ALFALFA H\textsc{i} data stacking – I. Does the bulge quench ongoing star formation in early-type galaxies?

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ABSTRACT

We have carried out an H\textsc{i} stacking analysis of a volume-limited sample of \(\sim 5000\) galaxies with imaging and spectroscopic data from GALEX and the Sloan Digital Sky Survey, which lie within the current footprint of the Arecibo Legacy Fast ALFA (ALFALFA) survey. Our galaxies are selected to have stellar masses greater than \(10^{10}\) M\(_{\odot}\) and redshifts in the range \(0.025 < z < 0.05\). We extract a subsample of 1833 ‘early-type’ galaxies with inclinations less than 70°, with concentration indices \(C > 2.6\) and with light profiles that are well fit by a De Vaucouleurs model. We then stack H\textsc{i} line spectra extracted from the ALFALFA data cubes at the 3D positions of the galaxies from these two samples in bins of stellar mass, stellar mass surface density, central velocity dispersion and NUV – r colour. We use the stacked spectra to estimate the average H\textsc{i} gas fractions \(M_{\text{H}\textsc{i}}/M_\ast\) of the galaxies in each bin. Our main result is that the H\textsc{i} content of a galaxy is not influenced by its bulge. The average H\textsc{i} gas fractions of galaxies in both our samples correlate most strongly with NUV – r colour and with stellar surface density. The relation between average H\textsc{i} fraction and these two parameters is independent of concentration index \(C\). We have tested whether the average H\textsc{i} gas content of bulge-dominated galaxies on the red sequence differs from that of late-type galaxies on the red sequence. We find no evidence that galaxies with a significant bulge component are less efficient at turning their available gas reservoirs into stars. This result is in contradiction with the ‘morphological quenching’ scenario proposed by Martig et al.

Key words: galaxies: evolution – galaxies: fundamental parameters – radio lines: galaxies.

1 INTRODUCTION

Galaxies have long been known to follow well-ordered sequences in many properties (see Roberts & Haynes 1994, for a review). In the simplest classification scheme, galaxies divide into spirals and ellipticals. In more complex schemes, these classes are partitioned into additional subclasses. Irrespective of the exact classification scheme, there are clear systematic trends in the bulge-to-disc ratios, surface brightnesses and in the concentration of light, all of which increase from spirals to ellipticals. Star formation rates and gas content decrease along this same sequence.

With the advent of large spectroscopic surveys of nearby galaxies, such as the Sloan Digital Sky Survey (SDSS; York et al. 2000), the relationships between galaxy properties that can be derived from the combination of optical imaging and spectroscopy, e.g. stellar mass, size, concentration index, star formation rate, metallicity and dust content, have now been systematized and quantified in considerable detail (e.g. Kauffmann et al. 2003b; Brinchmann et al. 2004; Tremonti et al. 2004; Baldry et al. 2004, 2006). Our understanding of how the neutral gas content of galaxies relates to other galaxy properties lags far behind.

The cold gas content of a galaxy is known to vary strongly with colour and star formation rate. The connection between gas content and galaxy morphological type remains unclear. Whereas star-forming spiral galaxies almost always contain H\textsc{i} gas, the H\textsc{i} content of early-type galaxies is considerably more difficult to predict. Some Es and S0s have neutral atomic hydrogen gas content similar to those of Sb–Sc type spirals, while others contain several orders of magnitude less H\textsc{i} (Roberts & Haynes 1994). It has been speculated that these variations may be an indication that the H\textsc{i} gas in ellipticals has an external origin (Knapp,
Turner & Cunniffe 1985), but direct proof of this conjecture is still lacking. Because the H I is on average more difficult to detect in early-type galaxies, the samples discussed in the literature have generally been quite small. Some of the largest systematic studies of gas in early-type galaxies were carried out in the 1980s. Knapp et al. (1985) analysed a sample of 152 nearby elliptical galaxies, of which 23 were detected in the H I line. These authors studied the distribution of the quantity $M_{HI}/L_B$ for these systems. In contrast to spiral galaxies, where the distribution $N(M_{HI}/L_B)$ has a well-defined mean value and a small dispersion, $M_{HI}/L_B$ spans a wide range in ellipticals. Wardle & Knapp (1986) extended this work to SO galaxies and found that the H I detection rate was twice as high compared to ellipticals. Some years later, Bregman, Hogg & Roberts (1992) carried out a study of the interstellar components of 467 early-type galaxies in the Revised Shapley Ames Catalogue and again reported a trend of increasing neutral gas content from E to Sa. These authors suggested that the cold gas in early types is associated mainly with discs and not with the bulge components of these galaxies. However, more recent studies that have mapped HI in nearby early-type galaxies (Morganti et al. 2006) have concluded that the HI can be organized in a variety of different configurations, e.g. in regular discs, in clouds, in rings or even in tidal tail-like structures.

One major problem that has plagued our understanding of cold gas in early-type galaxies is that the available HI data have been inhomogeneous. Large area, blind HI surveys such as the Arecibo Legacy Fast ALFA (ALFALFA; Giovanelli et al. 2005) survey offer uniform coverage over large regions of the sky and allow one to construct complete, unbiased samples of HI-selected galaxies. However, these surveys are shallow and do not in general detect gas-poor early-type galaxies. This limitation has been pointed out in recent papers by di Serego Alighieri et al. (2007) and Grossi et al. (2009), which used ALFALFA data to study an unbiased sample of early-type galaxies in the Virgo cluster region. They were able to compare the HI content of early-type galaxies drawn from field and group environments, but their average detection rates were much smaller than earlier studies based on incomplete and inhomogeneous data.

The Hubble morphological classification scheme is based on the optical appearance of a galaxy which in turn depends both on structural properties such as its bulge-to-disc ratio and on star formation rate. If we wish to understand the physical processes that regulate the neutral gas content of galaxies, it is preferable to analyse the effects of star formation and galaxy structure separately. Recently, Helmboldt (2007) studied 30 E and SO galaxies with signs of recent or ongoing star formation and concluded that such systems are more gas rich than E/0 galaxies with old stellar populations. The availability of sizes, surface brightnesses and parameters measuring the concentration of the light for samples of millions of galaxies made possible due to recent advances in large-scale CCD surveys and automatic image processing techniques, enable a new approach to understanding the interplay between stars and gas in early-type systems.

In this paper, we make use of stacking techniques to analyse whether the average HI gas fraction of a galaxy is affected by the presence of a significant bulge component. Stacking has now become a common tool to constrain the statistical properties of a population of objects that lack individual detections in a survey: by co-adding the signal from many objects with known sky positions and redshifts, the background noise can be decreased and one can recover the average HI flux of the ensemble. Stacking techniques have been applied to a wide variety of different astrophysical data. Examples include studies of faint radio active galactic nuclei (Hodge et al. 2009), studies of star formation in high-redshift Lyman break galaxies (Carilli et al. 2008), studies of the intracluster light using stacked optical images (e.g. Zibetti et al. 2005) and the soft X-ray properties of high-redshift quasars (Shen et al. 2006). Stacking has been applied to H I data as well, with the purpose of studying the HI properties of gas at redshifts that are currently not well probed by existing radio telescopes (individual detections of HI emission reach redshifts $z \sim 0.25$ and require extremely long integrations, Catinella et al. 2008). Chengalur, Braun & Wieringa (2001) stacked non-detections in different regions of a $z = 0.06$ cluster to investigate environmental effects. More recently, HI stacking was used by Verheijen et al. (2007) to probe the Butcher–Oelmer effect at $z \sim 0.2$, and by Lah et al. (2007, 2009) to attempt to constrain the HI content of star-forming galaxies at $z \sim 0.24$ and galaxies around a cluster at $z \sim 0.37$.

