M_\odot$ (blue with downward triangles). Thick solid lines show median values for the H\textsubscript{i} richness relative to the value at $t = 0$, defined for each galaxy as the time when it becomes a satellite (left axis). The green shaded area represents the 1σ dispersion for $10^{12} M_\odot \leq M_{\text{halo}} < 10^{13} M_\odot$. Dashed lines (with the colors and markers corresponding to the halo mass bins) correspond to median values for the sSFR relative to the value at $t = 0$ (right axis). The yellow line represents the H\textsubscript{i} richness fraction of central galaxies which have never been satellite (with $t = 0$ the time when their host halo mass is $\sim 10^{12} M_\odot$). This is used as a reference. Satellites take less time in large halos to remove their gas.
compute the $\text{H} \, \text{i}$ richness relative to the $\text{H} \, \text{i}$ richness at $t = 0$. We do this for three different halo mass bins $10^{11} \, M_\odot \leq M_{\text{halo}} < 10^{12} \, M_\odot$, $10^{12} \, M_\odot \leq M_{\text{halo}} < 10^{13} \, M_\odot$ and $10^{13} \, M_\odot \leq M_{\text{halo}}$, where the halo masses are those at the time of infall. The median $\text{H} \, \text{i}$ richness as a function of time is indicated by the red (with circles), green (with squares), and blue (with triangles) lines, respectively. The green shaded region represents the $1\sigma$ enclosed variation around the median for the $10^{12} \, M_\odot \leq M_{\text{halo}} < 10^{13} \, M_\odot$ case; the others are similar. And the yellow line, used as reference, shows the $\text{H} \, \text{i}$ richness fraction of central galaxies which have never been satellite, where $t = 0$ is the time when the galaxy has host halo mass of $\sim 10^{12} \, M_\odot$.

Satellite galaxies in large halos take less time to have their $\text{H} \, \text{i}$ removed than lower halo mass galaxies. There is only a small difference between $10^{11} \, M_\odot \leq M_{\text{halo}} < 10^{12} \, M_\odot$, $10^{12} \, M_\odot \leq M_{\text{halo}} < 10^{13} \, M_\odot$ halos, having a timescale of $> 1$ Gyr to be lowered to half of their initial $\text{H} \, \text{i}$ richness, while for $M_{\text{halo}} \geq 10^{13} \, M_\odot$ halos the timescale is significantly less than a Gyr. Hence gas removal begins quite rapidly, often in less than a single halo dynamical time, but nonetheless full stripping of $\text{H} \, \text{i}$ (e.g. less than 10% of initial $\text{H} \, \text{i}$ left) does not occur until several Gyr. Indeed, in the lowest mass bin, even after 5 Gyr the $\text{H} \, \text{i}$ is still typically $> 10$% of the initial value. Note that the scatter about the median (1$\sigma$ uncertainty; green shaded region) is quite large, so that the typical time to lose half the $\text{H} \, \text{i}$ at $1\sigma$ above the median is $> 3$ Gyr instead of $\sim 1.5$ Gyr. Hence at least some satellites continue to retain significant $\text{H} \, \text{i}$ for many Gyr even in high mass halos. We note that some SAMs have adopted the prescription that gas is fully stripped immediately or within a halo dynamical time when it enters into a massive halo (e.g. De Lucia et al. 2012), but this is an oversimplification that is unlikely to be correct even in the median case. Finally, it is important to recall from Figure 3.5 that the distribution of $\text{H} \, \text{i}$ richnesses in satellites is bimodal, meaning that the median evolution more broadly tracks the fraction of satellites that are having their $\text{H} \, \text{i}$ stripped, rather the evolution of any individual satellite. Hence the timescales here should be viewed as the typical timescale after infall at which $\text{H} \, \text{i}$ is stripped, but the stripping itself happens quite rapidly.

Since the decay is roughly log-linear, we can fit an exponential decay timescale for the $\text{H} \, \text{i}$ richness of the form $R_{\text{HI}} = e^{-t/\tau}$, where $R_{\text{HI}}$ is the ratio of $M_{\text{HI}}/M_\star$ relative to that at $t = 0$. For the $\text{H} \, \text{i}$ richness, the $e$-folding decay timescales are 2.63, 2.01, 0.70 Gyr for the $10^{11} \, M_\odot \leq M_{\text{halo}} < 10^{12} \, M_\odot$, $10^{12} \, M_\odot \leq M_{\text{halo}} < 10^{13} \, M_\odot$ and $10^{13} \, M_\odot \leq M_{\text{halo}}$.

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1 The dynamical time for an virialized isothermal halo is $\pi(1+z)^{1.5}$ Gyr, independent of halo mass, which is a reasonable approximation for real halos.

