RESOLVED $\hi$ IMAGING OF A POPULATION OF MASSIVE $\hi$-RICH GALAXIES WITH SUPPRESSED STAR FORMATION

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ABSTRACT

Despite the existence of well-defined relationships between cold gas and star formation, there is evidence that some galaxies contain large amounts of $\hi$ that do not form stars efficiently. By systematically assessing the link between $\hi$ and star formation within a sample of galaxies with extremely high $\hi$ masses (log $M_{\hi}/M_\odot > 10$), we uncover a population of galaxies with an unexpected combination of high $\hi$ masses and low specific star formation rates that exists primarily at stellar masses greater than log $M_*/M_\odot \sim 10.5$. We obtained $\hi$ maps of 20 galaxies in this population to understand the distribution of the $\hi$ and the physical conditions in the galaxies that could be suppressing star formation in the presence of large quantities of $\hi$. We find that all of the galaxies we observed have low $\hi$ surface densities in the range in which inefficient star formation is common. The low $\hi$ surface densities are likely the main cause of the low specific star formation rates, but there is also some evidence that active galactic nuclei or bulges contribute to the suppression of star formation. The sample’s agreement with the global star formation law highlights its usefulness as a tool for understanding galaxies that do not always follow expected relationships.

Key words: galaxies: evolution – galaxies: formation

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1. INTRODUCTION

Many theories of galaxy evolution assume that a galaxy’s evolutionary stage and its cold gas content are tightly linked. For example, it is often assumed that a depleted cold gas reservoir can explain why massive galaxies are redder and exhibit less active star formation, but recent observations have challenged this picture by identifying populations of galaxies that contain significant amounts of cold gas despite their low or moderate star formation rates (SFRs; Morganti et al. 2006; Serra et al. 2012; Young et al. 2013). Some attempts have been made to systematically search for these galaxies to understand them as a population. In this paper we pursue this line of reasoning by studying a sample of massive galaxies with an unusual combination of high $\hi$ masses and low specific star formation rates (sSFRs).

Galaxies that have more cold gas than expected can be placed into two broad categories: red, early-type galaxies with unexpected measurable $\hi$ and galaxies that have significantly more $\hi$ than their SFRs would suggest. In the first category, early-type galaxies were expected to be devoid of cold gas because they lack the spiral arms that indicate recent star formation. The first systematic imaging search for $\hi$ in early-type galaxies, motivated in part by the evidence for $\hi$ in individual early-types, found that $\hi$ is common at low levels in early-type galaxies in the field and could play an important role in their evolution (Morganti et al. 2006). More recent surveys have revealed that at least 32% of such galaxies have detectable $\hi$ and that 20% of early-type galaxies (ETGs) have regularly rotating disks of $\hi$ (Serra et al. 2012). Young et al. (2013) show that even red early-type galaxies have cold gas at detection rates of 10%—34% and that the detection rates are highest among the most massive (log $M_*/M_\odot > 10.5$) red early-types. Galaxies in the Serra et al. (2012) sample contain up to $10^{10}$ solar masses of $\hi$. Because galaxies with more than this amount of $\hi$ are rare, study of these galaxies has so far focused on individual galaxies rather than entire populations.

Galaxies with low rates of star formation compared to their cold gas content comprise a diverse population of not just red early-type galaxies but also massive spirals that are expected to contain cold gas but have a high gas content incommensurate with relatively low SFRs. The reasons for their low SFRs can be difficult to ascertain. Recent simulations and observations have attempted to determine which physical processes or conditions can prevent cold gas from collapsing and forming stars. In simulations the heating and disruption of gas by active galactic nuclei (AGN) feedback are frequently used to explain the low specific star formation rates ($sSFR = \text{SFR}/M_*$) of massive galaxies (e.g., Croton et al. 2006; Hopkins et al. 2008; Gabor et al. 2011). Gabor et al. (2011) showed that feedback from radio-mode AGNs can shut down star formation, but it is unclear how this would affect the cold gas reservoir (Ho et al. 2008; Fabello et al. 2011). Martig et al. (2009) show that morphological quenching can quench star formation in bulge-dominated galaxies without removing or heating the cold gas.

A high cold gas content may coexist with a low SFR in galaxies such as those with inefficient star formation in their outer disks. The outer disks could harbor large quantities of gas but observations have shown that their densities are low and typically dominated by $H_2$ over $H_\alpha$ (e.g., Wyder et al. 2009; Bigiel et al. 2010). Inefficient star formation is frequently attributed to a low gas surface density below a threshold level of 3–10 $M_\odot$ pc$^{-2}$ that is required for $H_\alpha$ to form and for star formation to proceed efficiently (Schaye 2004; Bigiel et al. 2008). Below this threshold level the SFR surface density decreases steeply; this downturn could be related to $H_\alpha$-derived...
star formation thresholds in outer disks such as those discovered by Martin & Kennicutt (2001).

Extended UV (XUV) disks and giant low surface brightness galaxies (GLSBs) are both populations of galaxies characterized by inefficient star formation. XUV-disks are defined by the presence of low-level UV flux beyond the main stellar disk. The prevalence of XUV-disks suggests that inefficient star formation in the outer disks of galaxies may be common (Thilker et al. 2007), especially around massive, bulge-dominated galaxies (Lemonias et al. 2011). GLSBs have a less stringent definition than XUV-disks, but are generally known to have low surface brightness disks at optical wavelengths and massive H$_1$ disks that extend well beyond the optical radius. Malin 1 (Pickering et al. 1997) is the prototypical GLSB, and several similar galaxies have been discovered (e.g., Morganti et al. 1997; Portas et al. 2010). Simulations have shown that extended low surface density gaseous disks may be common if the cold gas building up the gaseous disk has a high angular momentum (Kimm et al. 2011; Stewart et al. 2011; Lu et al. 2014).

It has become clear that cold gas and star formation are not always linked in obvious ways. To gain a deeper understanding of the role H$_1$ plays in galaxy evolution, both within the general population and in populations that deviate from the general population, it is necessary to have large, well-defined samples of galaxies with known star formation and gas properties. Recent large H$_1$ surveys such as the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2010) and the Arecibo Legacy Fast ALFA Survey (ALFALFA; Giovanelli et al. 2005) complement Galaxy Evolution Explorer (GALEX) and Sloan Digital Sky Survey (SDSS) data on star formation and galactic structure by providing key measurements of the cold gas in galaxies. The advent of large H$_1$ surveys such as these provides the first opportunity for us to select and study volume-limited populations of galaxies defined only by their gas content.

In this paper we take advantage of these recent H$_1$ surveys to assess the link between cold gas and star formation in a unique and systematic way. Although the term cold gas generally refers to both atomic and molecular gas, we only have information about H$_1$ so we refer to cold gas and H$_1$ interchangeably throughout the rest of the paper except when noted otherwise. We define a sample of massive ($\log M_\odot/M_\odot > 10.0$) H$_1$-rich galaxies to investigate the relationship between H$_1$ and star formation in this crucial stellar mass range in which galaxies become less actively star-forming. We uncover an intriguing population of galaxies at stellar masses $\log M_\odot/M_\odot > 10.5$ that exhibit surprisingly low SFRs despite their significant amounts of H$_1$. Because the galaxies were selected based on single-dish H$_1$ observations with Arecibo, there existed no information about the morphology or spatial extent of the H$_1$, which is crucial in determining why much of the H$_1$ is not participating in star formation. In this paper we describe the sample and report on the results of an H$_1$ imaging survey at the Jansky Very Large Array (VLA) intended as an observational test of the mechanisms acting to suppress star formation in these massive H$_1$-rich galaxies.

This paper is organized as follows. In Section 2 we select a sample of H$_1$-rich galaxies and we compare their star-forming and structural parameters to two control samples. This section motivates the observational test described in Section 3, in which we obtain H$_1$ imaging for massive H$_1$-rich galaxies with suppressed star formation. In Section 4 we discuss the implications of our results in terms of star formation suppression mechanisms. We summarize our findings in Section 5. In the Appendix we list notes on individual galaxies.

2. PROPERTIES OF MASSIVE H$_1$-RICH GALAXIES

2.1. Sample Selection

GASS (Catinella et al. 2010) is a targeted H$_1$ survey at Arecibo of $\sim 800$ galaxies with stellar masses in the range $10 < \log M_\odot/M_\odot < 11.5$ and redshifts in the range $0.025 < z < 0.05$. Each galaxy observed for GASS also lies in the ALFALFA, SDSS, and GALEX footprints, which yield homogeneously measured SFRs and stellar masses for the sample. Because GASS is unbiased and complete with respect to stellar mass, we can use it to define scaling relations and select samples based on those scaling relations that are representative of the galaxy population in the local universe. We use the GASS representative sample from Data Release 2 ($N = 480$; Catinella et al. 2012) to define a sample of galaxies that are H$_1$-rich for their stellar mass. (We defined the H$_1$-rich sample and the subsample for follow-up observations before the final data release in Catinella et al. (2013) was available, though that could be used now and should yield the same trends.) Our simple selection criterion, based only on H$_1$ mass and stellar mass, defines the H$_1$-rich sample to contain galaxies that have H$_1$ gas fractions in the top 5% of the GASS distribution. To determine where the top 5% lies, we sort the H$_1$ gas fractions, or upper limits on the gas fractions for non-detected GASS galaxies, and select the gas fraction that divides the bottom 95% from the top 5% (Figure 1(a)) in six evenly spaced stellar mass bins in the range $10.0 < \log M_\odot/M_\odot < 11.5$. We fit a line to these points that is parameterized as

$$\log M_{H_1}/M_\odot = a(\log M_\odot/M_\odot - 10) + k,$$

where $a = -0.75$ and $k = 0.02$. We consider all galaxies above the line to be H$_1$-rich for their stellar mass. A similar sample could be constructed using results of the bivariate H$_1$ mass function (Lemonias et al. 2013), but we chose this method for simplicity.

