ALFALFA H I data stacking – III. Comparison of environmental trends in H I gas mass fraction and specific star formation rate

Silvia Fabello,1⋆ Guinevere Kauffmann,1⋆ Barbara Catinella,1 Cheng Li,2 Riccardo Giovanelli3 and Martha P. Haynes3

1Max-Planck Institut für Astrophysik, D-85741 Garching, Germany
2Max-Planck-Institute Partner Group, Shanghai Astronomical Observatory, Nandan Road 80, Shanghai 200030, China
3Center for Radiophysics and Space Research, Cornell University, Ithaca, NY 14853, USA

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ABSTRACT
It is well known that both the star formation rate and the cold gas content of a galaxy depend on the local density out to distances of a few Mpc. In this paper, we compare the environmental density dependence of the atomic gas mass fractions of nearby galaxies with the density dependence of their central and global specific star formation rates. We stack H I line spectra extracted from the Arecibo Legacy Fast ALFA survey centred on galaxies with ultraviolet imaging from GALEX and optical imaging/spectroscopy from Sloan Digital Sky Survey. We use these stacked spectra to evaluate the mean atomic gas mass fraction of galaxies in bins of stellar mass and local density. For galaxies with stellar masses less than 10^{10.5} M☉, the decline in mean atomic gas mass fraction with density is stronger than the decline in mean global and central specific star formation rate. The same conclusion does not hold for more massive galaxies. We interpret our results as evidence for ram-pressure stripping of atomic gas from the outer discs of low-mass satellite galaxies. We compare our results with the semi-analytic recipes of Guo et al. implemented on the Millennium II Simulation. These models assume that only the diffuse gas surrounding satellite galaxies is stripped, a process that is often termed ‘strangulation’. We show that these models predict relative trends in atomic gas and star formation that are in disagreement with observations. We use mock catalogues generated from the simulation to predict the halo masses of the H I-deficient galaxies in our sample. We conclude that ram-pressure stripping is likely to become effective in dark matter haloes with masses greater than 10^{13} M☉.

Key words: galaxies: evolution – galaxies: ISM – radio lines: galaxies.

1 INTRODUCTION
Systematic studies of the dependence of galaxy properties on environment began with analyses of the relation between galaxy morphology and local density (Oemler 1974; Dressler 1980). It later became evident that star formation is more strongly affected by environment than morphology (Hashimoto et al. 1998). Large surveys, for example, the Sloan Digital Sky Survey (SDSS; York et al. 2000) and the Two-degree Field Galaxy Redshift Survey (2dFGRS; Colless et al. 2001) provided samples large enough to study the effects of local galaxy density on a multiplicity of galaxy properties. It was shown that the star formation and structural properties of galaxies depend strongly on their mass (e.g. Kauffmann et al. 2003; Shen et al. 2003; Baldry et al. 2004). Because of this, and because galaxy mass is itself correlated with environment, it is important to bin galaxies by mass before studying how their properties vary with local density. Several analyses showed that at fixed mass, the dependence of colour/star formation on density is stronger than that of structural properties such as concentration index and stellar surface mass density (Kauffmann et al. 2004; Li et al. 2006a; Bamford et al. 2009; Skibba et al. 2009). This suggests that environmentally driven processes lead to cessation of star formation in a galaxy, but do not strongly affect its structure.

An alternative way of quantifying environmental effects is to study how the properties of galaxies vary as a function of distance from the centres of groups and clusters. The ‘centre’ is usually defined as the position of the brightest galaxy in the system and the distance is usually scaled to the virial radius. One result that has emerged from such studies is that at fixed clustercentric distance, galaxy properties do not depend strongly on the mass of the group.

*E-mail: fabello.silvia@gmail.com (SF); gamk@mpa-garching.mpg.de (GK)
(Balogh et al. 2004; Van den Bosch et al. 2008). This does not agree with a scenario in which the ram-pressure effects are responsible for removing the cold interstellar medium in galaxies and shutting down star formation. Ram pressure depends on the square of the velocity at which a galaxy is moving through the surrounding gas, so it should operate more efficiently in galaxies in more massive dark matter haloes.

Larson, Tinsley & Caldwell (1980) suggested that the gas envelopes surrounding discs are most easily stripped by ram-pressure effects when they fall into a cluster. After a few Gyr, the galaxy will have converted its available cold gas into stars and because there is no infall of new gas, the galaxy will ‘starve’ and stop forming stars. This mechanism has long been part of semi-analytic models of galaxy formation (e.g. Kauffmann, White & Guiderdoni 1993). In recent years, the predictions of these models have been compared with data from SDSS and it has been found that the fraction of red satellites is higher in the models than in the data (Kimm et al. 2009; Weinmann et al. 2010). Star formation quenching time-scales must therefore be quite long (2–3 Gyr) in satellite galaxies (Wang et al. 2007). In the optical astronomy community, ‘slow gas starvation’ has thus come to be accepted as the main physical process determining how galaxies evolve in dense environments.

