FROM HI TO STARS: HI DEPLETION IN STARBURSTS AND STAR-FORMING GALAXIES IN THE ALFALFA Hα SURVEY

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ABSTRACT

HI in galaxies traces the fuel for future star formation and reveals the effects of feedback on neutral gas. Using a statistically uniform, HI-selected sample of 565 galaxies from the Arecibo Legacy Fast ALFA (ALFALFA) Hα survey, we explore HI properties as a function of star formation activity. ALFALFA Hα provides R-band and Hα imaging for a volume-limited subset of the 21 cm ALFALFA survey. We identify eight starbursts based on Hα equivalent width and six with enhanced star formation relative to the main sequence. Both starbursts and non-starbursts have similar HI-to-stellar mass ratios (MHI/M*), which suggests that feedback is not depleting the starbursts’ HI. Consequently, the starbursts do have shorter HI depletion times (tdep), implying more efficient HI-to-H2 conversion. While major mergers likely drive this enhanced efficiency in some starbursts, the lowest-mass starbursts may experience periodic bursts, consistent with enhanced scatter in tdep at low M*. Two starbursts appear to be pre-coalescence mergers; their elevated MHI/M* suggest that HI-to-H2 conversion is still ongoing at this stage. By comparing with the GASS sample, we find that tdep anticorrelates with stellar surface density for disks, while spheroids show no such trend. Among early-type galaxies, tdep does not correlate with bulge-to-disk ratio; instead, the gas distribution may determine the star formation efficiency. Finally, the weak connection between galaxies’ specific star formation rates and MHI/M* contrasts with the well-known correlation between MHI/M* and color. We show that dust extinction can explain the HI-color trend, which may arise from the relationship between MHI, MHI, and metallicity.

Key words: galaxies: evolution – galaxies: interactions – galaxies: ISM – galaxies: starburst – galaxies: star formation – radio lines: galaxies

1. INTRODUCTION

Gas inflows and outflows drive galaxy evolution by controlling the raw material from which stars form. The star formation history of the universe may reflect the history of gas accretion onto dark matter halos (e.g., Kereš et al. 2005; Prochaska & Wolfe 2009), and observed galaxy scaling relations may likewise trace the history of gas flows. For instance, the observed relations between galaxy stellar masses, star formation rates (SFRs), and metallicities may stem from variations in the efficiency with which galaxies accrete and expel gas (e.g., Dalcanton 2007; Mannucci et al. 2010; Davé et al. 2011a, 2011b; Lilly et al. 2013). The connection between gas content and star formation is a well-established result. Individual stars form from dense cores within molecular clouds (e.g., Myers & Benson 1983; Motte et al. 1998). On kiloparsec scales, a galaxy’s SFR surface density, ΣSFR, increases with the HI+H2 gas surface density, ΣHI+H2, as parameterized by the Kennicutt–Schmidt law (Kennicutt 1998b). More recent work shows that ΣHI, rather than ΣHI+H2, drives the Kennicutt–Schmidt law, even in HI-dominated regimes (Schura et al. 2011). Above a threshold density of ~10 M☉ pc−2, HI “saturates”; this column density is sufficient to shield molecular gas from photodissociation. Most gas above this threshold is molecular (e.g., Wong & Blitz 2002; Bigiel et al. 2008), resulting in no trend between SFR and HI in this density regime. Below this threshold, however, ΣSFR and ΣHI correlate, albeit with a large scatter, owing to the relation between ΣHI and ΣH2 (Schura et al. 2011).

Compared to the link between H2 content and SFR, the relationship between galaxies’ HI content and star formation is less straightforward. Galaxies’ HI typically extends to much larger radii than the stellar distribution (e.g., Broeils & Rhee 1997) and may constitute a gas reservoir for feeding future star formation. Accretion of gas from the intergalactic medium (IGM) may replenish this reservoir, and gas flows may bring HI inward, leading to star formation in the inner regions of galaxies. Prochaska & Wolfe (2009) suggest that galaxies’ HI disks exist at a constant, unstable density, with any subsequent accretion leading to the creation of stars and resulting in an SFR that traces the accretion rate. In massive galaxies, the total HI gas fraction correlates with signs of recent accretion, such as an outer metallicity drop, and this accretion appears to power star formation throughout the galaxy disk (Moran et al. 2012). The HI in low-mass galaxies, on the other hand, may not signify recent accretion. Low-mass galaxies tend to be more gas-rich than high-mass galaxies, and HI constitutes the dominant component of their interstellar medium (ISM). The long gas consumption times in such systems may indicate that star formation proceeds inefficiently. Alternatively, Kannappan et al. (2013) argue that star formation cannot keep pace with the rate of gas accretion, causing HI to accumulate. The relationship between HI and star formation may also change in dwarf galaxies owing to their lower metallicities.
At low metallicities and, consequently, low dust content, the formation of a given $\Sigma_{\text{H}_2}$ requires a higher $\text{H}_1$ column density (Krumholz et al. 2009). As a result, the relationship between $\text{H}_1$ density and $\text{H}_2$ formation differs for low-metallicity galaxies, with galaxies such as the Small Magellanic Cloud exhibiting a higher threshold density for $\text{H}_1$ saturation (Bolatto et al. 2011).

The advent of large $\text{H}_1$ surveys capable of resolving individual galaxies has clarified the connection between $\text{H}_1$ mass and galaxy properties. In particular, the Arecibo Legacy Fast ALFA (ALFALFA) survey is a blind 21 cm survey, which covers 7000 deg$^2$ and has detected $\sim$30,000 galaxies out to $z = 0.06$ (Giovanelli et al. 2005a, 2005b; Haynes et al. 2011). In conjunction with ALFALFA, the GALEX Arecibo Sloan Digital Sky Survey (SDSS; GASS; Catinella et al. 2010) and $\text{H}\alpha$ (Gavazzi et al. 2012) surveys have investigated $\text{H}_1$ and star formation in different galaxy regimes. GASS examines the $\text{H}_1$ content of massive galaxies ($M_\odot > 10^{10} M_\odot$) using additional Arecibo observations for galaxies undetected in ALFALFA. H$\alpha$ studies the effect of environment on $\text{H}_1$ content and star formation in ALFALFA galaxies within the Local Supercluster. The ALFALFA survey and related surveys have established scaling relations between $\text{H}_1$ gas fraction and galaxy stellar mass, stellar surface density, color, SFR, and specific SFR ($sSFR$; e.g., Catinella et al. 2010; Huang et al. 2012; Gavazzi et al. 2013). The positive correlations found between $\text{H}_1$ gas fraction and blue color or $sSFR$ imply a link between galaxies’ $\text{H}_1$ content and their current global star formation.

Starburst galaxies may depart from the typical relations between $\text{H}_1$ content and star formation, however. The Kennicutt–Schmidt law may differ for starburst galaxies, with starburst galaxies forming stars more efficiently from a given molecular gas mass (e.g., Kennicutt 1998b; Daddi et al. 2010; Genzel et al. 2010). One possible explanation for this increased efficiency is merger activity (e.g., Sanders et al. 1986; Young et al. 1986; Combes et al. 1994), and many starbursts appear to be interacting systems. If starbursts gain $\text{H}_1$ gas via major mergers instead of accretion, they may differ from non-starbursts in both their $\text{H}_1$ gas consumption times and $\text{H}_1$ gas fractions. In addition, owing to their young stellar populations, mechanical and radiative feedback will have a stronger effect on the ISM of starbursts. This feedback may decrease the $\text{H}_1$ gas fractions of starbursts by driving outflows or ionizing the neutral gas. Oey et al. (2007) suggest the latter scenario as an explanation for the lower $\text{H}_1$ gas fractions in starburst galaxies in the Survey for Ionization in Neutral Gas Galaxies (SINGG). The SINGG result contrasts with the ALFALFA and GASS trends of higher $\text{H}_1$ gas fractions in more highly star-forming galaxies and demonstrates that the $\text{H}_1$ content of starbursts requires further study.

Starburst galaxies present an opportunity to study the relations between neutral gas content, star formation, and feedback in extreme conditions. The $\text{H}_1$ gas fractions and kinematics of starbursts may reveal the mechanisms for triggering extreme star formation episodes and the impact of feedback on global gas content. Previous studies of $\text{H}_1$ in starbursts have focused on individual galaxies or optically selected samples (e.g., Yun et al. 1993; Huchtmeier et al. 2007; Oey et al. 2007; López-Sánchez et al. 2012). To systematically compare the $\text{H}_1$ properties and star formation efficiencies (SFEs) of gas-rich starbursts and gas-rich non-starbursts, we use the “Fall-sky” portion of the ALFALFA $\text{H}_1$ survey. ALFALFA $\text{H}_1$ is a volume-limited subset of the ALFALFA survey consisting of 1555 galaxies with follow-up $\text{H}_1$ and $R$-band imaging (Van Sistine et al. 2015). With the 565 galaxies in the completed “Fall sample” of the ALFALFA $\text{H}_1$ data set, we investigate the regulation of the $\text{H}_1$ gas supply throughout the star formation process.

2. DATA AND METHODS

2.1. The ALFALFA $\text{H}_1$ Survey

The recently completed ALFALFA survey is a blind 21 cm survey with Arecibo that covers 7000 deg$^2$ of sky. The $\text{H}_1$-selected ALFALFA $\text{H}_1$ survey consists of all ALFALFA-detected galaxies within two designated areas, a Fall-sky region and a Spring-sky region (Van Sistine et al. 2015). The Fall sample only includes galaxies with reliable $\text{H}_1$ detections (i.e., ALFALFA codes 1 and 2) and with recession velocities $v = 1460-7600$ km s$^{-1}$. These velocities correspond to distances of $\sim$20–100 Mpc, and the sample is volume limited for $M_{\text{HI}} > 10^{9.3} M_\odot$. $\text{H}_1$ masses, 21 cm velocity widths, and distances come from the ALFALFA catalog (Haynes et al. 2011). The selection of the most probable optical counterparts is described in Haynes et al. (2011); ambiguous optical identifications or blended $\text{H}_1$ signals from multiple galaxies occur approximately 10% of the time.

In this work, we consider the complete, ALFALFA $\text{H}_1$ Fall sample, which contains 565 galaxies; the full sample is described in Van Sistine et al. (2015). To compare the global star formation of these galaxies with their global $\text{H}_1$ content, we obtained $R$-band and $\text{H}_1$ imaging for the Fall-sky ALFALFA $\text{H}_1$ galaxies with the WIYN 0.9 m telescope and the Kitt Peak National Observatory (KPNO) 2.1 m telescope between 2006 September and 2012 October. The parameters of the ALFALFA $\text{H}_1$ survey, observations, and data reduction are described in Van Sistine et al. (2015). At the 20–100 Mpc distances of our sample, the observed $\text{H}_1$ emission typically extends over several tens of arcseconds in each galaxy, and the 3″ spectroscopic fiber of the SDSS does not accurately capture the total star formation.