Here, we use ALFALFA survey data to constrain the average HI gas fractions of an unbiased sample of massive early-type galaxies. We study how the HI content depends on parameters such as stellar mass, stellar mass surface density, concentration index, central velocity dispersion and UV/optical colour. The paper is structured as follows. In section 2 we describe the samples considered in this paper. The stacking analysis is described in Section 3. First we study HI gas fraction scaling relations for a complete sample of galaxies and then we compare our results with previous work (Section 4). The analysis of the H I properties of early-type galaxies is presented in Section 5. All distance-dependent quantities in this work are computed assuming $\Omega_m = 0.3, \Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

## 2 SAMPLE SELECTION

Measured redshifts are essential if we wish to recover an accurate estimate of the mean HI content of a population of galaxies using stacking techniques. Our sample is drawn from the ‘parent sample’ of the GALEX Arecibo SDSS Survey (Catinella et al. 2010, hereafter GASS-1), which is a sample of 12 006 galaxies with stellar masses greater than $10^{10} M_\odot$ and redshifts in the range $0.025 < z < 0.05$ selected from the SDSS main spectroscopic sample. The parent sample galaxies are located in the intersection of the footprints of the Data Release 6 of the SDSS (DR6; Adelman-McCarthy et al. 2008), the projected GALEX Medium Imaging Survey (MIS; Martin et al. 2005) and ALFALFA. The average uncertainty in the SDSS spectroscopic redshifts is extremely small (0.0002). As discussed in GASS-1 (see Section 3 for further details), the stellar masses are derived from SDSS photometry following Salim et al. (2007) and have typical errors smaller than 30 per cent. The choice of redshift range is determined by sensitivity limits in the H I observations and by the need to avoid redshift ranges where radio frequency interference (RFI) is a problem.

The acquisition of ALFALFA data is ongoing. Part of the data have already been catalogued and are available to the public (for the ALFALFA sky covered by SDSS; Giovanelli et al. 2007; Kent et al. 2008; Stirwalt et al. 2009). The ALFALFA 40 per cent data set to be released in late 2010 (Martin et al. in preparation; Giovanelli et al., in preparation) includes the following SDSS sky regions: $7.5^h < \alpha_{2000} < 16.5^h, +4^\circ < \delta_{2000} < +16^\circ$ and $+24^\circ < \delta_{2000} < +28^\circ$ and $22^h < \alpha_{2000} < 3^h, +14^\circ < \delta_{2000} < +16^\circ$.

Within the same sky region, the GASS sample contains 3530 galaxies; these constitute the parent sample for our study. We discard some objects because they have poor quality HI data (see Section 3.1), so that the final GASS–SDSS–ALFALFA sample (which...
we call sample A) is composed of 4726 objects. Of these, 23 per cent are galaxies with reliable ALFALFA detections (i.e. objects corresponding to ALFALFA detection codes 1 or 2). Panels (a), (b) and (c) of Fig. 1 show the stellar mass, redshift and NUV−r colour distributions of the galaxies in sample A. The NUV−r colours have been corrected for foreground Galactic extinction, but not for internal extinction. The ALFALFA detection rate is close to 23 per cent for each stellar mass bin in Fig. 1, but is clearly biased to blue-sequence objects (with NUV−r ≲ 3.5) as shown in panel (c). Finally, in panel (d) we plot NUV−r colour versus absolute r-band magnitude $M_r$ for the sample, with black dots representing the full sample and red points the galaxies detected by ALFALFA. Once again we see that the galaxies detected by ALFALFA are almost exclusively found on the blue sequence.

2.1 Galaxy parameters

The optical parameters we use are derived from the MPA–JHU SDSS DR7 release of spectrum measurements or from Structured Query Language (SQL) queries to the SDSS DR7 data base server. The UV parameters are extracted from the GALEX UV photometry by Wang et al. (2010). The reader is referred to section 5 of GASS-1 for more detailed descriptions.

The parameters used in this paper are the following: 1) stellar mass $M_\star$, 2) stellar mass surface density $\mu_\star$, defined as $\mu_\star = M_\star/(2\pi R_{50,z})$, where $R_{50,z}$ is the Petrosian radius containing 50 per cent of the flux in $z$ band in units of kpc, 3) the concentration index $C = R_{90}/R_{50}$, where $R_{90}$ and $R_{50}$ are the radii enclosing 90 and 50 per cent of the r-band Petrosian flux and 4) NUV−r colour. As already explained, the colour is corrected for Galactic extinction only. Corrections for internal dust attenuation are discussed and applied in Schiminovich et al. (2010), where they study the star formation properties of the GASS sample.

In addition to these quantities, we extract the following photometric parameters.

(i) The inclination $i$ to the line of sight is evaluated according to: $\cos i = b/a$, where $a$ and $b$ are the semimajor and semiminor axes from the r-band exponential fit, respectively ($b/a$ for the exponential fit is tabulated as $expAB_R$).

(ii) The likelihood parameters ($lndeV_r$ and $lndxsp_r$ from SDSS), which indicate how well the de Vaucouleurs and the exponential models fit the 1D r-band light profile of the galaxy.

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1 As discussed in Giovanelli et al. (2005), ALFALFA H I line detections are coded into two categories: Code 1 detections have a peak signal-to-noise ratio (S/N) greater than 6.5 and are reliable at greater than 95 per cent confidence; Code 2 detections, referred to as ‘priors’, have a lower S/N between 4.5 and 6.5 but an optical counterpart at the same known redshift. Their reliability is estimated to be greater than 85 per cent.

2 See http://www.mpa-garching.mpg.de/SDSS/DR7/ and http://cas.sdss.org/dr7/en/tools/search/sql.aspx
(iii) The central velocity dispersion $\sigma_{1/8}$ is derived from the SDSS parameter $veldisp$. These velocities are evaluated with the ‘direct fitting’ method\(^3\) using spectra measured within the 3-arcsec diameter fibre aperture. Only values between 70 and 420 km s\(^{-1}\) are reliable. We then correct $veldisp$ for aperture effects. Following Graves, Faber & Schiavon (2009a) and references therein, we scale the fibre velocity dispersion to that at 1/8 of the effective radius: $\sigma_{1/8} = veldisp(\frac{r_{fib}}{1/8}\bar{r}_{e})^{0.04}$, where $r_{fib} = 1.5$ arcsec and $r_{e}$ is the circular galaxy radius, defined as $r_{e} = R_{e}\sqrt{b/a}$. $R_{e}$ is the $r$-band de Vaucouleurs radius (tabulated as $devR_{r}$), and $a$, $b$ are now the major and minor axis from the de Vaucouleurs fit ($b/a$ is tabulated as $devab_{r}$). In general, this correction is small, $\sim5$ per cent. (Note that for galaxies included in sample A, $R_{e}$ has a mean value of 8.2 arcsec.)

\[ \begin{align*}
(a) & \quad \log M_{*}[M_{\odot}] \quad \text{N} \\
& \quad 10.0 \quad 10.5 \quad 11.0 \quad 11.5 \\
& \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \quad 350 \\
(b) & \quad z \quad \text{N} \\
& \quad 0.025 \quad 0.030 \quad 0.035 \quad 0.040 \quad 0.045 \quad 0.050 \\
& \quad 0 \quad 50 \quad 100 \quad 150 \quad 200 \quad 250 \quad 300 \\
(c) & \quad \text{NUV}-r \quad \text{N} \\
& \quad 0 \quad 2 \quad 4 \quad 6 \quad 8 \quad 10 \\
& \quad 0 \quad 100 \quad 200 \quad 300 \quad 400 \\
(d) & \quad M_{*} \quad \text{N} \\
& \quad -22 \quad -21 \quad -20 \quad -19 \quad -18 \quad -17 \quad -16 \\
& \quad 20 \quad 21 \quad 22 \quad 23 \quad 24 \quad 25 \quad 26 \\
\end{align*} \]

**Figure 2.** As in Fig. 1, except for the ETG sample.

### 2.2 ETG sample selection

In this paper, we have chosen to define ‘early-type’ galaxies purely in terms of their structural properties, without regard to their stellar populations or star formation rates. We note that our definition is in contrast to some definitions of ‘early-types’ in the literature, which have excluded galaxies with emission lines (e.g. Bernardi et al. 2003; Graves et al. 2009a). Our goal will be to explore the extent to which the presence or absence of a significant bulge component influences the H\(_{\text{I}}\) content of a galaxy, so we do not wish to bias our conclusions by selecting against bulge-dominated galaxies with emission lines.