1 this is partly due to the fact that those galaxies are of different masses and they become satellite at different $z$.
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10^{13} \, M_\odot \text{ and } 10^{13} \, M_\odot \leq M_\text{halo} \text{ bins, respectively, thus quantifying the more rapid H\textsubscript{i} loss in massive halos. In low mass halos, the timescales are comparable to the halo dynamical time, indicating that gradual processes such as starvation are the drivers, while in more massive halos it is much shorter than a halo dynamical time, suggesting a more efficient and local process. When taking a fix stellar mass range } 10^9 \, M_\odot \leq M_* \leq 10^{10} \, M_\odot, \text{ chosen to ensure that there are still many galaxies at the infall time above the resolution limit) the e-folding H\textsubscript{i} richness decay timescales become } 2.88, 1.84, 0.26 \text{ Gyr for the } 10^{11} \, M_\odot \leq M_\text{halo} < 10^{12} \, M_\odot, 10^{12} \, M_\odot \leq M_\text{halo} < 10^{13} \, M_\odot \text{ and } 10^{13} \, M_\odot \leq M_\text{halo} \text{ bins. Particularly for small satellite galaxies in massive halos, it takes an extremely small time for their H\textsubscript{i} to be stripped.}

To better understand the physical origin of the decline in H\textsubscript{i}, we can compare the decay in H\textsubscript{i} richness to that of the star formation rate. If the decline in H\textsubscript{i} is much faster than the decline in SFR, then this indicates preferential removal of H\textsubscript{i} relative to star-forming (molecular) gas, suggesting stripping. If the decline rates are comparable, then this can be most simply interpreted as starvation. In the absence of environmental effects, galaxies are in a steady state of accretion versus consumption (e.g. Dekel et al. 2009, Davé et al. 2012, Lilly et al. 2013). But if the accretion is truncated owing to environmental effects, leading to starvation, then as the H\textsubscript{i} runs out, the molecular gas will deplete, and hence the SFR will commensurately drop.

In Figure 3.8, the dashed-crossed lines analogously show the evolution of the specific SFR (\( \equiv \text{SFR}/M_* \)) in satellites once they fall into halos. For the lower mass halos, the timescale for sSFR decay is virtually identical to that of H\textsubscript{i} richness decay. This indicates that these galaxies are simply consuming their gas and it is not being replenished, resulting in a coincident drop in gas and SFR. Hence in } M_\text{halo} \lesssim 10^{12} M_\odot \text{ halos, starvation appears to be the key mechanism for H\textsubscript{i} attenuation, which occurs because the streams that feed low-mass halos generally feed the central galaxy rather than satellites. Wetzel et al. (2013) examined the decline in satellite SFR in (generally) higher mass halos, and also found that the timescale for SFR truncation is long, typically 2\text{~}4 \text{ Gyr. They also argued for a “delayed-then-rapid” decrease in sSFR, such that after infall, the sSFR remains mostly unchanged for this time after which it drops rapidly within a dynamical time } \ll 1 \text{ Gyr. In fact, this scenario is highly reminiscent of what our models predict for the H\textsubscript{i} content.}

For high mass halos, in contrast, the H\textsubscript{i} attenuates much more quickly than the sSFR. The post-infall evolution of sSFR is essentially independent of halo mass, indicating that the denser gas and galaxy environment around larger mass halos do not markedly affect gas consumption from an existing star-forming gas reservoir. The more rapid drop in H\textsubscript{i} suggests that ram pressure stripping is at work, since
this should affect the loosely-bound H\textsuperscript{i} much more than the dense star-forming gas. Hence the onset of a hot gaseous halo, even in fairly poor groups with $M_{\text{halo}} > 10^{13}M_\odot$, is already sufficiently to produce substantial ram pressure stripping (Cun-nama et al. 2014) of infalling H\textsuperscript{i}. Nonetheless, the SFR drop is mostly unaffected by ram pressure stripping, and remains consistent with simple starvation even in massive halos. The difference between the physics that results in the decline in SFR versus the decline in H\textsuperscript{i} in massive halos is an important prediction of these simulations, and can perhaps reconcile conflicting results regarding the ubiquity of ram pressure stripping in H\textsuperscript{i} cluster studies (e.g. van Gorkom et al. 2003) versus the much longer decay timescale of satellite star formation in massive halos (e.g. Wetzel et al. 2013).

### 3.4 H\textsuperscript{i} as a function of environment

In the previous section, we found that the H\textsuperscript{i} content of galaxies is reduced at high halo masses. Here we examine a related quantity, which is H\textsuperscript{i} content as a function of environment. Since halo mass is correlated with environment, e.g. as measured by the number of nearby galaxies, the reduction in H\textsuperscript{i} at high halo masses is expected to be qualitatively mimicked in high density regions. Such a trend is in agreement with GASS data of H\textsuperscript{i} content versus environment in Fabello et al. (2012). However, they inferred that environmental processes begin at $10^{13} M_\odot$, whereas our simulations predict that the suppression starts at $M_{\text{halo}} \approx 10^{12} M_\odot$. In this section we conduct a more detailed comparison to Fabello et al. (2012), in order to better understand what this data may be telling us about the impact of environment on H\textsuperscript{i}.