Although we use GASS to establish the criterion for selecting H$_1$-rich galaxies, we select the H$_1$-rich sample from ALFALFA, a blind, shallow wide-field H$_1$ survey that contains many more H$_1$ detections than GASS and whose sky footprint overlaps with that of GASS. Whereas GASS provides a complete census of H$_1$ in massive galaxies and can be used to derive quantiles of the distribution, ALFALFA mainly detects H$_1$-rich galaxies at the redshifts probed by GASS and so cannot be as easily used to quantify the full range of H$_1$ masses for massive galaxies. However, ALFALFA is complete over this volume to the H$_1$-rich gas fraction limits considered here and so is useful for selecting a large, unbiased sample of H$_1$-rich galaxies. We select the H$_1$-rich sample from the $\alpha_{H_1}$ subsample (Haynes et al. 2011). To ensure that the physical parameters for galaxies in the H$_1$-rich and GASS samples are measured homogeneously, the H$_1$-rich sample contains only ALFALFA galaxies that are also in the GASS parent sample ($N = 12,006$). There are 1102 unique matches (see Figure 1(b)) between the two samples, of which 258 meet the H$_1$-rich criterion and do not appear to be contaminated by neighboring galaxies. The final H$_1$-rich sample contains 258 galaxies with total H$_1$ masses in the range $10.0 < \log M_{H_1}/M_\odot < 10.75$ and a median mass of $\log M_{H_1}/M_\odot \sim 10.26$. The median gas fraction for the sample is $62\% \pm 38\%$.

To compare to the H$_1$-rich sample, we select a separate sample of ALFALFA galaxies with gas fractions in the range $-0.7 < \log$
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Figure 1. Top row shows the selection of the H\textsubscript{i}-rich galaxies. The top left panel shows H\textsubscript{i} gas fraction vs. stellar mass for GASS detections (gray points) and upper limits for GASS non-detections (gray triangles). The solid line shows the H\textsubscript{i}-rich selection, and the dotted line is the median of the GASS distribution. The top right panel shows the ALFALFA detections in the GASS parent sample. In the bottom four rows we compare the H\textsubscript{i}-rich sample (left column; blue points) to the constant gas fraction sample (right column; red circles) in terms of H\textsubscript{i} gas fraction, sSFR, star formation efficiency, and NUV − r color. Edge-on galaxies are highlighted as cyan points. Stars indicate the H\textsubscript{i} fractions and sSFRs of giant low surface brightness galaxies from Wyder et al. (2009). In panels (e) and (f), blue and red lines show the running medians for the H\textsubscript{i}-selected samples. The cyan line shows the same for the H\textsubscript{i}-rich sample excluding edge-on galaxies. The black dashed line in panels (e) and (f) shows the SF sequence from Schiminovich et al. (2007). The black dashed line in panels (g) and (h) shows the average SFE from Schiminovich et al. (2010). Contours enclose 5%, 10%, 25%, 50%, and 95% of the GASS parent sample. (A color version of this figure is available in the online journal.)

$M_{\text{HI}}/M_*$ < −0.4 across the full range of stellar mass. ALFALFA is also complete to these limits over the given redshift volume. We call this sample the “constant gas fraction” sample, which contains 285 galaxies. The median gas fraction for the sample is 29% ± 6%. The lower scatter in the average gas fraction compared to the H\textsubscript{i}-rich sample is by design.

2.2. Derived Quantities

The calculation of the SFRs used in this paper is described in detail in Schiminovich et al. (2010). We use their DC.D4NCUT SFRs, which are derived directly from near-UV luminosities. Star-forming galaxies, defined as having a 4000 Å break strength $D_n(4000) < 1.7$, are corrected for internal dust attenuation according to the method outlined in Johnson et al. (2007). Their method for determining dust corrections, based on UV and optical fluxes, was empirically calibrated using UV+IR measurements from GALEX and Spitzer. We calculate the H\textsubscript{i} gas fraction as the H\textsubscript{i} mass divided by the stellar mass, $M_{\text{HI}}/M_*$, such that the H\textsubscript{i} gas fraction can be greater than one. Stellar masses and AGN classifications are from the MPA-JHU SDSS DR7 catalog. AGN classes are described in Kauffmann et al. (2003). Galaxy sizes (e.g., $R_{90}$, $R_{50}$) and axis ratios are from the

5 http://www.mpa-garching.mpg.de/SDSS/DR7/
NASA-Sloan Atlas. We define edge-on galaxies as those with axis ratio \( b/a < 0.3 \). In Section 3.1.3 we estimate the SFR and \( \text{H} \) surface densities of GASS galaxies by assuming that the star formation is contained within \( R_{\text{H}} \) and that half of the total \( \text{H} \) is contained within \( R_{\text{H}} \). The latter is consistent with Wang et al. (2013), who show that the radius enclosing half of the \( \text{H} \) flux (their \( R_{50} \)) for normal galaxies is comparable to or less than the optical radius (half of \( D_{\text{e}} \)).

2.3. Results

First we examine how the SFRs of galaxies in the \( \text{H} \)-rich sample vary with stellar mass. One might naively expect \( \text{H} \)-rich galaxies to have uniformly high SFRs. To test this, in Figures 1(c) and (e) we plot the gas fractions and sSFRs of the \( \text{H} \)-rich galaxies versus stellar mass. Two distinct results are apparent: (1) The sSFRs of the \( \text{H} \)-rich galaxies decrease with increasing stellar mass faster than their \( \text{H} \) contents decrease; and (2) the scatter in their sSFRs increases with stellar mass, leaving many \( \text{H} \)-rich galaxies well below the star-forming sequence (dashed line; from Schiminovich et al. (2007)) at log \( M_{*}/M_{\odot} > 10.5 \). This population is the subject of our study in the next section.

Our \( \text{H} \)-rich sample contains galaxies that have extreme \( \text{H} \) contents for \textit{their stellar mass} so their \( \text{H} \) fractions necessarily decrease with stellar mass. However, the decreasing gas fraction cannot be the sole driver of the decreasing trend in sSFR because the sSFRs decline with a steeper slope (\( \alpha \sim -1.29 \)). To emphasize that the decreasing sSFRs are characteristic of \( \text{H} \)-rich galaxies in general and not just a sample of \( \text{H} \)-rich galaxies whose \( \text{H} \) gas fractions decrease with stellar mass, we compare the \( \text{H} \)-rich sample to the constant gas fraction sample, whose galaxies have higher-than-average gas fractions within the same narrow range with respect to stellar mass. Even though the gas fractions for galaxies in this sample remain constant with respect to stellar mass, their sSFRs decrease in the same way as for the \( \text{H} \)-rich sample. This inconsistent relationship between gas and star formation runs counter to the simple assumption that star formation history and is expected to be insensitive to extinction, mimics the distribution of sSFR, confirming the existence of a weaker link between gas fraction and sSFR at higher stellar masses. Although sSFRs for some edge-on galaxies may be underestimated by a factor of 10, it is unlikely that the decreasing sSFRs with stellar mass are driven by a higher proportion of edge-on galaxies at high stellar masses. To be sure, we show in Figure 1 that our results hold if we exclude edge-on galaxies from the \( \text{H} \)-rich sample. Finally, we note that there is generally more scatter in UV-derived SFR measurements for more massive galaxies (see Schiminovich et al. 2010), but it is unlikely to produce the strong trend we see.

The sSFRs of galaxies in the \( \text{H} \)-rich sample show that the relationship between \( \text{H} \) and star formation varies with stellar mass: at high stellar masses, star formation is suppressed even within galaxies that are \( \text{H} \)-rich for their stellar mass. In the next section we describe \( \text{H} \) imaging of 20 \( \text{H} \)-rich galaxies with low sSFRs. The resulting \( \text{H} \) maps provide insight into the physical conditions that can suppress star formation while maintaining a significant \( \text{H} \) reservoir at high stellar masses.

3. \textit{H} \textit{i} Imaging of Low-Star-Forming \textit{H} \textit{i}-Rich Galaxies

The low sSFRs in some massive \( \text{H} \)-rich galaxies suggest that star formation is being suppressed in some massive galaxies \textit{without the removal of} \( \text{H} \). The high gas fractions and low sSFRs in the most massive galaxies could be a signature of internal suppression of star formation, extended \( \text{H} \) disks with surface densities below that required for efficient star formation, or recently accreted gas that has not yet formed stars. The distribution and surface density of the \( \text{H} \) can provide key insight into the physical conditions of the cold gas in the galaxy, which can help us understand why the cold gas is not forming stars. We obtained followup \( \text{H} \) imaging with the Jansky VLA for a subset of the \( \text{H} \)-rich galaxies to understand the star formation suppression mechanisms at work in these galaxies. Below we
describe the galaxies selected for followup, the observations, and the conclusions we can derive from the observations.

