Chapter 3

From star forming to inactive galaxies: the global cold gas content up to $z = 0.12$

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Abstract

We investigate the global neutral hydrogen ($\text{H} \, \text{I}$) content and star formation properties of $\sim 1600$ galaxies up to $z = 0.12$ using stacking techniques. The observations were carried out with the Westerbork Synthesis Radio Telescope (WSRT) in the area of the SDSS South Galactic Cap (SSGC), where we selected a galaxy sample from the SDSS spectroscopic catalog. Multi-wavelength information is provided by SDSS, NVSS, GALEX, and WISE. We use the collected information to study H I trends with color, star-forming, and AGN (Active Galactic Nuclei) properties.

Using NUV - $r$ colors, galaxies are divided into blue cloud, green valley and red sequence galaxies. We detect H I in green valley objects with lower amounts of H I than blue galaxies, while stacking only produces a 3-$\sigma$ upper limit for red galaxies with $M_{\text{HI}} < 5 \times 10^8 \, \text{M}_\odot$ and $M_{\text{HI}}/L_r < 0.02 \, (\text{M}_\odot/\text{L}_\odot)$ (averaged over four redshift bins up to $z = 0.12$). We find that the H I content is more dependent on NUV - $r$ and infrared color, and less on ionization properties, in the sense that regardless of the presence of an optical AGN (based on optical ionization line diagnostics), green galaxies always show H I, whereas red galaxies only produce an upper limit. This suggests that feedback from optical AGN is not the (main) reason for depleting large-scale gas reservoirs, or the effect of this type of feedback is not instantaneous.

Galaxies with NVSS radio counterparts are divided into IR late-type and IR early-type galaxies based on the WISE color-color plot. We find that the radio emission in IR late-type galaxies stems from enhanced star formation, and this group is detected in H I. However, IR early-type galaxies lack any sign of H I gas and star formation activity, suggesting that radio AGN are likely to be the source of radio emission in this group.

The H I mass-luminosity ratio and H I-based star formation efficiency do not change signifi-
cantly as function of redshift up to $z = 0.12$, corresponding to $\sim 1.5$ Gyr in look-back time. Our stacking study will be extended to higher redshift with the next generation of radio telescopes. Future, large surveys will provide enough data to test the global H I content at earlier epochs of the Universe at lower, currently rather unexplored H I detection limit ($M_{HI} < 10^7 M_\odot$).

3.1 Introduction

The amount and conditions of cold H I gas in galaxies are, in a direct or indirect way, related to star formation (SF) processes and to black hole fuelling, therefore our knowledge of the H I properties is crucial to understand the intricate process of galaxy formation and evolution. Our knowledge of the gas content in various types of galaxies in the nearby Universe has increased substantially thanks to large single-dish H I surveys such as the H I Parkes All Sky Survey (HIPASS) (Meyer et al. 2004; Zwaan et al. 2005), the Arecibo Legacy Fast ALFA (ALFALFA) survey (Martin et al. 2005; Grossi et al. 2009) and detailed imaging surveys like WHISP (van der Hulst et al. 2004), THINGS (Walter et al. 2008), SAURON (Morganti et al. 2006; Oosterloo et al. 2010a) and ATLAS$^{3D}$ (Serra et al. 2012).

In the nearby Universe, in late-type, star forming galaxies the H I mass is well correlated with the total luminosity, the diameter of the stellar disk, and the maximum rotation speed (Toribio et al. 2011). Hence, scaling relations can be used to predict the amount of gas in these, typically blue galaxies. Red early-type galaxies, however, are an intriguing population when it comes to gas content and star formation properties. This group displays a large range of neutral hydrogen (H I) content from being very H I rich to being completely devoid of gas. Furthermore it is thought that feedback processes play an important role in affecting the gas reservoirs and consequently the star formation processes, particularly in massive, bulgy galaxies.

At higher redshift, H I studies are limited by sensitivity and bandwidth. However spectral stacking is an efficient technique to measure the average global H I content of galaxies. In combination with multiwavelength data, stacking also provides a powerful tool to study the cold gas properties in different galaxy groups (Lah et al. 2007, 2009; Fabello et al. 2011a,b; Verheijen et al. 2007; Dehaise et al. 2013; Gerb et al. 2013). Among these studies, Fabello et al. (2011a) noted that in massive galaxies the cold gas fraction most strongly correlates with NUV - r color and stellar surface mass density, or in other words with the star formation history of galaxies. More recently, Gerb et al. (2013) reported the detection of H I gas not only in normal SF galaxies, but also in LINERs (Low Ionization Nuclear Emission Region), a group often associated with AGN activity (Kaufman et al. 2003; Best & Heckman 2012). These studies show, in good agreement with SAURON and ATLAS$^{3D}$, that albeit in lower amounts, H I and star formation are present not just in typical SF galaxies (generally blue, late type spirals), but also in galaxies with older stellar populations, or in AGN.

