What Determines the H1 Gas Content in Galaxies? Morphological Dependence of the H1 Gas Fraction across the $M_*-$SFR Plane

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Abstract

We perform a stacking analysis of the H1 spectra from the Arecibo Legacy Fast ALFA survey for optically selected local galaxies from the Sloan Digital Sky Survey to study the average gas fraction of galaxies at fixed stellar mass ($M_*$) and star formation rate (SFR). We first confirm that the average gas fraction strongly depends on the stellar mass and SFR of host galaxies; massive galaxies tend to have a lower gas fraction, and actively star-forming galaxies show a higher gas fraction, which is consistent with many previous studies. Then we investigate the morphological dependence of the H1 gas mass fraction at fixed $M_*$ and SFR to minimize the effects of these parameters. We use three morphological classifications based on parametric indicator (Sérsic index), nonparametric indicator (C-index), and visual inspection (smoothness from the Galaxy Zoo 2 project) on the optical image. We find that there is no significant morphological dependence of the H1 gas mass fraction at fixed $M_*$ and SFR when we use the C-index. In comparison, there exists a hint of diminishment in the H1 gas mass fraction for ”smooth” galaxies compared with “nonsmooth” galaxies. We find that the visual smoothness is sensitive to the existence of small-scale structures in a galaxy. Our result suggests that even at fixed $M_*$ and SFR, the presence of such small-scale structures (seen in the optical image) is linked to their total H1 gas content.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Galaxy classification systems (582); Circumgalactic medium (1879)

1. Introduction

Morphologies of galaxies are known to be strongly correlated with their star formation activity. Late-type galaxies are actively star-forming in general, while star formation in early-type galaxies tends to be much less active. Historically, the most common approach to classify galaxy morphologies was visual inspection by human eyes (see Kennicutt 1998). With the advent of the large and digitalized format of astronomical data sets over the last few decades (and, accordingly, the significant increase of the galaxy sample size), it has become much more common to use analytical (or automated) classification, such as Sérsic index ($n$; Sérsic 1963), concentration parameter ($C$; often defined as the ratio between the half-light radius and 90% radius), stellar mass surface density, and bulge-to-total ratio (e.g., Strateva et al. 2001; Catinella et al. 2010; Wuyts et al. 2011; Fang et al. 2013; Cook et al. 2019, 2020). A strong correlation between the morphologies and the H1 gas content of galaxies has also been well established; i.e., late-type galaxies are gas-rich, while early-type galaxies tend to be gas-poor. Indeed, in past studies, the galaxy morphologies along the Hubble sequence were used to estimate their H1 gas mass (see Roberts & Haynes 1994), which is often used to quantify the “deficiency” of atomic hydrogen in galaxies residing in dense environments (H1 deficiency; Gavazzi et al. 2008; Boselli et al. 2010; Hughes et al. 2013).

With the recent large, H1 21 cm line surveys in the local universe, such as the GALEX Arecibo SDSS Survey (GASS; Catinella et al. 2013) and the Arecibo Legacy Fast ALFA (ALFALFA) survey (Haynes et al. 2018), it has become possible to investigate the morphological dependence of the H1 gas fraction of local galaxies in a more statistical way. By using the data from the GASS survey and various morphological classifications from the visual classification to the automated methods, Calette et al. (2018) reported that late-type galaxies tend to have a higher H1 gas fraction than early-type galaxies at a given stellar mass. While Calette et al. (2018) divided their sample into stellar mass bins, they did not split the sample by star formation rate (SFR). Because late-type galaxies tend to have higher SFRs than early-type galaxies in general and are expected to have a large gas reservoir, the morphological dependence reported in Calette et al. (2018) might be produced by the different SFR between the early- and late-type galaxy samples. Moreover, some outliers do not follow the general trend between the average star formation activity and gas content or galaxy morphology, such as the H1-excess systems (early-type galaxies with large H1 reservoirs and negligible star formation; Gerib et al. 2016, 2018) or passive spirals (e.g., George 2017; Guo et al. 2020; but see also Cortese 2012).