### 3.1. Sample

Galaxies in our H\textsuperscript{i}-rich sample are ideal for followup with the VLA because their high H\textsuperscript{i} fluxes (1.38–8.1 Jy km s\textsuperscript{-1}), previously measured at Arecibo for the ALFALFA survey, ensure they can be easily detected in a short amount of time. From the final H\textsuperscript{i}-rich sample of 258 galaxies we selected 20 galaxies for followup with the VLA from the population of galaxies with high H\textsuperscript{i} masses and low sSFRs, i.e., those that deviated from the star-forming sequence at high stellar mass. The final sample includes all H\textsuperscript{i}-rich galaxies with high stellar masses (log \(M_* / M_\odot > 10.6\)), low sSFRs (log sSFR < −10.75), and moderate-to-high axis ratios (\(b/a > 0.5\)) to avoid edge-on galaxies whose sSFRs might be artificially low due to internal dust attenuation. We refer to this subset of H\textsuperscript{i}-rich galaxies as the VLA sample. They are indicated in Figure 2 and their properties are listed in Table 1. In Figure 3 we display their SDSS color images.

One galaxy, GASS 11390, was removed from the sample because the VLA observations revealed no H\textsuperscript{i} signal above the level of the noise. In the Arecibo spectrum the galaxy is at the edge of the band, which possibly affected the calculation of the H\textsuperscript{i} mass for ALFALFA. We report on the results of the final sample below, which contains 19 galaxies.

We note that there exist several other ongoing studies of H\textsuperscript{i}-rich galaxies and we wish to distinguish our sample and our goals from theirs. The Bluedisks project, as described in Wang et al. (2013) uses H\textsuperscript{i} maps to understand the origin of the excess H\textsuperscript{i} in galaxies that have high H\textsuperscript{i} gas fractions compared to their predicted gas fractions. Their goal contrasts slightly with our goal, which is to understand why some galaxies with large H\textsuperscript{i} reservoirs do not have high sSFRs.

Huang et al. (2012) describe a study of H\textsuperscript{i}-rich galaxies observed by ALFALFA, HHighMass, that will include a multiwave-length analysis of galaxies with log \(M_{\text{H\textsuperscript{i}}}/M_\odot > 10.0\) and high H\textsuperscript{i} fractions. Their goal is similar to ours: understanding why some galaxies maintain large gas reservoirs without forming stars at a high rate, but they also include less massive galaxies.

Lee et al. (2014) present CO observations of a sample of 28 H\textsuperscript{i}-rich galaxies, including 8 low surface brightness (LSB) galaxies, all of which have relatively high stellar masses (log \(M_* / M_\odot > 9.6\)) and H\textsuperscript{i} masses (log \(M_{\text{H\textsuperscript{i}}}/M_* > 10.2\)). We refer to this work in Section 4.5 when we discuss the possible molecular gas content of galaxies in our sample.

### 3.2. Observations and Data Reduction

Observations with the VLA were conducted in 2013 June–July in spectral-line mode at 21 cm in C configuration. We selected integration times of 2 or 4 hr, including time for calibration (with standard flux calibrators 3C48, 3C147, and 3C286), for each galaxy depending on the H\textsuperscript{i} fluxes detected at Arecibo, optical sizes, and an assumed H\textsuperscript{i} diameter, \(D_{\text{H\textsuperscript{i}}} = 1.5D_{\text{opt}}\), where \(D_{\text{opt}} = 2R_\text{opt}\) using r-band measurements. We defined eight spectral windows to cover the velocity range needed to detect H\textsuperscript{i} emission at the systemic velocities of the galaxies (see Figure 4). Each spectral window had 256 channels covering a frequency range of 8 MHz for a frequency resolution of 31.25 KHz or a velocity resolution of about 7 km s\textsuperscript{-1}. The spectral windows were not evenly spaced in frequency space but were defined so that H\textsuperscript{i} emission from each galaxy would fall close to the middle of a spectral window. Some of the spectral windows overlapped significantly. For data reduction we used only the data from the spectral window within which the galaxy was closest to the center (except for GASS40245; see Appendix).

Data were reduced with CASA (McMullin et al. 2007) following standard calibration procedures. Bad data points were selected and flagged based on the calibration solutions and by-eye inspection of the visibilities. We determined the continuum by fitting a line to the line-free channels and subtracted the result.
We used the CASA task CLEAN to create data cubes from the calibrated data. Data cubes were built with 6 × 6 arcsec pixels and a velocity resolution of about 28 km s\(^{-1}\) by averaging four adjacent channels. The median size of the synthesized beam is 21 × 17 arcsec. We used a weighting scheme with a robustness parameter of 1 (Briggs 1995) to emphasize low signal-to-noise emission. The typical noise is 0.54 mJy per beam per channel; we CLEANed down to two times the noise level.

From the data cubes, we chose by eye which channels to include in the total \(H_\text{i}\) intensity maps (moment-0) and velocity (moment-1) maps. We selected only those channels containing emission that appeared in more than one adjacent channel and seemed to be associated with the galaxy. For all galaxies, we first chose which pixels to include by adjusting the flux thresholds until we reached a compromise between including enough low surface brightness flux and not too much noise. In practice, we convolved the original data cube with a 20 × 20 arcsec kernel and selected the flux threshold based on this convolved image to avoid including noise in the final moment maps. This image was used to define which 6 × 6 arcsec pixels of the original cube should be included in the moment maps. Thus, the final moment maps have 6 × 6 arcsec pixels based on the original, unsmoothed data cube. We masked any remaining noise in the moment maps to minimize its effect on the calculation of \(H_\text{i}\) masses, radial profiles, and \(H_\text{i}\) radii.

For three galaxies with low surface brightness \(H_\text{i}\) emission (15607, 19918, 47708) we generated moment maps using a method that is less likely to exclude low levels of emission. Instead of imposing a threshold, we selected regions of emission in the data cube that appeared in more than one adjacent channel and summed the flux in those regions to produce the \(H_\text{i}\) intensity and velocity maps.

### 3.3. Derived Quantities

Following Walter et al. (2008), we derived \(H_\text{i}\) quantities directly from the moment maps that were constructed and masked to limit spurious \(H_\text{i}\).

#### \(H_\text{i}\) mass

We calculated \(H_\text{i}\) masses by summing the flux in the \(H_\text{i}\) intensity maps and converting the flux to \(H_\text{i}\) mass in solar masses according to the following equation:

\[
\frac{M_{H_\text{i}}}{M_\odot} = \frac{2.356 \times 10^5}{1 + z} d_\odot^2 S,
\]

where \(d_\odot\) is the luminosity distance in Mpc and \(S\) is the flux in Jy km s\(^{-1}\).

#### \(H_\text{i}\) radius

We constructed radial profiles by summing the flux in concentric elliptical annuli defined by the axis ratio and position angle of the optical disk reported in the NASA-Sloan Atlas. The annuli were 6 arcsec in width; an average of 15 independent data points contributed to the measurement of the \(H_\text{i}\) radii. \(H_\text{i}\) fluxes were converted to surface brightness in solar masses per square parsec. We determined the radial profiles out to a radius determined by eye for each galaxy. We use the radial profiles to calculate \(R_{90,H_\text{i}}\), the radius that contains 90% of the total \(H_\text{i}\) flux. In the \(H_\text{i}\) intensity maps we also display the contour at which the \(H_\text{i}\) surface brightness drops to 1 \(M_\odot\) pc\(^{-2}\), which is equivalent to a column density of 1.25 \(10^{20}\) atoms cm\(^{-2}\). Other methods of calculating the extent of cold gas include measuring the maximum distance to a given isolophote (Serra et al. 2012; Davis et al. 2013).

#### \(H_\text{i}\) surface density

The surface density of gas can be measured locally, for individual regions within a galaxy (as in, e.g., Bigiel et al. 2008, 2010; Leroy et al. 2008), and globally, over the entire extent of a galaxy (as in Kennicutt 1998). To be consistent with the analysis of Kennicutt (1998), and because the distances to galaxies in this paper are large enough that there are only a few resolution elements per galaxy, we only calculate global \(H_\text{i}\) surface densities. The global surface density necessarily averages over important variations in the local surface densities; the \(H_\text{i}\) intensity maps in Figure 6 give some indication of these variations.

There are several ways of calculating the global \(H_\text{i}\) surface density. To provide a sense of the possible range of global \(H_\text{i}\) surface densities in these galaxies, we report the \(H_\text{i}\) surface density calculated in three ways. First we calculate the \(H_\text{i}\)
surface density averaged over the regions of the galaxy within the $1 \, M_{\odot} \, \text{pc}^{-2}$ isophote. This contour is shown on the $\text{H} \, \text{I}$ intensity maps. A benefit to this method of calculating $\text{H} \, \text{I}$ surface density is that it only includes regions of the galaxy that contain significant amounts of $\text{H} \, \text{I}$. Second, we use the $\text{H} \, \text{I}$ radii derived from these observations, $R_{90 \, \text{H} \, \text{I}}$, and the optical radii reported in the NASA-Sloan Atlas, $R_{90 \, \text{opt}}$, to compute the $\text{H} \, \text{I}$ surface densities within these regions—the $\text{H} \, \text{I}$ disk and the stellar disk. Kennicutt (1998) calculated the global $\text{H} \, \text{I}$ surface density within the stellar disk, but this measurement provides no information about the outer parts of the $\text{H} \, \text{I}$ disk since $\text{H} \, \text{I}$ disks tend to extend well beyond the optical disks of galaxies.