Figure 3.9 shows the mean H\textsuperscript{i} richness and specific SFR of galaxies as a function of the environment parameter $N$ from Fabello et al. (2012), relative to the H\textsuperscript{i} richness and sSFR for $N = 0$ galaxies (or $N > 0$ when we have very few galaxies at $N = 0$). For a given galaxy, $N$ is defined as the number of galaxies with $M_* > 10^{9.5} M_\odot$ within a cylinder, centered at that galaxy, of radius 1 Mpc and redshift path length of $\pm 500$ km s\textsuperscript{-1}. We choose two mass bins, $M_* = 10^{10} - 10^{10.5} M_\odot$ and $M_* = 10^{10.5} - 10^{11} M_\odot$ to compare to the observational data presented in Fabello et al. (2012). Blue represents the H\textsuperscript{i} richness, and red the sSFR as a function of $N$, with the solid lines (with circle markers) results from the simulations and the stars those from observations. The upper panel has no sSFR selection criteria while the lower panel selects only the galaxies with sSFR $\geq 10^{-11.2}$ yr\textsuperscript{-1}, i.e. it excludes quenched galaxies. The error bars on simulation represent $1\sigma$ uncertainty.

In both the simulations and data, there is an overall trend of dropping median
3.4 H$^{\text{I}}$ as a function of environment

Figure 3.9: Median H$^{\text{I}}$ richness (blue) and sSFR (red) of galaxies as a function of environmental parameter $N$ (see text) relative to their value for $N = 0$ galaxies. Solid lines (with circle markers) correspond to our simulated galaxies and stars to observational data from Fabello et al. (2012). The errorbars are 1σ uncertainty. Left and right panels correspond to galaxies with stellar masses $10^{10} M_\odot < M_* < 10^{10.5} M_\odot$ and $10^{10.5} M_\odot < M_* < 10^{11} M_\odot$, respectively, while the bottom panels include only galaxies with sSFR $\geq 10^{-11.2} \text{ yr}^{-1}$. The simulations show good agreement with observational data on the H$^{\text{I}}$ content fraction for star-forming galaxies whereas they show some excess of H$^{\text{I}}$ richness at high $N$ when considering the quenched galaxies.

H$^{\text{I}}$ richness and sSFR in denser environments. However, the simulation results are typically slightly higher than the observations particularly at high-$N$, implying that galaxies located in populated areas have somewhat too much H$^{\text{I}}$. This discrepancy is essentially all being driven by quenched galaxies; in the lower panel, we see that for star-forming galaxies, the predicted H$^{\text{I}}$ trends of the simulation are in very good agreement with the data, showing much less decline in dense regions.

The discrepancy in dense regions may be related to the excess in H$^{\text{I}}$ richness at $M_{\text{halo}} \sim 10^{13} M_\odot$ seen in Figure 3.7. This further indicates that, while overall the simulation broadly attenuate the H$^{\text{I}}$ content as observed, in detail there may be some discrepancies. Further observational constraints in the group regime are crucial for better understanding the physical processes responsible for H$^{\text{I}}$ removal in satellites.

A comparison with our vzw model excluding quenching is shown in Figure 3.10. This is to show the effect of quenching for a range of environmental conditions. In the case of the model without quenching (vzw), the change in H$^{\text{I}}$ richness relative to its H$^{\text{I}}$ richness at $N = 0$ in denser region is more pronounced. This shows
that the quenching model has a more significant qualitative impact with respect to environment than it does with respect to halo mass (cf. Fig. 3.7). For lower mass galaxies, there is very little difference between the quenching (ezw) and no-quenching (vzw) runs, since the quenching mass scale we impose is at the upper end of this mass range. For more massive galaxies (right panels), however, the difference between the two is clearer. Given the ad hoc nature of our quenching prescription, one should not read too much into these trends, but an important broader point is that observations of H\textsc{i} versus environment can provide stringent tests for models of star formation quenching.

3.5 H\textsc{i} radial halo profiles

So far we have focused on the properties of the total H\textsc{i} content within galaxies and halos. To investigate the physical processes by which environment affects H\textsc{i} in more detail, here we study the radial distribution of H\textsc{i} within halos.