A more recent study by Cook et al. (2019) used the extended GASS (Catinella et al. 2010, 2018) to investigate the relation between H1 gas mass and the bulge-to-total ratio (measured with the 2D Bayesian light profile fitting code, ProFit; Robotham et al. 2017) for local galaxies. They showed that the H1 gas mass of star-forming galaxies does not depend on the bulge-to-total mass ratio, suggesting that the presence of a bulge has little impact on their H1 gas content. However, we should note that Cook et al. (2019) selected star-forming galaxies by simply excluding the quiescent galaxy population based on the distance from the star formation main sequence (Catinella et al. 2018; Janowiecki et al. 2019). Also, their morphological classification is different from that of
Calette et al. (2018). In these ways, the sample definition and/or morphological classifications vary from study to study, making it difficult to interpret the impact of galaxy morphologies on their H I gas content.

In our study, we carry out a comprehensive analysis by using the multiple morphological indicators (Sérsic index, C-index, and visual smoothness) and dividing our sample by their stellar mass and SFR. We stack the radio spectra of galaxies from the ALFALFA survey to calculate the average gas fraction. Then we can compare the average H I gas content of galaxies with different morphologies at the same stellar mass and SFR.

The structure of this paper is as follows. In Section 2, we show our sample selection and summarize the galaxy information. The procedure to stack the radio spectra and the stacking result for our “star-forming” galaxy sample are summarized in this section. We then investigate the morphological dependence of the H I gas mass at fixed stellar mass and SFR in Section 3 and interpret our results in Section 4. Finally, we summarize our results in Section 5. Throughout this paper, we adopt a flat ΛCDM cosmology with Ωm = 0.3, Ωλ = 0.7, and H0 = 67.8 km s⁻¹ Mpc⁻¹ and a Chabrier initial mass function (Chabrier 2003).

2. Data and H I Spectral Stacking

To investigate the morphology dependence of the H I contents of local galaxies, we need not only H I information but also various parameters of host galaxies. A combination of the large data sets from the GALEX-WISE-SDSS Legacy Catalog 2 (GSWLC2; Salim et al. 2018) and ALFALFA survey enables us to study the H I gas properties of galaxies statistically.

Our sample is drawn from the GSWLC2, which contains the stellar mass and SFR of ~700,000 galaxies derived from the fitting of the spectral energy distribution for the multi-wavelength data set. We then cross-matched the GSWLC2 catalog with the MPA-JHU catalog (Abazajian et al. 2009) of the Sloan Digital Sky Survey (SDSS) DR7 to obtain the spectroscopic redshift of each target. We then select 32,717 galaxies (with 0.01 < z < 0.05) located within the ALFALFA H I 21 cm line survey footprint. Here we note that 14,252 galaxies having companions within the cutout region of radio spectra (4′; see Section 2.1) are excluded to avoid over-estimating H I gas mass and the effect of galaxy–galaxy interaction. To identify companions, we do not apply any criteria for stellar mass, color, or redshift. This method increases the number of discarded galaxies that are potentially not accompanied. However, in this study, we conservatively discard all galaxies having any companion within the cutout region of the H I emission line. In the following analysis, we restrict the sample to 18,465 galaxies with M* and SFR ranges of 9.0 < log₁₀M* < 12.0 and −2.0 < log₁₀SFR < 2.0. In addition, considering the possible effect of active galactic nuclei (AGNs) in our analysis, we exclude 7573 AGN host candidates from our sample using the BPT diagram (Kaufrmann et al. 2003). Here we used the [O III], [N II], Hα, and Hβ emission line fluxes of individual galaxies from the MPA-JHU catalog, while we exclude five galaxies for which any of the emission line fluxes are not properly measured in the MPA-JHU catalog. In this study, we use the remaining 10,887 galaxies as our parent “star-forming” galaxy sample.

2.1. H I Spectral Stacking

The H I gas mass, MHI, is derived from the 21 cm line flux (Roberts 1963) in this paper. Although the H I–detected source catalog from the ALFALFA survey is already public (Haynes et al. 2018), directly using the H I–detected source catalog may cause a potential bias toward the H I–rich galaxies due to the detection limit. The H I gas mass, MHI, is derived from the flux of the 21 cm line (S) following Equation (1) (Roberts 1963),

\[
\frac{M_{HI}}{M_\odot} = \frac{2.356 \times 10^5}{1+z} \frac{D_L(z)^2}{\text{Mpc}} \left( \frac{S}{\text{Jy km s}^{-1}} \right),
\]

where \(D_L(z)\) is the luminosity distance to the object. The lower limit of detectable H I gas mass depends on the distance to the object. More distant galaxies with less H I gas, therefore, might not be detected through the pipeline of the ALFALFA survey.