We note, however, that optical studies present a biased picture of how environment affects galaxies. In disc galaxies, atomic gas generally extends to substantially larger radii than the stars. Ram pressure will act primarily on low-density atomic gas in the outer regions of galaxies, rather than the dense molecular gas in their central regions. The first systematic studies of the dependence of the atomic gas content of galaxies on environment (Haynes, Giovanelli & Chincarini 1984; Giovanelli & Haynes 1985; Gavazzi 1987) found that disc galaxies in clusters exhibit a deficiency in H I content that strongly increases towards the cluster centre and that matches the predictions of the ram-pressure stripping model introduced by Gunn & Gott (1972). Integrated CO observations of cluster galaxies suggested that there is no deficiency of molecular gas in H I-deficient galaxies (Kenney & Young 1989), but resolved studies showed some evidence of CO depletion when the HI is stripped to within the optical disc (Vollmer et al. 2008; Fumagalli et al. 2009). Both results support the idea that ram-pressure stripping primarily affects gas in the outer regions of galaxies, proceeding inwards. Subsequent work by Gavazzi (1989), Cayatte et al. (1990), Kenney, Van Gorkom & Vollmer (2004) and Chung et al. (2009) emphasized the frequent presence of cluster galaxies with truncated HI discs which, together with examples of disturbed HI morphologies and one-side tails, also support the mechanism of ram pressure. Finally, smoothed particle hydrodynamics (SPH) simulations (Abadi, Moore & Bower 1999; Vollmer 2009) of galaxies orbiting through the intracluster medium then demonstrated that ram pressure can in fact be responsible for distorted HI discs similar to those seen in the observations.

The degree to which ram pressure may affect the interstellar medium of galaxies outside the rich cluster environment is not yet well understood. Available samples have generally been too small to quantify environmental effects across a large dynamic range in local density or dark matter halo mass. The state-of-the-art blind HI survey, the Arecibo Legacy Fast ALFA survey (ALFALFA; Giovanelli et al. 2005), does detect HI in galaxies in environments spanning a range of environments from voids to rich clusters, but ALFALFA is still a shallow survey so it will only detect gas-rich galaxies at redshifts greater than ~0.02. In this paper, we employ the stacking technique described in Fabello et al. (2011a, hereafter Paper I) to study the average cold gas content of galaxies as a function of local density for a sample of ~5000 galaxies with redshifts in the range of 0.025 < z < 0.05. By comparing the variation of the H I gas fraction with environment with the variation of their total and central specific star formation rates (sSFRs), we aim to constrain the environments in which ram-pressure stripping effects become important. As we have discussed, ram-pressure stripping will preferentially affect the low-density outer discs of galaxies, which are dominated by atomic gas where star formation is inefficient (Bigiel et al. 2010).

We begin by describing the data and the density estimator that we use in this analysis. We then compare the relative decrease in HI gas fraction and sSFR as a function of local density and compare our results with the results of semi-analytic models implemented on the Millennium II Simulation (Boylan-Kolchin et al. 2009). Discussion and conclusions are presented in the final section.

2 THE SAMPLE

Our galaxies are selected from the ‘parent sample’ of the GALEX Arecibo SDSS Survey (Catinella et al. 2010), which is a volume-limited sample of ~12,000 galaxies selected from the SDSS main spectroscopic sample with stellar masses greater than 10^{10} M\(_{\odot}\) and redshifts in the range of 0.025 < z < 0.05, and which lie in the intersection of the footprints of the SDSS Data Release 6 (Adelman-McCarthy et al. 2008), the GALEX Medium Imaging Survey (Martin et al. 2005) and the ALFALFA survey. We make use of sample A defined in Paper I, which consists of 4726 galaxies in the ALFALFA 40 per cent data set (Haynes et al. 2011). Only 23 per cent of sample A targets are detected by ALFALFA. We employ a stacking technique, which allows us to include the many non-detections. We refer the reader to Paper I for a comprehensive description of the stacking method; in this paper, we only provide a brief summary. Before proceeding, we also describe the parameters used in this analysis; these include stellar mass, global and fibre sSFRs (Section 2.2), and our adopted environmental tracer (Section 2.3).

2.1 ALFALFA data stacking

ALFALFA is a blind HI survey that used the ALFA multibeam receiver at the Arecibo telescope to scan 7000 deg\(^2\) of the sky over the velocity interval v(km s\(^{-1}\)) ≃ [−2500; 18000] (i.e. out to z ≃ 0.06). The data acquired are stored as smaller three-dimensional (3D) cubes of dimension 2.4’ × 2.4’ on the sky and 5500 km s\(^{-1}\) in velocity ‘depth’. The stacking process that we apply to ALFALFA data includes a series of steps, which can be summarized as follows.

(i) Create a catalogue of HI spectra

All our targets are selected from the SDSS spectroscopic survey, so we know their position on the sky and their redshift. We select the ALFALFA data cube which contains the target and integrate the signal from the galaxy over a sky region of 4 × 4 arcmin\(^2\) (our targets are always smaller than the telescope beam, whose FWHM is ~3.5 arcmin). For each spectrum we measure the root mean square (rms) noise, which is used later as a weight.

(ii) Stack spectra

We co-add the signals from N different sources located at different redshifts. First, we shift each spectrum to the target galaxy rest frame, so each spectrum is centred at zero velocity. We stack together the spectra S\(_i\) (i = 1, . . . , N) using their w\(_i\) = 1/rms\(^2\) as a weight, so that the final spectrum S_{stack} is

\[ S_{stack} = \frac{\sum_{i=0}^{N} S_i w_i}{\sum_{i=0}^{N} w_i}. \]
If we recover a signal in the stacked spectrum, we measure the integrated emission between the two edges of the $\text{H}_\text{i}$ profile, which are defined manually for each spectrum. If there is no detection, we evaluate an upper limit, assuming a 5σ signal with a width of 300 km s$^{-1}$, smoothing the spectrum to 150 km s$^{-1}$.