$\text{H}_1$ and $R$-band fluxes were measured for each galaxy individually using aperture photometry. The $\text{H}_1$ images were continuum-subtracted prior to flux measurement, and $R$-band fluxes were corrected for $\text{H}_1$ contamination within the bandpass. Of the 565 Fall sample galaxies, 542 galaxies are detected in $\text{H}_1$. To facilitate comparison with the literature, the quoted $\text{H}_1$ equivalent widths (EWs) are an observed quantity and are not corrected for extinction or $\text{[N\,II]}$ emission. For derived parameters, such as SFRs, the $\text{H}_1$ fluxes were first corrected for Galactic absorption using the Schlafly & Finkbeiner (2011) recalibration of the Schlegel et al. (1998) extinction maps. $\text{H}_1$ fluxes were then corrected for $\text{[N\,II]}$ contamination and internal absorption using the observed $R$-band absolute magnitudes ($M_R$) and scaling relations derived from a sample of 803 star-forming galaxies from the KPNO International Spectroscopic Survey (KISS; Salzer et al. 2000, 2005). These corrections are described further in

6 The WIYN 0.9 m telescope is operated by WIYN Inc. on behalf of a Consortium of partner Universities and Organizations (see www.noao.edu/0.9m for a list of the current partners). WIYN is a joint partnership of the University of Wisconsin at Madison, Indiana University, the University of Missouri, and the National Optical Astronomical Observatory.
Van Sistine et al. (2015). We compare these extinction corrections with corrections derived from Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) photometry in Section 2.4. After correcting the Hα emission for Galactic and internal extinction and [N ii] emission, we convert the Hα luminosities to SFRs. The ALFALFA Hα SFRs presented in Van Sistine et al. (2015) use the Kennicutt (1998a) calibration, which assumes a Salpeter (1955) initial mass function (IMF). Here we scale the Kennicutt (1998a) calibration to a Chabrier (2003) IMF and calculate the SFR as

\[
\text{SFR} = 4.6 \times 10^{-42} L(\text{H} \alpha),
\]

where \(L(\text{H} \alpha)\) is the Hα luminosity in erg s\(^{-1}\) and the SFR has units of \(M_\odot\) yr\(^{-1}\). The Chabrier (2003) IMF results in SFRs that are a factor of 1.7 lower than SFRs calculated with a Salpeter (1955) IMF.

2.2. Stellar Mass Estimation

To estimate stellar masses for our sample, we need to account for galaxy-to-galaxy variations in the stellar mass-to-light ratio (\(M/L\)). Bell & de Jong (2001) demonstrate that galaxy \(M/L\) ratios should vary systematically with star formation history and enrichment history, leading to a dependence of \(M/L\) on galaxy color. Accounting for the correlation between \(M/L\) ratio and color is particularly important to accurately estimate the masses of starburst galaxies, whose young stellar populations amplify the luminosities of all bands from the UV to the near-IR.

To correct for this effect, we obtain galaxy colors from the SDSS\(^8\) Ninth Data Release (Ahn et al. 2012). SDSS data are available for 513 of the 565 galaxies in the Fall sample. However, SDSS photometry can be problematic, particularly for low surface brightness or irregular galaxies. The SDSS deblending pipeline separates overlapping objects and sometimes incorrectly shreds one “parent” galaxy into multiple “children” (e.g., Abazajian et al. 2004; West et al. 2010). To determine whether shredding is a concern for our sample, we examine the SDSS data by eye for 10\% of the ALFALFA Hα galaxies. For 90\% of these galaxies, the \(g\) and \(r\) photometries of the brightest deblended child and the parent object agree to within 0.2 mag. We therefore select the brightest deblended child for each ALFALFA Hα galaxy from the SDSS catalog. As an additional check, for the full ALFALFA Hα Fall sample, we compare the SDSS \(r\)-band magnitudes with our \(R\)-band photometry. The photometric data from SDSS and the ALFALFA Hα \(R\)-band data show a tight, linear relationship (Figure 1), although noticeable outliers exist. An examination of the outliers shows that they are caused by SDSS deblending errors, overlapping or nearby bright stars, and incorrectly separated galaxy pairs. We treat the SDSS photometry as unreliable if it differs from a least-squares fit to the \(R\)-band data by more than 1 mag (Figure 1). We also eliminate the SDSS photometry for one additional galaxy with a discrepant \(g\)-band magnitude that results in an unrealistically red \(g - r\) color. We do not include these galaxies in any analyses that rely on SDSS-derived parameters, such as stellar masses or galaxy radii. These cuts lead to a sample of 489 ALFALFA Hα galaxies with SDSS photometry. Including the galaxies with uncertain SDSS photometry does not affect any of our conclusions in the following sections.

We calculate stellar masses using the SDSS \(r\)-band luminosities and the relationship between \(M/L\) ratio and \(g - r\) color from Table 7 of Bell et al. (2003). We first subtract the observed Hα fluxes from the \(r\)-band fluxes to ensure that nebular emission does not affect the galaxy colors or magnitudes. In addition, we subtract 0.093 dex from the Bell et al. (2003) \(M/L\) ratios to convert from a “diet” Salpeter (1955) IMF (see Bell & de Jong 2001) to a Chabrier (2003) IMF (Gallazzi et al. 2008; Zibetti et al. 2009). Systematic uncertainties from the assumed dust extinction and star formation histories dominate the uncertainties in the Bell et al. (2003) \(M/L\) ratios. Following Bell et al. (2003), we adopt a total systematic uncertainty of 0.1 dex for the \(M/L\) estimates. We also compare the resulting stellar mass estimates with the alternative prescription of Zibetti et al. (2009). While Bell et al. (2003) assume a smooth star formation history to model galaxy colors, Zibetti et al. (2009) consider the effect of bursts. As a result, masses obtained following Zibetti et al. (2009) are generally lower than the Bell et al. (2003) mass estimates (Figure 2). In particular, at the low-mass end, the stellar masses differ by about a factor of three. However, the relative stellar masses of the galaxies in the sample are only weakly affected. We use the Bell et al. (2003) stellar mass estimates for the rest of our analysis, but we note that using the Zibetti et al. (2009) mass estimates does not change our conclusions.

2.3. Selection of Starbursts

The existing literature contains a variety of definitions as to what constitutes a starburst galaxy (e.g., Knapen & James 2009; Bergvall et al. 2015). Common starburst definitions are based on high sSFRs or Hα EWs, high SFRs relative to similar-mass galaxies, high SFRs per unit area, or short gas consumption.

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the high SFR in the nuclear region but may not necessarily enhancements as well. A nuclear starburst, for instance, will formation enhancements, while others consider smaller-scale All masses were estimated using $r$-band luminosities and $g - r$ colors. The errors shown include the statistical photometric errors and the 0.1 dex scatter in the $M_*$-$L_*$-color relation (Bell et al. 2003). The Zibetti et al. (2009) stellar masses are lower, particularly at the low-mass end, owing to their adoption of bursty star formation histories.

times. In addition, some definitions only consider global star formation enhancements, while others consider smaller-scale enhancements as well. A nuclear starburst, for instance, will have a high SFR in the nuclear region but may not necessarily qualify as a starburst based on the galaxy’s total SFR.

Low-redshift studies often define starbursts as galaxies with high SFRs relative to their past average rates (e.g., Ostlin et al. 2001; Brinchmann et al. 2004; Lee et al. 2009; Bergvall et al. 2015). Here we adopt a similar definition and define starbursts as galaxies with Hα EWs greater than 80 Å. This EW corresponds to a birth rate parameter of $\sim 2$, i.e., the starbursts have instantaneous SFRs greater than or equal to twice their past average SFR (Lee et al. 2009). Since dust in starburst galaxies may attenuate the ionizing continuum radiation more than the optical stellar continuum, dust effects may lower the observed Hα EWs in starbursts (e.g., Calzetti 1997; Charlot & Fall 2000). The Hα EWs of the starbursts may therefore underestimate their true ratios of current to past star formation. Eight galaxies (1.4% of the sample) have EWs above the 80 Å cut (Figure 3), which is equivalent to an sSFR cut of approximately $6 \times 10^{-10}$ yr$^{-1}$. We list the EWs, SFRs, and Hα and stellar masses of the starbursts in Table 1.

We also consider an alternative definition of starbursts as galaxies that fall above the main sequence. Figure 4 shows a least-squares fit line to the SFRs and stellar masses of the sample. An additional six galaxies have SFRs more than $2\sigma$ above the best-fit line, although none are strong outliers above the main sequence. Table 1 summarizes the properties of these galaxies. Hereafter, we refer to these six galaxies as the “High SFR Starbursts” to distinguish them from the eight “High EW Starbursts” identified based on Hα EW.

Since we are incomplete below $M_{H\alpha} = 10^{9.3} M_\odot$, we may not detect all the starbursts in the Fall-sky volume. For a rough estimate of our completeness, we examine the larger, optically selected sample of Bothwell et al. (2009), which contains 1110 galaxies at distances less than $\sim 43$ Mpc. While the Bothwell et al. (2009) sample selection is less uniform than the ALFALFA Hα sample, it does contain a higher fraction of low-mass galaxies. Assuming the lowest ratios of $M_{H\alpha}$/SFR observed for late-type galaxies in the Bothwell et al. (2009) sample and converting to a Chabrier (2003) IMF, we should detect all starbursts with $M_\odot = 10^8 M_\odot$ and $sSFR \gtrsim 10^{-7}$ yr$^{-1}$ and all starbursts with $M_\odot = 10^9 M_\odot$ and $sSFR \gtrsim 10^{-8}$ yr$^{-1}$. However, we may miss any low-mass starburst galaxies whose gas is predominantly molecular. Although the few low-mass starbursts with CO measurements generally appear to have larger H1 masses than H2 masses (e.g., Kobulnicky et al. 1995; Stil & Israel 2002; Bravo-Alfaro et al. 2004; Israel 2005; Nidever et al. 2013), we caution that we may not detect the most extreme, low-mass starbursts with the highest H2/H1 ratios.

2.4. WISE Data

Dust extinction may substantially affect the observed star formation properties of the ALFALFA Hα galaxies. Using infrared measurements from WISE, we verify the accuracy of the ALFALFA Hα extinction corrections. Later, in Section 3.1.2, we use the WISE data to examine the relationship between dust and H1 content.