It is thought that quenching of star formation happens before the red sequence phase, in the green valley. The green valley is considered to be a transition population between blue and red galaxies, displaying residual star-formation signatures (Yi et al. 2005). Therefore, it is also interesting to explore the presence and amount of H I in this population, and to test possible differences in the gas and star formation properties with respect to gas-rich blue and gas-poor red samples.
3.2: Observations and sample selection

In Geréb et al. (2013), we used stacking techniques to test the HI properties of galaxies located in the area of the Lockman Hole (LH). In the LH study our selection of different groups of objects was limited by the small sample size. In this paper we present the global HI and SF properties of a larger sample, ~1600 galaxies. We confirm several trends derived by Geréb et al. (2013) and expand on these results. This work is made possible by the increase in the number of galaxies by an order of magnitude, allowing us to lower the detection limit by a factor of 4 using stacking techniques. In fact, stacking is a suitable and also efficient way to test HI content in such, relatively large samples. In addition to (Geréb et al. 2013), we study in more detail galaxies where quenching and feedback by AGN (radio/optical) are thought to be affecting the gas reservoirs, e.g. green valley objects and LINERs.

Large samples of galaxies (following our selection) also contain an increased number of potential AGN (optical and radio), making it possible to investigate the connection of cold gas with nuclear activity. According to the 1.4 GHz radio luminosity function, star forming galaxies dominate the luminosity distribution below radio power < 10^{23} W Hz^{-1}. Hence, in the low radio power regime we expect to detect a mix of AGN/SF galaxies. In this paper we explore the SF and AGN properties of the radio population extracted from NVSS, and we discuss the possibility of separating these phenomena using IR colors.

It is clear that a better measure of the global HI content seems to be crucial for our understanding of the cosmic evolution of HI. By tracking the redshift evolution of the global HI content and efficiency of star formation in galaxies, one might be able to test the availability of gas and the conditions under which star formation occurs at different epochs of the Universe. Recent results show that in the nearby Universe, the HI-based star formation efficiency (SFE = SFR/M_{HI}) – or the equivalent inverse, the time scale of cold gas consumption (t = M_{HI}/SFR) – is independent of other galaxy properties, such as stellar mass, stellar surface density, color, concentration (Schiminovich et al. 2010; Bigiel et al. 2011). This result was interpreted as a signature that external processes and/or feedback by SF/AGN, which processes regulate the HI gas fraction in galaxies, can be responsible for regulating star formation as well. In this paper we probe the global HI content and SFE properties up to z = 0.12. In a second paper, using the same dataset, the Ω_{HI} will be investigated in the same redshift range.

Throughout this paper the standard cosmological model is used, with parameters Ω_m = 0.3, Λ = 0.7 and H_0 = 70 km s^{-1} Mpc^{-1}.

3.2 Observations and sample selection

The HI observations were carried out with the Westerbork Synthesis Radio Telescope (WSRT) at 1.4 GHz, in the period May 2011 - October 2012, in the area of the SDSS South Galactic Cap (SSGC). Between the coordinates 21^h < RA < 2^h, 10^° < DEC < 16^° (J2000), 35 WSRT pointings were observed and used for HI spectral stacking.

The redshift range 0 < z < 0.12 is covered by 8 × 20 MHz bands with 128 frequency channels in each band (1280 - 1420 MHz, the bands overlap 3 MHz). The corresponding velocity resolution is ~38 km s^{-1}. The integration time is 12 hours for most of the observations. The synthesized beam is typically ~70 × 9 arcsec, the elongation of the beam being (mainly) the result of the low declination observations with the East-West WSRT array.
In each observed pointing, we use the Sloan Digital Sky Survey (SDSS, York et al. 2000) to pre-select our spectroscopic galaxy sample. The pre-selected sample is cross-correlated with the Galaxy Evolution Explorer (GALEX, Martin et al. 2005), providing 1595 galaxies that can be used for stacking. We also use the Wide-Field Infrared Survey Explorer (WISE, Wright et al. 2010) to obtain infrared (IR) data for our galaxies. The WISE sample is complete to the 99 percent level. In addition, a few (50, within a search radius of 15 arcsec) galaxies are identified with radio counterparts in the NRAO VLA Sky Survey (NVSS, Condon et al. 1998) survey. The collected multiwavelength data allows us to combine various galaxy parameters and investigate the HI properties of different galaxy groups.

