ALMaQUEST. IV. The ALMA-MaNGA QUEnching and STar Formation (ALMaQUEST) Survey

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Received 2020 June 26; revised 2020 August 27; accepted 2020 September 15; published 2020 November 12

Abstract

The ALMaQUEST (ALMA-MaNGA QUEnching and STar formation) survey is a program with spatially resolved $^{12}$CO(1–0) measurements obtained with the Atacama Large Millimeter Array (ALMA) for 46 galaxies selected from the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) DR15 optical integral-field spectroscopic survey. The aim of the ALMaQUEST survey is to investigate the dependence of star formation activity on the cold molecular gas content at kiloparsec scales in nearby galaxies. The sample consists of galaxies spanning a wide range in specific star formation rate (sSFR), including starburst (SB), main-sequence (MS), and green valley (GV) galaxies. In this paper, we present the sample selection and characteristics of the ALMA observations and showcase some of the key results enabled by the combination of spatially matched stellar populations and gas measurements. Considering the global ( aperture-matched) stellar mass, molecular gas mass, and star formation rate of the sample, we find that the sSFR depends on both the star formation efficiency (SFE) and the molecular gas fraction ($f_{\text{HI}}$), although the correlation with the latter is slightly weaker. Furthermore, the dependence of sSFR on the molecular gas content (SFE or $f_{\text{HI}}$) is stronger than that on either the atomic gas fraction or the molecular-to-atomic gas fraction, albeit with the small HI sample size. On kiloparsec scales, the variations in both SFE and $f_{\text{HI}}$ within individual galaxies can be as large as 1–2 dex, thereby demonstrating that the availability of spatially resolved observations is essential to understand the details of both star formation and quenching processes.

Unified Astronomy Thesaurus concepts: Star formation (1569); Interstellar medium (847); Galaxy quenching (2040); Extragalactic astronomy (506); Surveys (1671); Molecular gas (1073)

Supporting material: figure sets, machine-readable tables

1. Introduction

Star-forming galaxies are known to form a tight relationship in the total star formation rate (SFR)–total stellar mass ($M_\star$) plane, dubbed the global star-forming main sequence (SFMS or MS; Brinchmann et al. 2004; Daddi et al. 2007; Elbaz et al. 2007; Noeske et al. 2007; Whitaker et al. 2012). The normalization, shape, and scatter of the SFMS are found to depend on environment, morphology, and the redshift of galaxies (e.g., Lin et al. 2012, 2014; Whitaker et al. 2012; Koyama et al. 2013; Speagle et al. 2014; Jian et al. 2018). As star formation is regulated by both the amount of available gas and internal feedback processes, mapping the molecular gas, which is the fuel for star formation, is therefore key to understanding how galaxies evolve within and across the global SFMS. Likewise, the molecular gas content holds important clues as to why galaxies eventually halt their star formation and become quiescent.

The COLD GASS survey (CO Legacy Database for GASS; Saintonge et al. 2011) was the first systematic CO survey for hundreds of local galaxies with $M_\star > 10^{10} M_\odot$. The
M and 1010 stellar mass ratio. The SFMS is correlated strongly with both the molecular gas to stellar mass ratio (defined as $f_{\rm H_2} = M_{\rm H_2}/M_*$, which we simply refer to as molecular gas fraction for the rest of this paper) and the star formation efficiency ($\text{SFE} = \text{SFR}/M_{\star}$). In other words, the elevation or suppression of the SFR not only depends on the availability of gas but also on the conditions in the interstellar medium (see also Tacconi et al. 2013, 2018; Huang & Kauffmann 2014; Piotrowska et al. 2020). The ALLSMOG (APEX low-redshift legacy survey for molecular gas) survey (Bothwell et al. 2014; Cicone et al. 2017) complements the COLD GASS sample in the low-mass regime by observing a further 88 nearby star-forming galaxies with stellar masses between $10^8$ and $10^{10} M_\odot$ using the APEX telescope. The combination of xCOLD GASS and ALLSMOG samples reveals that the CO luminosity not only strongly correlates with stellar mass and SFR but also varies with other factors, such as metallicity and H I mass (hereafter $M_{\text{HI}}$; Cicone et al. 2017).

While surveys such as xCOLD GASS and ALLSMOG enable the exploration of the connection between the global gas content and SFR across a wide range of galaxy properties, as well as the variation of gas properties with respect to their positions on the SFR-$M_*$ plane, details of the physical processes that shape the SFMS and its evolution remain unclear. To take a step further, spatially resolved observations are required for three main reasons: (1) there is growing evidence that the SFR also traces $M_*$ at kiloparsec scales (Sánchez et al. 2013; Wuyts et al. 2013; Cano-Díaz et al. 2016; Abdurro’uf & Akiyama 2017; Hsieh et al. 2017; Ellison et al. 2018; Medling et al. 2018; Pan et al. 2018; Cano-Díaz et al. 2019; Vullcani et al. 2019; Wang et al. 2019; Morelli et al. 2020). This relation has been dubbed the “resolved” SFMS (rSFMS) and its existence suggests that the well-known global SFMS may be an ensemble effect of local processes. (2) Star formation takes places within giant molecular clouds (GMCs), whose sizes are on the order of hundreds of parsecs or even smaller. The star formation law that characterizes the relation between SFR and gas density, often referred to as the Schmidt–Kennicutt relation (or SK relation; Schmidt 1959; Kennicutt 1998), is also found to vary with the substructures of galaxies and galactocentric radius (e.g., Bigiel et al. 2008; Leroy et al. 2013; Usero et al. 2015; Rahmani et al. 2016; Utomo et al. 2017; Schinnerer et al. 2019; Chevance et al. 2020). (3) The spatial sequence of quenching (inside-out versus outside-in versus global) obtained from Integral Field Spectroscopy (IFS) observations provides powerful constraints on quenching mechanisms (González Delgado et al. 2014, 2016; Li et al. 2015; Tacchella et al. 2015; Ellison et al. 2018; Sánchez et al. 2018; Lin et al. 2019a; also see Sánchez 2020 for a review), particularly when combined with resolved gas observations (Lin et al. 2017). Obtaining a full picture of how the star formation is related to the global properties of galaxies and how it is quenched therefore requires mapping stars and gas in galaxies with sufficient spatial resolution and sensitivity.