(iii) Evaluate $\text{H}_\text{i}$ gas fractions

Our aim is to compute the average $\text{H}_\text{i}$ content of a given sample of galaxies, so we are interested in converting our recovered signal into an $\text{H}_\text{i}$ mass and subsequently into an average $\text{H}_\text{i}$ gas fraction. Once we measure an $\text{H}_\text{i}$ flux, we estimate the corresponding $\text{H}_\text{i}$ mass using

$$M_{\text{HI}} = \frac{2.356 \times 10^5}{1+z} \left( \frac{D_0(z)}{\text{Mpc}} \right)^2 \left( \frac{S_{\text{int}}}{\text{Jy km s}^{-1}} \right),$$

(2)

where $D_0(z)$ is the luminosity distance and $S_{\text{int}}$ is the integrated $\text{H}_\text{i}$ flux. The $\text{H}_\text{i}$ gas fraction is simply defined as $M_{\text{HI}}/M_\star$. Note that we weight each spectrum before stacking by $M_{\text{HI}}/(1+z)^2 D_0(z)^2$, to convert it into a measure of ‘gas fraction’ (see also the discussion in Paper I, Appendix A).

At the median redshift of sample A, the size of the Arecibo telescope beam corresponds to physical scales of 0.15 Mpc and may include more galaxies than the targeted one. For our gas fractions to be reliable, we apply a correction for contamination from close companions, as described in detail in Appendix A. In summary, for each galaxy which lies inside a region of the beam size $\pm 300$ km s$^{-1}$ around the main target, we estimate its gas fraction from photometry using the relation between colour, stellar mass surface density and $\text{H}_\text{i}$ gas fraction found by Zhang et al. (2009), and subtract it from the $\text{H}_\text{i}$ mass of the target galaxy. The corrections are always smaller than a few per cent even in the highest density bins.

2.2 Galaxy parameters

The optical parameters we use are drawn from the MPA-JHU SDSS Data Release 7 (DR7) of spectrum measurements or from Structured Query Language (SQL) queries to the SDSS DR7 data base server.1 We use ultraviolet (UV)/optical colours derived from convolving the SDSS images to the same resolution as the GALEX images; this is described in more detail in Wang et al. (2010).

The parameters used in this paper are the following.

**Stellar masses** $M_\star$ are derived from SDSS photometry using the spectral energy distribution (SED) fitting technique described in Salim et al. (2007) with a Chabrier (2003) initial mass function. sSFRs are defined as the star formation rate per unit stellar mass, SFR/$M_\star$ (yr$^{-1}$). We use two different measures of sSFR to trace different regions of the galaxies: a fibre and a global sSFR. (1) The fibre sSFR is measured inside the 3-arcsec SDSS fibre, and is therefore characteristic of the inner regions. At the median redshift of the sample ($z = 0.35$), the 3 arcsec diameter fibre subtends a physical length scale of 2.1 kpc. The radius enclosing 50 per cent of the $r$-band light for galaxies with stellar masses between $10^{10}$ and $10^{11}$ $M_\odot$ ranges from 2 to 3 kpc. So the fraction of the total galaxy light going down the fibre will be around 5–10 per cent. We acquire the fibre sSFRs from the MPA-JHU SDSS DR7 of spectrum measurements.2 Briefly, they are evaluated from the spectrum emission lines, to which a grid of photoionization models from Charlot & Longhetti (2001) is fitted, following the methods described in Brinchmann et al. (2004). For objects whose signal is contaminated by active galactic nucleus (AGN) emission or for objects with low signal-to-noise ratio (S/N) emission lines, the SFRs are derived indirectly from the 4000Å break strength. (2) The global sSFR is obtained by applying an SED fitting technique to the five optical and two GALEX UV total flux measurements. A more thorough discussion of this procedure is presented in Saintonge et al. (2011).

2.3 Local density estimator

Similar to other past studies of galaxy environment (e.g. Kauffmann et al. 2004; Blanton & Berlind 2007; Thomas et al. 2010), we define a density parameter for each galaxy as the number of neighbours with log $M_\star (M_\odot) \ge 9.5$ located inside a ‘cylindrical’ aperture of 1 Mpc radius and $\pm 500$ km s$^{-1}$ depth, centred on the target. Environmental effects are strongest if density is evaluated on scales comparable to the typical virial radii of the haloes hosting the galaxies in the sample. 1 Mpc is somewhat larger than the typical virial radius of haloes hosting $L_\star$ galaxies, but on smaller scales the number of tracer galaxies becomes too small and Poisson noise dominates.

We search for neighbours with log $M_\star (M_\odot) \ge 9.5$ in the MPA-JHU DR7 spectroscopic catalogue. We note that two SDSS fibres cannot be closer than 55 arcsec, so we might miss close companions. In order to correct for this ‘fibre collision’ effect, we follow the approach of Li et al. (2006b), who measured the angular two-point correlation function for the SDSS spectroscopic sample [$w_z(\theta)$] and for the parent photometric sample [$w_\gamma(\theta)$]. The ratio

$$F(\theta) = \frac{1 + w_z(\theta)}{1 + w_\gamma(\theta)}$$

is used to correct for the effect of fibre collisions. We adopt the correlation functions from Li et al. (2006a) and weight each neighbour by $F(\theta)$, where $\theta$ is the angular separation from the main target. In practice, fibre collision corrections on the estimate of $N$ are very small on average (~3 per cent).