3.3 Data reduction and H I stacking

The data were reduced using the MIRIAD package (Sault, Teuben, & Wright 1995). Bad data were flagged from the datasets, with extra care for the most prominent RFI in the lowest-frequency band (1280 - 1300 MHz).

The standard way to subtract the continuum is by fitting a low-order polynomial to the line-free channels. Our datasets cover a broad, 140 MHz bandwidth composed by 8 spectral windows. We fit each spectral band separately; however, we find that polynomial fitting is unsuccessful when strong HI lines are present close to the edge of the bands. These HI lines create a dip in the stacked spectra because of the bad continuum subtraction.

To avoid this effect, first we perform a continuum subtraction in the uv-plane, using the clean components of each field. The clean components were created as a result of deconvolution of the continuum images with the dirty beam. This subtraction step removes most of the continuum from the HI data cubes. However, we perform a second continuum subtraction by fitting a second-order polynomial to the spectra to subtract low-level residual continuum emission coming from very bright sources. Following these steps, we eliminate the dip from the stacked spectra.

Stacking is done similarly as described in Geréb et al. (2013), centred on the redshift of the galaxy to be stacked. Galaxies are stacked in four redshift ranges, between 0.02 < z < 0.12 each redshift range covers Δz = 0.02 (except the highest redshift range, 0.08 < z < 0.12). The average rms noise of the cubes is ~ 0.2 mJy/beam, which number is expected to decrease with the square root of the number of co-added sources.

3.4 Characteristics of the galaxies in the selected sample

Our main goal is to study/compare the HI properties of various groups of galaxies using large samples with available multiwavelength information. In order to do this, we define several sub-samples, using the collected multiwavelength data.

The color distribution of galaxies is known to consist of two main peaks, i.e. the blue cloud and the red sequence (Strateva et al. 2001; Baldry et al. 2004). At intermediate colours between blue and red galaxies an excess population is present in the distribution at fixed absolute magnitudes (Wyder et al. 2007). Intermediate, green colors can be due
3.4: Characteristics of the galaxies in the selected sample

Figure 3.1: 1. Color-magnitude diagram (top panel) 2. UV-optical color-color plot (bottom panel): The galaxies are color coded according to the color-magnitude selection by Wyder et al. (2007), i.e. blue cloud, green valley and the red sequence. Radio sources are marked by yellow squares.

...to a number of different phenomena, e.g. low level (residual) star formation activity (Yi et al. 2005), dusty galaxies, older stellar populations (Surzi et al. 2010).

Previous stacking studies, including our LH analysis, were carried out on galaxies separated into blue/red samples, which colors were defined based on optical $g - r$, or ultraviolet-optical $NUV - r$ selections (Fabello et al. 2011a; Geréb et al. 2013). To expand
Figure 3.2: 1. BPT diagram (top panel). Galaxies are color coded according to the color-magnitude selection by Wyder et al. (2007), i.e. blue cloud, green valley and the red sequence. The dashed line (Kauffmann et al. 2003) is separating SF galaxies (below the dashed line) from LINERs (between dashed and dotted line). Optical AGN are located above the dotted line (Kewley et al. 2001). Inactive galaxies do not appear in the diagram. 2. WISE IR color-color plot (bottom panel). The sources are color-coded according to the BPT selection. The vertical solid line is separating IR early-type (\([4.6\mu m] - [12\mu m] < 2\)) and IR late-type galaxies (\([4.6\mu m] - [12\mu m] > 2\)). Radio sources are marked by yellow squares.
on previous studies, in this paper we consider the green valley as a separate group. Following Wyder et al. (2007), in Fig 3.2 our objects are divided into blue cloud, green valley and red sequence objects based on NUV - r colors. To derive the color distribution of the galaxies, Wyder et al. (2007) utilizes the fit by Yi et al. (2005) to the NUV - r colors in function of the $M_r$ absolute magnitude: $\text{NUV} - r = f(M_r) = 1.73 - 0.17 M_r$. The red sequence is defined as the galaxies with $\text{NUV} - r > f(M_r) - 0.5$, blue galaxies have $\text{NUV} - r < f(M_r) - 2$, whereas green galaxies are the excess population between blue and red galaxies with $f(M_r) - 2 < \text{NUV} - r < f(M_r) - 0.5$ colors. The optical and UV apparent magnitudes are extracted from GALEX and SDSS, and K-corrected following Chilingarian et al. (2010); Chilingarian & Zolotukhin (2012). The NUV - r colors are corrected for Galactic extinction following Wyder et al. (2007).