Starting from sample A, we extracted a subset of early-type objects (ETG sample) with the following properties:

1. concentration index $C = \frac{R_{90}}{R_{50}} \geq 2.6$;
2. the likelihood that the light profile is fitted by a de Vaucouleurs model is greater than it is by an exponential one and
3. inclination less than 70° (this cut rejects the most inclined systems).

We note that the $C$ parameter has been shown to be an excellent indicator of the bulge-to-total ratio ($B/T$) derived from full 2D bulge/disc decomposition analysis (Gadotti 2009). A cut at $C \geq 2.6$ restricts the sample to galaxies with $B/T \geq 0.4$ (see fig.1 of Weinmann et al. 2009). For the present work we choose our default cut at $C \geq 2.6$, but we also experiment with cuts at larger values of $C$.

Application of our default cut leads to a final ETG sample consisting of 1833 objects. The properties of this sample are shown in Fig. 2. The solid histograms represent the entire sample and the red dashed histograms the subsample detected by ALFALFA. The stellar mass, redshift and the NUV–$r$ colour distributions are shown in panels (a), (b) and (c), respectively. The average ALFALFA detection rate for early-type objects is smaller ($\sim 9$ per cent) than for sample A. The colour–magnitude diagram is shown in panel (d). Most of the early-type targets lie on a well-defined red sequence. Some objects do scatter bluewards of the red sequence. Such objects may be star-forming, transitional or Seyfert galaxies (Schawinski et al. 2007). By selecting targets based on concentration index and inclination, we may also include objects with some disc

\(^3\)See http://www.sdss.org/DR6/algorithms/veldisp.html for more discussion.
component. In Fig. 3 we presents 1×1 arcmin$^2$ SDSS postage stamps of a randomly selected set of galaxies from our ETG sample, that have been ordered by increasing $C$.

3 ALFALFA DATA STACKING

The ongoing ALFALFA survey is scanning 7000 deg$^2$ of the high galactic latitude sky over the velocity interval $v$ (km s$^{-1}$) $\simeq [-2500; 18000]$ (i.e. out to $z \sim 0.06$) using a simple ‘minimum-intrusion’ drift scanning technique (Giovanelli et al. 2005) that exploits the seven-horn Arecibo $L$-band feed array (ALFA). For each of the seven beams, spectra are recorded separately for the two orthogonal polarizations, providing two independent samples. The 2D drift scan data from both polarizations and all beams covering a given portion of the sky are combined to form 3D cubes of dimension 2.4' × 2.4' on the sky and 5500 km s$^{-1}$ in velocity ‘depth’. We refer the reader to Fig. 4, where a schematic representation of one such data-cube is shown. We will refer to this depiction throughout the paper.

The raw spectral resolution of the ALFALFA data, before smoothing, is $\sim$5.5 km s$^{-1}$ and the angular resolution is $\sim$3.3 × 3.8 arcmin$^2$ (corresponding to the full width at half-maximum of each ALFA beam). The data cubes or ‘grids’ are constructed from the drift scan data so that each spatial pixel is 1 arcmin on a side. The 2D drift scans are flux calibrated using the real-time noise diode injection scheme; the position and flux scales of the final grids are updated using fits to the many radio continuum sources they contain (Kent et al. 2008). The ALFALFA processing scheme (Giovanelli et al. 2005) retains all individually recorded spectra for each ALFA beam and each of its polarizations separately; no filtering is performed to discard bad channels. In order to deal with poor quality data, the 2D data for each beam and polarization are visually inspected to flag bad records and frequency channels. The 3D grid construction then proceeds with knowledge of the flagged 2D pixels. Data quality in the final grid then may be limited by the absence of data in channels flagged as contaminated by RFI, weighted as poor by occasional instrumental problems or missing entirely because of incomplete sky coverage. In order to account for these effects, each 3D pixel of the data cube is assigned a quality weight $w$ during the data reduction process, which is a number ranging from 0 (unsuitable data) to 20 (good data), computed according to the availability and quality of data contributing to each pixel. The retention of the full data set and the construction of the accompany ‘weights map’ allows us to judge whether or not adequate data exist for each target so that it can be meaningfully included in the stacking process.

3.1 Creating a catalogue of H I spectra

We extract a spectrum for each galaxy in the sample. As discussed, all our targets are selected from the SDSS spectroscopic survey, so we know both their positions on the sky and their redshifts. We first select the ALFALFA data cube which contains the target and then follow a procedure that includes the following steps: (i) spectrum extraction; (ii) rms evaluation and (iii) final quality check.
Standing waves are periodic fluctuations in the background which occur less than 10. We also keep emission from companion galaxies. In order to detect (green, bottom) and an H\textsc{i} for each target, using the I\textsuperscript{3} × C\textsuperscript{s} spectrum is a histogram of flux density exp= for sample A is 10 arcsec), so we simply integrate for each pixel, which is a point in RA, Dec. and velocity, a value of flux density is recorded. For each target in sample A, we extract a spectrum at a given position of the sky, over the velocity range of the data cube which contains the source. Two examples of extracted spectra are shown on the right, illustrating an H\textsc{i} detection (green, bottom) and an H\textsc{i} non-detection (red, top).

3.1.1 Spectrum extraction

The signal from each target is integrated over a region of the data cube centred on its 3D position. Because noise increases with the square root of the integration area, integrating over too large a region lowers the quality of the spectrum without increasing the signal. Our GASS targets are always smaller then the ALFA beam (the mean R\textsuperscript{60} for sample A is 10 arcsec), so we simply integrate over a sky region of 4 × 4 arcmin\textsuperscript{2}. In Fig. 4, we illustrate how we extract spectra at two different positions in the sky inside the same data cube. The coloured regions indicate where the spectra would be evaluated.

The H\textsc{i} spectrum is a histogram of flux density S as a function of velocity. For each velocity channel \(x\), the corresponding flux density \(S_\text{x}\) is obtained by integrating the signal \(s(x, y)\) over the spatial pixels centred at the target galaxy position, as observed by a radio telescope of beam response pattern \(B\):

\[
S_\text{x} (\text{mJy}) = \frac{\Sigma_\text{x,} \Sigma_\text{y} s(x, y)}{\Sigma_\text{x,} \Sigma_\text{y} B(x, y)},
\]

where \(x, y\) are the sky coordinates (the two polarizations are kept separated). The expression above means that the spatially integrated profile is obtained by summing the signals over all the spatial pixels of interest and dividing by the sum of the normalized beam \(B(x, y)\) over the same pixels (for a detailed discussion, see Shostak & Allen 1980). The ALFALFA beam pattern can be approximated by

\[
B(x, y) = \exp \left[ -\frac{1}{2} \left( \frac{x}{\sigma_x} \right)^2 - \frac{1}{2} \left( \frac{y}{\sigma_y} \right)^2 \right],
\]

with \(\sigma_x = (2\sqrt{2\ln 2})^{-1} × 3.3\) arcmin, and \(\sigma_y = (2\sqrt{2\ln 2})^{-1} × 3.8\) arcmin (Giovanelli et al. 2005).