Recent spatially resolved observational programs, such as the EDGE (the Extragalactic Database for Galaxy Evolution)-CALIFA (Calar Alto Legacy Integral Field Area) survey and the PHANGS (Physics at High Angular resolution in Nearby Galaxies)-MUSE survey, are designed to combine the power of optical IFS and millimeter-wave interferometry observations to address key questions in star formation. The EDGE-CALIFA survey (Bolatto et al. 2017) observed 126 CALIFA-selected galaxies in $^{12}\text{CO}(1-0)$ and $^{13}\text{CO}(1-0)$ using the Combined Array for Millimeter-wave Astronomy (CARMA) with a spatial resolution ($\sim 1.4$ kpc) matched to CALIFA. This data set enables studies of the relationships between molecular gas, stellar mass, SFR, metallicity, and dust extinction on kiloparsec scales and their dependence on the global galaxy properties in a fairly large and representative local sample (e.g., Utomo et al. 2017; Colombo et al. 2018; Dey et al. 2019; Barreira-Ballesteros et al. 2020). The PHANGS-MUSE project observed 19 nearby galaxies selected from a subset of the PHANGS-ALMA survey (A. K. Leroy et al. 2020, in preparation), utilizing the Multi Unit Spectroscopic Explorer (MUSE) at the VLT. Both ALMA and MUSE observations achieve an angular resolution of $\sim 1''$, which corresponds to a physical scale of $< 100$ pc in their sample. Although modest in sample size, PHANGS-MUSE therefore offers exquisite spatial resolution. Combined, EDGE-CALIFA and PHANGS-MUSE offer complementary strengths for studying gas and star formation in the nearby universe.

While both EDGE-CALIFA and PHANGS-MUSE offer exceptional opportunities to study physical processes that govern star formation at (sub)kiloparsec scales, these samples mostly lie on the SFMS and hence do not cover a sufficiently wide range in specific SFRs (sSFR) to study the full gamut of processes from starbursts to quenching. In order to systematically understand the processes driving and regulating star formation, it is desirable to also include galaxies that are beyond the MS (in both directions). To test the feasibility of detecting resolved (kiloparsec-scale) CO in green valley galaxies, in Lin et al. (2017) we conducted a pilot ALMA study of three MaNGA-selected galaxies. It was found that the molecular gas fraction and SFE respond differently between bulge and disk regions as galaxies move away from the main sequence: the molecular gas fraction shows a stronger decline with respect to sSFR in bulges than in disks whereas SFE is reduced in both the bulge and disk regions (Lin et al. 2017), consistent with inside-out quenching.

In this paper, we introduce the ALMA-MaNGA QUEnching and STr formation survey (ALMaQUEST), which expands the pilot sample of Lin et al. (2017) by more than an order of magnitude, covering not only MS galaxies, but also starburst and green valley galaxies, all selected from the MaNGA survey. ALMaQUEST was designed to provide an extensive picture of the relationship between stellar populations, SFR, and gas at kiloparsec scales by taking advantage of IFS data from MaNGA and resolved $^{13}\text{CO}(1-0)$ observations from ALMA. Some of the main scientific questions that we aim to address with the ALMaQUEST survey include: (1) how are the properties of a galaxy’s gas content linked to the resolved SFMS? (2) What are the primary physical mechanisms responsible for quenching? (3) Are starbursting galaxies driven by elevated $f_{\text{H}_2}$ or enhanced SFE?

This work is a presentation of the ALMaQUEST data that can be used as a companion to the various science papers. In...
Section 2, we describe the survey design, sample selections, and the data products used in this work. Section 3 characterizes both the global and local molecular gas properties of the sample. Some example science cases enabled by this sample are described in Section 4. A summary of this work is given in Section 5.

Throughout this paper, we adopt the following cosmology: $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. We use a Salpeter initial mass function (IMF).

2. Sample and Observations

2.1. Sample Selection

The ALMaQUEST survey consists of ALMA 12CO(1–0) observations of galaxies selected from the MaNGA survey (Bundy et al. 2015; Yan et al. 2016a). ALMaQUEST compiles data sets from four individual ALMA programs–2015.1.01225.S, 2017.1.01093.S, 2018.1.00558.S (PI: Lin), and 2018.1.00541.S (PI: Ellison). It contains 46 unique galaxies with a wide range of sSFR, spanning from the green valley (hereafter GV), main sequence (hereafter MS), and up to the starburst (hereafter SB) regimes. While the majority of the targets are selected according to their global SFR, the 12 SB galaxies are required to lie on or above the MS and show elevated SFR relative to the control sample within 0.5 $R_e$ by at least 50% (see Ellison et al. 2020b for details). All of these observations adopt identical observing setups and reduction procedures. The locations of the 46 galaxies and all the MaNGA Data Release 15 (DR15) galaxies in the global SFR and $M_*$ plane are shown in Figure 1. The global measurements of SFR and $M_*$ are taken from the PIPE3D (Sanchez et al. 2016a, 2016b) value-added catalog (Sanchez et al. 2018), which sums the MaNGA spaxel measurements across the data cubes. Some basic quantities of the 46 ALMaQUEST galaxies are given in Table 1. Key information and characteristics of the ALMaQUEST survey can be found in the ALMaQUEST webpage: http://arc.phys.uvic.ca/~almaquest/.

![Figure 1. Distribution of the 46 ALMaQUEST galaxies (symbols) and all MaNGA DR15 galaxies (gray contours) in the global SFR and $M_*$ plane. SFR and $M_*$ are taken from the PIPE3D DR15 output. The purple stars and blue circles represent the starburst (Ellison et al. 2020b) and the remaining ALMaQUEST targets, respectively.](image-url)
to a roughly flat distribution in log $M_*$ (Wake et al. 2017). MaNGA uses the BOSS spectrographs (Smee et al. 2013) and couples them with hexagonal fiber bundles of different sizes (Drory et al. 2015). Each spectrum covers a wavelength range of 3500–10000 Å with a spectral resolution $\sim 60$ km s$^{-1}$. After dithering, MaNGA data have an effective angular resolution (FWHM) of 2″5 (Law et al. 2015), corresponding to a physical scale of 0.5–6.5 kpc. Data cubes are gridded with 0″5 spaxels. The methods used for sky subtraction and spectrophotometric calibration are described in Law et al. (2016) and Yan et al. (2016b), respectively.

The MaNGA data used in this work are based on the SDSS Data Release 15 (DR15) version processed by the MaNGA reduction pipeline (Law et al. 2016). Measurements of the $\Sigma_e$ and emission-line fluxes are taken from the public PIPE3D data products (Sánchez et al. 2016a, 2018). The stellar mass is obtained based on the best-fit stellar population model that describes the stellar continuum of a given spectrum. The best-fit stellar continuum is then subtracted from the reduced spectrum in order to obtain the emission-line measurements. All of the emission lines were extinction corrected using the Balmer decrement computed at each spaxel and a Milky Way extinction curve with $R_V = 3.1$ (Cardelli et al. 1989). The SFR is estimated based on this extinction-corrected H$\alpha$ flux following the conversion given by Kennicutt (1998) with a Salpeter IMF. $\Sigma_e$ and $\Sigma_{SFR}$ are computed using the stellar mass and SFR derived for each spaxel, normalized to the physical area of one spaxel with an inclination correction derived using the axis ratio from the MaNGA spaxel into regions where the dominant ionizing source is star formation, Li(N)ER, or Seyfert using the BPT diagnostic based on the [O$\text{III}$]/H$\beta$ versus [S$\text{II}$]/H$\alpha$ line ratios (Kewley et al. 2001, 2006). We require a signal-to-noise ratio (S/N) > 3 for the H$\alpha$ and H$\beta$ lines and S/N > 2 for the [O$\text{III}$] and [S$\text{II}$] lines when performing this classification.