We obtain 3.4, 4.6, 12, and 22 μm fluxes for the sample from the WISE All-sky Release Source Catalog (Wright et al. 2010; Cutri et al. 2012). Elliptical aperture photometry from WISE is available for sources identified in the Two Micron All Sky Survey (2MASS) Extended Source catalog (Jarrett et al. 2000). We use this elliptical aperture photometry, where it exists, for objects flagged as resolved sources in the WISE catalog and the profile fit magnitudes for all other sources. We then match each ALFALFA Hα galaxy to its closest WISE counterpart within 6″, the resolution at 3.4 μm. Following Jarrett et al. (2013), we apply the necessary color and magnitude corrections to the WISE photometry. Of the 565 ALFALFA Hα Fall galaxies, 263 galaxies have detections in all four WISE bands (3.4, 4.6, 12, and 22 μm) and an additional 95 galaxies have detections in three WISE bands (3.4, 4.6, and 12 μm).

The extinction corrections adopted for the ALFALFA Hα galaxies in Section 2.1 are based on the galaxies’ $R$-band luminosities. Since this is a statistical correction, it may not be correct on an individual galaxy basis. To test the adopted
Table 1
Properties of the ALFALFA Hα Starbursts

| ID         | R. A.\(^{a,b}\) | decl.\(^{a,b}\) | Distance\(^b\) | Hα EW (Å) | SFR \(\left(M_\odot \text{yr}^{-1}\right)\) | Log \(M_{H_\alpha}^{\ast}\) \(\left(M_\odot\right)\) | Log \(M_\alpha^{\ast}\) \(\left(M_\odot\right)\) | \(t_{dep}\) (Gyr) | \(A_\alpha\) | \(W_{20}/W_{50}\) |
|------------|----------------|----------------|----------------|-----------|---------------------------------|-----------------|--------------------|----------------|-------------|--------------|
| High-EW Starbursts | | | | | | | | | | |
| AGC 112546 | 01:31:20.6 | +28:48:29 | 66.4 | 286.6 ± 4.8 | 0.49 ± 0.23 | 8.7 ± 0.1 | 7.2 ± 0.1 | 1.1 ± 0.6 | 0.24 | ≤1.32 |
| AGC 330517 | 23:32:04.7 | +28:57:21 | 78.4 | 276.4 ± 4.8 | 6.2 ± 3.0 | 9.6 ± 0.1 | 8.0 ± 0.1 | 0.7 ± 0.4 | 0.68 | 1.43 ± 0.43 |
| AGC 122666 | 02:11:31.4 | +24:12:51 | 37.3 | 124.5 ± 4.3 | 0.02 ± 0.01 | 8.3 ± 0.1 | 7.6 ± 0.1 | 8.4 ± 4.4 | ... | ≤1.54 |
| AGC 120193 | 02:22:55.0 | +25:18:53 | 62.7 | 101.9 ± 2.0 | 0.63 ± 0.30 | 9.6 ± 0.1 | ... | 7.1 ± 3.7 | 0.18 | 1.24 ± 0.16 |
| AGC 333529 | 23:22:39.8 | +28:57:18 | 67.6 | 81.3 ± 6.1 | 0.05 ± 0.02 | 9.0 ± 0.1 | 7.9 ± 0.1 | 19.3 ± 10.1 | ... | 1.39 ± 0.15 |
| AGC 331191 | 23:28:48.9 | +24:52:10 | 71.2 | 80.4 ± 2.3 | 0.65 ± 0.31 | 9.6 ± 0.1 | 9.0 ± 0.1 | 5.9 ± 3.1 | 0.18 | 1.62 ± 0.33 |
| High-SFR Starbursts | | | | | | | | | | |
| AGC 122420 | 02:38:50.5 | +27:21:59 | 19.5 | 77.2 ± 2.1 | 0.03 ± 0.02 | 8.0 ± 0.1 | 7.3 ± 0.1 | 3.2 ± 1.8 | ... | ≤1.33 |
| AGC 320466 | 02:57:20.7 | +27:58:52 | 43.3 | 72.7 ± 8.1 | 0.06 ± 0.03 | 9.1 ± 0.1 | 7.7 ± 0.1 | 23.2 ± 12.2 | ... | ≤1.19 |
| AGC 330643 | 00:21:36.7 | +25:28:58 | 95.8 | 66.2 ± 1.3 | 0.06 ± 0.32 | 9.3 ± 0.1 | 9.1 ± 0.1 | 2.8 ± 1.5 | 0.29 | 1.13 ± 0.15 |
| AGC 330186 | 23:17:17.7 | +28:36:03 | 96.3 | 81.1 ± 3.0 | 1.97 ± 0.98 | 9.6 ± 0.1 | 9.7 ± 0.1 | 21.1 ± 1.1 | ... | ≤1.12 |
| UGC 470 | 00:44:14.4 | +26:50:35 | 72.7 | 66.9 ± 1.3 | 2.58 ± 1.24 | 10.2 ± 0.1 | 9.8 ± 0.1 | 5.9 ± 3.1 | 0.29 | 1.09 ± 0.01 |
| UGC 12821 | 23:52:23.6 | +28:46:15 | 91.7 | 40.7 ± 0.7 | 10.09 ± 4.98 | 9.9 ± 0.1 | 10.5 ± 0.1 | 0.7 ± 0.4 | 0.34 | 1.40 ± 0.10 |

Notes.

\(^a\) Coordinates of the detected H\(\alpha\) source.

\(^b\) Values from the ALFALFA catalog (Haynes et al. 2011).

\(^c\) The errors listed include the statistical photometric errors and the 0.1 dex scatter in the \(M/L\)-color relation.

\(^d\) R-band asymmetry.

extinction correction, we use the WISE and H\(\alpha\) observations to estimate extinction-corrected SFRs for individual galaxies. Wen et al. (2014) calibrate the WISE 12 and 22 \(\mu\)m bands as extinction indicators using the H\(\alpha\)/H\(\beta\) ratios from SDSS spectra of \(z < 0.25\) star-forming galaxies. Following Wen et al. (2014), we calculate

\[
\text{SFR} = 0.87 \times 10^{-41.27} L_{\text{H}\alpha, \text{obs}} + a \nu L_{\nu},
\]

where \(L_{\text{H}\alpha, \text{obs}}\) is the H\(\alpha\) luminosity without an internal extinction correction, and \(\nu L_{\nu}\) is the appropriate WISE luminosity. The coefficient \(a\) depends on the WISE band and extinction law adopted and ranges from \(-0.02\) to 0.04. The factor of 0.87 in the equation converts from the Kennicutt & Evans (2012) SFR calibration, which uses a Kroupa & Weidner (2003) IMF, to the Kennicutt (1998a) calibration and the Chabrier (2003) IMF used in Section 2.1. We calculate extinction-corrected SFRs using the WISE12 and 22 \(\mu\)m luminosities and assuming a Calzetti et al. (2000) extinction law.

We compare these SFRs with the ALFALFA H\(\alpha\) SFRs in Figure 5. Overall, the WISE-derived SFRs and ALFALFA H\(\alpha\) SFRs show reasonable agreement. A few galaxies show higher SFRs using the WISE extinction correction than the original ALFALFA H\(\alpha\) extinction correction. These galaxies show prominent dust lanes or appear reddened in SDSS images. For these particular objects, the original extinction correction used to derive the ALFALFA H\(\alpha\) SFRs is likely insufficient. The WISE-derived SFRs appear systematically lower than the ALFALFA H\(\alpha\) SFRs by \(-0.1\) dex for many galaxies, especially point-source WISE detections at moderate SFRs. The WISE profile-fit fluxes for these sources may be underestimated, as discussed in Cutri et al. (2012). In general, however, the WISE-based extinction corrections agree well with the adopted ALFALFA H\(\alpha\) extinction corrections.

3. RESULTS

3.1. H\(\alpha\) Gas Content

3.1.1. The H\(\alpha\) Gas Supply of Starbursts

Star formation is intimately linked with the cold gas content of galaxies. A large H\(\alpha\) supply may be necessary to fuel high
SFRs, but the resulting feedback may expel or ionize much of the H\textsc{i} gas. Given the extreme levels of star formation and feedback in starburst galaxies, we consider whether their H\textsc{i} content differs from the other galaxies in the ALFALFA H\textalpha{} sample. High H\textsc{i} gas fractions in starbursts may suggest that a large gas reservoir is a key precondition for triggering a starburst, while H\textsc{i} deficiencies might indicate that radiative feedback plays the dominant role in shaping starbursts’ ISM.

In non-starbursts, larger H\textsc{i} reservoirs do appear to lead to enhanced star formation. As shown by Huang et al. (2012) for ALFALFA galaxies, SFR correlates with $M_{\text{H\textsc{i}}}$ over almost 4 dex in H\textsc{i} mass, indicating a link between atomic gas and star formation. Since part of this trend may result from the tight relation between SFR and galaxy stellar mass, we examine whether highly star-forming galaxies have more H\textsc{i} than galaxies of a similar mass. In Figure 4, we show the ratio of $M_{\text{H\textsc{i}}}$ to stellar mass ($M_\ast$) as a function of SFR and $M_\ast$. For consistency with previous H\textsc{i} studies (e.g., Catinella et al. 2010; Huang et al. 2012), we refer to $M_{\text{H\textsc{i}}}/M_\ast$ as the H\textsc{i} gas fraction. Previous studies have found that at a given stellar mass, galaxies with higher SFRs tend to be more H\textsc{i} rich (e.g., Wang et al. 2011; Huang et al. 2012), and the ALFALFA H\textalpha{} sample likewise exhibits this trend. The larger, 40% complete ALFALFA sample (Huang et al. 2012) shows that this relation between SFR and H\textsc{i} content also holds at lower H\textsc{i} gas fractions than probed by the ALFALFA H\textalpha{} sample. However, while some of the starbursts’ SFRs are an order of magnitude higher than other galaxies of the same mass, their H\textsc{i} gas fractions do not show a comparable increase. In fact, the starburst H\textsc{i} gas fractions are similar to those of star-forming galaxies with much lower SFRs. In the starburst regime, H\textsc{i} content and star formation do not appear to be closely coupled.

The starbursts are H\textsc{i} rich relative to the ALFALFA H\textalpha{} sample as a whole, but this H\textsc{i} richness results from their lower-than-average stellar masses. Low-mass galaxies in general tend to be more H\textsc{i} rich (e.g., Gavazzi et al. 1996; Huang et al. 2012), and in most cases, the H\textsc{i} gas fractions of the starbursts are similar to other galaxies of the same mass. The relatively high $M_{\text{H\textsc{i}}}/M_\ast$ detection limit of the ALFALFA H\textalpha{} survey leads to a tight apparent relation between $M_{\text{H\textsc{i}}}/M_\ast$ and $M_\ast$; Figure 6 displays the least-squares fit to this relation for the non-starbursts in the sample. Most of the starbursts have $M_{\text{H\textsc{i}}}/M_\ast$ values that are within 1σ of the best-fit line. Only two of the high-EW starbursts and one high-SFR starburst have $M_{\text{H\textsc{i}}}/M_\ast$ ratios that appear high for their stellar mass, deviating by $>2\sigma$ from the main trend (Figure 6). Two starbursts even have lower-than-average H\textsc{i} gas fractions. This fact suggests that the high SFRs of the starbursts are not caused by an excess of H\textsc{i}, but rather by an enhanced efficiency of converting H\textsc{i} into molecular gas and stars.