We note that we discard any spectrum if more than 40 per cent of the pixels have a quality weight \(w\) less than 10. We also keep track of the three strongest continuum sources in an area covering 40 × 40 arcmin\textsuperscript{2} around each source; strong continuum sources can affect our spectra by creating standing waves.\(^4\)

3.1.2 Rms evaluation

For each spectrum we need to measure the rms noise, which will later be used as a weighting factor when we stack spectra. The rms has to be evaluated in regions of the spectrum where there is no emission from the target galaxy, and we also have to avoid spectral regions where there are any spurious signals (e.g. residual RFI that we failed to flag or H\textsc{i} emission from companion galaxies). In order to define the spectral region that might contain galaxy emission, we estimate its expected H\textsc{i} width as follows.

The expected width of the H\textsc{i} spectrum will depend on the rotational velocity of the galaxy as observed along the line of sight. We estimate the expected width \(w_{\text{TF}}\), for each target, using the Tully–Fisher relation. Following Giovanelli et al. (1997b), we use the SDSS i-band magnitude \([k-\text{corrected and corrected for Galactic and internal extinction as in equations (11) and (12) in Giovanelli et al. (1997a)] to estimate \(w_{\text{TF}}\), and the measured inclination of the galaxy to derive \(w_{\text{TF},o}\). We are aware that the Tully–Fisher relation does not hold for all morphological types and environments. We do not think this is a major issue, because these velocities are only used to estimate the region of the spectrum that should contain significant signal from the galaxy.

We then fit a first-order polynomial to the baseline after excluding the region of the spectrum containing signal from the galaxy. This step allows us to eliminate possible gradients in the background. (The top right panel in Fig. 4 shows an example of a spectrum where the baseline is tilted.) We perform a robust polynomial fit over the regions of the spectrum with high values of the quality

\(\text{ISO} = 25\text{ MHz}\)
\(\Delta v = 5.5\text{ km s}^{-1}\)

\(\text{Nch}=1024\)

\(\text{Dec} = 2.4^\circ\)

\(\text{RA} = 2.4^\circ\)

\(\text{vel, z, y, channels}\)

\(\text{NON DETECTION}\)

\(\text{DETECTION}\)

\(\text{km/s}\)

\(\text{mJy}\)

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factor $w$ and then evaluate the rms about the fit over the same region of the spectrum.

The average rms for the whole sample (for each polarization) is $3.6 \pm 0.5$ mJy. After averaging the two polarizations, an rms of $\sim 2.5$ mJy is obtained; this is comparable to the average rms of 2.2 mJy evaluated for published, reduced ALFALFA spectra.

### 3.1.3 Final quality check

After we have extracted the spectra, we visually inspect each of them. We check the extraction process, and we discard spectra with bad baselines caused by continuum sources and those with possible spurious signals close to the galaxy (e.g. if one polarization has a significantly stronger signal than the other or if there is a strong signal close to the object, which may arise from a companion galaxy). These cuts eliminate 624 objects in sample A (11 per cent of the initial sample).

### 3.2 The stacking method

We want to co-add the signals from $N$ different sources located at different redshifts. First we shift each spectrum to the galaxy rest frequency, so each spectrum is centred at zero velocity. We stack together the spectra $S_i$ ($i = 1, \ldots, N$) using their rms as a weight, a standard approach in stacking analysis. In doing this, the final spectrum $S_{\text{stack}}$ would be

$$S_{\text{stack}} = \frac{\sum_{i=0}^N S_i w_i}{\sum_{i=0}^N w_i}$$

$$w_i = \frac{1}{\text{rms}_i^2}.$$  

The stacking of the spectra is done separately for each polarization. Note that ALFALFA is a blind survey which scans the sky uniformly, so the rms for most spectra are similar. If the noise of the input targets is purely Gaussian, the rms of the stacked spectrum is expected to decrease as $1/\sqrt{N}$, where $N$ is the number of objects co-added. In reality, in addition to the Gaussian noise there are likely to be systematic components, e.g. standing waves (we discarded spectra dominated by standing waves, but a weak residual signal could still remain). Because of these additional noise sources, we expect the rms to approach a lower limit as the number of co-added spectra becomes very large.

In Fig. 5 we show how the measured rms of the stacked spectra decreases as a function of the number of co-added objects. We have stacked increasing numbers of randomly selected galaxies from sample A, and for each stack we evaluated an rms as described above. These measurements are shown as dots, while the dashed line shows the expected average rms value assuming Gaussian noise, i.e. $2.5/\sqrt{N}$ mJy. As expected, we see the trend flatten as $N$ approaches values of around 300, where the non-Gaussian noise becomes dominant. The rms continues to decline as $N$ increases, but at a slower rate.

After stacking, we manually process each ensemble spectrum. The reduction process includes the following steps. (i) We average the two polarizations. (ii) A default Hanning smoothing is performed on the spectrum. Depending on the signal-to-noise ratio (S/N), we may apply a boxcar smoothing to decrease the noise if the signal is marginal. Note that we never average over more than nine channels (corresponding to $\Delta v \sim 50$ km s$^{-1}$). (iii) Finally, the baseline is subtracted. We note that the baseline of a stacked spectrum is already almost flat, because the different noise features tend to cancel out when averaging many spectra.

Fig. 6 shows some examples of stacked spectra, obtained by stacking sample A galaxies in five different stellar mass intervals. The vertical axis in each panel shows flux density in mJy, while the horizontal one shows velocity in km s$^{-1}$. Since we shifted each object to the rest-frequency of each galaxy, the stacked signal is centred at zero velocity. For each stacked spectrum, the mass range and the number of objects stacked are reported, as well as the S/N of the detected $\text{H}^1$ signal. As explained above, when the S/N is low, we smooth the spectrum over up to nine channels as done, for example, for the last spectrum in Fig. 6. In the left-hand column of the figure, we show spectra obtained by stacking ALFALFA detections and non-detections. In the right-hand panel, we show the spectra obtained by stacking only the non-detections, demonstrating that the stacking process recovers a signal even if no individual galaxy is detected (dotted lines in Fig. 6 indicate the edges of the signal). Note that the rms decreases with increasing number of co-added objects. The width of the profile is smaller for less massive objects, as expected since they have on average lower circular velocities. If we recover a signal in the stacked spectrum, we measure the integrated emission between the two edges of the $\text{H}^1$ profile (see dotted lines in Fig. 6), which are defined manually for each spectrum. We expect the signal to be symmetric around zero velocity. Even if in some cases the SDSS redshift is slightly off-set with respect to the $\text{H}^1$ emission, the discrepancy will be random and will cancel out when co-adding multiple spectra (note that the SDSS redshift uncertainty is 0.0002, which corresponds to $\sim 60$ km s$^{-1}$).

We evaluate a S/N following Saintonge (2007). We define an $\text{H}^1$ detection if the S/N is greater than 6.5. If there is no detection, we evaluate an upper limit, assuming a $5\sigma$ signal with a width of $300$ km s$^{-1}$, smoothing the spectrum to 150 km s$^{-1}$. (The width of 300 km s$^{-1}$ is chosen because it corresponds to the peak of the distribution of velocity widths for galaxies in the GASS survey.)