2.3. ALMA Observations

Molecular gas observations in $^{12}$CO(1–0) (rest-frame 115.271204 GHz) were carried out with ALMA during Cycles 3, 5, and 6 using the Band 3 receiver. The observations were taken in the C43-2 configuration (synthesized beam FWHM $\sim 2″5$), thus matching the MaNGA resolution. We used a single pointing with a field of view (FOV) of $\sim$50′. The largest structure that we expect to be sensitive to is about 23′ ($\sim$14 kpc). Our spectral setup includes one high-resolution spectral window ($\sim$10 km s$^{-1}$) targeting $^{12}$CO(1–0) and one to three low-resolution spectral window (s) ($\sim$90 km s$^{-1}$) around the target line aimed at detecting/studying the continuum. On-target integration time varies from 0.2 to 2.5 hr and is set to have an S/N (CO) greater than 3 for more than 50% of spaxels with S/N (H$\alpha$) > 3. This setup was empirically shown in our pilot program (Lin et al. 2017) to be a good compromise between the required integration time and the number of spaxels sufficient for carrying out statistically meaningful analyses. The actual sensitivity achieved for individual sources is given in Table 1. The data were calibrated using the ALMA data reduction software CASA version 4.5 or 5.4 (Common Astronomy Software Applications; McMullin et al. 2007) and the standard ALMA pipeline.25 The systematic flux uncertainty associated with the calibration is typically 5%–10% in Band 3. Continuum is subtracted from the data in the visibility domain. Out of 46 ALMA QUEST objects, 4 (PLATEIFUs: 8084-3702, 8155-6101, 8615-3703, 8655-3701) are detected in the continuum.

The task CLEAN was employed to clean the continuum-subtracted data down to 1$\sigma$ and produce spectral line data cubes using Briggs weighting with a robust parameter of 0.5. The resultant native effective beam size for each target ranges from 1″6 to 2″8. Twenty-eight out of 46 galaxies have a native effective beam size comparable to the point-spread function (PSF) of MaNGA ($\sim 2″5 \pm 10%$), 14 galaxies have beam size $\leq 2″3$, and 4 have beam sizes $\sim 2″8$. In order to facilitate the comparison between ALMA and MaNGA, we re-imaged the data and adopted a user-specified pixel size (0″5) and restoring beam size ($2″5 \times 2″5$) to match the image grid and the spatial resolution of the MaNGA images. 

The final cubes have channel widths of 11 km s$^{-1}$ and rms noise ($\sigma_{\text{rms}}$) of $\sim$0.2–2 mJy beam$^{-1}$. The difference in $\sigma_{\text{rms}}$ between the data cube with the original beam size and our user-specified beam size is as small as <5% because the original beam size and the user-specified beam size are not significantly different.

In Figure 2, we show the 46 continuum-subtracted ALMA spectra centered on the position of the CO (1–0) line using the systematic velocity derived from the optical MaNGA redshift, integrated over the region enclosed by 1.5 effective radii ($R_e$). The zeroth to second moment maps (zeroth: integrated intensity, first: intensity-weighted velocity field, and second: intensity-weighted velocity dispersion) were constructed using the task IMMOMENTS in CASA. The integrated intensity maps were created by integrating emission from a velocity range set by hand to match the observed line profile shown in Figure 2 without any clipping in signal. Data in this velocity range were also used to generate velocity field and dispersion maps, with a 4$\sigma$ clipping applied to avoid noise contamination.

2.4. GBT HI Observations

H I-MaNGA is an HI follow-up campaign for the MaNGA survey. Complete details can be found in Masters et al. (2019), which we briefly summarize here.

H I-MaNGA uses the Green Bank Telescope to observe MaNGA galaxies at $z < 0.05$ lacking overlap with the ALFALFA survey (Haynes et al. 2018). The upper redshift limit is applied due to the declining sensitivity beyond this redshift. Observations are conducted in position-switching mode using the L-band receiver and VEGAS backend for a total (ON + OFF) time of 30 minutes per target. These integration times yield typical rms noise levels of 1.5–2 mJy after boxcar and hanning smoothing to a spectral resolution of $\sim$10 km s$^{-1}$.

H I-MaNGA data are reduced (including RFI flagging, smoothing, and baseline removal) usingGBTIDL. The spectra are visually inspected for the presence of a HI emission line, and in the case of a detection, the flux, line width, and central velocity of the spectral line are measured. For nondetections, a 3$\sigma$ upper limit is estimated assuming a line width of 25 7977-12705, 7977-3704, and 7977-9101 were calibrated with CASA version 4.5 because they were observed in an earlier cycle.
Fluxes and upper limits are converted to \( M_{\text{HI}} \) using \( M_{\text{HI}} = 2.36 \times 10^5 \times (D/\text{Mpc})^2 \times S_{21} \), where \( S_{21} \) is the flux of 21 cm emission line in units of Jy km s\(^{-1}\). Among the 46 ALMaQUEST galaxies, 26 and 7 galaxies are included in the \( \text{HI}-\text{MaNGA} \) and ALFALFA samples, respectively. In this study, we use the \( \text{HI} \) data from both the second...
data release of H\textsuperscript{}i-MaNGA (D. Stark et al. 2020, in preparation) and the ALFALFA catalog (Haynes et al. 2018).

2.5. Global Measurements

In Tables 2–3, we provide several key measurements for the 46 ALMAQUEST galaxies, including the area enclosed within 1.5 $R_e$, stellar mass, SFR, CO flux, $H_2$ mass, sSFR, SFE, and $f_{H_2}$. These integrated quantities are estimated in two ways: (1) by summing up the measured values over the area enclosed by 1.5 $R_e$ and (2) by summing over the areas within the MaNGA bundles. These values are given in Tables 2 and 3, respectively. The choice of 1.5 $R_e$ is driven by the bundle coverage of MaNGA observations as two-thirds of the MaNGA sample is required to be covered by the MaNGA IFU out to 1.5 $R_e$ and one-third of the sample is covered out to 2.5 $R_e$ (Wake et al. 2017).

The $H_2$ mass is computed from the CO flux by adopting a constant conversion factor ($\alpha_{CO}$) of 4.35 $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$ (e.g., Bolatto et al. 2013). We will discuss the effect of...
adopting a metallicity-dependent conversion factor in later sections (Sections 3.1 and 3.3). For the SFR measurement, only spaxels classified as star-forming using the [S\textsc{ii}] BPT diagnostic (Kewley et al. 2001, 2006) are included in this study.