To avoid this potential bias, we apply the H I stacking analysis following the previous studies (e.g., Fabello et al. 2011; Brown et al. 2015). The radio spectra around the H I 21 cm line of our sample (8′ × 8′ square) are extracted from the full-volume ALFALFA data cubes using R.A., decl., and cz in the MPA-JHU catalog regardless of the detection of the H I 21 cm line. A spectrum of one galaxy has two polarizations and contains flux, velocity, and quality weight \(w\) for each velocity bin. The quality weight \(w\) evaluates the effect of radio-frequency interference and/or hardware issues, ranging from zero (unusable data) to 1 (good data). We discard velocity bins with \(w < 0.5\) and take the average of two polarizations. If more than 40% of the velocity bins have \(w\) less than 0.5 in a spectrum, we exclude that spectrum from our stacking analysis. Forty galaxies are removed through this procedure. After that, the spectrum is rest-frame shifted using the redshift from optical spectroscopy so that the center of the H I 21 cm line should be set to 0 km s⁻¹. Also, the noise level of each spectrum is evaluated using the rms of the spectrum outside of the H I emission from the target galaxy (−1000 < \(v\) [km s⁻¹] < −500 and 500 < \(v\) [km s⁻¹] < 1000; see Section 3.3 in Fabello et al. 2011). If we stack the radio spectra without any weight, massive and/or nearby galaxies will significantly contribute to the resulting H I gas fraction \(f_{HI}\). In Equation (1), \(1 + z\) is not squared because it assumes that the H I 21 cm line flux \(S\) is rest-frame shifted correctly. However, because our calculation starts from the observed H I 21 cm line flux \(S_\text{obs}\), we have to weight \(1 + z\) in the rest-frame shifting. We solve this problem by changing the stacking weight from \((1 + z)/D_L M_*\) to \((1 + z)^2/D_L M_*\). We also note that we perform a stacking analysis only for the bins with a sample size of \(>10\).

After subtracting the baseline of a stacked spectrum by linear fitting, we calculate the average gas fraction in each bin by summing up the flux in the velocity range of −350 < \(v\) [km s⁻¹] < 350 (dashed lines in Figure 1). This velocity range is determined to cover the widest emission line after the stacking process to be performed in Section 2.2. Adopting a fixed velocity range may lead to an increase in the error of \(f_{HI}\) measurements. However, we decided to adopt this fixed velocity.
range for all of the stacked spectra to estimate the errors and upper limits for H I–undetected sources in a consistent manner. The flux error of each velocity component in a stacked spectrum is derived by propagating the rms from individual spectra before stacking (the light blue region in Figure 1). On the other hand, we adopt the bootstrap resampling approach when calculating the average gas fractions to consider (Efron 1982) the sampling errors. In the following analyses, we use the average of the gas fraction $F_{\text{H}I}$ and its standard deviation from 1000 times bootstrap resampling as the average gas fraction and its 1σ error. Here we note that the sampling error dominates the total error budget in our analyses.

2.2. Average H I Gas Fraction across the Star-forming Main Sequence

First, we simply divide our sample by the stellar mass and SFR ($\Delta M_* = \Delta \text{SFR} = 0.5$ dex) and carry out the stacking process as explained above. Figure 2 summarizes the number of galaxies included in each bin. The sample size tends to be small at the high-$M_*$ and/or low-SFR ends, and we do not perform H I stacking analyses for the bins with a sample size of $N < 10$. We note that the results presented in this paper mainly focus on galaxies on the star-forming main sequence.

In the left panel of Figure 3, the color-coding indicates the average gas fraction of galaxies at each stellar mass and SFR. Here we include the marginal detection down to a signal-to-noise ratio (S/N) = 3. It can be seen that the average gas fraction gradually changes with the stellar mass and SFR. The increasing gas fraction with increasing SFR at fixed stellar mass seen in this diagram is consistent with a picture that the rich gas reservoir supports active star formation (Tumlinson et al. 2017).

In the right panel of Figure 3, the color-coding is used for the traditional visual classification made by human eyes (see Section 3.3 for more details).