From Fig. 3.1 (bottom panel) it is clear that in case of the Gerèb et al. (2013) selection, our current green valley objects are part of the $g - r > 0.7$ (red) sample, and in the selection of Fabello et al. (2011a), green valley objects belong to the NUV - r < 4.5 (blue) sample.

We also use the Baldwin, Phillips & Terlevich (BPT) line ratio diagnostic diagram (Baldwin, Phillips & Terlevich 1981) to separate galaxies with different ionization properties (Fig. 3.2, top panel). The selection is done by using line fluxes from SDSS, similarly to Gerèb et al. (2013), but with one major difference. Galaxies, which were defined as LINERs (Low Ionization Nuclear Emission Region galaxies) in Gerèb et al. (2013), are now separated into LINER and optical AGN samples, using the more stringent demarcation by Kewley et al. (2001) for selecting AGN. Following the BPT classification, our sample includes star-forming (SF) galaxies, LINERs and optical AGN. Furthermore, a part (280 sources) of our sample is defined as optically inactive, with non-detected, or with maximum two detected lines (among [NII], Hα, [OIII], Hβ). In the relatively small sample of Gerèb et al. (2013), optically inactive galaxies were not detected in the radio continuum. However here, thanks to the increased number of objects, we also find a few optically inactive (non-star-forming) galaxies with associated radio counterparts. Such non-star-forming radio sources are good candidates for hosting low-luminosity radio AGN. Star forming galaxies in the BPT diagram in Fig. 3.2 (top panel) are mainly blue and green, while LINERs and optical AGN are green and red. Inactive galaxies are typically red, as in Paper1.

Radio sources are among the optically most luminous objects in each group in the color-magnitude diagram in Fig. 3.1 (top panel). From the 1.4 GHz radio luminosity function it is expected that radio AGN become dominant over star formation at radio power higher than $P > 10^{23}$ W Hz$^{-1}$ (Mauch and Sadler 2007). From the radio power distribution in Fig 3.3 we expect to have such powerful AGN, however the distribution shows that also low-power radio sources are present in the sample. In the low radio power regime it becomes more complicated to disentangle the contribution of SF and AGN to the radio continuum emission. This effect is well illustrated in the BPT diagram in Fig. 3.2 (top panel), where radio emission is detected both in SF galaxies and in LINERs/AGN.

IR colors were found to be efficient in disentangling SF and AGN activity in galaxies (Gerèb et al. 2013). With this goal in mind, we extract 3.4 $\mu$m, 4.6 $\mu$m and 12 $\mu$m magnitudes from WISE to constrain the IR color-color plot, presented in Fig 3.2 (bottom panel). The separation at the vertical line (at $[4.6\mu m] - [12\mu m] = 2$) in the IR color-color plot (Fig. 3.2, bottom panel) is often used in the literature to disentangle IR early- and
late-type galaxies (Wright et al. 2010; Sadler et al. 2013). The sample in this figure is color-coded according to the BPT diagram. IR late-type galaxies include star-forming galaxies and LINERs, whereas the IR early-type region is dominated by optical AGN and non-star-forming (inactive) galaxies. The IR early-type sample is associated with red galaxies at NUV - r > 5 in the color-magnitude diagram in Fig. 3.1 (top panel) and in the optical-UV color-color diagram (Fig. 3.1, bottom panel). As expected, radio sources in the IR late-type region are blue and green. Thus, star forming galaxies and potential (radio) AGN seem to be well separated by IR colors, and a more detailed analysis of the two radio groups is presented in Sec. 3.5.3.