### 3.3 Evaluating $\text{H}^1$ gas fractions

Our aim in stacking spectra is to characterize the average $\text{H}^1$ content of a given sample of galaxies, so we are interested in converting our recovered signal into an $\text{H}^1$ mass and also into an average $\text{H}^1$ gas fraction. For a single object, these two quantities are well defined.
Figure 6. Examples of stacked spectra for five stellar mass bins. The x-axis is velocity in km s$^{-1}$, the y-axis is H$\text{I}$ flux density in mJy. Since we shifted each object to its galaxy rest-frequency, the signal is centred at zero velocity. For each spectrum, the mass range and the number of objects stacked are reported, as well as its S/N. Dotted lines show the boundaries of the signal, inside which we integrate the flux. In some spectra, there are spikes/holes caused by poor quality data (note that the spectra containing the bad data were not discarded because the bad pixels are located away from the central regions of interest). Examples of bad regions occur in the first two rows between $v = -1500$ and $-1000$ km s$^{-1}$. Left column: stacked spectra using all galaxies. Right column: stacked spectra using only those galaxies that were not detected by ALFALFA. As expected, the signal is systematically lower for the right column.
The \( \frac{M_{\text{HI}}}{M_\odot} = \frac{2.356 \times 10^6}{1 + z} \left( \frac{D_L(z)}{(\text{Mpc})} \right)^2 \left( \frac{S_{\text{int}}}{(\text{Jy km s}^{-1})} \right), \)

where \( D_L(z) \) is the luminosity distance and \( S_{\text{int}} \) the integrated \( \text{H}_\text{i} \) line flux. A correction for \( \text{H}_\text{i} \) self-absorption is not applied to the \( \text{H}_\text{i} \) mass, as it is likely to be negligible (Haynes & Giovanelli 1984, Appendix B). The \( \text{H}_\text{i} \) gas fraction is simply defined as \( M_{\text{HI}}/M_* \).

For \( N \) individual detections (each with a flux measurement), the average value of their gas fractions can be defined by the weighted mean value:

\[
\left( \frac{M_{\text{HI}}}{M_*} \right)_{\text{av}} = \left( \frac{\sum_{i=0}^{N} \frac{M_{\text{HI},i}}{M_*} w_i}{\sum_{i=0}^{N} w_i} \right),
\]

where the \( w_i \) are defined as in equation (2).

When co-adding spectra, we need to take into account the fact that our targets span a significant range in redshift \( (z_{\text{max}} \approx 2z_{\text{min}}) \), so given the same \( \text{H}_\text{i} \) mass an object at the lowest redshift limit contributes four times more signal than one at the upper redshift limit. Because we are stacking mainly non-detected spectra we do not know how much each galaxy contributes to the total signal. Both the mean and median values of redshift and stellar mass may not be representative. In order to weight each spectrum in a consistent manner, we choose to stack ‘gas-fraction’ spectra \( S_i' \), where the signal that we co-add is no longer the flux \( S \) (mJy), but the quantity

\[
S_i (\text{mJy}) \rightarrow S_i' \left( \text{mJy Mpc}^{-2} \text{M}_\odot^{-1} \right) = \frac{S_i D_L(z_i)}{M_*}. \]

The stacking is performed according to equation (1). With this approach, the stacking creates an average object with respect to the \( \text{H}_\text{i} \) gas fraction of the individual galaxies used to build the stack. In Appendix A, we discuss an alternative approach to evaluating mean gas fractions from stacked spectra, and present comparisons between the two different methods.

We measure errors on the gas fractions using the jackknife method (Tukey 1977; Efron 1982), a statistical tool to estimate a confidence interval on a function of \( N \) measures. The purpose of computing jackknife errors on the mean \( \frac{M_{\text{HI}}}{M_*} \) fraction estimated from a stacked spectrum is to ascertain whether or not the signal is dominated by a few outliers. Schematically, given a function \( \tilde{a}(x_i) \) of \( N \) observations \( x_i \), the jackknife evaluates \( N \) partial estimates \( \tilde{a}_j \) of the function obtained by discarding one element per time. The jackknife estimate \( \tilde{a}^* \) is then the average of the pseudo-values \( \tilde{a}^*_j = N\tilde{a} - (N-1)\tilde{a}_j \). Finally, the sample variance on the pseudo-values is

\[
(\sigma_{\text{jack}})^2 = \frac{1}{N(N-1)} \sum_{j=1}^{N} (\tilde{a}^*_j - \tilde{a}^*)^2. \]

This can be used to provide a confidence interval on \( \tilde{a} - \tilde{a}^* \).

## 4 \( \text{H}_\text{i} \) Gas Fraction Scaling Relations for Massive Galaxies

In this section, we characterize how average \( \text{H}_\text{i} \) gas fraction depends on a variety of different properties for galaxies with stellar masses greater than \( 10^{10} \text{M}_\odot \). First we study the dependence on stellar mass \( M_* \), stellar mass surface density \( \mu_* \), concentration index \( C \) and colour \( \text{NUV} - r \) for galaxies in sample A. We then compare the same relations for galaxies in the bulge-dominated ETG sample (Section 5).

We begin by comparing our results with those of Catinella et al. (2010), who studied the correlation between \( \text{H}_\text{i} \) gas fraction and the properties listed above, for a complete sample of ~200 galaxies from the GASS survey with \( M_* > 10^{10} \text{M}_\odot \). In that survey, the \( \text{H}_\text{i} \) observations reached a much deeper flux limit compared with ALFALFA, so average \( \text{H}_\text{i} \) gas fractions could be derived using individual \( \text{H}_\text{i} \) detections, rather than by stacking. It is important to check whether our stacking method gives answers that are consistent with these published measurements.

In Figs 7 and 8, we present our results for sample A. In each panel, grey dots show the galaxies in sample A that were detected by ALFALFA. Green lines show the average values and 1σ confidence interval of \( \frac{M_{\text{HI}}}{M_*} \) from GASS-1 (see fig. 9 in that paper). Our own estimates of the \( \text{H}_\text{i} \) gas fraction derived from the stacked spectra are plotted as red circles, and the error bars on these points are evaluated using the jackknife method (equation 6). Note that the stacked spectra that yield the measurements, plotted as red circles in Fig. 7 (top panel), are shown in Fig. 6 (left-hand panel). At the bottom of each panel, we record the number of galaxies included in each stack, as well as the percentage of galaxies with ALFALFA detections. In cases where the stack includes more than a few 100 galaxies, the errors on the mean \( \text{H}_\text{i} \) fraction are negligible.

We note that we are able to measure an \( \text{H}_\text{i} \) gas fraction in every bin, even in the very reddest NUV-\( r \) colour bins where the ALFALFA detection rates are close to zero. The fact that the jackknife errors remain relatively small for these bins indicates that the stacked spectra are not dominated by signal from a small fraction of the galaxies.

We find that the average \( \text{H}_\text{i} \) gas fractions derived from the stacked spectra are in excellent agreement with the results reported in GASS-1. The point-by-point agreement is generally within 1σ, with the possible exception of the lowest stellar mass and stellar mass surface density bins, where we find gas fractions that are systematically lower than those reported in the GASS-1 paper. We caution that low-mass galaxies were somewhat underrepresented in the first GASS data release. Our error bars only indicate statistical errors and do not account for other effects, such as cosmic variance, so we do not think the discrepancy is significant.

As discussed in GASS-1, the \( \text{H}_\text{i} \) gas fraction is a decreasing function of stellar mass, stellar mass surface density, concentration index and colour. The slopes of these relations for our sample A are listed in the third column of Table 1. Here we only report the total change in \( \log \frac{M_{\text{HI}}}{M_*} \) for each relationship, which allows a comparison among the different properties:

\[
M_* : \quad \Delta \log \frac{M_{\text{HI}}}{M_*} = 0.20
\]

\[
C : \quad \Delta \log \frac{M_{\text{HI}}}{M_*} = 0.24,
\]

\[
\mu_* : \quad \Delta \log \frac{M_{\text{HI}}}{M_*} = 0.45.
\]

\[
\text{NUV} - r : \quad \Delta \log \frac{M_{\text{HI}}}{M_*} = 0.52.
\]

The correlations between gas fraction and both \( M_* \) and concentration index (Fig. 7) are weak. In contrast, the average value of \( \frac{M_{\text{HI}}}{M_*} \) drops by more up to a factor of 25 when plotted as a function of \( \text{NUV} - r \) colour or stellar mass surface density. Although stacking recovers the average trends of the population extremely well, it does not provide any information on the underlying scatter. This can only be studied with individual gas fraction measurements, as in GASS-1.