We cross-matched our sample constructed in Section 2.2 with the New York University Value-Added Catalog (NYU-VAGC; Blanton et al. 2005) and the full GZ2 catalog (Hart et al. 2016). This catalog contains 7712 objects, all of which have measurements of $M_*$, SFR, redshift, ALFALFA.
Here we use the same bin size for stacking as in Section 2.2 (marginal detection correlated with the SFR). We discuss the morphological impacts on the radio spectra, Sérsic n, C-index, and visual smoothness. We discuss the morphological impacts on the $M_\text{bulge}$–$F_{\text{HI}}$ relation with this new sample in the following subsections.

### 3.1. Sérsic Index

We use the Sérsic index $n$ measured in the $r$ band of individual galaxies published in NYU-VAGC. In this study, we select 498 early-type and 2856 late-type galaxies by applying $n > 3.5$ and $n < 1.5$, respectively. Red and blue contours in Figure 4 show the distribution of early- and late-type galaxies on the $M_\text{bulge}$–SFR diagram. Here we normalize the contours based on the total number of each population. Because we mainly focus on the galaxies on the star formation main sequence, the number of late-type galaxies is larger than that of early-type galaxies.

We then conducted the stacking analysis of the early-/late-type subsamples in the same way as described in Section 2.2. Here we use the same bin size for stacking as in Section 2.2 ($\Delta M_\text{bulge} = \Delta \text{SFR} = 0.5$ dex). The number of early-/late-type galaxies in each bin is shown in Figure 4.

The left column in Figure 5 shows the result. Panels (a) and (b) in Figure 5 show the relationship between the median stellar mass and the average $\text{HI}$ gas fraction when we divide our sample into late and early types by Sérsic $n$. As we did in Figure 3, we use the bins with $N \geq 10$ for each morphological type. The general trend does not change from Figure 3; the $\text{HI}$ gas fraction is anticorrelated with the stellar mass and correlated with the SFR.

We compute the difference of the $\text{HI}$ mass between early- and late-type galaxies with the same stellar mass and SFR, and they are plotted in Figure 5(c) as a function of stellar mass. This comparison is performed for the bins in which both populations have more than nine galaxies in Figure 4. Here we note that there are two classes of bin types in terms of the $\text{HI}$ detection.

1. Both populations have $S/N > 3$ (circles in Figure 5).
2. The $F_{\text{HI}}$ of late-type/disk/nonsmooth galaxies show $S/N \geq 3$, but early-type/bulge/smooth galaxies show $S/N < 3$ (triangles in Figure 5).

There are no bins with properties opposite those of class 2 for all morphological indicators. In Figure 5(c), we use large circles and normal triangles for classes 1 and 2, respectively. The number of bins in each class is summarized in Table 1.

Unfortunately, there are only two bins in class 1, and the remaining bins are class 2 or nondetection ($S/N < 3$). The $F_{\text{gas}}$ differences in these two class 1 bins are $\sim 0.09$ and $0.07$, suggesting that there is no significant difference in the $\text{HI}$ gas mass between late- and early-type galaxies at fixed $M_\text{bulge}$ and SFR in those bins. Outside of these two bins ($\log_{10} M_\text{bulge} < 9.0$ or $\log_{10} M_\text{bulge} > 10.5$), we could not detect $\text{HI}$ in the stacked spectra due to the poor statistics, especially for early-type galaxies.

We also conduct the same analysis with the different Sérsic $n$ criteria. Here early-/late-type galaxies are defined as those sitting in the top/bottom 20th percentile profile in the distribution of Sérsic $n$; i.e., $n < 1.25$ for late types and $n > 2.30$ for early types. This method enables us to match the total size of the subsamples.
and increase the number of bins in class 1. In the range of $9.5 < \log_{10} M_* < 10.5$ and $-0.5 < \log_{10} \text{SFR} < 0.5$, we find that there is no significant difference in the H I gas mass between early- and late-type galaxies. Using this method, however, the early-type subsample can include contaminants from “intermediate” morphology ($n \sim 2–3$). It is, therefore, difficult to conclude that there is no difference in H I gas mass fraction between early- and late-type galaxies at fixed stellar mass and SFR with this percentile approach.

### 3.2. Concentration Index

We also retrieve the $r$-band Petrosian half-light radii $R_{25}$ and $R_{90}$ from the NYU-VAGC catalog and calculate the C-index as a ratio of these two values ($R_{90}/R_{25}$). While the criteria of the C-index used for the morphological classification are different from study to study (e.g., Deng 2013; Koyama et al. 2019), we adopt $C > 2.8$ and $C < 2.5$ for bulge- and disk-dominated galaxies, respectively. We obtain 660 bulge and 5020 disk galaxies in total. Figure 6 shows the $M_*-$SFR diagram for bulge/disk galaxies. Binning width is the same as that in Section 3.1 ($\Delta M_* = \Delta \text{SFR} = 0.5$ dex), and the number of galaxies in each bin is also summarized in Figure 6.