Although the starbursts are not excessively H\textsc{i} rich for their stellar masses, they are also not H\textsc{i} deficient. This conclusion contrasts with the results of Oey et al. (2007) for starbursts in the SINGG sample. However, Oey et al. (2007) use R-band magnitude as a proxy for stellar mass and identify starbursts based on H\textalpha{} surface brightness, rather than EW. To compare with the SINGG results, we calculate the SFR surface density for a flat disk morphology as

$$\Sigma_{\text{SFR}} = \frac{\text{SFR}_{50}}{2\pi R_{50}^2},$$

where $R_{50}$ is the R-band half-light radius and SFR$_{50}$ is the SFR within that radius. We show the relation between $\Sigma_{\text{SFR}}$ and the ratio of $M_{\text{H\textsc{i}}}$ to R-band luminosity, $M_{\text{H\textsc{i}}}/L_R$, in Figure 7(a). Our
and color excess. Following Wen et al. (2012), the GASS sample of high-mass field galaxies shows that the best predictors of a galaxy’s color and stellar mass surface density, and in addition, any decrease in HI from photoionization may be offset by an increase in HI from H2 photodissociation.

3.1.2. The Connection between HI Gas Fraction and sSFR

The ALFALFA Hα galaxies indicate that H I gas fraction generally increases with sSFR, although the data show substantial scatter and this trend may flatten in the starburst regime. The relatively weak connection between sSFR or Hα EW and H I gas fraction (Figure 8) is seemingly at odds with the well-established tight correlation between H I gas fraction and NUV − r color (e.g., Catinella et al. 2010; Huang et al. 2012). For instance, the GASS sample of high-mass galaxies shows that the best predictors of a galaxy’s H I gas fraction are NUV − r color and stellar mass surface density (Catinella et al. 2010). Similarly, we observe a tight trend between H I gas fraction and SDSS g − r color (Figure 9(a)).

The weaker trend with Hα-derived sSFR and strong trend with g − r suggest two possible explanations: (1) dust extinction drives the close correlation between g − r color and HI, or (2) galaxies’ global H I content is more closely linked with the SFR averaged over long timescales than with instantaneous star formation (e.g., Kamann et al. 2013).

To estimate the effect of dust extinction on SDSS color, we use the WISE12 and 22 μm luminosities (see Section 2.4) to derive the E(g − r) color excess. Following Wen et al. (2014), we calculate E(B − V)

\[ \nu L_\nu = \frac{10^{0.4 k_{H_\alpha} E(B-V)} - 1}{a} \]

where \( \nu L_\nu \) is the 12 or 22 μm luminosity, \( L_{H_\alpha} \) is the Hα luminosity with no correction for internal extinction, \( k_{H_\alpha} \) is the reddening curve at Hα, and \( a \) is a coefficient that depends on the extinction law and WISE band used (Wen et al. 2014). We then convert E(B − V) to E(g − r), using the conversion in Yuan et al. (2013). The median AV values inferred for the ALFALFA Hα sample using the Calzetti et al. (2000) and Cardelli et al. (1989) extinction laws range from 0.45 to 0.6. These values are comparable to the face-on AV values calculated from radiative transfer models of spiral galaxies (Xilouris et al. 1999; Bianchi 2007; De Geyter et al. 2014). In Figures 9(b) and (c), we show the relation between M_HI/M_* and extinction-corrected g − r color. After correcting the SDSS g − r colors for extinction, the trend with H I gas fraction weakens substantially (Figure 9).

Dust extinction has the most dramatic effect on the galaxy color of the red, low-sSFR galaxies in our sample. We therefore run Bruzual & Charlot (2003) stellar population synthesis (SPS) models to confirm whether the above dust extinction corrections are realistic for low sSFR galaxies. We use the Padova 1994 isochrones at metallicities of 0.2 and 1 Z⊙ (Bressan et al. 1993; Fagotto et al. 1994) and the Chabrier (2003) IMF. To estimate the expected colors of the low-sSFR galaxies, we adopt a lognormal star formation history, as recommended by Gladders et al. (2013) for field galaxies. For present-day sSFRs of 10−12−10−11 yr−1 and peak star formation at z = 0.7–3, the intrinsic g − r colors range from 0.5 to 0.8. While not exhaustive, these models hint at the range of colors
we should expect for the reddest galaxies in the absence of dust.

The SPS models cannot reproduce the reddest observed $g - r$ colors, $(g - r) > 0.8$, even assuming peak star formation at $z \geq 6$. In fact, as suggested by the extinction-corrected colors in Figure 9, a wide range of star formation histories produces a relatively narrow range of stellar population colors. Colors redder than this range would then result from the effects of dust extinction. The WISE extinction-corrected colors in Figure 9 do appear more blue than predicted by the SPS models, with median $g - r$ colors of 0.2–0.3 using the 12 $\mu$m band and 0.4–0.5 using the 22 $\mu$m band. Although WISE is less sensitive at 22 $\mu$m than at 12 $\mu$m, the warm dust traced by the 22 $\mu$m band (Jarrett et al. 2013) may be a better indicator of the total stellar extinction than the polycyclic aromatic hydrocarbons traced by the 12 $\mu$m band. Adopting a more realistic, bursty star formation history in the models could also lead to better agreement with the WISE extinction-corrected colors. Regardless, both the WISE data and the SPS models suggest that dust extinction could be responsible for the tight correlation between $g - r$ color and HI gas fraction.

Figures 8 and 9 show that, in star-forming galaxies, HI gas fraction correlates weakly with sSFR; the tight connection between HI and $g - r$ color may stem almost entirely from a link between dust extinction and HI gas fraction. Nevertheless, we caution that ALFALFA misses most galaxies on the red sequence (Huang et al. 2012), and including this population may result in a clearer trend between color and HI gas fraction (see Gavazzi et al. 2013).

For our sample, the correlation between HI gas fraction and color may reflect an underlying trend between dust content and stellar mass. Figure 10 demonstrates that the WISE-derived extinctions from the 12 $\mu$m luminosities and Cardelli et al. (1989) extinction law correlate with stellar mass and anticorrelate with HI gas fraction. The results for the WISE 22 $\mu$m data and for the Calzetti et al. (2000) extinction law are similar. The outlier at the highest $E(B - V)$ in Figure 10 is UGC 1488, which has a high inclination, prominent dust lane, and signs of morphological disturbance. Higher-mass, star-forming galaxies have both higher dust masses and higher dust-to-gas ratios, owing to the galaxies’ higher average metallicities. Conversely, these same high-mass, dusty galaxies have low HI gas fractions, owing to higher $H_2$ conversion and SFEs or lower gas accretion rates relative to their gas consumption rates (e.g., Davé et al. 2011a; Kannappan et al. 2013).

The metallicities of galaxies set their dust content and ultimately drive the observed trend between $g - r$ color and HI gas fraction. Bothwell et al. (2013) show that the mass–metallicity relation of galaxies depends strongly on HI content. As a galaxy evolves, the balance of HI inflows, star formation, and outflows determines both its metallicity and its HI gas fraction. The tight trend between color and HI gas fraction is therefore a manifestation of the key role of HI gas flows in regulating galaxy metallicities.

3.1.3. Kennicutt–Schmidt Law

Although HI gas fraction and sSFR do not appear strongly correlated, gas surface density may be the more relevant parameter for star formation. According to the Kennicutt–Schmidt law (Kennicutt 1998b), galaxies with a higher SFR surface density should have a higher gas surface density. We calculate $\Sigma_{\text{SFR}}$ from Equation (3). Owing to the 3.5 resolution of the Arecibo beam, we do not have radii for the HI gas. However, HI diameters are observed to scale with galaxy optical diameters (e.g., Broeils & Rhee 1997; Swaters et al. 2002). Broeils & Rhee (1997) find that HI radii are typically 1.7 times larger than optical radii. We therefore use the SDSS radius containing 90% of the $r$-band light, $R_{90}$, to estimate the HI radius and calculate $\Sigma_{\text{HI}}$, as

$$\Sigma_{\text{HI}} = \frac{M_{\text{HI}}}{2\pi (1.7R_{90})^2}.$$  (5)

Since galaxies show substantial scatter in the ratios of their HI and optical radii (Broeils & Rhee 1997), these $\Sigma_{\text{HI}}$ values are only rough estimates.

We plot $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{HI}}$ for the sample in Figure 11. We find no clear correlation between the HI and SFR surface densities,
as indicated by the low Spearman’s rank correlation coefficient of 0.16. This lack of correlation is consistent with results that show that molecular gas primarily sets the Kennicutt–Schmidt law (Schruba et al. 2011). Most galaxies lie slightly below the threshold density of \(\sim 10 \, M_\odot \, \text{pc}^{-2}\) for conversion to molecular gas. On average, the starbursts tend to have elevated \(\Sigma_{\text{HI}}\), relative to the rest of the sample; the high-EW starbursts have an average \(\Sigma_{\text{HI}}\) more than three times higher than the non-starbursts, and the high-sSFR starbursts have an average \(\Sigma_{\text{HI}}\) two times higher than the non-starbursts. Higher surface densities may aid the conversion of atomic gas to molecular gas and fuel star formation. Alternatively, the starbursts may have more spatially extended \(\text{H}_1\) than the other galaxies, or they may have lower metallicities and higher \(\text{H}_1\) saturation thresholds (e.g., Bolatto et al. 2011). As with \(\text{H}_1\) gas fraction, the starbursts’ \(\Sigma_{\text{HI}}\) values tend to be high, but they do not differ dramatically from the non-starbursts in the sample.

Whether we consider sSFR, \(\text{H}_1\) EW, extinction-corrected \(g - r\) color, or \(\Sigma_{\text{SFR}}\), the \(\text{H}_1\) content of galaxies shows only a weak connection with star formation. The starbursts have high \(\text{H}_1\) gas fractions compared to the full ALFALFA \(\text{H}_1\) sample but show little to no increase in \(\text{H}_1\) gas fraction relative to similar-mass galaxies. These observations suggest that the \(\text{H}_1\) content of gas-rich galaxies remains relatively constant, even during a starburst episode. Any excess \(\text{H}_1\) is efficiently converted into \(\text{H}_2\), and photodissociation of \(\text{H}_2\) may balance the consumption or ionization of \(\text{H}_1\).