Figure 3.11 shows the H\textsc{i} richness of satellites as a function of the radial distance from the halo center, in units of the halo’s virial radius (something similar was done in Solanes et al. 2001). The main trend shows that at all radii, the H\textsc{i} richness always decreases with increasing halo mass. This is the same trend as shown in Figure 3.5, except here we additionally show that it occurs for every galaxies at all radii.
Figure 3.11: H\textsubscript{i} richness of satellites as a function of radial distance from the halo center in units of the virial radius. Lines of different colors show mean values for different halo mass bins, as indicated by the colorbar. Solid lines: fiducial model with quenching described in section 2.1, dashed lines: simulation model without quenching (for comparison).

Besides this overall reduction, there is a noticeable change in the H\textsubscript{i} richness profile with halo mass. In the low mass halos, we see that the H\textsubscript{i} richness of satellite galaxies is independent of their distance to the center of the halo, consistent with there being essentially no stripping of their gas content as the satellite falls deep into these halos. In contrast, in high mass halos there is a clear decrease in H\textsubscript{i} richness at small radii, with the trend gradually changing from no radial trend to a very steep one with halo mass. For the most massive halos ($M_{\text{halo}} \sim 10^{14} M_{\odot}$), satellite galaxies close to their centers are more than 2 orders of magnitude lower in H\textsubscript{i} richness than those near the virial radius, with most of the drop being within the inner half of the virial radius.

We also show in Figure 3.11 the result from our vzw model without quenching, showing a lower H\textsubscript{i} richness compared to our model, as also seen in Davé et al. (2013). However, the trends with radii and halo mass are identical, showing that quenching does not strongly impact the distribution of H\textsubscript{i} within halos.

In summary, the radial profile of H\textsubscript{i} richness shows no trend for lower-mass halos, but at $M_{\text{halo}} \gtrsim 10^{13} M_{\odot}$ there is a marked drop in H\textsubscript{i} richness towards the centre which becomes rapidly more pronounced at higher masses. This is qualitatively consistent with the idea that gas stripping is quite efficient in high mass halos that are abundant in hot hydrostatic gas. Further comparisons to observations will elucidate whether these simulations are capturing all the relevant processes accurately.
Chapter 4

Higgs evolution and mergers

4.1 Evolutionary tracks
Figure 4.1: Growth of 12 individual galaxies from $z=5$ to $z=0$. The blue lines show the $\text{H}_i$ mass evolution, the grey lines show the stellar mass evolution, and the red lines show the SFR (scale on the right axis). The green vertical lines indicate the redshifts at which galaxies have undergone a $< 1 : 3$ merger. The numbers on the top right corner are the halo mass and stellar mass at $z=0$, respectively (the color indicates whether the galaxy is central (blue) or satellite (red) at $z=0$). Red points (•) show that the galaxy is a central at the given redshift and yellow points (●) show that the galaxy is a satellite.
Figure 4.1 shows evolutionary tracks from $z = 5 \rightarrow 0$ for selected individual simulated galaxies spanning a range of final stellar masses and halo masses. The H\(_1\) mass evolution is shown with the blue lines, the grey lines show the stellar mass growth and the red lines show the SFR evolution (scale on the right axis). The dots indicate whether the galaxy was a central (red) or satellite (yellow) at that epoch. Vertical green lines show where identified < 1 : 3 mergers occur, as described in §2.3. We also show the log of the halo and stellar masses at $z = 0$ by the two numbers on the top right corner, where the colour of the numbers indicate whether the galaxy is central (blue) or satellite (red) at that redshift. Note that there are two roughly Milky Way-sized galaxies in terms of halo and stellar mass, in panels (k) and (l).

The tracks show that galaxies grow in H\(_1\) and stellar mass together, although in general the stellar mass grows more quickly than the H\(_1\) mass. We will show in the next section that in these simulations, this evolution is a result of the roughly constant relationship between H\(_1\) and stellar mass, and is not driven by redshift evolution of this relation. There is also a relationship between H\(_1\) growth and SFR, and in particular a merger (identified by the vertical lines) sometimes drives a rise in the SFR but can result in either a rise or decline in H\(_1\) mass; we will quantify this in §4.3. Another aspect depicted is the quenching prescription, as described in §2.1, which stops a galaxy from forming stars when it is located in a massive halo. For instance in panel (a), we can see that the galaxy is quenched just before $z = 0$ once it entered a massive halo, but its H\(_1\) gas is still available to eventually feed star formation. Conversely, in panel (b), the SFR starts decreasing in concert with the H\(_1\), and then eventually is fully truncated as the H\(_1\) is removed. The galaxy does not form stars anymore and the stellar mass even decreases as some of the star particles get stripped. Stripping is also seen in panels (c) & (d). In these two cases, the SFR does not vanish, but we see that once the galaxy crosses into a bigger halo the gas is quickly exhausted while the SFR decreases at a far lower rate: this confirms what we showed in Figure 3.8 with the red lines and the red dashed lines (most massive halo).