The middle column of Figure 5 shows the results of our H I stacking analysis when we use the C-index for morphological classification. Panels (d) and (e) in Figure 5 show the scaling relation for disk- and bulge-dominated galaxies. In panel (f), we show the difference between the disk and bulge samples by computing $M_{\text{H}, \text{disk}}/M_{\text{H}, \text{bulge}}$ at each stellar mass and SFR. The meanings of the symbols are the same as those in panel (c). The

| Table 1 | The Number of Bins for Classes 1 and 2 According to the S/N of the Stacked H I Flux |
|---------|------------------------------------------------------------------|
|         | Class 1 | Class 2 |
| $S/N_{\text{pop.1}}(F_{\text{HI}})$ | $>3$ | $>3$ |
| $S/N_{\text{pop.2}}(F_{\text{HI}})$ | $>3$ | $<3$ |
| Sérsic $n$ | 2 | 5 |
| C-index | 9 | 3 |
| Visual smoothness | 7 | 1 |

Note. “Class 1” means that H I is detected at S/N $> 3$ for both of the populations in that bin. “Class 2” indicates the case where the first population shows $S/N(F_{\text{HI}}) > 3$, while the second population has $S/N(F_{\text{HI}}) < 3$. There are no bins with properties opposite those of class 2. In the last row, we show the number of bins for each class and morphological index. Classes 1 and 2 are shown as circles and triangles in the bottom panels of Figure 5, respectively.
weighted average of \( \log_{10}(M_{\text{H, disk}}/M_{\text{H, bulge}}) \) of the class 1 bins \((S/N(F_{\text{HI}}) > 3\) for both bulge and disk populations) is 0.09 ± 0.10, suggesting that disk and bulge galaxies at fixed stellar mass and SFR have a similar amount of H1 gas on the star formation main sequence \((9.0 < \log_{10} M_* < 11.0)\). We verify that our results are unchanged even if we instead use the upper/lower 20th percentile in the distribution of the C-index to select bulge and disk populations \((C > 2.59\) and \(C < 2.07)\). Again, we note that the intermediate population can contaminate the morphological selection with this percentile approach.

### 3.3. Visual Classification with GZ2

The Galaxy Zoo project \((\text{Lintott et al. 2008})\) provides visual classifications of morphologies given by citizen scientists for a large number of galaxies observed in SDSS. In the Galaxy Zoo project, citizen scientists are asked to inspect galaxies’ images and choose their morphological class \((\text{e.g., elliptical, clockwise spiral})\). Following Galaxy Zoo, GZ2 \((\text{Willett et al. 2013})\) aims to describe more detailed morphological properties using a similar method to that of Galaxy Zoo. We here focus on the first question of GZ2: “Is the galaxy simply smooth and rounded, with no sign of a disk?” All participants in the GZ2 project are asked to choose one answer from “smooth and rounded,” “features or disk,” or “star or artifact.” Then, GZ2 calculates the “vote fraction” for each answer. Willett et al. \((2013)\) mentioned that, for most of the clean spirals in Galaxy Zoo, the vote fraction for “features or disk” in GZ2 is similar to that for spiral galaxies in Galaxy Zoo.

Hart et al. \((2016)\) revised the vote fraction with the idea that the actual distribution of the vote fraction should be independent of the redshift in the local universe. They remove the effect of size, luminosity, and redshift of galaxies and introduce the debiased vote fraction. Following the recommendation by the GZ2 project, we use this debiased vote fraction from Hart et al. \((2016)\) in this paper, rather than directly using the original vote fraction provided by Willett et al. \((2013)\).

We define “smooth” galaxies as those having the debiased vote fraction of >0.8 for “smooth and rounded” in GZ2. On the other hand, we define “nonsmooth” galaxies as those with the debiased vote fraction of >0.8 for “features or disk.” Here we follow the recommendation by Willett et al. \((2013)\) to use the criteria of the debiased vote fraction >0.8 when performing any morphological classification with GZ2. The bin size for our H1 stacking analyses is the same as that in Section 3.1 \((\Delta M_\text{s} = \Delta \text{SFR} = 0.5 \text{ dex})\), and Figure 7 shows the number of galaxies in each bin.