The distribution of the density parameters $N$ derived for sample A galaxies is shown in Fig. 1, left-hand panel (note that we actually plot $N + 1$ for convenience). Just under 50 per cent of the galaxies in our sample have zero or one neighbour. The right-hand panel shows the normalized stellar mass distribution for galaxies with 0–1, 2–5, 6–9 and $>10$ neighbours, following the colour legend in the left-hand panel. As can be seen, the stellar mass distributions do not change very much between the different density bins. As we will show, this is because most galaxies in the bin with $>10$ neighbours

![Figure 1](https://academic.oup.com/mnras/article-abstract/427/4/2841/971436/2843)

Figure 1. Left: normalized distribution of the density parameter $N$ (plotted as $N + 1$ for convenience). The colours indicate the four density bins we will use throughout the paper, as reported in the legend. Right: normalized stellar mass distribution for galaxies in each of the density bins.

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1 See http://www.mpa-garching.mpg.de/SDSS/DR7/ and http://cas.sdss.org/dr7/en/tools/search/sql.asp.

2 http://www.mpa-garching.mpg.de/SDSS/DR7/
are not in rich cluster environments, but in dark matter haloes of moderate mass ($\sim 10^{13} M_{\odot}$).

In Fig. 2, we show the spatial distribution of galaxies found around two objects in our sample with $N > 10$. On the left, we plot the galaxies projected on the sky in units of Mpc. The target galaxies are represented by the red dots and the black circles around them indicate the physical size of the Arecibo beam at the redshift of the target. On the right, we show the 3D distributions of the neighbours. The galaxy in the top row is the one with largest number of neighbours in sample A ($N = 72$). This galaxy lies in the far outskirts of the Coma cluster (the mean redshift of the Coma cluster is $cz = 6853 \pm 1082$ km s$^{-1}$ (Colless & Dunn 1996), and this galaxy lies at $cz = 7860$ km s$^{-1}$). Most of the Coma cluster is actually outside our redshift range, however. In the bottom row of Fig. 2, we show a typical galaxy with $N = 17$. As can be seen, such a galaxy is not in a cluster, but in a group.

3 COMPARISON OF THE DENSITY DEPENDENCE OF H I MASS FRACTIONS AND GLOBAL/FIBRE sSFRs

It is well known that both SFRs and H I gas fractions are smaller in galaxies in dense environments (e.g. Balogh et al. 2004; Cortese et al. 2011). As we have discussed, a comparison of how the H I mass fractions and the sSFRs of galaxies measured in their centres and in their outer regions depend on environment should constrain the physical origin of these effects. Because the atomic gas extends to larger radii and lower densities than the gas that traces the young stars, a comparison of the local density dependence of atomic gas mass fractions and central sSFRs should also provide considerable insight. In a pure starvation scenario, where there is no replenishment of the cold gas in the disc from cooling of the hot halo, we would expect the H I and the star formation to decrease at the same rate as a function of density. If ram-pressure stripping of the atomic gas is important, we would expect the H I to exhibit a stronger environmental dependence.

In this section, we compare the relative decrease in H I mass fraction, global and central sSFRs as a function of local density for galaxies in different stellar mass bins. We divide our sample (we do not consider galaxies with $M_* > 10^{11} M_{\odot}$ because of limited statistics) into two bins of stellar mass and four bins of local density. For each bin, we compute $M_{HI}/M_*$, global and fibre sSFRs. We then scale these values by dividing by the value measured for the lowest density bin ($0 \leq N \leq 1$) at the same stellar mass. In this way, we compare the relative decrease of each quantity with density.

Results are shown in Fig. 3. The orange solid lines represent the H I gas mass fractions, the blue solid lines show the global sSFRs and the green solid lines show the fibre sSFRs. Error bars are computed by bootstrap resampling 80 per cent of the galaxies included in the stacks. The dashed lines show results from models and are discussed in detail in the next section.

The top panels show results for the whole sample A, while the second and third panels investigate different subpopulations to gain better insight into the processes at work. In particular, the middle row focuses on galaxies with log $SFR/M_*$ (yr$^{-1}$) $\geq -11.2$. The cut is chosen because it is the minimum of the bimodal distribution of sSFRs of galaxies in our sample (see von der Linden et al. 2010). The bottom panels show results for disc-dominated galaxies, selected from sample A to have concentration indices less than 2.6. The concentration index is defined as the ratio of the radii enclosing 90 and 50 per cent of the r-band light and is quite tightly correlated with the bulge-to-total ratio ($B/T$) of the galaxy (Gadotti 2009), $C < 2.6$ corresponds to $B/T < 0.3$ (see also Weinmann et al. 2009). As can be seen, for galaxies with stellar masses in the range of $10 < \log M_* < 10.5$, there is a clear ordering in that the H I mass fraction declines most steeply as a function of local density, followed by the global and fibre sSFR. For galaxies with stellar masses in the range of $10.5 < \log M_* < 11$, there is no similar ordering.