For galaxies entering into less massive halos, Figure 3.8 showed that the decrease in gas fraction is very similar to the decrease of specific SFR. To illustrate this, there are two central galaxies that have entered more massive halos (being $M_{\text{halo}} < 10^{12} \, M_\odot$) shown in panels (e) & (f): the H\(_1\) content slowly decreases along with the SFR. Those galaxies don’t receive any gas infall and suffer starvation. The decrease in their gas content owes to the fact that they are still producing stars without much further gas replenishment. The two Milky Way-like galaxies (k) and (l) both undergo mergers at fairly late epochs, but in one case the merger reduces the H\(_1\) content and in the
other it boosts it. These tracks illustrate the diversity in trends that impact the H\textsubscript{i} evolution in galaxies that we explore next, and in particular the relationship between mergers and H\textsubscript{i} that we quantify below.

## 4.2 H\textsubscript{i} richness evolution with redshift

Our results above suggest that massive halos with hot gas are effective at stripping the H\textsubscript{i} from infalling satellites, while \( M_{\text{halo}} \lesssim 10^{12} M_{\odot} \) starve their satellites of H\textsubscript{i} over longer timescales. This explains the trend in §3.2 where the H\textsubscript{i} richness drops significantly for satellites relative to centrals in halos above this mass. In this section we examine at which cosmic epoch this trend appears, and how it evolves to the present day.

Figure 4.2 shows the evolution of the median H\textsubscript{i} richness versus halo mass (resolved galaxies only), similar to that in the lower panel of Figure 3.5 but now showing the redshift evolution from \( z = 3 \) to \( z = 0 \). As discussed in Davé et al. (2013), the H\textsubscript{i} richness at a given mass hardly evolves in time; in Davé et al. (2013) this was shown versus stellar mass, while here we show it versus halo mass, but as expected from abundance matching models (e.g. Behroozi et al. 2013) there is not much evolution in the \( M_\star - M_{\text{halo}} \) relation. At all redshifts we see the trend of lower H\textsubscript{i} richness in more massive systems, which continues roughly unabated to the highest halo masses probed.

In contrast to centrals, satellites at all redshifts show a turn-down in their H\textsubscript{i} richness relative to centrals at \( M_{\text{halo}} > 10^{12} M_{\odot} \). This is likely tied to the emergence of hot gaseous halos at this mass scale, which is roughly independent of redshift (Kereš et al. 2005). At the highest redshifts probed here (\( z = 3 \)), we do not have sufficient volume to probe satellites in halos significantly above this mass, but it seems that the trend remains consistent. We note that Davé et al. (2013) demonstrated that the H\textsubscript{i}-poor fraction of satellites is insensitive to the ad hoc quenching prescription (which is based on \( \sigma \), and so lower-\( \sigma \) satellites are generally unaffected), hence this is not what is driving the turn-down. Rather, the processes described in the previous section of strangulation and ram pressure stripping are predominantly responsible.

Figure 4.3 shows the median H\textsubscript{i} richness of resolved central and satellite galaxies from \( z = 5 - 0 \). We separate the galaxies into bins of stellar masses as shown in the figure by the colour coded lines, which represent the medians for all of the galaxies in each stellar mass bin at every redshift. In this case, we are only plotting galaxies at higher redshift that are the main progenitors of the resolved galaxies at \( z = 0 \), in order to examine the H\textsubscript{i} evolution in a fixed population.
4.2 H\textsc{i} richness evolution with redshift

Figure 4.2: Median H\textsc{i} richness as a function of halo mass at different redshifts, from $z=3$ (red) to $z=0$ (purple). Solid and dashed lines correspond to central and satellite galaxies, respectively.

The predominant trend is that galaxies are more H\textsc{i}-rich at early times. In all stellar mass bins, the satellite galaxies always have lower H\textsc{i} richness than the centrals. However, at $z \gtrsim 1.5$, the difference between satellites and centrals is very small, and the two track each other very well. Only at $z \lesssim 1.5$ does the satellite galaxies’ H\textsc{i} richness begin to depart significantly from that of the centrals. At higher redshift, it appears that gas stripping is not effective, at least over the halo mass range explored in these simulations. An interesting feature we see is the dip in H\textsc{i} richness at $1 \lesssim z \lesssim 2$ for the lowest mass central galaxies; these galaxies actually strongly increase their H\textsc{i} richness between $z = 1 - 0$. The origin of this is not entirely clear. The lowest mass satellites, meanwhile, show the strongest drop to $z = 0$, as they are most susceptible to stripping processes.