### 3.2. Star Formation Efficiency

Since the starbursts have slightly high, but not unusual, \(\text{H}_1\) content for their masses, their current SFRs imply a high \(\text{H}_1\)-to-\(\text{H}_2\) conversion efficiency. Following Schiminovich et al. (2010), we refer to the SFR per unit \(\text{H}_1\) gas mass as the \(\text{H}_1\)-based SFE. This parameter indicates how efficiently galaxies are able to tap into their \(\text{H}_1\) reservoirs and convert their \(\text{H}_1\) to molecular gas and stars. We calculate the inverse of the SFE,
In general, $t_{\text{dep}}$ decreases slightly with $M_\odot$ (Figure 13(a)), for masses below $10^{10} M_\odot$ (e.g., Bothwell et al. 2009; Huang et al. 2012). The high H\textsc{i} gas fractions and low SFE observed for the lowest-mass non-starburst galaxies may imply that their accretion rates exceed their rates of gas consumption (e.g., Huang et al. 2012; Kannappan et al. 2013), as a result of either inefficient inward gas transport or inefficient H\textsc{i}-to-H\textsc{2} conversion. However, the low-mass end also contains several galaxies with $t_{\text{dep}}$ an order of magnitude lower than the average for their stellar mass. In addition to their higher scatter in $t_{\text{dep}}$, the lowest-mass galaxies also appear to exhibit the largest scatter in sSFR (Figure 13(b)). Lee et al. (2007) explain the scatter in sSFR as an increase in “burstiness” at low stellar masses.

We examine this change in scatter quantitatively in Figure 13. In Figures 13(a) and (b), we fit the mean $t_{\text{dep}}$ and mean sSFR as a function of $M_\odot$ using the non-parametric local regression (LOESS) technique (Cleveland 1979) in R (R Core Team 2014). The LOESS method determines the mean at each $M_\odot$ by weighting data points based on their distance from the $M_\odot$ value of interest. To illustrate the scatter about this mean, we plot the absolute value of the residuals from the mean fit in Figures 13(c) and (d). A LOESS fit to the residuals supports our rough by-eye assessment that the scatter about the mean in both $t_{\text{dep}}$ and sSFR is highest among the lowest-mass galaxies. The gas richness of star-forming dwarf galaxies, combined with their wide-ranging SFE, suggests that H\textsc{i} gas may accumulate until a dynamical disturbance triggers gas inflows and compression.

Galaxy structure may also play a role in determining H\textsc{i}-to-H\textsc{2} conversion efficiency and setting the H\textsc{i} $t_{\text{dep}}$. Blitz & Rosolowsky (2006) argue that in disk galaxies, the midplane pressure sets the H\textsc{2}/H\textsc{i} ratio and hence the SFE. Since the midplane pressure should scale with stellar mass surface density, $\Sigma_*$ (e.g., Blitz & Rosolowsky 2004), we plot $t_{\text{dep}}$ as a function of $\Sigma_*$ in Figure 14. We calculate

$$\Sigma_* = \frac{M_\odot}{2\pi R_{50,r}}$$

where $R_{50,r}$ is the SDSS $r$-band Petrosian (1976) half-light radius. Figure 14 shows that for the ALFALFA H\textsc{\alpha} galaxies, $t_{\text{dep}}$ decreases with $\Sigma_*$, as expected if higher surface density disks convert H\textsc{i} to stars more efficiently.

However, this trend is the exact opposite of that found by Saintonge et al. (2012) for high-mass, optically selected GASS galaxies, where the mean H\textsc{i} $t_{\text{dep}}$ increases with $\Sigma_*$. We show the H\textsc{i} $t_{\text{dep}}$ and $\Sigma_*$ of the GASS sample (Catinella et al. 2010, 2012, 2013), calculated following Equations (6) and (7), in Figure 14. We only include GASS galaxies with H\textsc{i} detections, and we use the “representative” GASS sample, which includes gas-rich galaxies (Catinella et al. 2013). The GASS stellar masses are calculated from SDSS photometry (Catinella et al. 2013). We calculate SFRs from the tabulated GALEX UV photometry as described in Schiminovich et al. (2010), assuming a Chabrier (2003) IMF. Among massive galaxies, UV-based SFRs agree well with H\textsc{\alpha}-based estimates (e.g., Salim et al. 2007), which therefore permits a direct comparison with our sample.

The discrepancy between the ALFALFA H\textsc{\alpha} galaxies and the GASS galaxies is likely due to the quenching of star formation in more massive galaxies. Figure 14 shows that the scatter in $t_{\text{dep}}$

The H\textsc{i} gas depletion timescale, as

$$t_{\text{dep}} = \frac{M_{\text{HI}}}{\text{SFR}},$$

and we show the relation between $t_{\text{dep}}$ and sSFR in Figure 12. The starburst H\textsc{i} depletion times are listed in Table 1. Most of the sample shows no correlation between sSFR or EW and H\textsc{i} depletion time. However, the starbursts tend to have short H\textsc{i} depletion times, despite the fact that they are H\textsc{i} rich. All the high-EW starbursts and four out of six high-sSFR starbursts have H\textsc{i} gas fractions above the sample median, and only two starbursts have depletion times below the sample median. In particular, the two strongest or youngest starbursts, as measured by EW, have both the highest H\textsc{i} gas fractions and among the highest SFE. Saintonge et al. (2011b) suggest that weak starbursts in the high-mass GASS sample may not be able to access H\textsc{i} easily, since they have the same H\textsc{i} $t_{\text{dep}}$ as non-starbursts. In contrast, our starbursts do show lower $t_{\text{dep}}$, which may indicate that lower-mass starbursts are efficiently converting H\textsc{i} to H\textsc{2} and stars.
values of spheroidal galaxies are independent of sSFR = surface h \text{S}.

Despite their high HI content, most starbursts have shorter gas during the quenching process. The lack of a trend with increases dramatically above a \( \Sigma_* \) of \( 10^{8.7} \, M_\odot \text{kpc}^{-2} \), identified as a “quenching threshold” by Catinella et al. (2010) and Saintonge et al. (2011a). The H\(_1\) depletion times of the few ALFALFA H\(_\alpha\) galaxies in this high stellar surface density regime are consistent with those of the GASS population. Saintonge et al. (2012) suggest that galaxies with high stellar surface densities may be more stable to fragmentation due to their bulge-dominated morphologies (e.g., Ostriker & Peebles 1973) or may no longer have access to their H\(_1\) reservoir.

We use the SDSS surface brightness profile fits of Simard et al. (2011) to quantify the morphologies of the GASS galaxies. These fits are not available for the ALFALFA H\(_\alpha\) galaxies, which fall in the more recent, SDSS DR9 sky coverage. Following Simard et al. (2011), we adopt a bulge+disk model if the probability that the bulge+disk model is not required is below 0.32; if the probability is higher, we use a pure Sérsic model. Figure 15 shows that the GASS disk galaxies continue the trend of decreasing \( t_{\text{dep}} \) with \( \Sigma_* \) seen in the ALFALFA H\(_\alpha\) sample, while spheroid-dominated galaxies deviate to higher \( t_{\text{dep}} \). Although all the offset galaxies appear to be bulge dominated, they show no discernible trend between bulge-to-disk ratio and \( t_{\text{dep}} \).

The spheroidal galaxies also appear offset to lower sSFRs (Figure 16(a)) compared to the rest of the GASS and ALFALFA H\(_\alpha\) galaxies, supporting the idea that they have quenched their star formation. Interestingly, at a given \( \Sigma_* \), the \( M_{H_\alpha}/M_* \) values of spheroidal galaxies are independent of sSFR (Figure 16(b)), indicating that the dispersion in \( t_{\text{dep}} \) at the high \( \Sigma_* \) end is not the result of a wide range in H\(_1\) content. Instead, the low-sSFR galaxies appear unable to use their HI efficiently. In terms of absolute \( M_{H_\alpha} \), galaxies with the highest H\(_1\) masses tend to live just below the quenching threshold (Figure 16(c)); galaxies with higher \( \Sigma_* \) must have lost or consumed their H\(_1\) gas during the quenching process. The lack of a trend with bulge-to-disk ratio or \( M_{H_\alpha}/M_* \) among the quenched galaxies suggests that differences in the spatial distribution of the H\(_1\) gas may account for their variation in SFE.

While the spheroidal galaxies exhibit the highest \( t_{\text{dep}} \) for their \( \Sigma_* \), starbursts have low \( t_{\text{dep}} \) relative to galaxies of a similar \( M_* \) or \( \Sigma_* \) (Figures 13–16). Many studies have pointed out the role mergers may play in enhancing SFE (e.g., Solomon & Sage 1988; Combes et al. 1994; Bouché et al. 2007; Di Matteo et al. 2007; Bournaud et al. 2011). Turbulence and gas flows during major mergers can lead to the efficient formation of molecular gas, shifting the ISM gas distribution to higher densities (Bournaud et al. 2011; Powell et al. 2013). During a gas-rich merger, the total gas fraction of a galaxy may increase owing to the addition of new gas; however, if the distribution of gas becomes skewed to higher gas densities, the H\(_2\) gas fraction may increase more strongly than the H\(_1\) gas fraction. This scenario could potentially explain the moderately high H\(_1\) gas fractions and short \( t_{\text{dep}} \) of the ALFALFA H\(_\alpha\) starbursts.

### 3.3. Morphology and Mergers

The starbursts’ morphologies and kinematics may demonstrate whether dynamical disturbances are enhancing the SFE. One measure of morphological disturbance is the 180° rotational asymmetry. We calculate the R-band asymmetry, \( A_R \), following Conselice et al. (2000b), as

\[
A_R = \min \left( \frac{\sum |I_0 - I_{180}|}{\sum |I_0|}, \frac{\sum |B_0 - B_{180}|}{\sum |B_0|} \right),
\]

where \( I_0 \) is the original image, \( I_{180} \) is the image rotated by 180°, \( B_0 \) is a background region, and \( B_{180} \) is the background region rotated by 180°. We sum over all the image pixels within the Petrosian radius (Petrosian 1976) at the \( \eta = 0.2 \) surface.
Figure 13. (a) $t_{\text{dep}}$ and (b) sSFR as a function of $M_*$ The red line shows the mean value at each $M_*$, as determined by an LOESS non-parametric local regression fit. The black lines show the 95% confidence intervals of the mean. In panels (c) and (d) we show the absolute value of the residuals about the mean fits in the upper panels. The red line shows an LOESS fit to the residuals, and the black lines again show the 95% confidence intervals. Low-mass galaxies show higher scatter about the mean for both $t_{\text{dep}}$ and sSFR.

Figure 14. $t_{\text{dep}}$ as a function of $\Sigma_e$ for the ALFALFA Hα sample (black circles, diamonds, and triangles) and the GASS sample (gray crosses). Below the “quenching threshold” of $\Sigma_e = 10^{8.7} \text{M}_\odot \text{pc}^{-2}$ (Catinella et al. 2010; Saintonge et al. 2011a), $t_{\text{dep}}$ decreases with increasing $\Sigma_e$. The black cross indicates the median statistical errors for the ALFALFA Hα sample, and the dashed line indicates the Hubble time.