3.5 Results

3.5.1 Stacking in color

Before we look at the HI content of blue cloud/green valley/red sequence objects, first we compare our current measurements with the results from the LH study. In Fig 3.4 (top panel) we use g – r optical colors to evaluate the HI mass and mass-luminosity ratio of blue/red galaxies in our current, larger sample. In the LH field, in the redshift range 0.06 < z < 0.09 we measured $M_{HI} = 6.12 \pm 0.4 \times 10^9$ M$_\odot$ and $M_{HI}/L_r = 0.38 \pm 0.02$ (M$_\odot$/L$_\odot$) in the blue ($g - r < 0.7$) population, whereas red ($g - r > 0.7$) galaxies contain lower amounts of gas, with $M_{HI} = 1.8 \pm 0.2 \times 10^9$ M$_\odot$ and $M_{HI}/L_r = 0.08 \pm 0.01$ (M$_\odot$/L$_\odot$). In the redshift range of the LH studies (0.06 < z < 0.09), the new measurements in Fig. 3.4 (top panel) are consistent with the results of the LH.

The HI mass and mass-luminosity ratio for blue cloud, green valley and red sequence objects are also presented in Fig 3.4 (bottom panel). We detect HI in blue and green
objects, however unlike in the LH studies, red galaxies do not show an H\textsc{i} detection\(^1\). The non-detection of red galaxies is the consequence of the different color selection, and in fact, our non-detection is in good agreement with previous results from the literature. Fabello et al. (2011a) reported H\textsc{i} non-detection in red galaxies with NUV - r > 4.5, which color limit is similar to our red sequence definition (see color-color plot in Fig. 3.1, bottom panel). Using stacking techniques here we expand on the results of Fabello et al. (2011a), and we confirm the H\textsc{i} non-detection found in red galaxies at low 3-\(\sigma\) limit of \(M_{\text{HI}} < 5 \times 10^8\) M\(_\odot\) and \(M_{\text{HI}}/L_r < 0.02\) (M\(_\odot\)/L\(_\odot\)) (with values averaged over the four redshift bins).

As expected, the global H\textsc{i} content is decreasing from the blue population towards red galaxies in Fig. 3.4. Green valley objects are a transition population from H\textsc{i} point of view, showing lower amounts of H\textsc{i} than the blue population, however unlike red galaxies, green valley objects are not completely devoid of gas.

Finally we note that similarly to what previous studies have found (Freudling et al. 2011; Delhaize et al. 2013), the global H\textsc{i} mass-luminosity ratio does not change signif-

\(^1\) We note that in the first redshift bin we find a tentative H\textsc{i} detection in red galaxies at the 3-\(\sigma\) level, with \(M_{\text{HI}} < 3.8 \times 10^8\) M\(_\odot\) and \(M_{\text{HI}}/L_r < 0.03\) (M\(_\odot\)/L\(_\odot\)). Higher redshift bins are not detected.

Figure 3.4: H\textsc{i} mass (left) and mass-luminosity ratio (right) of galaxies divided in different colors. (Top panel): Blue and red galaxies selected from \(g - r\) colors as in Geréb et al. (2013). (Bottom panel): our current color selection of blue cloud, green valley and red sequence objects.
significantly up to $z = 0.12$. We expand on previous studies by separating the sample into different groups in Fig. 3.4. We show that even when galaxies are divided into several groups, the global HI content (mass-luminosity ratio) shows only little variations as function of redshift.

### 3.5.2 The HI properties of LINERs and optical AGN

The HI stacking results of SF, LINER, optical AGN and inactive galaxies are presented in Fig. 3.5. Besides SF galaxies, HI is detected in LINERs and optical AGN, which result is in good agreement with the Geréb et al. (2013) study. Thanks to the higher number of objects in the SSGC, we can lower the HI detection limit and confirm the HI non-detection of optically inactive galaxies down to the 3-$\sigma$ level of $M_{HI} < 6 \times 10^8 M_\odot$ and $M_{HI}/L_r < 0.03$ ($M_\odot/L_\odot$) (averaged over the four redshift bins).

Within a certain population, the HI mass-luminosity ratio does not change significantly with redshift up to $z = 0.12$. However, the HI gas fraction in Fig. 3.5 seems to decrease from the SF population towards optical AGN, and inactive galaxies are devoid of gas.

In the BPT diagram in Fig. 3.2 (top panel), LINERs and optical AGN are mostly green or red. We want to test whether the lower HI content in LINERs/AGN is the result of galaxies being redder (with older stellar populations, dustier), or it is related to ionization/AGN feedback properties. To do this, in the following analysis we select a group of potential AGN based on the BPT diagram, and we use IR and NUV - $r$ colors to test the color dependence of HI in the selected groups.