## 5 \( \text{H}_\text{i} \) Study of a Complete Sample of ETG Galaxies

In this section, we ask whether bulge-dominated galaxies with \( M_* > 10^{10} \text{M}_\odot \) lie on the same \( \text{H}_\text{i} \) scaling relations as the general
Figure 7. Red circles: average gas fractions of sample A galaxies derived from stacking are plotted as a function of stellar mass $M_*$ (top) and concentration index $C$ (bottom). The points are plotted at the mean value of $M_*$ or $C$ for the galaxies in the bin. The red line (upper panel) show a linear fit to these results, which are compared with the average H$_\text{i}$ gas fractions from the GASS-1 paper (green lines). Green dashed lines show the 1$\sigma$ uncertainties on the GASS-1 estimates. Grey dots show galaxies with ALFALFA detections from sample A. The numbers written in the panels indicate the numbers of objects co-added in each bin (Tot), and the percentage of them directly detected by ALFALFA (per cent Det). The values plotted are reported in Table 1, fourth and fifth columns.
The population of galaxies with $M_\star > 10^{10} M_\odot$. Our goal is to determine whether the presence of the bulge plays a role in regulating the rate at which gas is consumed into stars, for example by stabilizing the disc (e.g. Martig et al. 2009). In order to test the role of the bulge in a clean way, we must account for the fact that the physical properties of galaxies are strongly correlated. If one selects a subsample of bulge-dominated galaxies from the parent sample $A$, one will automatically select a sample of galaxies with higher stellar masses, higher stellar mass surface densities and redder colours. It is therefore important to understand whether or not bulge-dominated galaxies differ in $\mathrm{H}^\prime$ content from the parent sample at fixed values of these parameters.

*Figure 8.* Average gas fractions of sample $A$ galaxies derived from stacking are plotted as a function of stellar mass surface density $\mu_\star$ (top) and NUV$-r$ colour (bottom). Symbols and colours as in Fig. 7. The values plotted are reported in Table 1, fourth and fifth columns.
Our results are presented in Figs 9 and 10 and in Table 1. In all the plots, blue circles are the average gas fractions obtained from stacking the ETG sample and the error bars are evaluated using the jackknife method (equation 6). Upside-down triangles indicate the upper limit in the case of a stack that yields a non-detection. The red lines (circles) show the fits to the mean H I gas fraction relations obtained for sample A. Our main result is that the average H I gas fractions of bulge-dominated galaxies are significantly lower (by approximately a factor of 2) than those of the parent sample at a given value of stellar mass. A similar, but weaker reduction in the average H I gas fraction contrasted between low and high stellar mass objects is shown in Figs 9 and 10. The H I content of galaxies more massive than 10¹¹ M☉ represents the further cut in concentration index, black ones the cut in inclination).

In Fig. 11, we show how the average gas fractions of galaxies in the ETG sample vary as a function of position in the 2D plane of colour versus stellar mass density. Bulge-dominated galaxies are mainly found on the red sequence, but there is a minority population with bluer colours. We adaptively bin the sample in two dimensions by recursively dividing the plane into axis-aligned rectangles. We stop dividing a region when a further split would lower the S/N below the detection threshold of 6.5. Fig. 11 (bottom panel) shows the final binning used. In each bin the measured gas fraction (expressed as a percentage of the stellar mass) is reported. In Fig. 11 (top panel) we colour-code the (NUV−r)−μ* plane according to gas fraction. The H I content decreases going from left to right (towards increasing stellar mass surface density) and from bottom to top (towards redder colours). The most significant variation is clearly along the colour direction.

### 5.1 A Test of the morphological quenching scenario

The idea that galaxy discs are more resistant to the formation of bars, spiral density waves and other instabilities, if they are embedded within a dynamically hot halo or bulge, has its origins in early work by Ostriker & Peebles (1973). Recently, Martig et al. (2009) have proposed this so-called ‘morphological quenching’ mechanism as a way of explaining why present-day bulge-dominated galaxies on the red sequence cease growing in stellar mass in environments where they were formed.

| x       | (x) | a     | <(M_HI/M*)> | N  | <(M_HI/M*)> | N  | <(M_HI/M*)> | N  | <(M_HI/M*)> | N  |
|---------|-----|-------|-------------|----|-------------|----|-------------|----|-------------|----|
| Log M*  | 10.16 | -0.78 ± 0.03 | 0.22 ± 0.008 | 1734 | 0.056 ± 0.009 | 493 | 0.091 ± 0.011 | 311 | 0.118 ± 0.019 | 139 |
| 10.45   | 0.128 ± 0.005 | 1538 | 0.036 ± 0.005 | 566 | 0.056 ± 0.006 | 389 | 0.049 ± 0.006 | 294 |
| 10.74   | 0.079 ± 0.004 | 1025 | 0.033 ± 0.004 | 516 | 0.043 ± 0.005 | 351 | 0.041 ± 0.005 | 328 |
| 11.03   | 0.044 ± 0.004 | 430 | 0.015 ± 0.004 | 246 | 0.018 ± 0.003 | 183 | 0.014 ± 0.004 | 178 |
| 11.28   | 0.026 ± 0.005 | 63 | 0.016 ± 0.004 | 43 | 0.007* | 32 | 0.009* | 25 |
| C       | 1.97 | -0.59 ± 0.03 | 0.288 ± 0.013 | 420 | - | - | - | - | - |
| (R_0/R_0) | 2.32 | 0.242 ± 0.008 | 1149 | - | - | - | - | - | - |
| 2.71    | 0.124 ± 0.006 | 1464 | - | - | - | - | - | - | - |
| 3.08    | 0.064 ± 0.004 | 1409 | - | - | - | - | - | - | - |
| 3.40    | 0.044 ± 0.007 | 287 | - | - | - | - | - | - | - |
| Log μ*  | 7.99 | -0.87 ± 0.03 | 0.481 ± 0.025 | 193 | - | - | - | - | - |
| 8.27    | 0.328 ± 0.011 | 625 | 0.293 ± 0.082 | 8 | 0.336 ± 0.109 | 5 | 0.435 ± 0.154 | 3 |
| 8.56    | 0.185 ± 0.008 | 1003 | 0.112 ± 0.018 | 148 | 0.107 ± 0.019 | 120 | 0.139 ± 0.047 | 41 |
| 8.86    | 0.087 ± 0.008 | 1371 | 0.077 ± 0.006 | 661 | 0.071 ± 0.007 | 461 | 0.073 ± 0.010 | 258 |
| 9.13    | 0.050 ± 0.003 | 1237 | 0.043 ± 0.004 | 857 | 0.037 ± 0.004 | 591 | 0.036 ± 0.004 | 535 |
| 9.40    | 0.034 ± 0.006 | 287 | 0.035 ± 0.008 | 183 | 0.029 ± 0.011 | 89 | 0.020 ± 0.005 | 124 |
| NUV−r   | 2.20 | -0.38 ± 0.01 | 0.543 ± 0.024 | 209 | 0.351 ± 0.091 | 14 | 0.301 ± 0.121 | 10 | 0.569 ± 0.293 | 3 |
| 2.82    | 0.298 ± 0.009 | 855 | 0.253 ± 0.019 | 123 | 0.220 ± 0.020 | 77 | 0.247 ± 0.038 | 29 |
| 3.58    | 0.156 ± 0.007 | 760 | 0.127 ± 0.011 | 211 | 0.125 ± 0.014 | 127 | 0.152 ± 0.020 | 74 |
| 4.40    | 0.079 ± 0.006 | 609 | 0.073 ± 0.009 | 278 | 0.072 ± 0.013 | 180 | 0.084 ± 0.011 | 118 |
| 5.24    | 0.032 ± 0.004 | 909 | 0.032 ± 0.005 | 669 | 0.027 ± 0.005 | 468 | 0.022 ± 0.004 | 387 |
| 5.89    | 0.023 ± 0.004 | 621 | 0.024 ± 0.004 | 490 | 0.014 ± 0.004 | 349 | 0.021 ± 0.004 | 315 |
| Log σ   | 1.90 | - | 0.149 ± 0.014 | 287 | 0.077 ± 0.020 | 76 | 0.085 ± 0.026 | 50 | 0.058 ± 0.016 | 99 |
| 2.01    | 0.135 ± 0.009 | 483 | 0.089 ± 0.014 | 169 | 0.074 ± 0.016 | 114 | 0.059 ± 0.006 | 302 |
| 2.10    | 0.077 ± 0.005 | 738 | 0.054 ± 0.007 | 353 | 0.047 ± 0.008 | 234 | 0.059 ± 0.010 | 136 |
| 2.20    | 0.053 ± 0.005 | 711 | 0.041 ± 0.004 | 439 | 0.042 ± 0.006 | 287 | 0.048 ± 0.006 | 252 |
| 2.29    | 0.023 ± 0.003 | 436 | 0.022 ± 0.003 | 322 | 0.022 ± 0.004 | 222 | 0.025 ± 0.004 | 246 |
| 2.40    | 0.010 ± 0.002 | 167 | 0.012 ± 0.002 | 141 | 0.008* | 112 | 0.009* | 123 |
Figure 9. The dependence of the average H\textsc{i} gas fraction on stellar mass $M_\star$ (top) and on central velocity dispersion $\sigma$ (bottom) for the ETG sample (blue symbols). The relations found for sample A are shown in red for comparison (the fit for the $M_\star$ relation, the actual points for $\sigma$). Upside-down triangles indicate upper limits in the case of a non-detection. The numbers written in the panels indicate the numbers of objects co-added in each bin (Tot), and the percentage of them directly detected by ALFALFA (per cent Det). Grey dots show sample A galaxies with ALFALFA detections. We have also applied more stringent cuts to the ETG sample, as explained in the text: cyan circles represent a sample with $C > 3$ (52 per cent of the original ETG sample); black circles are for a sample with $b/a > 0.6$ (or inclination lower than $55^\circ$ – 68 per cent of the original sample). The values plotted for each ETG sample are reported in Table 1, sixth–11th columns.
where they continue to accrete gas. In their picture, a disc with similar gas content will be much less efficient at forming stars if it is embedded in a galaxy with a significant bulge component. As stated in the abstract of their paper, 'our mechanism automatically links the colour of the galaxy with its morphology and does not require gas consumption, removal or termination of the gas supply'.