Figure 15. $t_{\text{dep}}$ as a function of $\Sigma_e$ for the ALFALFA Hα non-starbursts (black circles) and starbursts (diagonals) and the GASS sample (colored circles and crosses). The GASS galaxies are colored by bulge-to-disk ratio from the Simard et al. (2011) SDSS fits. The crosses indicate GASS galaxies for which a pure Sérsic profile is preferable; red crosses indicate a Sérsic index $\geq 2$, and purple crosses indicate a Sérsic index $< 2$. 

brightness level, where \( \eta \) is the ratio of the intensity at a given radius to the average intensity within that radius. We also scale the background region area to this radius. The minimization finds the rotational center that produces the lowest asymmetry value. Prior to the calculation, all images are background-subtracted, and we mask all stars within approximately five galaxy radii using the IRAF\(^9\) task \texttt{imedit}. As recommended by Conselice et al. (2000b), we adopt a signal-to-noise ratio (S/N) cut of 100. Below this value, the scatter in \( A_R \) dramatically increases, and 41\% of these low-S/N ALFALFA H\(\alpha \) galaxies have unphysical negative \( A_R \) values.

We show images of the eight high-EW and six high-sSFR ALFALFA H\(\alpha \) starbursts and their calculated asymmetries in Figure 17 and list the asymmetry values in Table 1. The eight starbursts with S/N \( > 100 \) have asymmetries ranging from 0.18 to 0.68, higher than the median sample asymmetry of 0.14. Conselice (2003) suggests that asymmetries above \( \sim 0.35 \) indicate major mergers. Figure 18 shows the asymmetries of the sample as a function of H\(\alpha \) EW. All the starbursts have slightly elevated asymmetries, and two (AGC 330517 and AGC 330500) are clearly major mergers. However, we find equally disturbed galaxies at lower values of H\(\alpha \) EW, indicating that not all H\(\alpha \)-rich mergers are starbursts.

If some of the starbursts are merging systems, they appear to be near coalescence. Simulations of major mergers also indicate that the peak star formation activity should occur at this time (e.g., Mihos & Hernquist 1994; Cox et al. 2008; Lotz et al. 2010a). Intriguingly, the two most asymmetric starbursts, AGC 330517 and AGC 330500, are also the high-EW starbursts with the highest offsets from the H\(\alpha \) gas fraction and stellar mass relation (see Figure 6). High gas fraction mergers experience more extended star formation, which causes them to appear asymmetric over a longer timescale (Lotz et al. 2010b). Alternatively, these two starbursts may be in an earlier merger stage than the other starbursts, prior to coalescence, when they have not yet consumed or expelled much of their H\(\alpha \) gas. The individual merging galaxies in AGC 330517 and AGC 330500 are still distinguishable in Figure 17, which supports this possibility. The other six starbursts with asymmetry measurements have \( A_R \sim 0.2 \)–0.3, only slightly higher than the average asymmetry of the full sample. These lower asymmetries could simply reflect clumpy star formation in these galaxies (e.g., Conselice et al. 2000b; Fossati et al. 2013), as appears to be the case for UGC 12821, or they could indicate a mild dynamical disturbance. The three most massive high-sSFR starbursts, AGC 330186, UGC 470, and UGC 12821, show spiral structure and no signs of a major interaction. However, the presence of a nearby bright star blocks a full view of AGC 330186, and the galaxy does appear somewhat asymmetric in its structure. Minor disturbances may cause the enhanced star formation in these spirals. AGC 120193, AGC 331191, and AGC 102643 show more obvious signs of morphological disturbance, with extended, asymmetric tails visible in their broadband images. The lower asymmetries in some of the starbursts could also be consistent with a later merger stage; the simulations of Lotz et al. (2010a) show that the peak star formation in major mergers may occur a few hundred Myr after the peak asymmetry. Mild asymmetries of \( A_R \sim 0.2 \) correspond to this peak star-forming, coalescence stage in mergers. If these less asymmetric high-EW starbursts are indeed late-stage mergers, their lower H\(\alpha \) gas fractions relative to the more asymmetric starbursts AGC 330517 and AGC 330500 suggest that dynamical disturbances trigger the efficient conversion of H\(\alpha \) into H\(_2\) throughout the merger. The

\(^9\) IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
more asymmetric, earlier-stage mergers, such as AGC 330517 and AGC 330500, still exhibit excess H\textsc{i}, which may be consumed or ionized by the end of the starburst phase.

Disturbed gas kinematics may also be a sign of galaxy interactions. The H\textsc{i} velocity profiles of merging galaxies often exhibit asymmetries or wide, high-velocity wings due to an excess of high-velocity gas (e.g., Gallagher et al. 1981; Mirabel & Sanders 1988). To quantify this high-velocity excess, we calculate the ratio of the H\textsc{i} velocity width at 20\% of the peak flux to the width at 50\% of the peak, \( W_{20}/W_{50} \), as suggested by Conselice et al. (2000a). Since the ALFALFA velocity resolution is 10 km s\(^{-1}\), we calculate an upper limit to \( W_{20}/W_{50} \) for galaxies with \( W_{20}/W_{50} < 10 \) km s\(^{-1}\). We show the H\textsc{i} width ratios and H\textalpha\ EWs of the sample in Figure 19 and Table 1. All of the high-EW starbursts have H\textsc{i} width ratios greater than the sample median, although as with morphological asymmetry, high H\textsc{i} width ratios occur in non-starbursts as well. In simulations of merging galaxies, Powell

Figure 17. Morphologies of the eight high-EW ALFALFA H\textalpha\ starbursts (top panel), organized in order of H\textalpha\ EW (see Table 1). The highest-EW starburst is at the upper left, and the lowest-EW starburst is at the lower right. The bottom panel shows the morphologies of the six high-sSFR starbursts organized by decreasing sSFR. The ALFALFA H\textalpha\ R-band images appear in red, SDSS g-band images appear in green, and the continuum-subtracted H\textalpha\ emission is shown in blue. All images have a logarithmic brightness scale. AGC 120193 does not have SDSS images. The solid white line in each panel corresponds to 5 kpc. The R-band asymmetries are indicated for the eight starbursts with S/N >100. The yellow region above AGC 330500 is a bright star.
et al. (2013) find that interaction-driven turbulence, rather than supernova feedback, creates the high gas velocity dispersions observed in mergers. They argue that this enhanced turbulence increases the SFR by shifting the gas distribution to higher densities. The observed H I gas disturbances are therefore a possible cause of the high SFEs in the high-EW starbursts.

Noninteracting dwarf galaxies may also show broad wings in their H i profiles, however, and the high $W_{50}/W_{90}$ ratios of the starbursts do not necessarily prove that they are interacting (e.g., Gallagher et al. 1981). We display the H i velocity profiles of the high-EW and high-sSFR starbursts in Figure 20. While the H i profiles of several starbursts appear broad or irregular, the profiles of some of the lower-mass starbursts, especially AGC 112546 and AGC 122866, appear quite narrow and only have upper limits on $W_{50}/W_{90}$. For comparison, we show examples of non-starburst H i profiles in Figure 21. For each starburst, we randomly selected a non-starburst counterpart with $M_\alpha$ within ~0.5 dex and with a similar S/N H i spectrum. Since one starburst, AGC 120193, does not have SDSS photometry, we selected a non-starburst with $M_\alpha$, within 0.5 dex. The H i velocity profiles of the four most massive high-EW starbursts, AGC 330517, AGC 120193, AGC 330500, and AGC 331191, do appear to have broader wings than the straight-sided profiles of the non-starbursts. However, the profiles of the four lower-mass high-EW starbursts ($M_\alpha < 10^8 M_\odot$) are indistinguishable from non-starburst profiles of similar-mass galaxies. We caution that the resolution of the H i spectra may be too low to accurately probe the profile shapes of these galaxies. Nevertheless, as discussed in Section 3.1.1, the low-mass starbursts also have H i gas fractions comparable to those of low-mass non-starbursts. Therefore, the global H i gas fraction may not be the primary physical parameter that sets the level of star formation in low-mass galaxies. Infalling gas clouds are one possible trigger of star formation in dwarf galaxies (e.g., Gordon & Gottesman 1981; López-Sánchez et al. 2012; Verbeke et al. 2014). Verbeke et al. (2014) show that this type of interaction may generate multiple starburst episodes; disturbed gas kinematics may only be observable during the initial starburst and with favorable viewing orientations. These low-mass starbursts may therefore no longer show H i disturbances and may have consumed some of their H i during a prior burst.

The high-sSFR starbursts generally show more ordered H i velocity profiles than the high-EW starbursts. As with the some of the high-EW starbursts, two galaxies (AGC 122420 and AGC 102643) have inconclusive H i profiles as a result of low resolution or low S/N. The other high-sSFR starbursts show no obvious disturbances. The more massive spirals AGC 330186 and UGC 470 have straight-sided profiles indicative of orderly rotation, while the Gaussian profile of UGC 12821 is likely due to its face-on orientation (e.g., Haynes et al. 1998). Finally, the H i-rich, low surface brightness galaxy AGC 320466 also shows ordered rotation in its H i gas. With a high $M_\alpha/M_\odot = 25$, much of AGC 320466’s H i gas may not reside near its star-forming regions. Unlike the broad profiles of several of the high-EW starbursts, the ordered velocity profiles of most of the high-sSFR starbursts do not indicate any major disturbances.

Although the traditional picture of merger-driven star formation emphasizes nuclear starbursts, recent studies have suggested that mergers may also cause a substantial increase in extended star formation (e.g., Ellison et al. 2013; Powell et al. 2013). In Figure 22, we show the fraction of star formation within $R_{50}$ for starbursts and non-starbursts. We only include galaxies with an S/N > 10 in the H o photometry. Three starbursts (AGC 112546, AGC 122866, and AGC 331191) show highly concentrated star formation, with more than 80% of their H o emission contained within $R_{50}$. However, other starbursts, particularly AGC 120193 and AGC 333529, show H ii regions offset from the main R-band center of the galaxy. The majority of the star formation in these two starbursts is outside $R_{50}$. Gas flows in starbursts fuel nuclear star formation in many, but not all, cases.