First we create a combined sample of LINERs and optical AGN, considering all galaxies above the dashed line in the BPT diagram in Fig 3.2 (top panel). In Paper1 we show that IR colors are efficient in separating H1-rich and H1-poor LINERs. The former group is associated with star formation activity, however H1-poor LINERs are non-star-forming. In Fig 3.2 (bottom panel), 63% of LINERs/AGN are located in the IR late-type region in the WISE color-color plot in Fig. 3.2 (bottom panel). The late-type region is dominated by star forming galaxies, and this suggests that a large fraction of LINERs in this region could be also associated with (low-level) star-formation. Based on our results
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**Figure 3.6:** (Top panel): H\textsubscript{I} mass (left) and H\textsubscript{I} mass-luminosity ratio (right) of LINERs and optical AGN with green and red colors. (Bottom panel): The same H\textsubscript{I} measurements for LINERs and optical AGN separated into WISE late-type and early-type region samples. Upper limits are marked by dashed lines in all plots.

**Figure 3.7:** H\textsubscript{I} mass (left) and mass-luminosity ratio (right) of radio sources in the IR late- and early-type regions.
from Paper1, we expect H I detection in these IR late-type LINERs.

In Fig. 3.6 (top panel) the stacked profiles of LINERs and AGN are separated into IR late- and early-type galaxies. As expected, we detect H I in the IR late-type sample. However, galaxies in the IR early-type region do not show a significant detection at the 3-σ limit of $M_{HI} < 1.05 \times 10^9 \text{M}_\odot$ and $M_{HI}/L_r < 0.04$ ($\text{M}_\odot/\text{L}_\odot$) (averaged over the four redshift bins). With this test we confirm the result of the LH study, that the presence of H I is well correlated with IR colors, even in the sample of LINERs and optical AGN.

After testing the IR color dependence, we also stack LINERs/AGN separated into green and red samples based on NUV - $r$ colors. In Fig. 3.6 (bottom panel), H I is concentrated in green objects among LINERs/AGN, whereas red galaxies are not detected in H I at the 3-σ limit of $M_{HI} < 9.7 \times 10^8 \text{M}_\odot$ and $M_{HI}/L_r < 0.04$ ($\text{M}_\odot/\text{L}_\odot$) (averaged over the four redshift bins). This suggests that even those galaxies in which the presence of an AGN is expected to be more likely (LINER/AGN) do show H I detections, however this depends on their color. This is a strong indication that the H I content is well correlated with the NUV - $r$ color and the SF history of the galaxies, while the effect of AGN feedback on the gas content is less significant.

These results show that both NUV - $r$ and IR colors are efficient in separating H I-rich and H I-poor galaxies. To understand the relation of the NUV - $r$ vs. IR color selection, we study in more detail the color distribution of galaxies in the IR late- and early-type region. We find that red galaxies are the bulk of the IR early-type sample, while IR late-type galaxies are mainly green and blue. Hence, the correlation between NUV and IR colors explains that we detect similar amounts of H I in the two different selections.

### 3.5.3 AGN and SF properties of the radio population

As we have shown in Sec 3.5.2 and in Geréb et al. (2013), we can use IR colors to separate star forming galaxies from non-star-forming samples (potential AGN). Now we do the same analysis with radio-selected NVSS objects (see Sec 3.4 for information on the separation of radio sources).

The stacking results of the two radio groups, IR early- and late-type galaxies separated at $[4.6 \mu m] - [12 \mu m] = 2$, are presented in Fig. 3.7. We detect H I in IR late-type galaxies, however in the IR early-type region H I reveals a non-detection with a mass and mass-luminosity upper limit of $M_{HI} < 1.95 \times 10^9 \text{M}_\odot$ and $M_{HI}/L_r < 0.03$ ($\text{M}_\odot/\text{L}_\odot$). The H I non-detection of IR early-type galaxies is consistent with the fact that in our color selection scenario these are red objects. IR late-type galaxies are green and blue. The low mass-luminosity ratio of H I detections in IR late-type galaxies with respect to e.g. LINERs/optical AGN in Fig. 3.6, is partly the result of the high optical luminosity of radio-detected objects, which are among the brightest sources in the color-magnitude diagram in Fig. 3.1 (top panel).

The radio power distribution of IR late-type and IR early-type galaxies is presented in Fig. 3.8. The two distributions have different shapes, with a wide, $D = 0.504$ maximum distance between the two cumulative distribution functions. According to the Kolmogorov-Smirnov test, the probability that the two distributions are different is 99%.