To test whether the 'morphological quenching' process is truly important in maintaining the low observed rates of star formation in red sequence galaxies, we have performed the following experiment. We have binned galaxies with $C < 2.6$ and $C > 2.6$ in the 2D plane of NUV−$r$ colour versus stellar mass (note that we use the same bin boundaries for both samples). We stack the H I spectra of

Figure 10. Average H I gas fraction dependence on stellar mass surface density $\mu_*$ (top) and NUV−$r$ colour (bottom) for the ETG sample. Symbols and colours are the same as described in Fig. 9. The values plotted for each ETG sample are reported in Table 1, sixth–11th columns.
Figure 11. Average $\text{H}_1$ gas fraction dependence in the 2D plane of stellar mass surface density $\mu_*$ and NUV–$r$ colour for galaxies in the ETG sample. In the top panel the dots show individual objects, while the colours show the (interpolated) gas fractions measured with the stacking as a function of position in the plane (the colour scale key is included above the plot). The bottom panel shows the adopted binning. For each bin, the gas fraction measured from the stacked spectrum is noted.
the galaxies in each bin and calculate the average \( H_\text{i} \) gas fraction, as explained above. In Fig. 12, we report for each bin the ratio between the gas fraction of the disc-dominated (DD) objects and the bulge-dominated (BD) ones, i.e.

\[
r = \frac{M_{H_\text{i}}/M_*\text{DD}}{M_{H_\text{i}}/M_*\text{BD}}.
\]

If the morphological quenching scenario is correct, then at fixed stellar mass, we would expect to find higher average \( H_\text{i} \) gas fractions for bulge-dominated galaxies on the red sequence than for disc-dominated galaxies on the red sequence.

The results in Fig. 12 show that in general the opposite is true. Gas fractions are always slightly higher for the disc-dominated galaxies than for bulge-dominated ones. The gas fraction differences do appear to be largest for red sequence galaxies with \( \text{NUV} - r > 5 \), but the sign of the difference contradicts the predictions of Martig et al. (2009).

It is important to check that our result is not simply due to extinction effects. Some of the reddest, gas-rich disc-dominated objects may actually be heavily obscured systems that will move blueward when dust corrections are applied. Following Schiminovich et al. (2010), we have applied dust corrections to the \( \text{NUV} - r \) colours of the galaxies in our sample with \( D_n(4000) < 1.7 \).

In order to make up for the loss of red sequence galaxies with \( \text{NUV} - r > 5 \), but the sign of the difference contradicts the predictions of Martig et al. (2009). In their paper, Schiminovich et al. use a volume-limited sample of 200 galaxies from the GASS survey to explore the global scaling relations associated with the ratio \( \text{SFR}/M_{H_\text{i}} \), which they call the \( H_\text{i} \)-based star formation efficiency. They found that the average value of this star formation efficiency has little variation with any galaxy parameter, including the concentration index.

6 SUMMARY

We have carried out a stacking analysis using ALFALFA scans of a volume-limited sample of \( \sim 5000 \) galaxies with imaging and spectroscopic data from \textit{GALEX} and the SDSS. The galaxies have stellar masses greater than \( 10^{10} M_\odot \) and redshifts in the range \( 0.025 < z < 0.05 \). We extract a subsample of 1833 ‘early-type’ galaxies with inclinations less than 70°, with concentration indices \( C > 2.6 \), and with light profiles that are well fitted by a De Vaucouleurs model. We then stack the ALFALFA spectra of the galaxies from these two samples in bins of stellar mass, stellar surface mass density, central velocity dispersion and \( \text{NUV} - r \) colour, and we use the stacked spectra to estimate the average \( H_\text{i} \) gas fractions \( M_{H_\text{i}}/M_* \) of the galaxies in each bin.

Our main result is that \( H_\text{i} \) gas fractions of both early-type and late-type galaxies correlate primarily with \( \text{NUV} - r \) colour and stellar mass surface density. The relation between average \( H_\text{i} \) gas fraction and these two parameters is independent of \( C \), and hence of the bulge-to-disc ratio of the galaxy. We note that at fixed stellar mass, early-type galaxies do have lower average \( H_\text{i} \) fractions than late-type galaxies, but this effect does not arise as a direct
consequence of the presence of the bulge and we discuss possible implications below.

We have also tested whether the average $\text{H} \, i$ gas content of bulge-dominated galaxies differs from that of late-type galaxies at fixed values of NUV$-r$ and $\mu_*$. We find no evidence that red-sequence galaxies with a significant bulge component are less efficient at turning their available gas reservoirs into stars. This result is in contradiction with the ‘morphological quenching’ scenario proposed by Martig et al. (2009).

7 DISCUSSION

We now consider possible implications of this work.

(1) The $\text{H} \, i$ content of a galaxy is independent of its bulge-to-disc ratio. This can be understood if the following two conditions are satisfied. (1) The $\text{H} \, i$ gas in early-type galaxies is always associated with discs or with material that is in the process of settling into discs. (2) The formation of the galactic disc is decoupled from the formation of the bulge. One way that condition (2) could be satisfied is if the disc is formed from gas that accretes well after the bulge formation event, so that the amount and the configuration of the accreted material is not in any way related to properties of the bulge, such as its mass or its velocity dispersion.