4. DISCUSSION

4.1. H i and Star Formation

The ALFALFA H o galaxies confirm previous observations that at a given stellar mass, more H i-rich galaxies typically have higher SFRs (Wang et al. 2011; Huang et al. 2012). Since a high H i gas fraction relative to other galaxies of a similar mass may indicate the presence of recently accreted gas
(e.g., Moran et al. 2012), this trend may suggest that H\textsubscript{I} accretion actively fuels star formation in low-redshift galaxies. Nevertheless, the scatter in the $M_{\text{H\textsubscript{I}}}/$SFR ratio at a constant stellar mass shows that additional factors affect the ability of galaxies to access fresh H\textsubscript{I} fuel and efficiently convert it to H\textsubscript{2}. In particular, the starbursts generally show high H\textsubscript{I}-based SFEs (i.e., short H\textsubscript{I} depletion times) compared to similar-mass galaxies (Section 3.2). We also find that the starbursts’ H\textsubscript{I} gas fractions are not unusually elevated for their stellar mass, despite their much higher SFRs (Section 3.1.1). Therefore, in most cases, a high efficiency of H\textsubscript{I}-to-H\textsubscript{2} conversion, rather than a large influx of gas, is generating their high levels of star formation. Dynamical disturbances are a likely cause of this enhanced efficiency, allowing the starbursts to transport H\textsubscript{I} gas inward and generate high gas column densities more easily than non-starbursts (e.g., Barnes & Hernquist 1991; Di Matteo et al. 2007; Hopkins et al. 2013).

The balance between H\textsubscript{I} infall and feedback may lead to a relatively stable H\textsubscript{I} supply in gas-rich starbursts. Addition of H\textsubscript{I} gas through interaction with a gas cloud or gas-rich galaxy may initially raise the H\textsubscript{I} gas fraction. This excess H\textsubscript{I} quickly disappears, however, as gas compression or turbulence

Figure 20. H\textsubscript{I} velocity profiles of (a) the high-EW starbursts and (b) the high-sSFR starbursts, ordered as in Figure 17.
resulting from these interactions efficiently converts the HI gas to H$_2$ and stars. As the starburst progresses, the HI gas fraction may stabilize instead of continuing its decrease. The starburst may not affect HI gas in the outer galaxy, and photodissociation of molecular gas may replenish HI in the inner regions. Indeed, previous observations have demonstrated that photodissociated gas may be a significant component of the ISM in the inner regions of starburst galaxies (e.g., Stacey et al. 1991). Radiative feedback does not appear sufficient to deplete the HI gas in the starbursts through ionization, and the two high-EW starbursts with the highest ratios of H$\alpha$ luminosity to HI mass (i.e., the shortest $t_{dep}$) also show the highest HI gas fractions. After the starburst, the remaining HI reservoir may continue to fuel star formation, or additional feedback mechanisms, such as supernovae, may ultimately quench the burst.

**4.2. The Link between H$\alpha$, Metallicity, and Dust**

For the ALFALFA H$\alpha$ sample as a whole, we find that galaxies’ sSFRs and HI gas fractions are only weakly correlated (Section 3.1.1). This result contrasts with the strong observed correlation between galaxy color and HI gas fraction.
identified in previous studies (e.g., Kannappan 2004; Zhang et al. 2009; Catinella et al. 2010; Huang et al. 2012), which suggests that galaxy sSFRs are linked to their H I content (e.g., Zhang et al. 2009; Huang et al. 2012). We likewise observe a tight correlation between H I gas fraction and $g - r$ color. For our sample of gas-rich galaxies, we demonstrate that dust extinction, rather than star formation, drives the tight trend between H I and color.

In essence, the H I–color relation is a manifestation of the well-known galaxy mass–metallicity relation (e.g., Lequeux et al. 1979; Tremonti et al. 2004). Recent studies suggest that galaxies in fact lie on a fundamental plane of stellar mass, SFR, and metallicity (Lara-López et al. 2010; Mannucci et al. 2010), known as the “fundamental metallicity relation.” Gas content likely drives this relation (e.g., Davé et al. 2012; Lilly et al. 2013), and Bothwell et al. (2013) show that a fundamental relation exists between H I mass, stellar mass, and metallicity. In this model, $M_{\text{H I}}/M_*$ and metallicity should anticorrelate. Since more metal-rich galaxies have higher dust content, we would therefore expect galaxies with high $M_{\text{H I}}/M_*$ to have less dust extinction and bluer colors.

Several processes could produce the proposed relation between galaxy stellar mass, H I content, and metallicity. Over their lifetimes, galaxies with higher stellar masses will have both consumed more H I gas and produced more metals via star formation. In addition, the higher potential wells of more massive galaxies should allow them to retain metals more effectively (e.g., Davé et al. 2011a). At a given stellar mass, galaxies that have experienced a recent inflow of metal-poor gas from the IGM should have lower overall metallicities, as well as higher H I content. Finally, we note that the elevated dust content of metal-rich galaxies will also allow them to convert their H I gas to H$_2$ more efficiently by shielding molecular gas from UV radiation (e.g., Krumholz et al. 2009; Bolatto et al. 2011), thereby reducing their H I content further. This connection between H I content and dust extinction provides a natural explanation for the observed relation between H I gas fraction and color. H I inflows and outflows are fundamentally important to the evolution of galaxy metallicities, while galaxy metallicity may also influence the H I supply by promoting H$_2$ formation.

4.3. Galaxy Structure and H I Conversion

Another factor that may enhance the conversion of H I to H$_2$ is galaxy structure. We find that the H I depletion time in disk-dominated systems anticorrelates with stellar surface density (Section 3.2). This relation may indicate that higher disk midplane pressure aids the formation of molecular clouds and increases the H$_2$/H I ratio, as proposed by Blitz & Rosolowsky (2006). However, alternate theories of H$_2$ formation based on self-shielding (e.g., Krumholz et al. 2009) may result in a similar stellar surface density scaling relation (Fu et al. 2010). Early supernova feedback in low-mass galaxies may lead to the delayed infall of H I gas, resulting in an increased H I content and longer depletion time at the present day (Fu et al. 2010). By suppressing past star formation episodes, this efficient feedback should also lead to lower present-day stellar surface densities.

We only observe this correlation between H I depletion time and stellar surface density in disk galaxies, however. We show that high-mass, early-type galaxies from the GASS sample (Catinella et al. 2013) do not follow a similar relation. Within this early-type sample, we find no correlation between H I depletion time and morphology, which suggests that bulge strength is not affecting the current SFE in these galaxies. Instead, we suggest that the scatter in SFE results from differences in the spatial distribution and surface density of the H I gas.

4.4. Mergers and H I Conversion

For several of the starbursts, major mergers may induce their high SFRs and high H I-to-H$_2$ conversion efficiencies (Section 3.3). During interactions, tidal torques propel gas toward the center of galaxies, thereby raising the gas column density (e.g., Barnes & Hernquist 1991) and allowing galaxies to access their external H I supply. Furthermore, turbulent motions during the merger may compress gas clouds (Elmegreen et al. 1993), leading to a higher fraction of dense gas and a higher H$_2$/H I ratio (Powell et al. 2013). Starbursts also appear to form stars from H$_2$ more efficiently than non-starbursts (e.g., Kennicutt 1998b), perhaps as a result of the higher mean density and shorter free-fall time in their ISM (Krumholz et al. 2012). A merger scenario could therefore explain the moderate H I but high SFRs of at least some of the ALFALFA H$_\alpha$ starbursts.

Evidence of morphological and kinematical disturbances supports a merger origin for several of the starbursts. We find that the high-EW starbursts’ optical morphologies are more asymmetric and their H I velocity profiles have wider wings than most of the non-starbursts. Merger simulations predict that the peak star formation activity should occur near coalescence (e.g., Mihos & Hernquist 1994; Cox et al. 2008; Lotz et al. 2010a), consistent with the starbursts’ morphologies. The highest asymmetries, however, should appear shortly before coalescence. Interestingly, our two most asymmetric starbursts, which appear to be in this merger stage, also have higher-than-average H I gas fractions for their stellar mass. Their high H I gas fractions suggest that H I conversion to H$_2$ may be an ongoing process during merger-driven star formation (e.g., Hibbard & van Gorkom 1996).

Owing to the unresolved nature of the Arecibo H I observations, we do not know the surface density of the H I gas in the ALFALFA H$_\alpha$ starbursts. However, we find that
they have above-average ratios of $M_{\text{H}_1}$ to the galaxy optical area. Therefore, either they lie closer to the maximum column density threshold for H$_1$, which would aid H$_2$ formation, or their H$_1$ is significantly more extended than the optical disk. For instance, extended H$_1$ tidal tails may contain a large fraction of the H$_1$ gas in merging galaxies (e.g., Hibbard & van Gorkom 1996).

The evidence for mergers among the lowest-mass starbursts is less clear, in part because of their lower S/N optical images and H$_1$ spectra. Their H$_1$ velocity profiles do not noticeably differ from the profiles of low-mass non-starbursts, which may indicate a lack of kinematical disturbances. Resolved H$_1$ observations likewise indicate that ordered kinematics are not uncommon in dwarf starbursts (Lelli et al. 2014). However, if the dwarf starbursts experience periodic bursts, any initial disturbance may no longer be evident (e.g., Verbeke et al. 2014). We observe an increased scatter in SFE at the low-mass end of our sample, which supports this scenario of episodic bursts in dwarf galaxies. Supernova feedback may have a stronger effect in the low potential wells of dwarf galaxies, leading to temporary quenching and a renewed burst of star formation as neutral gas falls back into the galaxy (e.g., Lee et al. 2007; Verbeke et al. 2014). Higher-resolution imaging and H$_1$ spectral observations will be necessary to determine whether or not the dwarf starbursts are merging systems.

Finally, the spiral structure and orderly H$_1$ velocity profiles of the three highest-mass starbursts, AGC 330186, UGC 470, and UGC 12821, suggest that they are not experiencing a major merger. UGC 470 has a higher-than-average gas fraction for its stellar mass and is known to have an unusually extended H$_1$ disk (Dowell 2010). It is also the only starburst in the sample with a typical H$_1$ depletion time for its stellar mass or $\Sigma_{\text{SFR}}$ (Figures 13 and 14). Unlike the other starbursts, UGC 470’s excess gas supply, rather than a high H$_1$-to-H$_2$ conversion efficiency, may account for its enhanced star formation. Minor mergers or other minor disturbances may temporarily increase the SFR for AGC 330186 and UGC 12821, and most of the H$_1$ disk may remain undisturbed.