3. Results

Having introduced the characteristics of the ALMaQUEST survey and the associated data products, in this section we present the molecular gas contents of ALMaQUEST galaxies and their relationships with the stellar populations, both globally and locally.

3.1. The Integrated (Global) Scaling Relations: SFR, \( M_\text{st} \), and \( M_\text{H}_2 \)

It has been pointed out that the position of galaxies in the global SFR--\( M_\text{H}_2 \) plane is driven by the combination of variations in both \( f_\text{H}_2 \) and SFE (e.g., Tacconi et al. 2013;
Sargent et al. 2014; Saintonge et al. 2016, 2017). In this subsection, we present the relations between the integrated quantities, i.e., the total SFR, total stellar mass, and the total H$_2$ mass, for the ALMaQUEST sample. Particularly, we investigate whether the variation in sSFR is primarily driven by the change in SFE or $f_{H_2}$. In Figure 3, we present the correlations among the global SFR, $M_*$, and $M_{H_2}$, measured within the areas enclosed by 1.5 $R_e$ as given in Table 2 (hereafter referred to as the aperture-matched measurements), although we note that the trends shown in Figure 3 remain unchanged if the MaNGA bundle-integrated properties (Table 3) are used. In all three panels, the typical uncertainties in each measurement are shown in the upper-left corners. For SFR and $M_*$, the uncertainties represent the typical errors in the SFR and $M_*$ measurements, whereas the uncertainty in $M_{H_2}$ takes into account both the measurement error and the uncertainty in the CO-to-$M_{H_2}$ conversion factor, with the latter being the dominant factor (see the end of this section).

The top panel of Figure 3 shows the aperture-matched SFR versus $M_*$ (within 1.5 $R_e$) for the ALMaQUEST sample (blue symbols). We also overplot the distributions of the xCOLD GASS sample (Saintonge et al. 2017) shown as the gray symbols. An offset of 0.26 dex has been added to the xCOLD GASS SFR and $M_*$ measurements to account for the conversion from the Chabrier to the Salpeter IMF. For xCOLD GASS, only galaxies detected in CO are shown here for clarity. The top panel of Figure 3 is analogous to the SFR versus $M_*$ shown in Figure 1 but differs in the sense that the measurements in the latter are output by PIPE3D, which integrates values over the entire MaNGA bundle data cubes and uses all spaxels regardless their BPT classifications, whereas here we only consider star-forming spaxels within 1.5 $R_e$. As a result, the SFR distribution is generally lower in Figure 3 compared to that in Figure 1. Some galaxies with very few star-forming spaxels even have substantially lower SFR compared to the PIPE3D output. It can be seen that while most of the ALMaQUEST galaxies remain in the MS and GV regimes, there are, however, a few (~5) galaxies falling into the quiescent population.

The middle panel of Figure 3 displays the global SK relation for the ALMaQUEST sample, color-coded by the sSFR. The blue line represents a gas depletion time (1/SFE) of 1 Gyr to guide the eye. It can be seen that galaxies with higher (lower) sSFR tend to populate the upper (lower) end of the SFR–$M_{H_2}$ relation, suggesting a strong role of SFE in determining the sSFR of galaxies. This is in good qualitative agreement with previous studies on the global molecular gas content, which found a strong relationship between SFE and sSFR (e.g., Huang & Kauffmann 2014; Bolatto et al. 2017; Saintonge et al. 2017).

In the bottom panel of Figure 3, we show $M_{H_2}$ as a function of $M_*$, which is the global version of the molecular gas main sequence (MGMS; Wong et al. 2013; Lin et al. 2019b). It was previously found that these two quantities for typical star-forming galaxies are almost linearly correlated with each other (e.g., Cicone et al. 2017). As our sample consists of both galaxies on and below the SFMS, we are able to explore how galaxies with different sSFR populate in this diagram. It can be seen that at a fixed sSFR, there appears to be a large spread in the molecular gas-to-stellar mass ratio, i.e., $f_{H_2}$, and vice versa. The variation in sSFR with respect to $f_{H_2}$ is hence less obvious compared to that with respect to SFE. We also notice that while the galaxies with sSFR $< 10^{-11}$ yr$^{-1}$ span a wide range in terms of the molecular gas-to-stellar mass ratio, their values extend to the regime below 1%, suggesting a strong depletion of molecular gas within 1.5$R_e$ in some of the galaxies with low sSFR.

To better quantify the relative contributions between SFE and $f_{H_2}$ to the sSFR, Figure 4 shows the correlations between SFR with respect to SFE (left panel) and $f_{H_2}$ (right panel). The ALMaQUEST and xCOLD GASS measurements are shown in blue and gray symbols, respectively. It can be seen that both samples follow very similar trends, although the ALMaQUEST survey shows several outliers from the sSFR versus $f_{H_2}$ relation. This is likely due to the fact that the CO-detected sample of the ALMaQUEST extends to lower sSFR regime. The Kendall correlation analysis for the ALMaQUEST sample shows that the correlation between sSFR and SFE ($\tau = 0.67$) is slightly stronger compared to that between SFR and $f_{H_2}$ ($\tau = 0.54$). However, one potential caveat in interpreting this result is that the SFE spans a much wider range (four orders of magnitude) than the $f_{H_2}$ does, owing to the inclusion of a data point with SFE $\sim -12$. To test if the tighter correlation seen between the sSFR and SFE is driven by the dynamical range effect, we repeat the analysis by excluding the lowest SFE data point. We find that the $\tau$ value only slightly decreases from 0.67 to 0.66 in this case and remains greater than the correlation between sSFR and $f_{H_2}$.

In summary, both SFE and $f_{H_2}$ contribute to the variation in sSFR of galaxies, although SFE is found to play a slightly stronger role in governing the sSFR of galaxies. A similar trend has also been seen in previous studies, which found a comparable contribution of $f_{H_2}$ and SFE in the regulation (e.g., Saintonge et al. 2017; Piotrowska et al. 2020).

As described in Section 2.5, the global SFR here are estimated using the star-forming spaxels classified with the [S II] BPT diagnostic (Kewley et al. 2001, 2006). To test if our results are stable against different choices of area types included in the SFR calculation, in the Appendix, we also show the results using all spaxels or an alternative BPT classification scheme based on the [N II] diagnostic (Kauffmann et al. 2003). The former has a caveat that the total SFR can be overestimated because the non-star-forming spaxels where the H$_2$ emissions powered by non-star-formation mechanisms are also included. In both cases, we also see positive correlations between sSFR and SFE and between SFR and $f_{H_2}$. While the dependence of sSFR on SFE or $f_{H_2}$ are comparable in the case of all spaxels considered, the correlation with respect to SFE is found to be slightly stronger than with respect to $f_{H_2}$ in the case where only [N II] BPT-classified star-forming spaxels are included, in good agreement with the result based on the [S II] BPT method.