As we have discussed, sample A does include galaxies located at the edge of the Coma cluster. In order to check the extent to which the effects seen in Fig. 3 are caused by a subpopulation of cluster galaxies, we exclude Coma cluster galaxies from our analysis and replot the mean gas fraction and sSFR curves in Fig. 4. In practice, we exclude 12 galaxies with stellar masses greater than $10^{10} M_{\odot}$ within $3^\circ$ and $\pm 2000$ km s$^{-1}$ of the centre of the Coma cluster. As can be seen, the decrease in both the average H I gas mass fraction and the global and sSFRs as a function of density becomes somewhat weaker when the Coma galaxies are discarded, but the ordering remains the same. As we will discuss later, our results thus support a scenario in which ram-pressure stripping affects low-mass galaxies in moderate-density environments.

As can be seen by comparing the results for star-forming galaxies and disc-dominated galaxies with the results obtained for ‘all’ galaxies, a significant part of the decrease in H I gas mass fraction as a function of density is driven by processes acting on star-forming, disc-dominated systems. In contrast, in the high mass bin, there is no significant decline in H I mass fraction as a function of local density for star-forming, disc-dominated galaxies. Most of the decline in H I mass fraction for massive galaxies seen in the top right-hand panel must thus be driven by an increase in the fraction of passive, early-type galaxies in dense environments.

It is also interesting to compare the decrease in the H I gas mass with the decrease in the central sSFR measured within the fibre. The decrease in central sSFR is driven by passive, early-type galaxies.
in both stellar mass bins. The processes acting on atomic gas discs apparently do not affect the central sSFRs at all, at least over the range of local densities probed by our sample.

3.1 Comparison with models

So far, we have tentatively interpreted our results as possible evidence for the effect of ram-pressure acting on the atomic gas in discs in low-mass galaxies in environments characteristic of galaxy groups. We do not, however, have information about the spatial distribution of the gas in our galaxies. We have made an ‘ansatz’ that on average the gas will be more spatially extended than the star formation and that ram pressure will more strongly affect the H\textsc{i} gas in the outskirts of galaxies than the star-forming (i.e. molecular) gas.

In this section, we compare our data with results from semi-analytic models where ram-pressure stripping of the cold interstellar medium of galaxies is not taken into account. We show that these models predict relative trends in cold gas mass fractions and sSFRs that do not agree with the observations.
Figure 4. The relative dependence of $\text{H}^i$ gas fraction (orange), the global specific star formation rate (blue) and the fibre specific star formation rate (green) as a function of local density for galaxies with $10 < \log M_* < 10.5$. The left-hand panels show results for galaxies in sample A, all (top) or only the star-forming ones (bottom); the right-hand panels show analogous results when galaxies in the vicinity of the Coma cluster are removed.

We make use of outputs from the semi-analytic models of Guo et al. (2011, hereafter Guo11) implemented on the Millennium II Simulation, which are publicly available for download at http://www.mpa-garching.mpg.de/galform/millennium-II/.

In these models, the cold interstellar medium of a galaxy is distributed in a disc with size that scales as the product of the virial radius and the spin parameter of its host halo. Cold gas is supplied both by infall of diffuse gas and by gas from accreted satellites. Cold gas is depleted by star formation and reheated to the hot phase by supernovae. The total SFR in the disc scales with its total cold gas content following a simplified version of the Kennicutt (1998) law. Stars will not form in a disc unless the total cold gas mass exceeds a certain critical value, which is set by the condition that its surface density is large enough for the gas to be gravitationally unstable (Toomre 1964). In the model, this stability criterion is a global rather than a local one.

Tidal effects, ram-pressure stripping and radio AGN feedback act on the diffuse gas associated with each galaxy and prevent it from cooling, condensing and forming new stars. As shown in fig. 3 of Guo11, the implementation of these quenching processes in the models leads to trends in the fraction of actively star-forming galaxies as a function of projected distance from the centres of rich clusters that are in relatively good agreement with observations.

We make use of a set of 100 mock SDSS galaxy catalogues from the Guo11 model that match both the sky mask and the magnitude and redshift limits of the SDSS DR7 sample. These are the same mock catalogues that were used for interpreting SDSS data in a recent paper by Li et al. (2012). Detailed description of the methodology for constructing the mocks can be found in Li et al. (2006b, 2007).

We begin by extracting a volume from each mock catalogue that is exactly matched in redshift and sky area coverage to ALFALFA sample A. We select galaxies with $\log M_* (M_\odot) = [10; 11.5]$, and then apply the same method used for the observations to compute a local density parameter ($N$) by counting the neighbours more massive than $M_* = 10^9 M_\odot$ inside a cylinder of 1 Mpc radius and depth $\pm 500 \text{ km s}^{-1}$.

In Fig. 5, we compare the fractions of quenched objects, defined as galaxies with $\text{SFR}/M_* \leq 10^{-11.2}$ yr$^{-1}$, in the real sample and in the mock catalogues. Results are shown for two stellar mass bins and we normalize the quenched fraction $N_q/N$ in each density bin to the value for isolated objects with $N = 0$. Red lines show results for the real data and black dotted lines are for the model galaxies. The error bars on the data are obtained by bootstrap resampling. For the models, the error bars represent the variance over the 100 mock catalogues. As can be seen, the models and the data agree quite well. The fraction of quenched low-mass galaxies is somewhat higher in the data than in the models in the highest density bin ($N > 10$), where the disagreement is at about 2$\sigma$ level.