4.5. H$_1$ Cycles in Starbursts

We therefore propose the following picture for the cycling of H$_1$ and star formation throughout the strongest starburst episodes. In the intermediate-mass starbursts, a gas-rich major merger triggers the star formation. As the two galaxies approach coalescence, the total stellar mass of the system increases. Since the two individual galaxies have H$_1$ gas fractions typical of lower-mass galaxies, the combined system appears to have a higher H$_1$ mass than other galaxies of a similar total mass. Strong tidal torques drive H$_1$ gas outward to form tidal tails and inward to fuel star formation. At this time, the system appears progressively more morphologically disturbed, and the increased gas flows and turbulence create kinematically disturbed H$_1$ profiles. The two most asymmetric starbursts in our sample, AGC 330517 and AGC 330500, are possible examples of this stage, exhibiting disturbed morphologies, disturbed H$_1$ kinematics, and elevated H$_1$ gas fractions. As the H$_1$ gas flows inward, turbulence and gas compression efficiently convert H$_1$ to H$_2$, reducing the H$_1$ gas fraction and increasing the SFR. Although the gas flows bring H$_1$ inward, star formation is not necessarily restricted to the nuclear region, consistent with recent simulations (e.g., Powell et al. 2013) and with the varied H$_\alpha$ morphologies of the ALFALFA H$_\alpha$ starbursts (Section 3.3). Turbulent, dense clumps may arise throughout the merging disks, and the precise merger configuration affects the spatial distribution of star formation. The influx of H$_1$ gas raises the ISM column density, and the SFR increases to the point where supernova-driven turbulence supports the enhanced weight of the ISM (Ostriker & Shetty 2011).

Peak star formation occurs near final coalescence, as the morphological disturbances are fading (e.g., Lotz et al. 2010a), which may explain the slightly lower asymmetries of some of the starbursts (e.g., AGC 120193 and AGC 331191). However, at the time of the peak SFR, the turbulent motions driving star formation are still high (Powell et al. 2013) and the H$_1$ kinematics should still show higher velocities, as we observe in the high-velocity wings of the high-EW ALFALFA H$_\alpha$ starbursts’ H$_1$ profiles. The H$_1$ content also begins to drop, owing to the enhanced H$_2$ fraction and photoionization. Nevertheless, the starbursts still maintain a large H$_1$ supply, comparable to similar-mass non-starburst galaxies (Section 3.1.1). Radiative feedback does not completely ionize the starbursts’ H$_1$ reservoirs and may only ionize the H$_1$ gas near the starburst region (e.g., Hanish et al. 2010). In addition, H$_2$ photodissociation may compensate for the ionization of H$_1$ in the inner regions. Consistent with this scenario, recent H$_1$ observations of post-merger galaxies demonstrate that star formation and feedback do not noticeably deplete the H$_1$ reservoirs of merging galaxies (Ellison et al. 2015). Ultimately, gas consumption or feedback terminates the starburst, and the final merged galaxy exhibits a higher stellar mass, higher metallicity, and lower H$_1$ gas fraction than its individual progenitors.

Lower-mass galaxies may experience recurrent starbursts, leading to the enhanced scatter in $I_{\text{dep}}$ and sSFR in the low-mass end of our sample. They may accumulate H$_1$ from the IGM until a dynamical disturbance initiates strong star formation. For instance, this initial trigger could be a merger with another galaxy, an interaction with a dark matter subhalo (Helmil et al. 2012), or a merger with a gas cloud. In the case of a gas cloud merger, the initial interaction should raise the H$_1$ content and disturb the H$_1$ kinematics, but may not trigger an immediate starburst (Verbeke et al. 2014). Subsequent infall from the gas cloud or enhanced turbulence may then induce a later starburst. The morphology of the star formation should vary depending on the nature of the interaction and the gas cloud trajectory, consistent with the range of H$_\alpha$ morphologies we observe (Section 3.3).

Regardless of the cause of the initial burst, supernova feedback rapidly quenches the initial starburst owing to the low potential well of the galaxy (e.g., Dekel & Silk 1986; Stinson et al. 2007; Hopkins et al. 2014). This feedback may increase the H$_1$ velocity dispersion, but these kinematical disturbances should lag the peak star formation (Verbeke et al. 2014). After the starburst dies down, the reaccretion of previously expelled gas may trigger a series of subsequent starbursts (e.g., Lee et al. 2007; Stinson et al. 2007). In addition, massive star clusters formed in a prior burst may generate torques that continue to drive H$_1$ gas inward (e.g., Elmegreen et al. 2012) to fuel future starbursts. Thus, low-mass starbursts may lack the clear signs of kinematical disturbances that should characterize higher-mass interacting starbursts, as illustrated by the similar H$_1$ velocity profiles of the low-mass starbursts and non-starbursts in our sample (Section 3.3). These starburst cycles
may gradually reduce a dwarf galaxy’s H I reservoir but are unlikely to deplete it entirely, given the starbursts’ high H I gas fractions. As with the more massive starbursts, photodissociation may not affect the outer H I gas and may be balanced by photodissociation near the starburst. Consequently, the H I gas fractions of low-mass starbursts may also remain relatively constant, with little variation with respect to non-starbursts, and may provide a plentiful neutral gas supply capable of fueling multiple starburst episodes. The similar H I gas fractions of the ALFALFA Hα starbursts and non-starbursts agree with this scenario (Section 3.1.1), as do observations of the H I content of interacting dwarf galaxies relative to isolated dwarfs (Stierwalt et al. 2015). By quickly quenching star formation, the high feedback efficiencies in the dwarf starbursts may prevent rapid increases in metallicity or stellar mass. This scenario is consistent with the flat star formation histories and relatively inefficient star formation inferred for dwarf galaxies (e.g., Behroozi et al. 2013).

The dwarf starbursts’ periodic star formation mode may be particularly relevant to high-redshift star formation. Milky Way progenitors at z ≈ 2 may accrete gas from the IGM in discrete episodes that trigger enhanced star formation (Woods et al. 2014). However, as with the dwarf starbursts, feedback efficiently expels the gas and delays its consumption (e.g., Woods et al. 2014). As a result, these galaxies may have variable SFRs and may maintain an elevated H I content that fuels later star formation (e.g., Hopkins et al. 2014). However, unlike z = 0 galaxies, z = 2 galaxies experience higher accretion rates from the IGM (e.g., Kereš et al. 2005). High-redshift galaxies may therefore have higher average SFRs and larger gas reservoirs than we observe for the ALFALFA Hα sample. Feedback and variable SFRs in low-mass galaxies also have important implications for the reionization of the IGM. Wyithe & Loeb (2013) argue that by suppressing star formation, efficient feedback may reduce the contribution of the lowest-mass galaxies to reionization. Constraining the starburst duty cycle in dwarf galaxies is therefore important to understanding both galaxy star formation histories and reionization.

5. SUMMARY

The ALFALFA Hα survey represents the first opportunity to compare the properties of gas-rich starbursts and non-starbursts within a statistically uniform H I-selected sample. In this work, we analyze the H I gas fractions, H I depletion times, H I kinematics, and optical morphologies of 14 starbursts within the 565 galaxies that make up the ALFALFA Hα Fall-sky sample. This sample illuminates the roles of gas accretion and feedback in determining the H I content of starburst galaxies and in triggering and sustaining star formation.

Our main results are as follows.

1. On average, the ALFALFA Hα galaxies with higher instantaneous sSFRs tend to have slightly higher H I gas fractions, but this trend is weak and shows substantial scatter. Galaxies with sSFRs that differ by an order of magnitude may still have the same H I gas fraction, and most of the starburst galaxies have H I gas fractions similar to galaxies with significantly lower SFRs. In contrast, we observe a tight trend between H I gas fraction and g − r color. We show that dust extinction, rather than recent star formation, is primarily responsible for the tight H I-color correlation. This link between dust extinction and H I gas fraction likely stems from the relation between stellar mass, metallicity, and H I content in galaxies (Bothwell et al. 2013).

2. Disk galaxies lie on a sequence of decreasing H I depletion time with increasing stellar surface density. The observed trend is consistent with the idea that higher midplane pressures encourage the formation of H2 from H I (Blitz & Rosolowsky 2006). Disk galaxies from the GASS sample (Catinella et al. 2010, 2013) also fall on this sequence, while spheroid-dominated systems are offset to higher H I depletion time. The spread in the H I depletion times of the spheroids reflects a spread in sSFR but shows no trend with either H I gas fraction or bulge-to-disk ratio. Instead, the spatial distribution of H I in early-type galaxies likely determines whether gas clouds can reach the necessary densities to form molecular gas.

3. Gas-rich starbursts are able to maintain a relatively constant H I supply. Most of the 14 starbursts show little to no increase in MHI/M* or log(HI/H2) relative to galaxies of a similar mass; by the time of the starburst episode, any excess atomic gas has already been converted into H2. However, we do find a few exceptions to this scenario. The extended H I disk of UGC 470 may fuel its elevated star formation. In addition, the two most optically asymmetric starbursts, which appear to be in a pre-coalescent merger stage, do show some evidence for enhanced H I gas fractions. These asymmetric galaxies suggest that the conversion of excess H I to H2 is an ongoing process during mergers.

4. Ionization does not appear to substantially deplete the starbursts’ H I gas, and photodissociation of H2 may compensate for decreases in H I due to consumption and ionization. Although we do not find that starbursts are unusually H I rich, we also do not find that starbursts are H I deficient, as suggested for starbursts in the SINGG sample (Oey et al. 2007). Instead, high-sSFR galaxies span a wide range of H I gas fractions. The similarity of the H I gas fractions of starbursts and non-starbursts may indicate that the intense ionizing radiation of the starbursts does not penetrate to the outermost regions hosting much of the H I mass.

5. The starbursts use their H I more efficiently than the rest of the sample, as indicated by their lower H I depletion times relative to galaxies of a similar mass or stellar surface density. Major mergers may cause these high efficiencies in at least some of these starbursts, as suggested by the starbursts’ asymmetric optical morphologies and the wide H I velocity profile wings in several starbursts. The high optical asymmetries of two starbursts are consistent with major mergers. The lower but slightly elevated asymmetries of an additional six starbursts may indicate either more minor disturbances or mergers near coalescence, the merger phase predicted to cause the largest enhancement in SFR. Finally, consistent with recent merger simulations (e.g., Powell et al. 2013), we find that extended, rather than nuclear, star formation may dominate the morphologies of some starbursts.

6. While some of the starbursts are likely mergers, the lowest-mass starbursts, with M* < 10^8 M☉, do not show clear evidence of disturbed optical morphologies or H I kinematics. These dwarf starbursts may undergo periodic

\[ \text{M}^* \text{= mass} \]
bursts, possibly triggered by a previous interaction, in which case unusual gas kinematics might not be apparent (Verbeke et al. 2014). Large fluctuations in SFR appear characteristic of dwarf galaxies (e.g., Lee et al. 2007), and the dwarf galaxies in our sample also show a larger scatter in SFE than more massive galaxies. The large, apparently sustainable HI gas fractions of low-mass starbursts may remain in the galaxy’s extended HI reservoir.

The ALFALFA Hα galaxies demonstrate that while starbursts may differ dramatically from non-starbursts in their molecular gas content, the atomic gas fractions of starbursts and non-starbursts are similar. Efficient conversion of atomic to molecular gas reduces any H I excess, and the localized starbursts may differ dramatically from non-starbursts in their characteristics.

The ALFALFA Hα galaxy sample shows that the localized starbursts may differ dramatically from non-starbursts in their characteristics.
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