**SFR surface density.** We also calculate the SFR surface density in three ways, averaging over the same three regions we used for the $\text{H} \, \text{I}$ surface density. To determine the SFR within each region, we scaled the SFR from $\text{GALEX}$ by the fraction of far-UV light contained within the given region, which assumes that the dust correction is uniform across the galaxy.

**Velocity spectra.** In Figure 5 we compare the velocity spectra from this survey to the ALFALFA spectra. The velocity resolution for the VLA spectra is coarser because we smoothed the
cubes as described above. There is general agreement between the spectra except in cases where we do not recover the total H\textsc{i} mass that ALFALFA detected (see the next section). In some cases the spectra match at the peaks but the VLA is missing some flux close to the systemic velocities. This flux might be harder to detect because the H\textsc{i} in channels close to the systemic velocity could, in a given channel, cover a larger physical area and subsequently have lower surface brightness below the noise level. We are probably not missing any high surface brightness gas, but there might be lower surface brightness gas that we are unable to detect, the presence of which would only strengthen the conclusions of this paper.

3.4. Results

3.4.1. H\textsc{i} Morphology

In Figure 6 we display the total intensity and velocity maps and the intensity maps overlaid on SDSS and GALEX images. It is clear that while all of the galaxies in the VLA sample exhibit H\textsc{i} emission well beyond the optical disks, the precise morphology of the H\textsc{i} varies widely. However, all 19 of our galaxies have H\textsc{i} that extends beyond the stellar disk and exhibit regularly rotating disks, placing them in the D category of Serra et al. (2012). As pointed out in Serra et al. (2012), regularly rotating disks of H\textsc{i} have likely been in place for several gigayears, while less settled H\textsc{i} morphologies might be the result of recent accretion or interactions. We comment on the role of external events such as these below.

We also calculated the concentration of the H\textsc{i} using the proxy $R_{90\text{H}1}/R_{50\text{H}1}$ and found no clear trends with respect to sSFR or SFE. This could mean that the star formation suppression mechanisms acting on the gas are independent of the precise distribution of H\textsc{i}.

3.4.2. H\textsc{i} Radii and Masses

The derived quantities described above are listed in Tables 2 and 3. We can compare the H\textsc{i} masses calculated from the VLA observations to the H\textsc{i} masses derived from the ALFALFA Arecibo observations as a check on the VLA observations. In general, the H\textsc{i} masses derived from the VLA are within 0.3 dex of the ALFALFA masses. There are four galaxies whose VLA mass deviates from the ALFALFA mass by more than 0.3 dex. These include 15607, 19918, and 47708, all of which have lower column density H\textsc{i} than most of the other galaxies in the sample. It is likely that the rest of the H\textsc{i} exists in an extended disk at even lower column densities that the VLA, with our several-hour integration times, was not sensitive to. If this is the case, then the H\textsc{i} radii should be considered lower limits and the H\textsc{i} surface densities upper limits. We found no evidence of radio continuum sources that could be absorbing the H\textsc{i}, artificially lowering the H\textsc{i} masses. Another galaxy with a low H\textsc{i} mass is 25285. Half of the data for this observation were corrupted and unusable so we did not achieve the sensitivity we wanted. The H\textsc{i} measurements for 25285 should also be considered lower limits.

We take the systematic and statistical errors on the H\textsc{i} masses as the lower and upper bounds on the errors. We take the systematic error to be 0.18 dex, the mean discrepancy between the ALFALFA and VLA masses. We calculate the statistical error on the H\textsc{i} mass to be 0.04 dex based on the average noise per channel of 0.5 mJy beam$^{-1}$. The error on the H\textsc{i} radius will scale with this error since our ability to calculate accurately the H\textsc{i} radius depends on our ability to detect H\textsc{i}.

In Figure 7 we compare $R_{90\text{H}1}$ to $R_{90\text{opt}}$. All of the galaxies in our sample have H\textsc{i} disks that extend beyond the optical disks and almost all of the H\textsc{i} disks have radii that are twice as large as the optical radii. The median ratio of $R_{90\text{H}1}/R_{90\text{opt}}$ is 2.6. There exists no obvious comparison sample since galaxies in the VLA sample span a wide range of morphologies and a narrow range of stellar masses and H\textsc{i} masses. The H\textsc{i}-to-optical ratio for our sample is higher than that for a sample of 68 early-type disk galaxies (S0-Sab) in Noordermeer et al. (2005), who report ratios of 1.72 for Sa/Sab galaxies and 2.11 for S0/S0a galaxies. While only 2 out of 68 galaxies in their sample have $R_{\text{H}1}$ > 40 kpc, almost all of the galaxies in our sample have $R_{\text{H}1}$ > 40 kpc. A noticeable difference between their sample and ours
is that 18% of the galaxies in their sample have H\textsubscript{i} disks that lie within the stellar disks. They ascribe the smaller H\textsubscript{i} disks to ram-pressure stripping and other types of interactions because most of the galaxies with $R_{H\textsubscript{i}} < R_{\text{opt}}$ show signs of interactions. Our results here are consistent with that found in Wang et al. (2013) for a sample of H\textsubscript{i}-rich galaxies, though their sample includes some galaxies with lower stellar masses and lower H\textsubscript{i} masses.
Figure 6. H\textsubscript{i} intensity and velocity maps for galaxies in the VLA sample, 5 arcmin on a side. The column on the far left shows the H\textsubscript{i} intensity maps with lines of constant surface brightness indicated (red, green, and blue contours indicate 0.2, 1.0, and 5.0 $M_{\odot}$ pc\textsuperscript{-2}). The scalebar indicates 20 kpc. The next column shows the velocity maps; the velocity range for each map roughly corresponds to the velocity ranges in Figure 5. The third and fourth columns show the surface brightness contours overlaid on the SDSS $r$-band and GALEX NUV images. Blue dashed ellipses indicate $R_{90\text{H}i}$ and red dashed ellipses indicate $R_{90\text{opt}}$. The beam size is shown in the lower left corner. SDSS and GALEX images were scaled to the same resolution as the H\textsubscript{i} maps and were obtained from the NASA-Sloan Atlas and MAST. (A color version of this figure is available in the online journal.)

3.4.3. The Star Formation Law

To understand the origin of the low sSFRs for galaxies in the VLA sample, it is crucial to determine not just the extent of their H\textsubscript{i} disks but also the surface density of H\textsubscript{i} within the H\textsubscript{i} disks. The H\textsubscript{i} surface density provides information about which types of suppression mechanisms are at work in these galaxies. Based on work showing that star formation is inefficient at low gas
surface densities, low $\text{H}\text{I}$ surface densities alone could explain low sSFRs. If galaxies in the VLA sample have high $\text{H}\text{I}$ surface densities, then something else must be preventing the gas from forming stars. In combination with the SFR surface density, the $\text{H}\text{I}$ surface density can tell us if these galaxies follow well-established relationships between cold gas and star formation, with both low gas and SFR surface densities as in the lower part of the star formation law, or if there is something unique about these galaxies.

We compare the three calculations of $\text{H}\text{I}$ surface densities in the left panel of Figure 8. The $\text{H}\text{I}$ surface density calculated within the $1 \ M_\odot \ \text{pc}^{-2}$ isophote and within $R_{90\text{H}\text{I}}$ have similar distributions. Since Figure 6 shows that $R_{90\text{H}\text{I}}$ and the $1 \ M_\odot \ \text{pc}^{-2}$ isophote map out similar regions, this is expected. $\Sigma_{\text{H}\text{I}}$ within the
Figure 6. (Continued)