We note that our results described above are drawn based on a constant value of $\alpha_{CO}$. To examine the potential effect of this assumption, we also consider two types of varying $\alpha_{CO}$, one taken from Sun et al. (2020), which takes into account the metallicity dependence alone, and the other from Narayanan et al. (2012), which considers the dependence on both the CO line intensity and metallicity. In the first method, we adopt Equation (4) of Sun et al. (2020):

$$\alpha_{CO} = 4.35(Z/Z_\odot)^{-1.6} M_\odot pc^{-2}(K km s^{-1})^{-1},$$

(1)

where $Z$ is the (linear) gas-phase abundance and $Z_\odot$ is the solar value. The gas-phase metallicity in log can be calculated

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$^{26}$ We note that the xCOLD GASS measurements are not made strictly within 1.5$R_e$ and thus the data are not entirely comparable.
through the O3N2 calibrator (Pettini & Pagel 2004):

\[
12 + \log (O/H) = 8.73 - 0.32 \times O3N2.
\]  

In the second method, we utilize Equation (11) of Narayanan et al. (2012):

\[
\alpha_{\text{CO}} = \frac{\min[6.3, 10.7 \times W_{\text{CO}}^{-0.32}]}{(Z/Z_\odot)^{0.65}},
\]

where \(W_{\text{CO}}\) is the CO line intensity in units of K km s\(^{-1}\). The metallicity is calculated for spaxels with S/N > 3 for H\(_2\) and H\(_\beta\) and S/N > 2 for [O III] 5007 and [N II] 6584. For spaxels that do not fulfill the above criteria, we set the metallicity to be the solar value. Although this approach may not be ideal, it offers an approximate view of the level of potential impacts on our derived results. For a given galaxy, we then compute \(\alpha_{\text{CO}}\) based on the median value of the spaxel-based metallicities. With the varying \(\alpha_{\text{CO}}\) applied, we find that over the entire ALMaQUEST sample, the difference in the global H\(_2\) mass relative to the original global H\(_2\) mass based on a constant value can be as large as 0.27 dex with an average value of ~0.05 and ~0.14 dex in method 1 and method 2, respectively. The latter is then combined with the measurement error to calculate the uncertainty of \(M_{\text{H}_2}\), that is shown in Figure 3. We then proceed with the same analysis and find that despite a systematic offset seen in the \(M_{\text{H}_2}\) measurement, the varying \(\alpha_{\text{CO}}\) does not affect any trends in the global results presented in this section.

### 3.2. The Role of H\(_1\) Gas

While star formation is closely related to the molecular gas (Wong & Blitz 2002; Gao & Solomon 2004; Wu et al. 2005; de los Reyes & Kennicutt 2019), the atomic gas, particularly atomic hydrogen, dominates the cold gas mass budget on galactic scales and provides the fuel for future star formation. Although this paper focuses on the influence of molecular gas on star formation, a subset of the ALMaQUEST galaxies have been observed in H\(_1\) previously (see Section 2.4), which allows us to investigate the connection between gas and star formation from the atomic hydrogen point of view (e.g., Boselli et al. 2014; Catinella et al. 2018). For example, one can study the dependence of sSFR on the atomic gas fraction (\(M_{\text{H}_1}/M_\star\)), which represents the availability of cold gas reservoir, as well as on the molecular-to-atomic gas ratio (\(M_{\text{H}_2}/M_{\text{H}_1}\)), which is related to the efficiency of transforming the atomic gas into the molecular phase. Different from the CO observations, the H\(_1\) data were taken with single-dish telescopes and have a beam size that well exceeds the optical diameter of the galaxy. The H\(_1\) mass used here is hence the “total” H\(_1\) mass rather than the aperture-matched quantity, such as the SFR, \(M_\star\), and \(M_{\text{H}_1}\) used in the previous section.

There are 33 ALMaQUEST galaxies that overlap with the H\(_1\)-MaNGA (Masters et al. 2019) and ALFALFA (Haynes et al. 2018) observations, of which 18 are detected in H\(_1\) with S/N > 5. Figure 5 shows their distributions in the SFR versus \(M_\star\) plane (blue: H\(_1\) detected; brown: H\(_1\) undetected) with respect to the rest 13 ALMaQUEST galaxies without H\(_1\) observations (green triangles). Proportionally, there are...
fewer high stellar mass galaxies with $\text{H} \, \text{I}$ observations (blue + brown symbols) compared to the rest of the ALMaQUEST sample (green symbols). Among the $\text{H} \, \text{I}$ sample, galaxies with and without $\text{H} \, \text{I}$ detections are distributed similarly, albeit with small sample sizes.

We compute $M_{\text{HI}}/M_*$ and $M_{\text{H}_2}/M_{\text{HI}}$ for all 33 galaxies covered by the $\text{H} \, \text{I}$ observations and use the upper limits of $M_{\text{HI}}$ in the case of nondetection. According to the $M_{\text{HI}}/M_{\text{H}_2}$ ratios, the 18 $\text{H} \, \text{I}$-detected galaxies are all $\text{H} \, \text{I}$-dominated (with respect to $M_{\text{H}_2}$) systems. In Figure 6, we plot the dependence of sSFR on $M_{\text{HI}}/M_*$ and $M_{\text{H}_2}/M_{\text{HI}}$ in the left and right panels, respectively. We perform the Kendall correlation analysis for two cases, one only for the 18 galaxies with solid $\text{H} \, \text{I}$ detections and the other including the additional 15 galaxies with upper limits. In both cases (with/without upper limits), the dependence on $M_{\text{HI}}/M_*$ and $M_{\text{H}_2}/M_{\text{HI}}$ is weaker, compared to the dependence of sSFR on SFE or $f_{\alpha}$ presented in Figure 4, suggesting that sSFR is more linked to the molecular gas budget than to the atomic gas. Nevertheless, it is worth noting that the dependence of sSFR on $M_{\text{HI}}/M_*$ found in our sample is weaker than the results from earlier studies built upon larger samples (Saintonge et al. 2016; Catinella et al. 2018). Furthermore, in our case without upper limits considered, the correlation is slightly stronger in the sSFR versus $M_{\text{HI}}/M_*$ relation than in the sSFR versus $M_{\text{H}_2}/M_{\text{HI}}$ relation, whereas the trend is reversed when the upper limits are taken into account. This shows that galaxies without $\text{H} \, \text{I}$ detections have a significant impact on the strength of the correlation. Therefore, our results should be taken with caution given that the current ALMaQUEST $\text{H} \, \text{I}$ sample size is still limited.