The result is shown in the right column of Figure 5. As we performed for Sérsic index and C-index in the previous subsections, we show in panels \((g)\) and \((h)\) the scaling relation for nonsmooth and smooth galaxies, respectively. Panel \((i)\) shows the difference between these two populations at fixed \(M_*\) and SFR. Interestingly, smooth galaxies tend to have a significantly lower gas fraction than nonsmooth galaxies, and we find that there are six bins where both nonsmooth and smooth galaxies are detected at \(S/N(F_{\text{HI}}) > 3\) (class 1). The weighted average of \(\log_{10}(M_{\text{H, nonsmooth}}/M_{\text{H, smooth}})\) is 0.71 ± 0.11, suggesting a significant difference in H1 gas fraction between the smooth and nonsmooth galaxies at fixed stellar mass and SFR in the range of \(9.0 < \log_{10} M_* < 10.5\). This is the main result of our paper. We find no bin where H1 is detected only for smooth galaxies. This result is also unchanged even if we use the percentile approach to define smooth and nonsmooth galaxies, as we did in Sections 3.1 and 3.2.

### 4. Discussion

The morphological dependence of the H1 gas mass in local galaxies has been discussed for decades \((\text{e.g., Roberts & Haynes 1994})\). The H1 gas mass is known to depend on the stellar mass and SFR of host galaxies \((\text{e.g., Brown et al. 2015})\). On the other hand, the morphology of galaxies is also related to the stellar mass and SFR \((\text{e.g., Kauffmann et al. 2003})\). These relationships between multiple parameters make it difficult to understand the real impact of galaxy morphologies on their H1 gas mass content.

In our study, we divide our sample into small bins on the \(M_*-\text{SFR}\) plane \((\Delta M_\text{s} = \Delta \text{SFR} = 0.5 \text{ dex})\). The galaxies in each bin are further divided by their morphology with three morphological indicators: Sérsic \(n\), C-index, and visual smoothness. Our study revealed that visually smooth galaxies have a lower gas fraction than nonsmooth galaxies at fixed stellar mass and SFR. Such a morphological trend is not observed when we use the C-index \((\text{Figure 5})\). Below, we will discuss the potential candidates that may affect the H1 gas content of galaxies and why we see morphological dependence only when we use visual smoothness.
4.1. Stellar Mass, SFR, and Environment

When investigating the effect of galaxy morphology on the H I gas mass, it is crucial to exclude the impact of other properties of galaxies. Many previous papers show that H I gas mass strongly depends on the stellar mass of host galaxies (\(M_* - M_{HI}\) scaling relation; e.g., Fabello et al. 2011; Brown et al. 2015; Healy et al. 2019). A simple approach to remove the stellar mass dependence is to check the H I scaling relations of each subsample. Calette et al. (2018) compared the H I scaling relation of late- and early-type galaxies and concluded that late-type galaxies have a higher H I gas fraction than early-type galaxies at all stellar mass ranges. However, the stellar mass is not the only parameter that determines the H I gas mass of the host galaxies, and other parameters can also affect the scaling relation (Cortese et al. 2011; Brown et al. 2015; Cook et al. 2019). For example, Cook et al. (2019) studied the impact of the bulge-to-total mass ratio on the H I scaling relation and found no significant effect of the morphology when they limited their sample to the star-forming galaxies. They argued that the morphological dependence of the H I scaling relation reported in previous studies originates from the correlation between the star formation activity and galaxy morphology at fixed stellar mass. On the other hand, the amount of molecular hydrogen in the star-forming galaxy is shown to be approximately fixed in a wide range of bulge-to-total mass ratios, whereas that of H I can change by a factor of 100 (see Figure 10 in Catinella et al. 2018). This is also supported by Koyama et al. (2019), who showed similar molecular gas mass fractions for green valley galaxies with different morphologies (classified by C-index) at fixed stellar mass and SFR.