We can also view the evolution in bins of halo mass rather than stellar mass, as shown in Figure 4.4. We focus here on low-mass satellites since they are most strongly impacted by H\textsc{i} removal processes, namely satellites with $10^9 \, M_\odot < M_* < 10^{10} \, M_\odot$.* Figure 4.4 shows the H\textsc{i} richnesses from $z=5$ to $z=0$ for different $z = 0$ halo mass bins for satellites that are in the above stellar mass range at $z = 0$. Again, we see that at $z \lesssim 1$ there is a marked drop in the H\textsc{i} richness of satellites, but only in the most massive halos ($M_{\text{halo}} \gtrsim 10^{13} \, M_\odot$). The redshift at which H\textsc{i} removal becomes important is a strong function of halo mass, consistent with the idea that stripping

*If we were to choose a lower mass range, then the galaxies cannot be tracked back in time very long before becoming unresolved, hence we focus on a bin that is comfortably above our resolution limit.
**Figure 4.3:** Median H\textsc{i} richness as a function of redshift for central galaxies (solid lines) and satellites (dashed lines) in different stellar mass bins, increasing from $M_\ast \sim 10^{8.6} \, \text{M}_\odot$ (purple) to $M_\ast \sim 10^{11.3} \, \text{M}_\odot$ (red). We only include resolved galaxies at $z = 0$ and their most massive progenitors at higher redshifts.

**Figure 4.4:** Median H\textsc{i} richness as a function of redshift for satellites in different halo mass bins, increasing from $M_{\text{halo}} \sim 10^{11.3}$ (purple) to $M_{\text{halo}} \sim 10^{14.2}$ (red). We only include satellites in the stellar mass range $10^9 \, \text{M}_\odot < M_\ast < 10^{10} \, \text{M}_\odot$ at $z=0$ and their most massive progenitors at higher redshifts.
begins when the halo mass crosses a mass threshold (Figure 4.2) coincident with the onset of a substantial hot gaseous halo.

### 4.3 H I in mergers

Mergers have a significant impact on galaxy evolution. Major mergers, if between gas-rich galaxies, typically induce bursts of star formation (Mihos & Hernquist 1996) that move galaxies well off the so-called star formation main sequence* of SFR versus \( M_* \) (Noeske et al. 2007), and hence are partly responsible for setting the scatter around the main sequence. It is worth noting that the stars when put on graph with respect to their colors against their brightness present a formation main sequence is a region in a form of a band where lays distinctive group of stars in a form of a band when plotted in graph Finlator & Davé (2008) argued that departures from the "equilibrium" mass-metallicity relation are driven by stochastic fluctuations in accretion, of which mergers are the most extreme example, and Davé et al. (2013) suggested that this is also reflected in the H I content at a given \( M_* \). In this section we investigate the impact that major mergers have on the H I content of galaxies, and in particular we quantify how much scatter in the relationship between \( M_{\text{HI}} \) (or H I richness) and \( M_* \) is induced by mergers.

Figure 4.1 shows that mergers in many cases result in a burst of star formation. What this means for H I is unclear: we might expect a decrease of H I content owing to gas consumption that is too rapid for replenishment, but it could be that the H I might be increased if this gas is fueling the burst. From Figure 4.1, it is however unclear whether the merger increases or decreases the H I fraction. For instance, in Figure 4.1 (c)(at \( z \sim 0.5 \)), (f) or (h) we can see variations in the decrease in gas content. Conversely to those cases, we also encounter situations where the gas content keeps increasing, such as in Figure 4.1(c)(at \( z \sim 1.75 \)) or (k). One possible impact for mergers may, therefore, be to increase the scatter in the relationship between H I and stellar mass. Here we more quantitatively consider how mergers alter the H I content of the galaxies.

Figure 4.5 quantifies the impact of mergers on the scatter in H I richness. Here we show the distribution of the ratios of the H I richness after and before every snapshot (black histogram) compared to those after and before a \( > 1:3 \) merger (red histogram). The black histogram (for all galaxies) shows a tiny shift of the histogram towards values below 1 (median \( \approx 0.95 \)), which means that typical galaxies have their H I richness decreased slightly at a later time. This is anticipated if we refer to

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*main sequence is the general trend clearly visible on plots of SFR versus \( M_* \) of galaxies.
Figure 4.5: The effects of major mergers on the H\textsubscript{I} content of galaxies. We compare the distribution of ratios of the H\textsubscript{I} richness after and before every snapshot for all galaxies (black histogram) to the distribution of ratios after and before every $> 1 : 3$ merger (red histogram). Shaded regions contain 90\% of the data for the control (grey shade) and merger (red shade) samples, with spreads of $\sim 0.44$ dex and $\sim 0.75$ dex, respectively. Median values are indicated by the vertical dashed lines. Mergers increase the median H\textsubscript{I} richness of galaxies, while the most prominent feature is the increased width of the distribution, interpreted as simple stochasticity.