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2 We note that in the first redshift bin we tentatively detect H I in IR early-type LINERs/AGN at the 5-σ level, with $M_{HI} < 9 \times 10^8 \text{M}_\odot$ and $M_{HI}/L_r < 0.05$ ($\text{M}_\odot/\text{L}_\odot$). Higher redshift bins are not detected.

3 In the first redshift bin we tentatively detect H I in red AGN/LINERs at the 3-σ level with $M_{HI} < 9 \times 10^8 \text{M}_\odot$ and $M_{HI}/L_r < 0.05$ ($\text{M}_\odot/\text{L}_\odot$). Higher redshift bins are not detected.
3.5: Results

![Figure 3.8](image).

Figure 3.8: Cumulative fraction of the radio power distribution in IR late-type and IR early-type galaxies. We measure $D = 0.504$ for 35 IR late-type, and 15 IR early-type galaxies.

implying that statistically IR late-type and IR early-type galaxies have a different radio power distribution. The mean radio power of IR late-type galaxies is $\log(P) = 22.5 \text{ W Hz}^{-1}$, whereas as expected, IR early-type galaxies are typically more powerful, with a mean $\log(P) = 23 \text{ W Hz}^{-1}$. Along with the lack of star formation and H$^1$ gas, the high radio power supports that radio emission in the IR early-type region is due to radio AGN.

3.5.4 The global SFR and SFE up to $z = 0.12$

In Geréb et al. (2013) we found that the presence of H$^1$ provides favourable conditions for star formation not just in blue, but also in optically red ($g - r > 0.7$), LINER galaxies. In this paper, in Sec 3.5.1 and Sec 3.5.2 we show that the H$^1$ content of galaxies is well correlated with their star formation history (color), therefore we want to test the efficiency of star formation in different types of galaxies, bearing in mind their H$^1$ content. The star formation rate (SFR) in our sample is derived from the NUV flux, following Schiminovich et al. (2010). The SFR formula accounts for dust attenuation by combining UV-optical colors (NUV - $r$) and the $D_n(4000)$ index of galaxies. The latter index is an indicator of the presence of young stellar populations.

In each redshift bin, the H$^1$-based star formation efficiency is defined as the average SFR over stacked H$^1$ mass, i.e. $\Sigma SFR/\Sigma M_{H^1}$.

The plots in Fig. 3.9 show that up to $z = 0.12$, the SFE shows little variation with redshift. However the SFR properties do change for different galaxy groups, i.e. from the blue cloud towards the red sequence, or from SF galaxies towards optical AGN and inactive galaxies.

In Fig. 3.9, green valley objects show lower SFR than blue galaxies, however these
two groups reveal similar, efficient star formation, with little variations around SFE $\approx 10^{-9.5}$ yr$^{-1}$, corresponding to a gas consumption time scale of $t \sim 3 \times 10^9$ yr. However, red galaxies lack any sign of HI gas and star formation activity.

In Sec 3.5.2 we found that the HI content is better correlated with IR and NUV - $r$ color rather than with ionisation/AGN properties, and from Fig. 3.9 it seems that the same applies to the star formation properties as well. Similarly to the HI gas properties, star formation is concentrated in green/blue LINERs and optical AGN, while in red AGN (including LINERs) the level of star formation is negligible. Furthermore, the NUV - $r$ and the IR WISE selections yield very similar results. The SFR is $\sim 1$ M$_\odot$ yr$^{-1}$ in green and IR late-type LINERs in Fig. 3.9. The efficiency of SF is relatively low in both groups, with SFE $\lesssim 10^{-9.6}$ yr$^{-1}$.

Finally, the SFE of radio sources in the IR late-type region (Fig. 3.9) is the most enhanced amongst all groups investigated in this paper, corresponding to gas consumption time scales of $t = 10^9$ yr.
3.5: Results

Figure 3.9: - continued.
3.6 Discussion and summary

Our stacking results show that galaxies in the green valley are detected with lower amounts of H\textsc{i} than blue galaxies, but unlike red galaxies, they are not completely depleted of cold (H\textsc{i}) gas. This result indicates that green valley objects are an intermediate population also from H\textsc{i} point of view.