Because all of the analyses presented in this work are performed at fixed stellar mass and SFR, our results should not be affected by different stellar masses or SFRs. It is true that there remains a possibility that there is a small difference in the distribution of stellar mass and/or SFR within the small (\(M_* - SFR\)) bin. We calculate the median \(M_*\) and SFR for smooth and nonsmooth galaxies in each bin (\(\delta M_*\) and \(\delta SFR\)) and confirm that the difference is very small for all of the bins used in Figure 5 (\(\delta M_* \lesssim 0.08\) and \(\delta SFR \lesssim 0.11\)). By recalling Figure 3, the small difference existing in each bin cannot explain the large difference (0.71 dex) in the gas fraction between smooth and nonsmooth galaxies.

Although we consider that the stellar mass and star formation activity are the primary parameters that determine the H I gas content of galaxies, their surrounding environments may also affect the H I scaling relation. Observations revealed that late-type galaxies in dense environments tend to have less H I gas than those in the general field (e.g., Haynes & Giovanelli 1984; Solanes et al. 2001), likely due to environmental processes such as galaxy–galaxy interactions or ram pressure stripping (Gunn & Gott 1972; Moore et al. 1998; Cortese et al. 2021). It is also true that early-type galaxies in the traditional Hubble sequence (ellipticals/S0s) tend to be located in cluster environments in the local universe (e.g., Dressler 1980; Bamford et al. 2009).

To check the environment of smooth and nonsmooth galaxies, we investigate the halo mass of smooth and nonsmooth galaxies. By cross-matching our sample with the SDSS DR7 group catalog from Yang et al. (2008), we obtain the halo mass of galaxies. We then divide these galaxies into small bins of stellar mass and SFR as used for our stacking analysis (\(\Delta M_* = \Delta SFR = 0.5\) dex) and carry out the Kolmogorov–Smirnov (K-S) test on the halo mass distribution of two populations. We find that the \(p\)-values are \(>0.05\) for most of the bins, suggesting that we cannot rule out the null hypothesis that the two populations are drawn from the same parent population. Therefore, it is unlikely that our results shown in Figure 5 are affected by the dense environment.

We note again that the morphological difference in the H I gas fraction is visible only when we use visual smoothness for the morphological classification. We do not see the difference when we use the C-index (Figure 5(f)), consistent with the conclusion of Cook et al. (2019). A question here is, what is the visual smoothness? We will discuss this in Section 4.2 and attempt to identify the reasons responsible for the different behavior when we use smoothness as a morphological indicator.

4.2. Visual Smoothness

We introduce the visual smoothness as a parameter describing the appearance of galaxies. In our analysis, smooth and nonsmooth galaxies are determined by the debiased vote fraction of each answer to the first question in GZ2 (Willett et al. 2013), “Is the galaxy simply smooth and rounded, with no sign of a disk?” This unique classification distinguishes between the H I–rich and H I–poor population at fixed \(M_*\) and SFR, but what determines the visual smoothness of galaxies? To interpret the visual smoothness, we investigate how the visual smoothness correlates with the other two morphological parameters used in this study (Sérsic \(n\) and C-index; see Figure 8).

From Figure 8, we realize that both smooth and nonsmooth galaxies are distributed over a wide range in Sérsic \(n\) and C-index. The distribution of smooth galaxies has a peak around \(n \sim 1\), corresponding to a pure exponential disk, and there are nonsmooth galaxies at \(n \sim 4\), which corresponds to the de Vaucouleurs profile. For the C-index, smooth and nonsmooth galaxies have a different distribution in the bottom panel of Figure 8, but the distribution of the smooth galaxies is peaked at \(C \sim 2.5\), which is actually used to select “disk” galaxies in Section 3.2. Figure 8 suggests that the visual smoothness judged by the citizen scientists is not simply identifying early-/late-type or bulge-/dislike morphologies. We show examples of the optical images of our nonsmooth and smooth galaxies from SDSS DR12 in Figure 9. The stellar mass, SFR, Sérsic \(n\), and C-index of these galaxies are fixed at \(10.0 < \log_{10} M_* < 10.5\), \(0.0 < \log_{10} SFR < 0.5\), \(1.0 < n < 1.5\), and \(2.0 < C < 2.5\). In other words, only visual smoothness is different between the six galaxies in the top and bottom panels of Figure 9.

By visually inspecting the optical images in Figure 9, we realize that many of the smooth galaxies show prominent bulge and disk structure. It is likely that the citizen scientists’ critical features to identify nonsmoothness would be the small structures like spiral arms and/or a prominent bar structure within the galaxies. Indeed, nonsmooth galaxies in Figure 9 seem to have spiral arms or a prominent bar structure (top six panels), while smooth galaxies do not have such a small-scale structure (bottom six panels). Although the Sérsic \(n\) and C-index are the morphological indicators commonly used to describe the overall light profile from the core to the outskirts of galaxies, it would not be possible to identify such small-scale structures by those automated parameters.