Table 2
Derived H i Quantities

| GASS ID | AA ID    | $\log A M_{\text{HI}}$ ($M_{\odot}$) | $\log VLA M_{\text{HI}}$ ($M_{\odot}$) | Flux  (Jy km s$^{-1}$) | $R_{90M_{\text{HI}}}$ (kpc) | $R_{90\text{opt}}$ (kpc) | $V_{\text{helio}}$ (km s$^{-1}$) | Frequency (MHz) | $t_{\text{int}}$ (hr) | MYS AO (mJy/beam/channel) |
|---------|----------|------------------------------------|---------------------------------------|--------------------|-----------------------------|--------------------------|-----------------------------|-----------------|----------------|--------------------------|
| 11390   | 332599   | 10.3                               |                                      | ···                | ···                         | ···                      | 11.7                        | 12420           | 2              | 0.500                    |
| 13340   | 232760   | 10.5                               | 10.3                                 | 1.9               | 100.0                       | 12.0                     | 14608                       | 1351.743        | 4              | 0.400                    |
| 15607   | 213794   | 10.3                               | 9.9                                  | 0.9               | 39.9                        | 14.8                     | 14163                       | 1353.348        | 2              | 0.535                    |
| 17705   | 6072     | 10.4                               | 10.5                                 | 6.4               | 68.7                        | 20.8                     | 10646                       | 1370.052        | 2              | 0.559                    |
| 19918   | 181103   | 10.4                               | 9.9                                  | 0.8               | 48.3                        | 15.5                     | 13933                       | 1354.726        | 2              | 0.524                    |
| 23187   | 5737     | 10.6                               | 10.5                                 | 3.4               | 52.5                        | 25.8                     | 14956                       | 1349.613        | 4              | 0.380                    |
| 25285   | 8395     | 10.3                               | 9.6                                  | 0.7               | 28.6                        | 17.5                     | 11462                       | 1366.260        | 4              | 0.590                    |
| 26806   | 4652     | 10.3                               | 10.1                                 | 3.4               | 40.5                        | 17.0                     | 8773                        | 1378.873        | 2              | 0.760                    |
| 29304   | 9515     | 10.7                               | 10.7                                 | 4.9               | 60.6                        | 23.7                     | 14017                       | 1354.044        | 2              | 0.490                    |
| 40245   | 8907     | 10.5                               | 10.2                                 | 2.7               | 57.0                        | 26.0                     | 11745                       | 1364.925        | 2              | 0.510                    |
| 41063   | 231506   | 10.5                               | 10.4                                 | 3.8               | 61.1                        | 19.4                     | 11386                       | 1366.572        | 2              | 0.542                    |
| 42262   | 251252   | 10.4                               | 10.2                                 | 2.0               | 72.5                        | 13.0                     | 12575                       | 1360.990        | 2              | 0.497                    |
| 45267   | 9157     | 10.3                               | 10.1                                 | 2.5               | 45.1                        | 18.1                     | 10868                       | 1368.916        | 2              | 0.700                    |
| 45357   | 9195     | 10.5                               | 10.3                                 | 1.9               | 51.7                        | 25.2                     | 14986                       | 1349.485        | 4              | 0.440                    |
| 45404   | 9094     | 10.6                               | 10.6                                 | 6.7               | 72.4                        | 19.3                     | 11410                       | 1366.388        | 2              | 0.550                    |
| 45664   | 9234     | 10.7                               | 10.8                                 | 10.5              | 91.6                        | 12.8                     | 10890                       | 1368.675        | 2              | 0.740                    |
| 47677   | 723039   | 10.4                               | 10.0                                 | 1.6               | 60.4                        | 12.3                     | 12219                       | 1362.553        | 2              | 0.560                    |
| 47708   | 722779   | 10.3                               | 9.7                                  | 0.7               | 51.7                        | 20.2                     | 13483                       | 1356.573        | 2              | 0.535                    |
| 51390   | 4109     | 10.5                               | 10.3                                 | 2.1               | 61.9                        | 24.8                     | 13706                       | 1355.550        | 4              | 0.500                    |
| 57949   | 6861     | 10.5                               | 10.2                                 | 2.1               | 41.3                        | 21.3                     | 13303                       | 1357.382        | 2              | 0.500                    |
The similarities in the distribution of the H\textsc{i} within the galaxies are significant. All the surface densities among the galaxies are similar, with one exception that will be pointed out later. The optical disks also have a similar distribution, with one exception at high surface densities, which will be discussed later.

Figure 7 shows a 2-to-1 relationship between SFR and H\textsc{i} within the optical disk, with one exception at higher surface densities. Most galaxies have H\textsc{i} surface densities that match the observations in Bigiel et al. (2009), above which most of the cold gas is in molecular form. We elaborate on this point below.

We compare the three calculations of SFR within the stellar disk in the right panel of Figure 8. S\textsubscript{SFR} within the stellar disk is lower than the other measures of SFR surface density because most of the star formation is contained within the stellar disk. S\textsubscript{SFR} within the H\textsc{i} disk is lower since a similar amount of star formation is being averaged over a much larger surface area.

A direct comparison between SFR and H\textsc{i} surface densities is in Figure 9. Since GASS galaxies have single-dish H\textsc{i} measurements from Arecibo, which does not provide spatial information, we cannot compare the H\textsc{i} surface densities for the VLA galaxies directly to the H\textsc{i} surface densities for more typical galaxies. Instead, we first examine how well GASS and VLA galaxies follow theoretical predictions for the relationship between SFR and H\textsc{i} surface densities by assuming that their gas-phase metallicities are typical, e.g., that half of the H\textsc{i} lies within the optical disk. We display these predicted surface densities for star-forming and non-star-forming galaxies from GASS and for the VLA galaxies separately in the left panel of Figure 9. We compare them to curves for the theoretical predictions for the relationship between SFR and H\textsc{i} surface densities by assuming that their gas-phase metallicities are typical, e.g., that half of the H\textsc{i} lies within the optical disk.

Table 3

| GASS ID | \(\Sigma_{\text{H\textsc{i}}}(\text{M}_\odot\text{pc}^{-2})\) | \(\Sigma_{\text{H\textsc{i}};\text{opt}}(\text{M}_\odot\text{pc}^{-2})\) | \(\Sigma_{\text{H\textsc{i}}};\text{opt}^{1.1}\text{M}_\odot(\text{M}_\odot\text{kpc}^{-2})\) | \(\Sigma\text{SFR};\text{H\textsc{i}}(\text{M}_\odot\text{kpc}^{-2})\) | \(\Sigma\text{SFR};\text{opt}(\text{M}_\odot\text{kpc}^{-2})\) | \(\Sigma\text{SFR};\text{opt}^{1.1}\text{Msun}(\text{M}_\odot\text{kpc}^{-2})\) |
|---------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 13340   | -0.20           | 0.02            | -0.83           | -5.49           | -5.62           | -5.36           |
| 15601   | 0.19            | 0.39            | 0.44            | -4.28           | -4.12           | -3.57           |
| 17705   | 0.32            | 0.41            | 0.75            | -4.14           | -4.08           | -3.16           |
| 19918   | -0.03           | 0.20            | 0.42            | -4.10           | -3.94           | -3.15           |
| 23187   | 0.58            | 0.55            | 0.70            | -3.58           | -3.67           | -3.13           |
| 25285   | 0.17            | 0.49            | 0.39            | -3.50           | -3.50           | -3.15           |
| 26806   | 0.34            | 0.51            | 0.59            | -3.81           | -3.72           | -3.13           |
| 29304   | 0.56            | 0.54            | 0.86            | -4.00           | -4.01           | -3.38           |
| 40245   | 0.20            | 0.32            | 0.20            | -3.99           | -4.03           | -3.58           |
| 41063   | -0.03           | 0.09            | -0.07           | -4.51           | -4.86           | -3.54           |
| 45267   | 0.31            | 0.35            | 0.44            | -3.87           | -3.95           | -3.14           |
| 45357   | 0.34            | 0.43            | 0.39            | -3.76           | -3.72           | -3.22           |
| 45404   | 0.36            | 0.39            | 0.43            | -4.12           | -4.13           | -3.30           |
| 46644   | 0.31            | 0.41            | 0.62            | -4.57           | -4.51           | -3.88           |
| 47670   | -0.05           | 0.26            | 0.23            | -4.95           | -4.69           | -4.29           |
| 47705   | -0.20           | 0.10            | 0.03            | -3.16           | -3.95           | -3.75           |
| 51390   | 0.16            | 0.30            | 0.21            | -4.07           | -4.07           | -3.52           |
| 57949   | 0.48            | 0.46            | 0.64            | -3.42           | -3.49           | -2.89           |

Note. All surface densities are shown in log base 10.
et al. (2012) showed that H1-rich galaxies tend to have lower metallicities beyond $R_{90}$. The theoretical curves include H1 and H2 and we only have H1 measurements. Any measurable H2 would shift the galaxies to the right in the plot. We highlight the surface density predictions for solar metallicities in the VLA sample, which overlap somewhat with the non-star forming galaxies but are further from the theoretical curves than the average galaxy. At this location, they lie below the star formation law with low SFR surface densities compared to their high H1 surface densities. If this were their true location in this plane, then we would need to appeal to factors other than low H1 surface densities that can prevent gas from forming stars.

In the right panel of Figure 9 we show the true locations of the H1-rich galaxies based on the VLA observations. It is significant that the H1-rich galaxies in the VLA sample lie remarkably close to the theoretical curve for solar metallicities in the region of the plot in which the SFR surface density drops steeply as H1 surface density also decreases. The location of the galaxies in the $\Sigma_{\text{SFR}}-\Sigma_{\text{H1}}$ plane suggests that the relationship between cold gas and SFR surface densities in these galaxies conforms to theoretical expectations and that the discrepancy between their low sSFRs and high H1 masses is simply due to the distribution of H1, which yields low gas surface densities. The outlier in this plot and the only galaxy with $\log \Sigma_{\text{SFR}} < -5$ is GASS 13340, which has the most extended H1 disk and very little star formation.

Although it appears that low H1 surface densities could be a major reason for the low total sSFRs in the VLA galaxies, other mechanisms likely contribute. As seen in Bigiel et al. (2008) and Leroy et al. (2008), at low gas surface densities a narrow range of gas surface densities can yield a wide range of SFR surface densities, which we also see in our sample. To explain this phenomenon, there must exist factors other than the gas surface density that regulate the relationship between cold gas and star formation. We consider factors related to the internal structure of the galaxy: concentration index and AGN classification.