In our previous paper (Geréb et al. 2013) we used $g-r$ colors to disentangle blue and red objects (vertical line at $g-r = 0.7$), and obtained an H\textsc{i} detection in red galaxies. From Fig. 3.1 (bottom panel) it is clear that our current green valley objects are part of the $g-r > 0.7$ (red) sample. However, in other color selection scenario (Fabello et al. 2011a), green valley objects belong to the NUV - $r < 4.5$ (blue) sample. This comparison illustrates that different color selections result in different H\textsc{i} populations, and the contribution of the green valley seems to play a crucial role.

We do not detect H\textsc{i} in red galaxies at the limit of $M_{\text{H\textsc{i}}} < 5 \times 10^8 \, M_\odot$ and $M_{\text{H\textsc{i}}}/L_r < 0.02 \, (M_\odot/L_\odot)$ (averaged over four redshift bins). Even though this is a relatively low detection limit, lower H\textsc{i} masses have been detected before by direct observations of the SAURON and ATLAS\textsuperscript{3D} samples. Stacking is a promising technique to lower the detection limit and explore the $<10^7 \, M_\odot$ H\textsc{i} mass regime of galaxies using large samples of galaxies. This will be made possible by future H\textsc{i} surveys with the next generation of radio telescopes, e.g. Apertif (Oosterloo et al. 2010b), the Australian Square Kilometre Array Pathfinder (ASKAP, DeBoer et al. 2009), and MeerKat (Booth et al. 2009).

There are indications that by the time galaxies reach the green valley, they develop bulges and bigger central black holes (Schiminovich et al. 2007). These galaxies are more likely to host AGN, which phenomena is thought to be able to deplete cold gas reservoirs by feedback processes. Therefore, intriguing is the detection of H\textsc{i} in AGN, where it is expected that feedback processes deplete the cold gas reservoirs. It seems that, if they are green/blue, even galaxies with higher ionization properties (LINERs and optical AGN) do contain cold gas. This suggests that optical AGN are not the (main) reason for depleting gas reservoirs, or that AGN-driven gas depletion is not an instantaneous effect in galaxies. In agreement with previous studies, our results show that the presence of H\textsc{i} is better correlated with IR and NUV - $r$ color rather than with ionization properties.

We do not detect any H\textsc{i} gas in radio sources located in the IR early-type region ([4.6 $\mu$m] - [12 $\mu$m] < 2 in the WISE color-color plot) down to the 3-$\sigma$ detection limit of $M_{\text{H\textsc{i}}} < 2 \times 10^9 \, M_\odot$ and $M_{\text{H\textsc{i}}}/L_r < 0.02 \, (M_\odot/L_\odot)$ (averaged over the 4 redshift bins). The lack of H\textsc{i} gas along with the high average radio power of log(P) = 23 W Hz$^{-1}$ suggest that the radio emission in this population can not originate from star formation. Therefore, radio AGN are likely to be responsible for the radio continuum emission in IR early-type galaxies.

Our estimates for the SFR and SFE agree well with the results of previous studies (Schiminovich et al. 2010). Our results suggest that SF goes hand in hand with the H\textsc{i} properties, and in galaxies where cold gas (H\textsc{i}) is present, conditions are favourable for (residual) SF to be seen. Furthermore, it seems to be true for most of the sample that in galaxies where there is more gas, also the SFR is higher (blue cloud, SF galaxies). However, exceptions can be found, e.g. in radio sources in the IR late-type region in Fig 3.7, where small amounts of gas are associated with very efficient star formation. The lack of H\textsc{i} and the high level of residual star formation suggest that these galaxies recently went through an intense star-formation period, and this led to a significant depletion
of H I in these galaxies. The radio emission is likely the result of this enhanced star formation activity from the recent past in these sources. We note that three SF galaxies are located in the QSO/Seyfert region of the color-color plot ([3.4 $\mu$m] - [4.6 $\mu$m] > 0.5), and for these galaxies the presence of an AGN counterpart can not be excluded.

In Figs. 3.4, 3.5, 3.6 and in Fig 3.7, the H I mass-luminosity ratios do not change significantly in function of redshift, suggesting that the global H I content remains relatively constant up to $z = 0.12$. Furthermore, the global SFE displays a similar behaviour, remaining relatively constant in the covered redshift range. In fact, throughout our paper we see a good correlation between the presence of H I and star formation properties. As Schiminovich et al. (2010) argue, this can be interpreted as an indications that the H I content and SF are regulated by the same process, e.g. feedback effects, galaxy environment.

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