3.3. Resolved Properties of the ALMaQUEST Sample

As our main science goals of the ALMaQUEST survey rely on small-scale properties of galaxies, we also constructed spatially resolved intensity and velocity maps for individual galaxies using the procedures described in Section 2.3. In Figure 7, we show the SDSS optical image, MaNGA $H\alpha$ intensity, ALMA CO(1−0) integrated intensity, velocity, and velocity dispersion maps for the 46 ALMaQUEST galaxies. In general, it is evident from these maps that the $H\alpha$ flux does not always trace the CO(1−0) emission. Because $H\alpha$ is a good tracer of SFR in regions where the photon ionization is dominated by star formation and CO(1−0) mass can be converted into the $H_2$ mass, the discrepancy in the spatial distributions between $H\alpha$ and CO(1−0) hence indicates a possible variation of the SFE within a galaxy.

To further illustrate this point, we display maps for various physical quantities in Figure 8, including stellar mass surface density $\Sigma_*$, $H_2$ mass surface density ($\Sigma_{H_2}$) using a constant $\alpha_{CO} = 4.35$, extinction-corrected SFR surface density ($\Sigma_{\text{SFR}}$),
$f_{\text{H}_2}$, and SFE. Figure 8 shows that neither $f_{\text{H}_2}$ nor SFE is a constant across a given galaxy, as also been shown in previous studies of nearby galaxies (e.g., Leroy et al. 2008; Huang & Kauffmann 2015; Utomo et al. 2017; Colombo et al. 2018; Dey et al. 2019; Schinnerer et al. 2019). To quantify the variation, we plot the histograms of sSFR, $f_{\text{H}_2}$, and SFE computed on a spaxel-by-spaxel basis for the star-forming spaxels of 46 ALMaQUEST galaxies in Figures 9, 10, and 11, respectively. In the bottom-right panel of each figure (Figures 9–11), we show the combined distributions from all 46 galaxies. When looking at the combined ensemble of spaxels, the distributions of all three quantities (sSFR, $f_{\text{H}_2}$ and SFE) are close to a Gaussian in log space. For the rest of the panels, the blue and green vertical lines show the median value of the histogram and the globally averaged value in a given galaxy, respectively. It can be seen that all of these quantities show a large spread (typically spanning one to two orders of magnitude within a galaxy), meaning that there is a strong variation even within a single galaxy. Some of the variations are found to be associated with the radial position of the galaxies while some are not (H.-A. Pan et al. 2020, in preparation). Figures 9–11 therefore serve as a caveat that using a global value may not properly capture the “intrinsic” gas content of galaxies (also see Sánchez 2020). Therefore, spatially resolved gas observations are critical in order to characterize the properties of gas and their connections to the star formation activity.

To see if the SFE and $f_{\text{H}_2}$ variations are driven by the adoption of a fixed $\alpha_{\text{CO}}$, we repeated the same analyses with a metallicity and/or CO intensity-dependent $\alpha_{\text{CO}}$ as described in Section 3.1. While there is a systematic offset ($<0.14$ dex) in the resulting SFE and $f_{\text{H}_2}$, the overall distributions of the SFE and $f_{\text{H}_2}$ remain very similar even if we adopt a varying $\alpha_{\text{CO}}$. This suggests that the internal variations seen in the SFE and $f_{\text{H}_2}$ are intrinsic and not caused by the choices of $\alpha_{\text{CO}}$. In a set of companion papers, we present in detail how the $f_{\text{H}_2}$ and SFE are distributed spatially and which physical parameters are correlated most strongly with the dispersion of $f_{\text{H}_2}$ and SFE (Ellison et al. 2020a, 2020b; H.-A. Pan et al. 2020, in preparation).

4. ALMaQUEST Key Science Papers

The combination of spatially resolved stellar populations and emission-line measurements from the MaNGA data and the gas properties derived from the ALMA observations enable a variety of kiloparsec-scale investigations. While the primary goal of this paper is to present the main features of the ALMaQUEST survey, here we also highlight some key science applications, which are presented in more detail in a series of ALMaQUEST papers.

4.1. Kiloparsec-scale Scaling Relations

The process of star formation is described by two well-known scaling relations: the so-called SK relation (Schmidt 1959; Kennicutt 1998), which relates the SFR to the underlying gas abundance, and the SFMS (Brinchmann et al. 2004; Daddi et al. 2007; Noeske et al. 2007; Lin et al. 2012; Whitaker et al. 2012; Speagle et al. 2014), a tight correlation between the SFR and the stellar mass. While the SK relation can be easily understood as the stars forming within molecular clouds, the origin of the SFMS has been hotly debated (e.g., Kelson 2014; Tacchella et al. 2016; Hsieh et al. 2017; Matthee & Schaye 2019; Hani et al. 2020; Morselli et al. 2020).

With the MaNGA-based measurements of $\Sigma_{\text{SFR}}$ and $\Sigma_{\text{g}}$ and the ALMA-based $\Sigma_{\text{H}_2}$, we are able to discuss the relationships among the three quantities on kiloparsec scales. In Lin et al. (2019b), we showed that $\Sigma_{\text{SFR}}, \Sigma_{\text{g}},$ and $\Sigma_{\text{H}_2}$ computed for star-forming spaxels of MS galaxies form a linear 3D correlation in log scale. Each pair of these three quantities form a tight correlation, the resolved SFMS (rSFMS; i.e., $\Sigma_{\text{SFR}}$ versus $\Sigma_{\text{g}}$),
the resolved SK relation (rSK; i.e., $\Sigma_{\text{SFR}}$ versus $\Sigma_{\text{HI}}$), and the resolved molecular gas MS (rMGMS; i.e., $\Sigma_{\text{H}_2}$ versus $\Sigma_{\text{SFR}}$). By comparing the strength of the correlations and the magnitude of their scatters, we argue that rSFMS is the least fundamental, but rather a natural consequence of the combination of the rSK and rMGMS relations. This result is later supported by Morselli et al. (2020), who study the same scaling relations for five nearby spiral galaxies at 500 pc scale, and by Ellison et al. (2021) based on a complementary approach applied to the ALMaQUEST sample.

4.2. What Drives the Central Starburst?

Previously, it has been shown that local starbursts are preferentially driven by central SFR enhancement (e.g., Morselli et al. 2017; Ellison et al. 2018; Tacconi et al. 2018).
Figure 8. Physical products of the ALMaQUEST sample. From left to right: stellar mass surface density, H$_2$ mass surface density, SFR surface density, gas fraction, and star formation efficiency. An S/N $> 3$ cut in the CO flux is applied. Only spaxels classified as the star-forming regions using the [S II] BPT criteria (Kewley et al. 2001, 2006) with an S/N $> 3$ cut in the H$\alpha$ and H$\beta$ lines and S/N $> 2$ cut in the [O III] and [S II] lines are shown in the SFR map.