In Figure 10 we show the $\Sigma_{\text{SFR}}-\Sigma_{\text{H1}}$ plane again, indicating the concentration index and AGN classification for each galaxy. Some interesting trends are apparent, which point to the structure of the galaxy possibly playing a role in the suppression of star formation. In the left panel we indicate whether each galaxy has no AGNs, a low signal-to-noise AGN, a weak AGN (with Oiii luminosity < $10^{7} L_{\odot}$), or a spectrum indicating the presence of an AGN and star formation. Except for GASS 13340, evidence for the presence of an AGN becomes more common toward lower SFR surface densities. There exists a similar trend with respect to concentration, with more bulge-dominated galaxies exhibiting lower SFR surface densities. We discuss the implications of these trends below.

4. THE SUPPRESSION OF STAR FORMATION IN MASSIVE H1-RICH GALAXIES

A number of factors regulate the relationship between cold gas and star formation, and although the H1 maps move us closer to understanding the relationship between these quantities in galaxies in the VLA sample, it is still difficult to draw firm conclusions. In the previous section we showed that low H1 surface densities and the presence of a bulge might prevent H1-rich galaxies from forming stars at high rates. These situations are commonly invoked to explain low SFRs in quenched galaxies, but we emphasize that our galaxies are not “quenched” in the traditional sense: they have a surplus of cold gas and they are still forming stars, albeit at a low rate. In this section we delve into the observational and theoretical evidence for these star formation suppression mechanisms to understand not just if these mechanisms are acting in these galaxies but how we might be able to use additional data to draw firmer conclusions.

We discuss in detail how AGN feedback and the presence of a bulge can suppress star formation and we describe why galaxies in the VLA sample might harbor long-lived low-surface-density H1 disks. We also explain why recent gas
accretion probably cannot account for the extreme H\textsc{i} masses in these galaxies. Finally, we discuss why galaxies with an unexpected combination of high H\textsc{i} masses and low sSFRs become common only at high stellar masses. We do not consider here environmental quenching mechanisms, such as ram-pressure stripping (e.g., Tonnesen et al. 2007), which remove substantial amounts of gas from galaxies, though it would be interesting to see if galaxies in the VLA sample are preferentially in extremely isolated environments, such as voids, where gas-rich galaxies are found with a higher frequency (Kreckel et al. 2012). We do know that the H\textsc{i}-rich galaxies are not cluster galaxies, but a thorough examination of their environments and a possible link between their environments and their gas and star-forming properties is beyond the scope of this work.

4.1. AGN Feedback

AGNs can inhibit star formation in at least three distinct ways, which can occur simultaneously but in different proportions within a given galaxy. AGNs can remove potentially star-forming gas from galaxies via outflows; the energy released by AGNs can contribute to the existence of a hot halo, preventing future gas accretion; and AGNs can inject energy into the gas reservoir such that it is unable to collapse and form stars but stays within the galaxy. Most observational studies of star formation suppression via AGNs focus on the detection of outflows as evidence that AGNs can remove enough gas to significantly affect a galaxy’s SFR (e.g., Cano-Díaz et al. 2012; Yuma et al. 2013; Förster Schreiber et al. 2014), but this type of suppression via AGNs cannot explain the large cold gas contents in the H\textsc{i}-rich galaxies. The buildup of a hot halo that prevents gas accretion cannot explain why the cold gas already within the galaxy is stable against star formation, so is not helpful in explaining our results. The third scenario, in which AGN feedback disrupts the cold gas enough to prevent it from forming stars, could explain our results and is the scenario we discuss below.

Because simulations have only just begun to include a multiphase interstellar medium (ISM; e.g., Davé et al. 2013), to our knowledge none exist that specifically address how the H\textsc{i} that remains in a galaxy is affected by AGN feedback (though Gabor & Bournaud (2013) note that in gas-rich $z \sim 2$ galaxies AGN feedback is not strong enough to disrupt dense
clouds of star-forming gas). Observational studies of AGN hosts with measured H\textsc{i} masses show that H\textsc{i} can remain at high levels in galaxies with AGNs: Ho et al. (2008) and Fabello et al. (2011) show that AGN hosts contain just as much H\textsc{i} as do their counterparts without AGNs. If massive galaxies can simultaneously contain AGNs and large H\textsc{i} reservoirs, how, if at all, is the AGNs affecting the H\textsc{i} reservoir? Direct observational evidence of this is lacking, but Nesvadba et al. (2010) show how AGN feedback prevents the molecular gas from forming stars in the H\textsc{2}-luminous radio galaxy 3C 326. Like the H\textsc{i}-rich galaxies in this paper, 3C 326 N contains a substantial amount of cold gas ($M_{\text{H}_2} = 10^9 M_\odot$) but a surprisingly low SFR. They found that mechanical energy from the AGN that was injected into the ISM heated the molecular gas enough to make it stable against star formation but still detectable as H\textsc{2}.

It is possible that a similar mechanism that heats the H\textsc{i} is at work in some of the massive H\textsc{i}-rich galaxies discussed here. If this is so, H\textsc{i}-rich galaxies with AGN should have a lower SFR surface density than comparison galaxies with the same H\textsc{i} surface density. In Figure 10 we show that this is indeed the case: galaxies with lower SFR surface densities tend to have evidence of an AGN. However, the only true AGN in the VLA sample are weak, with $O_{\text{III}}$ luminosities less than $10^7 L_\odot$, so it is unclear if they are powerful enough to affect the large quantities of gas in the galaxies in the VLA sample.

### 4.2. Morphological Quenching

One way in which star formation can be suppressed without removing or heating the cold gas is via morphological quenching, in which a galaxy’s bulge stabilizes its gas disk against star formation. Martig et al. (2009) explain that gas disks embedded in bulge-dominated galaxies may exhibit SFRs a factor of 10 lower than similarly massive gas disks in spiral galaxies for two reasons: bulge-dominated galaxies lack a stellar disk that contributes to the self-gravity of a gas disk and naturally have higher epicyclic frequencies, which can increase the Toomre $Q$ parameter above the critical value for star formation. This scenario is also seen in simulations at redshift $z \sim 2$ (Agertz et al. 2009; Ceverino et al. 2010) and is supported by observations at $z \sim 2$ in which star-forming galaxies have higher values of $Q$ at their centers where a bulge dominates (Genzel et al. 2014). In the local universe, lower H\textsc{i} and H\textsc{2} SFEs in bulge-dominated galaxies compared to late-type galaxies provide some evidence for morphological quenching (Saintonge et al. 2012).

Martig et al. (2013) find that the effectiveness of morphological quenching depends on the precise gas content of the galaxy. Early-type galaxies with low cold gas fractions (1.3% in their simulation) contain gas disks that are stable against star formation and do not fragment. Early-type galaxies with higher gas fractions (4.5% in their simulation) have gas disks that do fragment but form stars less efficiently than similar gas disks embedded in a spiral galaxy because a smaller fraction of their cold gas is in a very dense ($>10^4$ cm$^{-2}$) phase. The reduced fragmentation due to morphological quenching effectively lowers the fraction of cold gas in dense phases, which in turn lowers the global efficiency of star formation. Taking into account the range of possible gas fractions, Martig et al. (2013) report that gas disks embedded in bulge-dominated galaxies form stars two to five times less efficiently than do gas disks with a similar gas surface density embedded in spirals.

While a direct comparison between the Martig et al. (2013) simulations and our H\textsc{i}-rich galaxies is impossible because the H\textsc{i}-rich galaxies in this paper have much higher gas fractions, ranging from 15% to over 60%, their results suggest that bulges could play a role in lowering the SFE in some of our H\textsc{i}-rich galaxies. Martig et al. (2013) emphasize that morphological quenching is not strong enough to drive the evolution of all galaxies onto the red sequence, but could be a contributing factor alongside other quenching mechanisms.

Martig et al. (2013) show in the radial profiles of their simulated galaxies that the gas surface density increases to greater than $10^2 M_\odot$ pc$^{-2}$ at the centers of the galaxies. The gas in this density regime is likely molecular, which would create a central hole in a map of the H\textsc{i} flux. Some galaxies in the VLA sample do exhibit an H\textsc{i} depression in the center. If galaxies with little H\textsc{i} in their centers do have central H\textsc{2} and no sign of central star formation, this could be evidence of morphological quenching. If the center lacks cold gas altogether, it is unclear if morphological quenching is at work. H\textsc{i} observations of galaxies in the VLA sample could bring clarity to this scenario.

Since all of the H\textsc{i}-rich galaxies described here have high gas fractions, which Martig et al. (2013) find lower the effect of morphological quenching, and most have low gas surface densities, which according to Martig et al. (2013) heighten the effect of morphological quenching, we cannot draw any definitive conclusions about the effect of morphological quenching in our sample except to say that it could be playing a role in the more highly concentrated galaxies based on the recent simulations and observations demonstrating its effects. In Figure 10 we identify the H\textsc{i}-rich galaxies based on their concentration index; there is some evidence that the more bulge-dominated galaxies have lower SFR surface densities at a given H\textsc{i} surface density, though it is unlikely that morphological quenching can affect the very extended gas disks in the VLA sample. Morphological quenching is unlikely to play a role in less bulge-dominated galaxies.