As we have discussed, in the models there are a variety of processes that quench star formation in galaxies. Feedback from radio AGN acts to prevent gas from cooling on to the central galaxies of...
The mock catalogues generated from the semi-analytic models are used to calculate the fraction of galaxies of given stellar mass that are satellite systems as a function of the density parameter $N$. Black curves show results for all galaxies in the mass bin, green curves show results for disc-dominated galaxies and blue curves show results for star-forming galaxies. The error bars indicate the variance in the satellite fraction estimated from the 100 mock catalogues.

dark matter haloes, whereas tidal effects and ram-pressure stripping of the hot gas will affect ongoing star formation in satellite galaxies.

In Fig. 6, black curves show the fraction of model galaxies of given stellar mass that are satellites as a function of the density parameter $N$. As can be seen, in the lower stellar mass bin ($10 < \log M_* < 10.5$), the fraction of satellite galaxies increases very strongly as a function of $N$. For $N = 5$, 60 per cent of galaxies are satellites and for $N > 10$, the fraction of satellites is around 0.9. This means that the analysis of the full sample of low-mass galaxies in this paper is likely to probe the physical processes relevant to satellite rather than to central galaxies. In the higher stellar mass bin ($10.5 < \log M_* < 11$), the fraction of satellites at intermediate values of $N$ is smaller. However, for $N > 10$, the fraction of satellite systems still reaches values greater than 0.8.

Green and blue curves show satellite fractions as a function of local density for disc-dominated and star-forming galaxies, respectively. The satellite fractions for disc-dominated galaxies are almost the same as for the whole sample. However, for star-forming galaxies, satellite fractions are much lower. In fact, in the models, the star-forming galaxy samples are dominated by central galaxies at all densities, so such samples may not be efficient probes of tidal and ram-pressure stripping processes.

We now study relative trends in cold gas mass fraction and sSFR in the models, and compare these to what is seen in the data. In Fig. 3, orange and blue dashed lines show the cold gas fractions and global sSFRs of the model galaxies as a function of density parameter $N$. As can be seen, the main result is that the sSFR decreases more strongly as a function of local density than the cold gas mass fraction. This is seen in both stellar mass bins. The effect is very strong in the top and bottom panels, which show results for all galaxies and for disc galaxies selected according to their bulge-to-disc ratios. The effect becomes considerably weaker if the sample is restricted to galaxies with ongoing star formation (middle panel), because these are mainly central galaxies.

In the models, ram pressure acts only on the diffuse gas halo surrounding satellites. One might think that this would imply that star formation and the cold gas remain closely coupled. The apparently puzzling result that the star formation (dashed blue line) is more strongly affected by environment than the cold gas (dashed orange) is a consequence of the fact that in galaxies where the cold gas mass has fallen below the threshold value, star formation shuts down and cold gas is no longer consumed.

In Fig. 7, we compare the relations between gas mass fraction versus global sSFR for model galaxies (black dotted) and sample A galaxies (red solid) found in rich environments ($N \geq 7$) where satellite galaxies dominate. We remind the reader that sample A gas fractions are estimated using stacked spectra and errors are computed via bootstrapping. For the models, we plot the mean HI gas mass fraction and the errors represent the variance between the 100 mock catalogues. As can be seen, the relation between gas fraction and sSFR is much steeper in the real data than in the models (the red triangle indicates an upper limit). In the real Universe, satellite galaxies are not usually left with an inert reservoir of low-density cold gas unable to form stars. We suggest that this

\footnote{We note that the models do not include molecular gas as a separate phase. The average molecular-to-atomic ratio in present-day galaxies is about one-third (Saintonge et al. 2011). If the atomic gas fraction is observed to drop by a factor to 0.5 of its field value and the molecular gas is unaffected, the total cold gas mass fraction will drop two-thirds of its field value. Accounting for the molecular component will not, however, cause a reversal in the trend between cold gas fraction and sSFR.}
is because such reservoirs are more easily stripped from the galaxy than currently assumed in the models.

In summary, the implementation of star formation quenching processes in the semi-analytic models produces relative trends in gas mass fraction and sSFR that disagree with observations.

4 SUMMARY AND DISCUSSION

In this work, we have used a complete, volume-limited sample of nearby galaxies with $M_\star > 10^{10} M_\odot$, with coverage by the ALFALFA, SDSS and GALEX surveys, to study how the average H I content and the global and central sSFRs of galaxies depend on local density at fixed stellar mass.

Our main new result is that H I gas mass fraction and sSFR do not scale with local density in the same way. For galaxies with stellar masses less than $10^{10.5} M_\odot$ the atomic gas mass fractions decline most strongly as a function of density, followed by their global and central SFRs. The same ordering is not seen for more massive galaxies.

In order to interpret this result, we compare our results with mock galaxy catalogues generated using the semi-analytic recipes of Guo11 implemented on high-resolution cosmological simulations of structure formation in a Λ cold dark matter Universe. We demonstrate that the local density parameter that we have defined is tightly correlated with the fraction of galaxies that are satellite rather than central galaxies.

In the Guo11 models, star formation in satellite galaxies shuts down as a result of gas ‘starvation’ – tidal and ram-pressure forces remove the gaseous haloes surrounding the satellites, and as a result, cooling and infall of new gas on to these systems cease. The SFRs in satellites decline as their cold gas reservoir is used up. Eventually, the surface density of cold gas falls below the critical threshold value for star formation to occur, and star formation stops entirely. The models thus predict that the average sSFRs of galaxies should decrease with $N$ more strongly than their H I gas mass fractions, which is exactly the opposite to what is seen in observations.