Our results suggest that galaxy morphologies defined by Sérsic \(n\) and the C-index are not identical to the classification made by human eyes. We note that we are not discussing which is the best indicator of galaxy morphologies. We suggest that
the visual smoothness can better distinguish gas-rich and gas-poor populations at fixed stellar mass and SFR. We should also note that our sample is limited to the local universe (0.01 < z < 0.05), so that the physical resolution is high (typically 0.94 kpc at z = 0.033). This might help citizen scientists to identify small structures in the galaxies.

It would also be important to understand the effect (or bias) produced by the redshift of galaxies on the visual classification of the citizen scientists in GZ2. As shown in Figure 4 of Willett et al. (2013), the fraction of smooth galaxies increases with redshift, while the nonsmooth population decreases. This trend is not surprising because the physical resolution becomes poorer for more distant galaxies, and thus it becomes more difficult to identify small-scale structures within more distant galaxies. Hart et al. (2016) corrected the vote fraction by removing the bias produced by the different redshifts. Because we use the debiased vote fraction derived by Hart et al. (2016), our results would not be affected by the redshift effects. Figure 10 shows the redshift distributions of our smooth and nonsmooth galaxies in each (M* , SFR) bin. This plot suggests that smooth galaxies tend to have higher redshifts than nonsmooth galaxies below the star formation main sequence, while this trend is often reversed for galaxies located above the main sequence. The H I mass discrepancy between smooth and nonsmooth galaxies reported in Figure 5(i) is seen regardless of the stellar mass or SFR of galaxies, and therefore it is unlikely that the different redshift distribution within each (M*, SFR) bin has significant impacts on the elevated H I mass excess in the nonsmooth galaxy population.

Our results suggest that the existence of small-scale structures in the galaxies (e.g., spiral arms) would be the key to determining the H I gas fraction. These small-scale structures might be missed by the C-index and Sérsic n because they are roughly tracing the overall light profile. In contrast, human eyes are more sensitive to such internal structures, and this would be the main cause of the different morphological dependence of H I gas mass when we use the C-index or visual smoothness for the morphological classification. Considering the fact that the amount of molecular hydrogen is almost constant (Catinella et al. 2018; Koyama et al. 2019), our result suggests that nonsmooth galaxies have a larger amount of H I that is not involved in star formation than smooth galaxies, even at the same stellar mass and SFR. More detailed theoretical approaches and/or observations of atomic gas kinematics within the galaxies are necessary to understand the missing link between the small structures likely caused by the local instability (e.g., Toomre 1977) and the global properties of H I gas in galaxies (e.g., Romeo 2020). It is expected that simulations will allow one to trace the motion of gaseous and stellar components within galaxies. However, in most
use the C-index for morphological classification, while we do find a significant morphological difference (~0.7 dex) when we use visual smoothness as a morphological indicator (Figure 5). Unfortunately, we could not obtain any clear trend from our analysis with Sérsic index due to the small number of early-type galaxies. Because we fixed the stellar mass and SFR of two morphological populations when comparing the H1 gas mass, our result is free from any bias by the stellar mass and SFR. We also investigate the environmental impact on our results. We performed the K-S test and found p-values of >0.05 for most of the bins. We therefore conclude that our results are not affected by galaxies in dense environments like galaxy clusters.

Finally, we study how the visual smoothness correlates with the other two morphological indicators. By comparing the distributions of Sérsic $n$ and C-index for nonsmooth and smooth galaxies, we find that the visual smoothness judged by the citizen scientists is different from the traditional automated distinction between early-/late-type or bulge/disk morphologies, at least in the local universe (Figure 8). We also compare the optical images of nonsmooth and smooth galaxies in Figure 9. We notice that only nonsmooth galaxies have small-scale structures within the galaxies. Therefore, we consider that the existence of small-scale structures would be the key to determining the $F_{HI}$ of local galaxies. Because Sérsic $n$ and the C-index are the indicators that describe the overall light profile from the center of the galaxies to the outskirts, the small-scale structure would be missed by those parameters. The potential link between the small-scale structure and the global $F_{HI}$ should be revealed with future spatially resolved observations and theoretical approaches.

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