(The complete figure set (8 images) is available.)
However, it remains unclear whether the boost of SFR in central regions is primarily caused by the increased gas fraction or greater SFE. Pinning down the relative importance between these two scenarios provides key constraints on the physical processes responsible for starbursts. Using the 12 starbursting galaxies from ALMaQUEST, we show in Ellison et al. (2020b) that the central starburst is mainly driven by an elevated SFE. Only one-quarter of the sample shows signs of mergers morphologically, indicating that other mechanisms may also produce central starbursts.

### 4.3. What Regulates the SFR in the Star-forming Main Sequence?

Recent IFS studies have shown that the tight correlation between the global SFR and $M_*$ may in fact originate from the rSFMS at kiloparsec scales (e.g., Cano-Díaz et al. 2016; Hsieh et al. 2017; Ellison et al. 2018; Pan et al. 2018; Cano-Díaz et al. 2019). As mentioned in Section 4.1, we further show that the rSFMS is due to a combination of both rSK relation and the rMGMS (Lin et al. 2019b). The rSFMS relation, however, shows a significant scatter of $\sim 0.25$ dex. In Ellison et al. (2020a), we investigate the dependence of the scatter around the rSFMS ($\Delta\Sigma_{\text{SFR}}$) on the variation in $f_{\text{H}_2}$ and SFE to shed light on the physics regulating the scatter of star-forming spaxels around the rSFMS. We found that the change in SFE is the primary cause for $\Delta\Sigma_{\text{SFR}}$ while the variation in $f_{\text{H}_2}$ is a secondary factor (but see also Dey et al. 2019; Morselli et al. 2020).

### 4.4. Gas Properties in Green Valley Galaxies

Our pilot study (Lin et al. 2017) of the CO content of three GV galaxies suggests that the suppression of SFR in these “below MS” galaxies can possibly be attributed to the deficit in the gas fraction in the central regions of galaxies, accompanied with a reduction in both the gas fraction and SFE in the disks. With a sample size tenfold larger, we can more rigorously investigate the link between the star formation suppression and the changes in the gas fraction and SFE (L. Lin et al. 2020, in preparation). Also, we will characterize the radial distributions of gas fraction and SFE in GV galaxies compared with those in MS galaxies (H.-A. Pan et al. 2020, in preparation).
4.5. The Nonuniversality of Resolved Scaling Relations

It is now well established that global relations, such as the SK and SFMS, arise as a result of resolved scale correlations that exist on scales of kiloparsecs or less (Wong & Blitz 2002; Bigiel et al. 2008; Schruba et al. 2011; Leroy et al. 2013; Sánchez et al. 2013; Cano-Díaz et al. 2016; González Delgado et al. 2016; Hsieh et al. 2017). The existence of such tight relations on kiloparsec scales indicates that they may reflect fundamental physical processes that are regulating the distribution of gas and its processing into stars. Testing the variation of these scaling relations and quantifying the global properties on which they depend will therefore provide insight into the universality of the star formation process and its sensitivity to local environmental conditions. Although past works have investigated the variation of either the rSK (e.g., Schruba et al. 2011; Leroy et al. 2013) or the rSFMS (e.g., Abdurro’uf & Akiyama 2017; Pan et al. 2018; Cano-Díaz et al. 2019; Vulcani et al. 2019) relation, the ALMaQUEST sample offers us the opportunity to investigate the variation in all three scaling relations (rSK, rSFMS and rMGMS), as well as study the interplay between them. In Ellison et al. (2021), we demonstrate that all three of the resolved scaling relations exhibit significant variation, although this variation is significantly smaller for the rMGMS than for the rSFMS. In Ellison et al. (2021), we also demonstrate that the variation in these scaling relations correlates with global galaxy properties such as total stellar mass, Sérsic index, and sSFR.

4.6. The Cold Molecular Gas–Metallicity Relation in MaNGA Galaxies

Several works based on SDSS spectroscopy have demonstrated the existence of a three-dimensional relation between metallicity, stellar mass, and SFR (the so-called fundamental metallicity relation or FMR; Lara-López et al. 2010; Mannucci et al. 2010; Salim et al. 2014). Such a relation is naturally predicted by several theoretical models (Davé et al. 2011; Lagos et al. 2016; Torrey et al. 2019; Trayford & Schaye 2019) as a consequence of a more fundamental link between metallicity, stellar mass, and gas content. Models predict that the scatter across the mass–metallicity relation is driven by the
competition between phases dominated by gas accretion and metal dilution and subsequent periods of enrichment and low gas fraction. In accordance with the observed FMR, at fixed stellar mass, galaxies with higher SFR are predicted to have lower metallicities.

Bothwell et al. (2013) and Brown et al. (2018) studied the role of atomic gas using SDSS spectroscopy matched with H I observations from the ALFALFA survey. Both studies agreed that the FMR is stronger when considering the H I gas mass, rather than the SFR as the parameter driving the scatter across the mass–metallicity relation. Bothwell et al. (2016a, 2016b) revise the role of gas on the FMR by considering molecular gas. They find that $M_{H_2}$ is the third parameter for the FMR and is favored over both total (atomic + molecular) gas mass and SFE. These findings provide observational confirmation of the importance of gas content, and in particular star-forming molecular gas, in driving the FMR.

Extensions of global scaling relations involving metallicity to resolve kiloparsec-scale regions have been investigated thanks to large IFS surveys, like CALIFA, SAMI, and MaNGA. A resolved mass–metallicity relation (Sánchez et al. 2013; Barrera-Ballesteros et al. 2016) is found to exist on kiloparsec scales, and the existence of a secondary dependence of $\Sigma_{\text{SFR}}$ is the subject of active research (Barrera-Ballesteros et al. 2016; F. Belfiore et al. 2020, in preparation; also see Section 6.4 of Maiolino & Mannucci 2019 for a recent review). With ALMaQUEST, we are now able to investigate the importance of $\Sigma_{H_1}$ in setting the scatter of the resolved mass–metallicity relation and assess its relative importance with respect to $\Sigma_{\text{SFR}}$.

4.7. The Connection between the Balmer Decrement ($BD = H\alpha/H\beta$) and the CO(1−0) Line Luminosity and Total Molecular Gas Mass

The dust absorption, traced by the reddening and extinction of starlight, has been used to estimate the gas content in the Milky Way (e.g., see Bohlin et al. 1978; Lada et al. 1994; Pineda et al. 2010) and more recently in external galaxies (Brinchmann et al. 2013; Concas & Popesso 2019; Piotrowska et al. 2020). In particular, Concas & Popesso (2019) found an empirical relation between the dust extinction, traced by the Balmer decrement ($BD = H\alpha/H\beta$), and the total molecular gas mass in a sample of 222 local galaxies. By following this approach, we will explore whether the local $BD-M_{\text{gas}}$ relation

![Figure 11. Distributions of SFE calculated on a spaxel-by-spaxel basis for 46 ALMaQUEST galaxies using only star-forming spaxels. The blue and green vertical lines represent the median of the histogram and the globally averaged value (within 1.5$R_e$) of the individual galaxy, respectively. The gray dashed lines represent the constant value of log$_{10}$ SFE (yr$^{-1}$) = −9 as a reference line. The last panel shows the distribution of spaxels from all 46 galaxies.](image)
and its connection with gas metallicity could be applied at local scales (see also Barrera-Ballesteros et al. 2020), testing a new empirical method to trace the cold gas reservoir in galaxies. The ALMaQUEST sample allows us to extend the study of such relation in galaxies that are above, below, and on the SFMS.