We suggest that the assumption in the models that ram pressure acts only on the diffuse gas surrounding galaxies is wrong. A question one might ask is whether the H I-deficient galaxies in our sample are located in environments where ram-pressure stripping could plausibly occur. In Fig. 8, we plot the distribution of dark matter halo masses that host galaxies in our mock catalogue with stellar masses in the range of $10 < \log M_\star < 10.5$ and local environment parameter $N > 7$ (solid curve) and $N < 7$ (dotted curve). $N \geq 7$ corresponds to environments where the mean gas mass fraction of galaxies of this mass bin has dropped by more than a factor of 2 with respect to ‘isolated’ galaxies with $N = 0$. As can be seen, the majority of such galaxies are in dark matter haloes with masses in the range of $10^{13} - 10^{14} M_\odot$, i.e. they are in galaxy groups rather than clusters. In contrast, most galaxies in the same stellar mass range with $N < 7$ are located in dark matter haloes with masses less than $10^{12} M_\odot$, which are not expected to have a hot gas atmosphere (Birnboim & Dekel 2003). We conclude, therefore, that in order to bring the models into agreement with observations, ram-pressure effects would need to strip atomic gas from galaxies in dark matter haloes more massive than $10^{13} M_\odot$.

One might ask whether tidal forces are likely to be more effective than ram pressure at stripping material from galaxies in lower density environments. Tidal interactions between galaxies can affect both the gas and the stars in these systems. The tidal force scales as $M d^2$, where $M$ is the mass of the neighbouring galaxy and $d$ is its separation. In Fig. 9 (top panel), we analyse trends in H I gas mass fraction and sSFR as a function of the summed tidal force from the surrounding galaxies. We use the projected distance as the measure of galaxy separation – this is not strictly correct, but it is a better indicator of true separation than a 3D estimate in rich groups and clusters where galaxy peculiar velocities are large. We also look at trends in H I gas fraction and sSFR as a function of the distance to the nearest neighbour (bottom panel). The distances are 2D projected ones. The left-hand and right-hand columns correspond to the two bins of $M_\star$ as labelled at the top of the diagram. Error bars are evaluated by bootstrap re-sampling the galaxies in the stack.
the nearest neighbour (Fig. 9, bottom panel). We find very weak effects as a function of both quantities. In addition, we do not observe the same ordering of HI gas mass fraction, global and fibre sSFR seen in Fig. 3 when we plot these quantities as a function of the summed tidal force. However, we note that the relevant tidal force is not the current one, at the current separation, but the maximum tidal force, experienced at the closest separation, which generally occurred in the past. Further investigation will be necessary to make conclusive statements as to the role of tidal stripping in producing the effects that we see.

We also caution that the analysis presented in this work is only statistical in nature. When stacking, it is not possible to distinguish between the effects of starvation or ram-pressure mechanisms in individual galaxies. Without resolved gas maps, we have no information on the spatial extent or the morphology of the atomic gas in the galaxies in our sample, which would more clearly diagnose ram-pressure stripping in individual systems. It would also be very interesting to study relative trends in gas and stars not only as a function of local density, but as a function of dark matter halo mass. This could be done by correlating the available ALFALFA data with group catalogues generated from the SDSS (Yang et al. 2007). With the full ALFALFA data set, it will be possible to measure the decrease in HI for increasing group/clustercentric distance, which would put stronger constraints on ram-pressure stripping mechanisms. Eventually, the all-sky surveys planned at the Westerbork telescope (APERTIF; Verheijen et al. 2008) and at the Australian SKA Pathfinder telescope (ASKAP) will scan the sky in the 21-cm line with much better sensitivity and resolution than currently possible and produce data sets that are ideal for studying the environmentally driven processes that are important in understanding galaxy evolution.

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APPENDIX A: CORRECTION FOR BEAM CONFUSION

The Arecibo telescope is a single dish of 305 m in diameter and has an FWHM beam of $\sim 3.5$ arcmin at 21 cm, which corresponds to a physical scale of 150 kpc at the mean redshift of the galaxies in our sample ($z \leq 0.037$). Confusion of signals coming from different galaxies within the beam at similar redshift is thus of possible concern. An example of such a case is shown in Fig. A1, where two additional companion galaxies are located within the beam. The SDSS image of the galaxy is shown on the left and the yellow circle indicates the Arecibo beam size. In the right-hand upper panel, the resulting spectrum obtained with Arecibo is shown. The vertical lines flag the expected central velocities of the three objects from their SDSS redshifts.

As discussed in Paper I, section 3, we visually inspected each spectrum and discarded the ones with a strong signal close to the galaxy but not centred at the expected redshift, so the galaxy shown in Fig. A1 will actually be discarded from the sample. In our analysis, confusion will arise from the stacking of non-detected HI emission, or if the companion and main target have almost exactly the same redshift.

In previous work (Paper I; Fabello et al. 2011b) we did not apply any correction for possible confusion. For the environmental analysis, confusion may be larger, especially in the high-density bins where galaxies are more clustered. In order to identify confused objects, we search the MPA-JHU spectroscopic sample of galaxies with $M_\star > 3 \times 10^9 M_\odot$ for objects with projected distance smaller than the beam FWHM and velocity separation smaller than 300 km s$^{-1}$. If the velocity difference is larger than this value, the HI signals will not overlap. Companions at large velocity separation may increase the noise in the baseline, but do not affect the measured gas content. Around 20 per cent of sample A targets have at least one companion that meet these criteria.