Figure 4.3 and Figure 4.4 where the H\textsubscript{I} richness decreases towards low redshift. Each area under the histograms is normalized to make a fairer comparison. This serves as a reference for the distribution of H\textsubscript{I} richness ratio before and after mergers.

The post-merger ratio (red histogram) shows two effects. First, the H\textsubscript{I} richness is increased, with a median ratio of 1.21. This suggests that mergers generally boost the H\textsubscript{I} fraction, which occurs concurrently with an increase in SFR and decrease in metallicity (Davé et al. 2013). This is consistent with the trend that high-H\textsubscript{I} galaxies have recently received a substantial input of new gas (Moran et al. 2012), and that such an input also fuels new star formation. It is inconsistent with the idea that the H\textsubscript{I} gets “used up” in a merger. The overall trend of higher H\textsubscript{I} content in higher SFR galaxies is consistent with observations (Robertson et al. 2013).

A second trend from Figure 4.5 is that the scatter in relative H\textsubscript{I} richness is larger in post-merger galaxies than in the overall sample. This suggests that mergers do indeed increase the scatter of the H\textsubscript{I} richness at a given mass. The range of ratios enclosing 90\% of galaxies rise from $\sim 0.44$ dex in the overall case to $\sim 0.75$ dex in the post-merger case.

A useful plot for understanding how H\textsubscript{I} participates in the baryon cycle is via a
4.3 H\textsubscript{i} in mergers

Figure 4.6: Deviations of sSFR (top) and metallicity (bottom) from their median values at a given $M_*$ against the deviation of the H\textsubscript{i} richness from its median value at a given $M_*$ (see text for details). The density of galaxies in each deviation plot is indicated by the background color scale, with the black and blue contours containing $\sim 68\%$ and $\sim 95\%$ of the galaxies, respectively. Yellow crosses and red circles show deviations for galaxy mergers with mass ratios $> 1:2$ and $> 3:4$, respectively. The grey and red solid lines show linear fits for all galaxies and major mergers, respectively.

deviation plot, which quantifies second parameter variations in relationships versus a single quantity, such as stellar mass. An example of such a second parameter trend is the so-called fundamental metallicity relation (Mannucci & Cresci 2010, Lara-López et al. 2010), in which galaxies at a given stellar mass show lower metallicity at higher star formation rates.

Figure 4.6 shows two deviation plots. This quantifies the deviation of each galaxy from the overall trend given by the median value in each stellar mass bin. We first fit a spline to the median relationship between SFR and $M_*$, and $M_{HI}$ and $M_*$. For each value of $M_*$, we then subtract the quantity from its corresponding median spline-fit value. This gives the deviation for each quantity, which we can then plot against each other.

The upper panel shows the deviation of the sSFR from its median value at a given $M_*$ ($\Delta \log s\text{SFR}$) against the deviation of the H\textsubscript{i} richness from its median value at a given $M_*$ ($\Delta \log M_{HI}/M_*$). The lower panel similarly shows a deviation plot of metallicity versus H\textsubscript{i} richness. To avoid congested plots, we chose to make density plots with two contours containing $1\sigma$ (black) and $2\sigma$ (blue) of the resolved galaxies. We fit a power law for all the galaxies (grey line), and for those which have just undergone a major merger between the last two snapshots (red line).

From the top panel, we can see that recent mergers follow a different relation than the overall galaxy population. In particular, galaxies with high sSFR also tend
to have high $\text{H} \text{i}$ richness, but that after a merger the sSFR is enhanced more than the $\text{H} \text{i}$ richness. The grey line is similar to what was shown in Davé et al. (2013), in which it is explained that recent gas accretion tends to boost SFR. The point of Figure 4.6 is that mergers boost the SFR above the overall relation owing to general stochastic fluctuations in accretion, more so than the $\text{H} \text{i}$.

For comparison, the bottom panel shows a deviation plot of $\text{H} \text{i}$ richness versus metallicity. This shows that galaxies with increased $\text{H} \text{i}$ richness show a decreased metallicity at a given stellar mass. In contrast to the sSFR case, here the trend for all galaxies is identical to recently merged galaxies, showing that low metallicity goes hand-in-hand with higher $\text{H} \text{i}$ content independent of whether a merger happened. This is consistent with the idea that recent infall that boosts $\text{H} \text{i}$ brings in lower metallicity gas. This shows that $\text{H} \text{i}$ traces metallicity in the baryon cycle, while the SFR is specifically boosted by interactions.