### 4.3. Below-threshold Cold Gas

Inefficient star formation can result from low cold gas surface densities, which can be present in H\textsc{i}-rich galaxies if the H\textsc{i} extends over a large surface area. As noted above, H\textsc{i} disks generally extend well beyond stellar disks, and this is something we see in the VLA sample as well. Galaxies selected by H\textsc{i} tend to be more extended than those that are selected optically (Huang et al. 2012).

Extended H\textsc{i} disks will form stars inefficiently only if the disks do not contain substantial amounts of H\textsc{2}, the immediate precursor to star formation. Observations confirm that the outskirts of gaseous disks tend to be H\textsc{i}-dominated. Bigiel et al. (2008) show that in local spirals, H\textsc{i} extends well beyond the radius at which SFR and H\textsc{2} become negligible. In Leroy et al. (2008) the molecular fraction, $\Sigma_{\text{H}_2}/\Sigma_{\text{H}_1}$, decreases steadily with radius, and in Martin & Kennicutt (2001) the total (H\textsc{i} + H\textsc{2}) gas surface density profile decreases more quickly than the H\textsc{i} surface density profile. Schaye (2004) shows that extended gas disks tend to be H\textsc{i}-dominated because the transition from the neutral to the molecular phase proceeds efficiently only above a critical gas surface density of $3 \times 10^{-2} M_\odot$ pc$^{-2}$. A critical surface density of $9 M_\odot$ pc$^{-2}$ is confirmed observationally by Bigiel et al. (2008), above which cold gas is mostly molecular.

Our observed galaxies have H\textsc{i} surface densities that fall below the critical gas surface density, indicating that the gas disks in the VLA sample are likely H\textsc{i}-dominated. Where H\textsc{i} dominates over H\textsc{2}, star formation necessarily proceeds at a slower rate. Observations show that in the outskirts of galaxies where H\textsc{i} dominates, and in dwarfs that are H\textsc{i}-dominated
throughout, the local SFE decreases with radius (Bigiel et al. 2008; Leroy et al. 2008). Integrated and local measurements show that there is a break in the star formation law such that at gas surface densities below the critical density, galaxies exhibit SFR surface densities a factor of five below the extrapolation of the star formation law at higher gas surface densities (Wyder et al. 2009; Bigiel et al. 2008). Wyder et al. (2009) show that this downturn, which is equivalent to a lowering of the SFE at low gas surface densities, agrees with work by Krumholz & McKee (2005) and Blitz & Rosolowsky (2006) predicting lower H\textsubscript{2} fractions in low surface density gas. The galaxies in the VLA sample lie in the part of the star formation law in which star formation is least efficient. Thus, the low sSFRs in the galaxies in the VLA sample are reasonable given their H\textsubscript{i} surface densities.

For the phenomenon of extended, low surface density H\textsubscript{i} disks to be common, the extended H\textsubscript{i} disks must be long-lived. Simulations have shown that extended low surface density gaseous disks may result when galaxies accrete from the intergalactic medium (IGM) cold, dense filaments, which have higher angular momenta than the dark matter halo and prevents efficient gas transport to the disk (Kimm et al. 2011; Stewart et al. 2011). A more likely scenario for the massive galaxies in the VLA sample, which might not accrete gas directly from cold filaments in the IGM, is described in Lu et al. (2014). They show that extended gas disks with H\textsubscript{i} surface densities below the critical density for star formation can result when the gas disks are built up by gas cooling from large radii within the hot halo.

Populations of galaxies in the local universe that are defined by inefficient outer star formation include GLSBs and XUV-disks. Galaxies in the VLA sample might be analogs of GLSBs: in Figure 1 we show that GLSBs and the VLA sample lie in the same region of the H\textsubscript{i} gas fraction—stellar mass plane. The prevalence of XUV-disks (Thilker et al. 2007; Lemonias et al. 2011) confirms that inefficient star formation in extended disks is common. Galaxies in the VLA sample are probably not XUV-disks (except for 45664) because their UV images do not show evidence of recent star formation within the extended H\textsubscript{i}, but galaxies in the VLA sample and XUV-disks might represent different stages of the life of an extended H\textsubscript{i} disk.

4.4. Recent Gas Accretion

If galaxies in our sample recently accreted cold gas, it is possible that the gas simply has not been in the galaxy long enough to collapse and form stars. Kereš et al. (2005) show that it generally takes 0.5 Gyr for the cosmic SFR to react to new gas accretion. To determine whether this scenario could account for the high H\textsubscript{i} masses and low SFRs of galaxies in our sample, we must consider, first, whether we expect galaxies at this mass scale to be accreting gas and at what rate, and, second, whether we see any evidence of recent accretion in the optical images and H\textsubscript{i} maps.

Simulations have shown that the ways in which galaxies accrete gas depend on their mass, environment, and redshift. At z ~ 0, gas that is accreted onto galaxies above a critical halo mass is shock heated to the virial temperature and likely stays warm (Birnboim & Dekel 2003; Dekel & Birnboim 2006; Kereš et al. 2005). Gas that is accreted onto galaxies below the critical halo mass tends to enter a galaxy in the form of cold streams from the IGM. Depending on the precise way in which one relates halo mass to baryonic mass, this critical mass could lie just below the stellar mass at which many H\textsubscript{i}-rich galaxies with low SFRs are found. Thus, galaxies like those in our sample are probably accreting gas that is shock-heated and it is unclear whether that will ultimately cool into H\textsubscript{i}.

For recent accretion to account for the large amount of excess H\textsubscript{i} in our H\textsubscript{i}-rich galaxies, we would expect to see large tidal features indicative of major accretion events in the H\textsubscript{i} maps or optical imaging. We do not see any obvious signatures of accretion events in the VLA sample and the H\textsubscript{i} maps suggest that galaxies in the VLA sample have regularly rotating, settled disks. GASS 45664 is the possible exception, with an H\textsubscript{i} distribution whose peak is offset from the stellar disk. The regions with the strongest H\textsubscript{i} emission exhibit prominent spiral arms, but other regions with significant H\textsubscript{i} do not have signs of star formation. This combination of UV-bright features embedded in an extended H\textsubscript{i} disk that does not show signs of star formation elsewhere suggests that we are seeing this galaxy in the process of re-building its stellar disk after a major accretion event.

In this initial study of H\textsubscript{i} morphologies, we cannot assess the distribution and kinematics of the H\textsubscript{i} at the level done by Sancisi et al. (2008) because our observations do not have the required depth. That type of analysis could reveal lesser accretion events based on the presence of gas at anomalous velocities, but such lesser accretion events are unlikely to yield the high H\textsubscript{i} masses in the VLA sample. It appears that much of the cold gas in galaxies in the VLA sample has been retained as the galaxies evolved since there is no evidence that major episodes of accretion brought in large amounts of cold gas.

4.5. The Emergence of Low-star-forming H\textsubscript{i}-rich Galaxies at High Stellar Masses and the Role of H\textsubscript{2}

The results of our analysis of H\textsubscript{i}-rich galaxies in Section 2 are twofold: (1) that a population of H\textsubscript{i}-rich galaxies with surprisingly low sSFRs exists, and (2) that this population primarily exists above a stellar mass of log $M_\star = 10.5$. H\textsubscript{i} imaging allows us to understand the suppression of star formation in these galaxies. A separate question is why galaxies with an excess of H\textsubscript{i} compared to their SFRs become common above a threshold stellar mass.

Some evidence exists to show that as stellar mass increases, not only do sSFRs decrease, but so does the efficiency with which galaxies convert their cold gas into stars. Young et al. (2013) show that cold gas (H\textsubscript{2} or H\textsubscript{i}) content up to $10^9 M_\odot$ does not measurably affect the UV-optical colors of massive (log $M_\star > 10.7$) galaxies. They also find that less massive early-type galaxies with cold gas are blue while more massive early-type galaxies with measurable cold gas are red. Even when massive galaxies have significant amounts of H\textsubscript{2}, which is one step closer to forming stars than H\textsubscript{i}, they are unlikely to form stars at a high rate. Although the H\textsubscript{2}-based SFE is constant with respect to stellar mass (Schiminovich et al. 2010), the H\textsubscript{2}-based SFE decreases as stellar mass increases (Saintonge et al. 2011b). Young et al. (2013) show that massive galaxies have older single stellar population ages than less massive galaxies with the same H\textsubscript{i} fraction. Together, these findings present a picture in which the most massive galaxies do not form stars even if they have the cold gas necessary to do so.

A significant H\textsubscript{i} mass compared to SFR could be a sign that a galaxy is lacking H\textsubscript{2} and is suffering from inefficient conversion from H\textsubscript{i} to H\textsubscript{2}. Huang et al. (2012) suggest this is why their H\textsubscript{i}-selected sample has lower SFEs than an optically selected sample. An abundance of H\textsubscript{i} compared to H\textsubscript{2} might be more common in more massive bulge-dominated galaxies.
et al. (2011a) find that the detection rate of H\textsubscript{i} and H\textsubscript{2} drops significantly among more bulge-dominated galaxies and that above these detection thresholds, galaxies have mostly H\textsubscript{i} if they have any cold gas at all. Similarly, red galaxies are more likely to be detected in H\textsubscript{i} than H\textsubscript{2} (Young et al. 2013).