We now attempt to establish whether this hypothesis is correct. At fixed total stellar mass, we found that galaxies with larger $C$ have lower gas fractions than galaxies with smaller $C$ (Fig. 9, upper panel). If the gas is associated mainly with the disc, then the ratio $M_{\text{HI}}/M_{\ast,\text{disc}}$ should not depend on $C$. We have fitted the Weinmann et al. (2009) relation between $B/T$ and $C$. Our bilinear fit result is $C = (1.19 + 2.28)B/T$. For each galaxy in our sample, we compute $M_{\ast,\text{disc}}$. In Fig. 13, we plot $M_{\text{HI}}/M_{\ast,\text{disc}}$ as a function of log $M_\ast$ for ETG and for sample A galaxies. As can be seen, the difference in gas fraction between the two samples is greatly reduced when the $\text{H} \, i$ mass is divided by the disc stellar mass. For reference, the red and blue lines on the plot show $M_{\text{HI}}/M_{\ast,\text{total}}$, as in Figs 7 and 9 (upper panels).

We note that our result that the $\text{H} \, i$ fraction of early-type galaxies depends on the size of the galaxy, but not on its bulge properties, is opposite to what is found for bulge stellar populations. In a recent paper, Graves, Faber & Schiavon (2009b) carried out an analysis of 16 000 nearby quiescent galaxies with 3-arcsec aperture spectra from the SDSS. Their paper demonstrates convincingly that mean stellar age, [Fe/H], [Mg/H] and [Mg/Fe] scale strongly with the velocity dispersion of the bulge, but there is no dependence on $R_e$ at a fixed value of $\sigma$. We thus infer that the star formation history of the central bulge does not depend on the size of the galaxy. Our own results show that the present-day gas content of early types does depend on size. This again argues for bulge and disc formation processes that are decoupled.

(2) Galaxies with significant bulge component are not less efficient in turning their available gas into stars. One possible explanation of this result is that the rate of gas consumption in galactic discs is primarily regulated by externally driven rather than internally generated instabilities. In recent work, Chakrabarti & Blitz (2009) present an analysis of the observed perturbations of the $\text{H} \, i$ disc of the Milky Way and infer the existence of a dark subhalo that tidally interacted with the Milky Way disc. In addition to dark subhaloes, luminous satellite galaxies are observed to interact with galactic discs. Finally, the dark matter environment at the centres of present-day haloes is neither static nor in equilibrium. Gao & White (2006) used the Millennium Simulation to study asymmetries in dark matter halo cores. They found that 20 per cent of cluster haloes have density centre separated from barycentre by more than 20 per cent of the virial radius, while only 7 per cent of Milky Way haloes have such large asymmetries. Because early-type

![Figure 13](https://example.com/figure13.png)

**Figure 13.** Average disc gas fractions of sample A (red circles) and ETG sample galaxies (blue circles) as a function of total stellar mass $M_\ast$. The lines show the results obtained measuring the total gas fraction, as in Figs 7 and 9 (upper panels). Grey dots show galaxies with ALFALFA detections from sample A.
galaxies reside in more massive dark matter haloes than late-type galaxies (Mandelbaum et al. 2006), their discs may be subject to considerably larger externally driven perturbations. All these effects may counteract the stabilizing effect of the bulge.

Further tests of the proposed external origin of the gas in early-type galaxies will come from more detailed analysis of its spatial distribution and kinematics. By studying the relation between gas and stellar angular momentum in early-type galaxies, one can hope to gain further understanding of how the gas was accreted. Studies of this nature are planned as part of the next generation of integral-field spectroscopy studies of nearby early-type galaxies, e.g. the ATLAS3D survey (http://www-astro.physics.ox.ac.uk/atlas3d/).

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APPENDIX A: COMPARISON OF TWO DIFFERENT STACKING PROCEDURES

In this section we compare two different methods for deriving mean HI gas fractions from stacked spectra.

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Figure A1. (a) Dependence of the rms of the stacked spectra on the number of objects in the stack. The red dots are obtained by stacking ‘gas fractions’. The black ones by stacking H\textsc{i} line fluxes. The dashed line is the expected \(1/\sqrt{N}\) dependence [note that the black points have been multiplied by the average squared distance and divided by the average \(M_\star\) in order to have the same units as the red points (mJy Mpc\(^2\) M\(_\odot\)^{-1})]. (b) Comparison of average gas fractions obtained with the two different stacking methods applied to sample A galaxies with ALFALFA detections. Red circles are averages obtained using method 2, and green triangles/blue squares are from method (1), when mean or median values of \(z\) and \(M_\star\) are used in equation (A1), respectively. The stars are the means obtained from averaging the catalogued ALFALFA fluxes. Grey dots show the ALFALFA detections. The numbers of objects co-added in each bin is reported below.

Figure A2. Comparison of average gas fractions obtained with the two different stacking methods, applied to all sample A galaxies. Symbols and colours are the same as Fig. A1.
Stacking HI fluxes: in the first method, we derive the average HI gas fraction using the equation
\[
\frac{M_{\text{HI}}}{M_*} = \frac{2.356 \times 10^5 \, D_L^2(\langle z \rangle) \Sigma_{i=0}^N w_i}{1 + \langle z \rangle} \frac{\Sigma_{i=0}^N \Sigma w_i}{\Sigma_{i=0}^N w_i},
\]
where \(\langle z \rangle\) is the mean redshift of the stacked galaxies and \(\langle M_* \rangle\) is their mean stellar mass. The main limitation is that this method may produce biased results if galaxies in the bin span a significant range in redshift or stellar mass. By stacking mainly non-detected spectra, we do not know how much each galaxy contributes to the total signal. This approach will work best if the bins are small. We note that our redshift range is compact enough so that
\[
D_L^2(\langle z \rangle) \simeq \langle D_L(z) \rangle^2 \simeq \langle D_L^2(z) \rangle.
\]
We choose to split each stellar mass bin into three sub-bins in redshift: [0.025;0.033], [0.033;0.042], [0.417;0.050]. For each of these sub-bins, we evaluate the mean stellar mass \(\langle M_* \rangle\), and split the sample into two further bins according to \(M_* \gtrsim \langle M_* \rangle\). We stack the spectra in each of the six sub-bins, measure a flux and evaluate a gas fraction using both the average and median values of \(z\) and \(M_*\). Then we evaluate the final gas fraction by averaging the six values obtained (weighted by the number of objects co-added).

Stacking ‘gas fractions’: this approach is described in Section 3.2 and is the one that is adopted throughout the main body of this paper.

First, we checked that the rms of the co-added spectra decreases as \(1/\sqrt{N}\); when method (2) is applied, i.e. by multiplying the flux by distance and stellar mass, we are in fact rescaling the noise in the spectra in a sensible way. Results are shown in Fig. A1 (panel a): red circles are obtained by stacking ‘gas fractions’, black circles are obtained by stacking fluxes. The black points have been multiplied by the average squared distance and divided by the average \(M_*\) in order to have the same units as the red points (mJy Mpc\(^2\) M\(_\odot\)^{-1}). The dashed line is the expected \(1/\sqrt{N}\) dependence, which is still recovered using method (2).

We then compared the results of stacking methods (1) and (2). We divided all the galaxies in sample A that were detected by ALFALFA (detection codes 1+2) into five stellar mass bins. We compare results from the different stacking methods with the results obtained by averaging together the individual catalogued measurements. The results are shown in Fig. A1 (panel b), where red circles show results obtained using method (2), and green triangles/blue squares are from method (1), when mean or median values of \(z\) and \(M_*\) are used in equation (A1), respectively. The stars show the results from averaging together the individual detections. Grey dots show the ALFALFA detections. The signal recovered from the stacking is consistent with the mean value of the individual detections for each bin. The two different stacking methods yield results that are also consistent with each other. Small differences of around \(\sim 10\) per cent in \(M_{\text{HI}}/M_*\) do occur in the two largest mass bins that contain the fewest objects.

We also compared results for the different methods including the non-detections. In Fig. A2 we show the same correlations studied in Section 4 for sample A, computed using different methods. Symbols are the same as described above. Once again, we obtain good consistency.

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