5. Summary

We introduce the ALMaQUEST survey, an ALMA program that maps the CO distributions on kiloparsec scales for 46 galaxies selected from the MaNGA IFS survey. Whereas the MaNGA data deliver kiloparsec-scale maps of SFR surface density, stellar mass surface density, and metallicity, the ALMA observations provide spatially matched maps of molecular gas. Combined, the ALMA + MaNGA data set yields a superlative view of star formation in nearby galaxies. The targets of the sample include SB, MS, and GV galaxies, allowing one to study the properties of cold ISM, star formation, stellar population, and ionized gas systematically across various galaxy populations.

When looking at the global (aperture-matched) stellar mass, H$_2$ mass, and SFR, it is found that the locations of galaxies with respect to the SK relation (i.e., the SFE) is closely related to the sSFR (see the middle panel of Figure 3 and the left panel of Figure 4). On the other hand, there exists a large scatter in the H$_2$ mass versus stellar mass relation (and hence $f_{\text{HI}}$) at a given sSFR (see the bottom panel of Figure 3 and the right panel of Figure 4), although galaxies with low sSFR do exhibit significantly lower H$_2$ mass as opposed to those with high sSFR at a given stellar mass (bottom panel of Figure 3). In general, galaxies with different sSFR are segregated more by their star formation efficiency (SFE) than their molecular gas fractions ($f_{\text{HI}}$). This is further supported through a correlation analysis, in which we find that the sSFR has a slightly stronger dependence on SFE than on $f_{\text{HI}}$. On the other hand, we show that there is a weaker dependence of the sSFR on the atomic gas fraction ($M_{\text{HI}}/M_*$) or the molecular-to-atomic gas fraction ($M_{\text{HI}}/M_{\text{H}_2}$) compared to the dependence on SFE and/or $f_{\text{HI}}$. However, a larger and deeper H I sample is required to draw a robust conclusion.

When comparing the CO and H$_2$ distributions within individual galaxies, we find that these two quantities do not always trace each other. We show that in a given galaxy, there is a substantial variation in the sSFR, $f_{\text{HI}}$, and SFE for regions classified as star-forming spaxels (Figures 9–11). Therefore, using a single global measurement may not be able to capture the detailed physics regulating the star formation within a galaxy. In the forthcoming papers, we will investigate in more detail the changes of the sSFR, SFE, and $f_{\text{HI}}$, as well as the correlations among these three parameters, as a function of various global and local galactic properties.

We thank the anonymous referee for helpful comments. This work is supported by the Academia Sinica under Career Development Award CDA-107-M03 and the Ministry of Science & Technology of Taiwan under the grant MOST 107-2119-M-001-024 and 108-2628-M-001-001-MY3. S.F.S. thanks CONACYT CB-285080 and FC-2016-01-1916, and PAPIIT-DGAPA-IN100519 (UNAM) grants for supporting this project. R.M. acknowledges ERC advanced grant 695671 “QUEENCH” and support by the Science and Technology Facilities Council (STFC). L.L. and H.-A.P. thank the U. of Victoria for hosting during the visit to work on this project. L.L. thanks Sophia Y. Dai and Z. Zheng for providing useful suggestions to improve the content of this paper.

The authors would like to thank the staff of the East-Asia and North-America ALMA ARCs for their support and continuous efforts in helping produce high-quality data products. This paper makes use of the following ALMA data: ADS/JAO.ALMA#2015.1.01225.S, ADS/JAO.ALMA#2017.1.01093.S, ADS/JAO.ALMA#2018.1.00541.S, and ADS/JAO.ALMA#2018.1.00558.S. ALMA is a partnership of ESO (representing its member states), NSF (USA), and NINS (Japan), together with NRC (Canada), MOST and ASIAA (Taiwan), and KASI (Republic of Korea), in cooperation with the Republic of Chile. The Joint ALMA Observatory is operated by ESO, AUI/NAOJ, and NAOJ.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS website is www.sdss.org. SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU)/University of Tokyo, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatory of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional/MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University, and Yale University.

Appendix

Tests on the Effect of the Global Quantity Estimates

The main results concerning the global SFR of the ALMaQUEST sample presented in this work are primarily based on the SFR integrated over the areas classified as “star-forming” using the [S II] BPT diagnostic (Kewley et al. 2001, 2006). In this section, we test whether our results, specifically for the relation between sSFR and SFE and between sSFR and $f_{\text{HI}}$, are impacted by the choices of integrated areas or not. We repeat our analyses in two cases: (a) by summing $\Sigma_{\text{SFR}}$ over all spaxels within 1.5 $R_e$ regardless of the BPT types and (b) by summing $\Sigma_{\text{SFR}}$ over only the star-forming spaxels (also within 1.5 $R_e$) classified by the [N II] BPT diagnostic (Kauffmann et al. 2003), to be compared with the results presented in Section 3.1, which is based on the [S II] BPT method. The caveat of case (a) is that the SFR could be overestimated because the H$_\alpha$ emissions might be powered by
mechanisms other than star formation in non-star-forming spaxels.

Figure A1 displays the sSFR versus SFE (left panel) and sSFR versus $f_{\text{H}_2}$ relations (right panel) when all types of spaxels are used. A moderate correlation ($\tau = 0.56$) with high significance ($p < 10^{-7}$) is seen in both panels, suggesting that both SFE and $f_{\text{H}_2}$ contribute to the variation of sSFR. In Figure A2, we plot the same relations by integrating only the [N II] BPT-classified star-forming spaxels. Similar to Figure 4, a stronger correlation strength ($\tau = 0.78$) is found in the sSFR versus SFE relation, with respect to the sSFR versus $f_{\text{H}_2}$ relation ($\tau = 0.49$).

In summary, positive correlations are found in both the sSFR–SFE and sSFR–$f_{\text{H}_2}$ relations in all the three situations we have tested, including the two cases presented here and the one in Section 3.1. The strength of the correlation for the sSFR–SFE relation is found to be more sensitive to the choices of the types of spaxels used for the total SFR calculation, whereas the sSFR–$f_{\text{H}_2}$ relation is more stable. Nevertheless, the main conclusion that the sSFR depends on both SFE and $f_{\text{H}_2}$ holds in all cases.

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