Lee et al. (2014) measure the H\textsubscript{2} in 28 H\textsubscript{i}-rich galaxies with stellar masses and H\textsubscript{i} masses similar to those for our sample. 15 out of 20 normal galaxies and 4 out of 8 LSB galaxies were detected. Their high H\textsubscript{2} contents place them at the high end of the H\textsubscript{2} gas fraction distribution shown in Saintonge et al. (2011a), but their cold gas reservoirs are still dominated by H\textsubscript{i} over H\textsubscript{2} by a factor of 2–3. Although our sample was selected differently from theirs to include only H\textsubscript{i}-rich galaxies with low sSFRs, there is still no evidence that H\textsubscript{i}-rich galaxies in general are molecular-dominated.

Although we do not have H\textsubscript{2} measurements for the VLA sample, we assume based on the results of Saintonge et al. (2011a), Young et al. (2013), and Lee et al. (2014) and on the low sSFRs in these galaxies that they do not contain significant quantities of H\textsubscript{2}. What, then, is hindering the conversion from H\textsubscript{i} to H\textsubscript{2} in massive galaxies? Fu et al. (2010) predict that a high spin parameter λ (usually associated with more massive galaxies) is related to less efficient H\textsubscript{i}-to-H\textsubscript{2} conversion. Huang et al. (2012) show that at a given stellar mass, galaxies with higher H\textsubscript{i} fractions are in dark matter halos with higher spin parameters, which probably means that they are more extended since their halos have higher angular momenta. Although this phenomenon is no longer obvious at stellar masses above M* > 10.5, Huang et al. (2012) generally find that H\textsubscript{i}-selected galaxies reside in halos with high spin parameters and are more extended. If massive H\textsubscript{i}-rich galaxies tend to have more extended H\textsubscript{i} disks than is typical, then the conversion from H\textsubscript{i} to H\textsubscript{2} must be weak because much of the gas lies beyond the radius at which the conversion proceeds efficiently (Schaye 2004).

### 5. SUMMARY AND CONCLUSIONS

We used two recent large H\textsubscript{i} surveys, GASS and ALFALFA, to define and select a sample of massive galaxies (log M*/M\odot > 10) that are extremely H\textsubscript{i}-rich for their stellar mass. The H\textsubscript{i}-rich galaxies have H\textsubscript{i} fractions in the top 5% for their stellar mass and have H\textsubscript{i} masses greater than 10\textsuperscript{10} M\odot. Within the H\textsubscript{i}-rich sample, we examined the relationship between H\textsubscript{i} and star formation as a function of stellar mass. We found that even though the H\textsubscript{i} fractions of the H\textsubscript{i}-rich galaxies decrease with stellar mass, their sSFRs decrease at a stronger rate. This trend of decreasing sSFRs revealed a sample of H\textsubscript{i}-rich galaxies with surprisingly low sSFRs at the high end of the stellar mass range (log M*/M\odot > 10.5).

To understand the physical conditions producing this unexpected combination of very high H\textsubscript{i} masses and low sSFRs, we obtained H\textsubscript{i} maps at the VLA of 20 of these galaxies. The H\textsubscript{i} maps yield the distribution of the H\textsubscript{i} along with the extent and surface density of the H\textsubscript{i} within the H\textsubscript{i} disk. We found that the H\textsubscript{i} surface densities are low enough that the galaxies fall in the region of the Σ\textsubscript{sSFR}–Σ\textsubscript{H\textsubscript{i}} plane in which inefficient star formation is common. In this regime, a narrow range of H\textsubscript{i} surface densities can yield a wide range of SFR surface densities.

Because the H\textsubscript{i} surface densities for the galaxies in the VLA sample are low, their low sSFRs are not unexpected. However, other conditions, including the internal structure of the galaxies, could also contribute to their low sSFRs. We found that galaxies with the lowest SFR surface densities are more likely to be bulge-dominated and exhibit stronger evidence of AGNs. However, because bulge-dominated galaxies are generally more likely to host AGN, it is unclear whether the AGN or the structure of the galaxy (in the form of morphological quenching) is contributing to the suppression of star formation. Future observations of the molecular gas in these galaxies could provide some insight. A more detailed morphological analysis of the H\textsubscript{i} akin to that in Holwerda et al. (2011) could also provide some clues, but the distances to these galaxies coupled with the short integration times of the observations described here make that type of work less robust.

It is not obvious that the same star formation suppression mechanisms must operate in other types of galaxies with less H\textsubscript{i}, but it is worth considering how these results might apply to other populations of galaxies with low sSFRs. Since all of the galaxies in the VLA sample have low H\textsubscript{i} surface densities, there is no strong evidence that high concentration index or AGN are driving the low sSFRs, but they seem to be contributing. As we have shown, ascertaining the driving factor behind suppressed star formation is not straightforward even when maps of the cold gas are available. Nevertheless, it could be worth examining in further detail how the H\textsubscript{i} distributions and H\textsubscript{i} surface densities vary with stellar mass within populations of galaxies with less cold gas to see if the same conditions apply in less extreme galaxies. Of course some massive galaxies have low sSFRs because they lack the cold gas necessary for star formation to proceed, but we have shown that star formation drops with stellar mass even among populations of galaxies that have extremely high quantities of H\textsubscript{i}, so other conditions must be at work in the broader population.

Although galaxies in the VLA sample appeared to challenge the star formation law with their unexpected combination of high H\textsubscript{i} masses and low sSFRs, the sample actually conforms to the global star formation law. We have shown that the star formation law is an important tool for understanding the relationship between gas and star formation in galaxies that appear to be outliers. Placing other atypical galaxies, such as XUV-disks, GLSBs, or galaxies transitioning between the red and blue sequences, on the Σ\textsubscript{sSFR}–Σ\textsubscript{H\textsubscript{i}} plane could improve our understanding of these important populations.

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APPENDIX

NOTES ON INDIVIDUAL GALAXIES

13340. Red galaxy with faint extended features. Double-horned profile in ALFALFA. Very faint signal in the UV.

15607. Inclined, possible S0. Blue, edge-on galaxy less than 1 arcmin away with no redshift. Double-horned profile in ALFALFA.

17705. Face-on spiral with possible ring and faint blue outer structure. This galaxy is at \( z = 0.035 \); reddish spiral 2 arcmin away at \( z = 0.036 \). Very narrow, highly peaked double-horn profile in ALFALFA.

19918. Broad ALFALFA spectrum with one narrow peak on one side.

23187. Tightly wound spiral. Lopsided double-horned profile in ALFALFA. Strong UV flux extends to edge of faint optical disk.

25285. Tightly wound spiral with blue arms. Double-horned profile in ALFALFA. Two lobes of H\textsc{i} on each side of galaxy. Half of VLA data were corrupted.

26806. Tightly wound spiral with at least one faint, blue, extended arm. Very strong double-horn structure in ALFALFA spectrum. Strong UV flux extends beyond main stellar body.

29304. Reddish main body with faint blue outer arms. Double-horned spectrum in ALFALFA.

40243. Reddish featureless galaxy with faint extended structure and one prominent blue tail/arm. Wide double-horned spectrum in ALFALFA. UV flux coincides only with main stellar body.

41063. Reddish tightly wound spiral. UV flux coincides only with main stellar body.

42262. Inclined spiral. Wide ALFALFA spectrum with peak only at low-velocity end.

45267. Reddish center with blue flocculent spiral arms in outskirts of galaxy. Double-horned profile in ALFALFA.

45357. Inclined spiral. Broad and faint ALFALFA spectrum. Strong UV flux through main stellar body. Two H\textsc{i} lobes on each side of galaxy, maybe indicative of an H\textsc{i} ring.

45404. Ring-like galaxy with very extended diffuse light. Blue arm of star formation 20 arcsec away from galaxy and unattached (in optical). Double-horned profile in ALFALFA. Best spectral window had bad data; very close to edge of spectral window used here.

45664. Featureless elliptical with two very long blue arms that are strong in the UV but appear unattached to main galaxy at optical wavelengths. More bright, patchy UV surrounds galaxy. This galaxy is at \( z = 0.0364 \); red barred spiral 1 arcmin to the north at \( z = 0.038 \). Another at 2 arcmin at \( z = 0.038 \). Broad, uneven ALFALFA spectrum, sloping upward at higher velocities. Several bright patches of H\textsc{i}, many of which coincide with bright patches in UV.

47677. Featureless elliptical at optical wavelengths. Very little UV flux. Blue edge-on galaxy 3 arcmin away at same redshift. Red edge-on galaxy 2.5 arcmin away at similar redshift. Reddish inclined galaxy 1 arcmin away at similar redshift. Faint blue spiral very nearby at same redshift. Is this a group or overdensity? Lopsided ALFALFA spectrum with more flux at low velocities.

47708. Edge-on galaxy with strong dust lane. Very little UV flux. Broad and faint ALFALFA spectrum. Prominent H\textsc{i} structure offset from but in line with galaxy.

51390. Early-type barred spiral. UV flux extends beyond main stellar body. Triple-peaked spectrum in ALFALFA.

57949. Spiral with tightly wound blue arms and knot of star formation at the tip of an arm. UV flux coincides with optical flux. Double-horned profile in ALFALFA, with much stronger peak at higher velocities.

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