In order to correct for confusion, we proceed as follows.

1) We estimate the expected gas content of each companion, using the relation between colour, stellar mass surface density and HI gas fraction derived by Zhang et al. (2009):

$$\log \left( \frac{M_{\text{HI}}}{M_\star} \right) = -1.732 (g - r) + 0.215 \mu_i - 4.084, \quad (A1)$$

where $\mu_i$ is the surface brightness in the $i$ band, and $g$ and $r$ are SDSS magnitudes corrected for Galactic extinction.

2) We estimate the actual signal contaminating the stacked spectrum. First, we apply a correction factor to the emission from the companion ($f_1$) using the projected distance between the target and the companion. The beam profile can be approximated with a 2D Gaussian with $\sigma_x = (2\sqrt{2} \ln 2)^{1/2} \times 3.3$ arcmin and $\sigma_y = (2\sqrt{2} \ln 2)^{1/2} \times 3.8$ arcmin, so that its response decreases at the edges. The bigger companion in Fig. A1, for example, lies at a projected distances of $x \simeq 0.4$ arcmin and $y \simeq 1$ arcmin from the target. Therefore, $f_1 = \exp[-0.5(x/\sigma_x)^2 - 0.5(y/\sigma_y)^2] = 0.8$ of its flux would be recorded. Likewise, only part of the signal from the companions will actually overlap with the main target in velocity space. To estimate this second correction factor ($f_2$), we calculate the expected HI line widths of both the main target ($w_{\text{TF}}$) and the companion ($w_{\text{c}}$), assuming a box-shape profile. To evaluate the observed width we use a Tully–Fisher relation as in Paper I (section 3.2), where $w_{\text{obs}} = w_{\text{TF}} \sin(\text{incl})$ and $w_{\text{TF}}$ is evaluated following the relation

$$w_{\text{TF}} = (2.5 - 1.2 \log \left( \frac{M_\star}{10^9 M_\odot} \right)) \times 210 \text{ km s}^{-1},$$

Figure A1. Example of possible signal confusion inside the Arecibo beam. Left: SDSS image of the galaxy GASS 49727 and its companions. The yellow circle indicates the 3.5 arcmin Arecibo beam. Right: the spectrum obtained with Arecibo. On top, the main target (black solid line) and the two companions (coloured dotted lines) central velocities are flagged. On the bottom, the shadowed regions show how we would model the HI signals, as described in the text.
from Giovanelli et al. (1997), and using the SDSS $i$-band magnitude, $k$-corrected and corrected for Galactic and internal extinction (as in equations 11 and 12 in Giovanelli et al. 1997). The correction factor $f_2$ is given by the velocity overlap ($\Delta w$) between $w_i$ and $w_c$: $f_2 = \Delta w / w_c$. As an example, in Fig. A1 (bottom spectrum), the dashed regions represent how we would have modelled the three signals contributing to the spectrum. In the example, the entire flux from the green companion contributes to the measured signal ($f_2 = 1$), because it overlaps fully with the main target emission (black region). In contrast, the pink companion contributes only a very small fraction of its emission to the signal (overlap of $f_2 = 0.06$).

(3) For companions with separation from the main target $\Delta v > 50$ km s$^{-1}$, we check that the H I mass predicted using equation (A1) lies below the ALFALFA upper limit. If an H I mass lies above the limit, the corresponding companion should have been flagged during visual inspection of the spectrum. Failure to detect such a companion actually implies that the Zhang et al. estimate of the H I content is too high; we then reset our estimate of the gas mass of the companion to the actual ALFALFA upper limit.

(4) Finally, we subtract the contributions from all the confused companions to the H I mass measured from the stacked spectrum, as follows.

Because of the weight we apply to the spectra of the individual galaxies, a gas fraction measured from the stacked spectrum is (Paper I, section 3.3)

$$\frac{M_{HI}}{M_*} = \frac{2.356 \times 10^5}{\Sigma_i w_i} \sum_i \frac{D_L^2(z_i) S_i}{(1 + z_i) M_{x,i} w_i},$$

(A2)

where $D_L(z)$ is the luminosity distance, $S$ is the integrated H I flux and $w = 1/\text{rms}^2$ and $i$ is the index running over the individual galaxies. The total signal $S_i$ is actually the real emission from the main target ($S_t$) plus the ones from the confused objects ($S_c$), weighted for the two factors described in point (2):

$$S_i = S_t + \sum_c f_{1,c} f_{2,c} S_c.$$

We can rewrite equation (A2) as

$$\frac{M_{HI}}{M_*} \left( \frac{M_{HI}}{M_*} \right)_t + \frac{2.356 \times 10^5}{\Sigma_i w_i} \sum_i \frac{D_L^2(z_i)}{(1 + z_i) M_{x,i}} w_i,$$

And finally, if we substitute the companions' gas fractions estimated from photometry ($gf_c$), as described in equation A1, we obtain

$$\left( \frac{M_{HI}}{M_*} \right)_t \frac{M_{HI}}{M_*} + \frac{1}{\Sigma_i w_i} \times \sum_i \left[ \frac{D_L^2(z_i)}{(1 + z_i) M_{x,i}} \sum_c \left( f_{1,c} f_{2,c} gf_c (1 + z_c) \right) \right] .$$

As mentioned in the paper, confusion corrections are always small. Even in the highest density bins, the correction factor is smaller than few per cent.

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