Overall, mergers have a minor but noticeable impact on the $\text{H} \text{i}$ content of galaxies, increasing it immediately after the merger, and adding to the scatter in $\text{H} \text{i}$ richness. However, the increase in $\text{H} \text{i}$ is essentially consistent with simple stochasticity in accretion within the baryon cycle, without there being an additional increase owing to the merger as seen in the case of SFR. We note that owing to the limited time resolution of our snapshots, and possibly the low spatial resolution that is unable to resolve the galaxies' internal structure, this analysis may be underestimating the impact of mergers. More detailed simulations, and associated comparisons with data, can help us disentangle the roles of all the components of galaxies in mergers.
Chapter 5

Summary

We investigate the properties of H\textsubscript{i} in galaxies drawn from a cosmological hydrodynamic simulation including galactic outflows that reproduces many key observed properties of H\textsubscript{i}. We focus on studying the relationship between H\textsubscript{i} and environment, quantified either via halo mass, centrals versus satellites, or local galaxy density. We also examine evolutionary trends in H\textsubscript{i} versus redshift, and study how mergers influence H\textsubscript{i} content. Our main results are summarized as follows:

• Our simulation shows very good agreement with the observed ALFALFA HIMF, and furthermore shows good agreement with the observed HIMF broken into stellar mass bins based on GASS data, particularly for non-quenched galaxies. This suggests that the scatter between $M_{\text{HI}}$ and $M_*$ is generally well-reproduced in our simulation, providing a second-order test of our models.

• The H\textsubscript{i} content of central galaxies is governed primarily by the halo mass, with a positive correlation that is steeper and tighter at $M_{\text{halo}} < 10^{12} \, M_\odot$. The median H\textsubscript{i} richness of centrals decreases slowly with halo mass, which continues up to the highest masses probed.

• For satellites, the median H\textsubscript{i} mass is relatively independent of the halo mass. However, the median H\textsubscript{i} richness shows a significant drop for $M_{\text{halo}} > 10^{12} \, M_\odot$, and an emergence of a bimodal distribution in which the drop is driven by an increasing fraction of satellites essentially devoid of H\textsubscript{i}.

• When a galaxy falls into a more massive halo, its H\textsubscript{i} is attenuated. This trend occurs at all halo masses. However, the trend is strongly accelerated in halos with $M_{\text{halo}} > 10^{12} \, M_\odot$. The median e-folding timescale for removal is $\sim 2 \, \text{Gyr}$ in lower mass halos, but only 0.7 Gyr in $M_{\text{halo}} \approx 10^{13} \, M_\odot$ halos.
• A comparison to star formation rate attenuation shows that the SFR is also attenuated once a galaxy becomes a satellite, but that there is no strong acceleration of this in massive halos. The physical implication is that star formation and H\textsc{i} attenuation are consistent with starvation in lower mass halos, while in more massive halos, the SFR still drops owing primarily to starvation while the H\textsc{i} is strongly affected by additional gas stripping processes associated with the presence of a hot gaseous halo.

• The H\textsc{i} richness at a given halo mass does not evolve much with redshift out to $z \sim 3$. There continues to be a rapid drop in the satellites’ H\textsc{i} richness at $M_{\text{halo}} > 10^{12} \, M_\odot$. The median H\textsc{i} richness in all galaxies drops from $z = 5 \rightarrow 0$, with the satellites tightly tracking the centrals down to $z \sim 1$ and then dropping rapidly below that. The drop is tightly correlated with halo mass, starting first in the highest mass halos at $z \gtrsim 1$, while low-mass halos show no strong drop in the satellite H\textsc{i} richness at late times.

• In low mass halos, the H\textsc{i} richness of satellite galaxies is independent of their distance to the central galaxy; whereas at high halo mass ($M_{\text{halo}} \geq 10^{13} \, M_\odot$), galaxies become H\textsc{i} poorer towards the centre, indicative of strong gas stripping processes.

• Mergers cause a modest increase in the H\textsc{i} richness, while also increasing the scatter in H\textsc{i} richness. These deviations are consistent with being an extreme example of a stochastic fluctuation in accretion, rather than being driven by internal processes particularly associated with the merger as is the case with the SFR.

These results show that environment has a major impact on the H\textsc{i} content of galaxies, but this impact is mostly confined to more massive galaxies with $M_{\text{halo}} > 10^{12} \, M_\odot$. The fact that hot gaseous halos tend to develop around this mass scale in our simulations (Gabor & Davé 2012), as expected from simple cooling timescale arguments (Birnboim & Dekel 2003), suggests that the presence of hot gas is the main driver for environmental effects, particularly for satellite galaxies. In future work we will examine this connection in more detail, using more physically-motivated models for star formation quenching and with simulations that use improved numerical techniques to better model such stripping processes. The steps to be followed for modeling the star formation quenching is not yet clear but we hope we will be able to find consistent and physical based correlations by, perhaps, manipulating observational data and looking at the relationship between the quenching time and the gas
content. The model will then be implemented in the simulations to better predict for future surveys. This work sets the baseline for such future studies, and highlights a new set of observational comparisons that can provide crucial constraints on the evolution of gas in galaxies.
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