The ALMaQUEST Survey XV: The Dependence of the Molecular-to-Atomic Gas Ratios on Resolved Optical Diagnostics

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Abstract

The atomic-to-molecular gas conversion is a critical step in the baryon cycle of galaxies, which sets the initial conditions for subsequent star formation and influences the multi-phase interstellar medium. We compiled a sample of 94 nearby galaxies with observations of multi-phase gas contents by utilizing public H I, CO, and optical IFU data from the MaNGA survey together with new FAST H I observations. In agreement with previous results, our sample shows that the global molecular-to-atomic gas ratio ($R_{\mathrm{mol}} \equiv \log M_{\mathrm{H_2}}/M_{\mathrm{H\ I}}$) is correlated with the global stellar mass surface density μ_* with a Kendall' s τ coefficient of 0.25 and $p < 10^{-3}$, less tightly but still correlated with stellar mass and NUV− r color, and not related to the specific star formation rate (sSFR). The cold gas distribution and kinematics inferred from the H I and CO global profile asymmetry and shape do not significantly rely on R_{mol}. Thanks to the availability of kpc-scale observations of MaNGA, we decompose galaxies into H II, composite, and AGN-dominated regions by using the BPT diagrams. With increasing R_{mol}, the fraction of H II regions within 1.5 effective radius decreases slightly; the density distribution in the spatially resolved BPT diagram also changes significantly, suggesting changes in metallicity and ionization states. Galaxies with high R_{mol} tend to have high oxygen abundance, both at one effective radius with a Kendall' s τ coefficient of 0.37 ($p < 10^{-3}$) and their central regions. Among all parameters investigated here, the oxygen abundance at one effective radius has the strongest relation with global R_{mol}, but the dependence of gas conversion on gas distribution and galaxy ionization states is weak.

Full Text

Preamble

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The ALMaQUEST Survey XV: The Dependence of the Molecular-to-Atomic Gas Ratios on Resolved Optical Diagnostics

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Abstract: The atomic-to-molecular gas conversion is a critical step in the baryon cycle of galaxies, which sets the initial conditions for subsequent star formation and influences the multi-phase interstellar medium. We compiled a sample of 94 nearby galaxies with observations of multi-phase gas contents by utilizing public H i, CO, and optical IFU data from the MaNGA survey together with new FAST H i observations. In agreement with previous results, our sample shows that the global molecular-to-atomic gas ratio (Rmol log MH2/MH i) is correlated with the global stellar mass surface density μ∗ with a Kendall' s τ

coefficient of 0.25 and $p < 10-3$, less tightly but still correlated with stellar mass and NUV−r color, and not related to the specific star formation rate (sSFR). The cold gas distribution and kinematics inferred from the H i and CO global profile asymmetry and shape do not significantly rely on Rmol. Thanks to the availability of kpc-scale observations of MaNGA, we decompose galaxies into H ii, composite, and AGN-dominated regions by using the BPT diagrams. With increasing Rmol, the fraction of H ii regions within 1.5 effective radius decreases slightly; the density distribution in the spatially resolved BPT diagram also changes significantly, suggesting changes in metallicity and ionization states. Galaxies with high Rmol tend to have high oxygen abundance, both at one effective radius with a Kendall's τ coefficient of 0.37 ($p < 10-3$) and their central regions. Among all parameters investigated here, the oxygen abundance at one effective radius has the strongest relation with global Rmol. The dependence of gas conversion on gas distribution and galaxy ionization states is weak. In contrast, the observed positive relation between oxygen abundance (µ∗) and Rmol indicates that the gas conversion is efficient in regions of high metallicity (density).

Keywords: Galaxies, baryon cycle, radio lines, H i 21 cm, atomic-to-molecular gas conversion

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1 Introduction

Gas is the fundamental raw material for star formation in galaxies and plays a crucial role in galaxy formation and evolution (e.g., [56, 57, 66, 69, 94]). The cold gas predominantly consists of neutral atomic hydrogen (H i) and molecular hydrogen (H2). Within the baryon cycle, atomic gas collapses to form dense molecular gas, which directly fuels star formation in galaxies. While the tight relations between star formation and molecular gas—both in terms of surface density (the Schmidt-Kennicutt law, [38, 56, 66, 70, 83, 104]) and global mass (e.g., [43, 97])—have been extensively studied, insufficient research has been conducted to adequately investigate the connection between the atomic-to-molecular gas conversion process (H i-H2) and factors such as metallicity or ionization states.

The H i-H2 conversion primarily depends on the mid-plane pressure [11, 12, 41], radiation field [41], and metallicity [62]. The dominant factor is the mid-plane pressure, which is proportional to the surface density of both gas and stars after assuming a thin disk with balanced gravitational forces [11]. The radiation field influences molecular gas dissociation, while metals and dust act as catalysts in the H i-H2 conversion. Leroy et al. [66] found that the surface density ratio of H2 to H i for spiral and dwarf galaxies increases with local stellar mass surface density and mid-plane pressure, while decreasing with galactic radius. Theoretically [62, 63] and observationally [9], molecular hydrogen can stably exist against dissociation through self-shielding when the H i surface density exceeds 9 M pc−2 at solar metallicity. Both semi-analytic models [62, 87] and hydrodynamical simulations [64] support these results.

The global molecular-to-atomic gas ratio (Rmol log MH2/MH i) describes the efficiency of gas conversion and constrains the physical properties of the interstellar medium (ISM, [15]). Rmol shows a weakly increasing trend with global stellar mass M∗, stellar mass surface density µ∗, and NUV−r color for galaxies with log (M∗/M) $\geq$ 10.0 [95]. These relations become stronger when extending to the low-mass end and with larger samples [15, 16, 23]. Stark et al. [110] found a positive relation between Rmol and enhancements of central star formation in spirals, though this enhancement is not applicable to massive early-type galaxies. When µ∗ 10ˆ8.7 M pc−2, the cold gas reservoir is depleted or expelled; otherwise, Rmol is positively correlated with µ∗ [94]. Additionally, the spatial distribution of H i and H2 may play a crucial role in their conversion.

Optical diagnostics that infer galaxy ionization states and metallicity may be important for understanding the physics of gas conversion. Ionization states can be inferred through optical diagnostics such as BPT diagrams [6], which characterize ionization using strong optical emission lines including Hα \$ 6564, *H* \$ \$ \$4862, [S II] λ\$ \$6716, 6731, [N II] λ\$ \$6548, 6583, and [O III] λ\$ 4959, 5007.*Forinstance, lineemissionfromgalaxiesorregionscanbecategorizedintoHii, composite, andAG* *dominatedemissionsbasedontheirpositionsinthe*[*OIII*]/*H* \$ versus [N II]/Hα ([N II] BPT) plane following Kewley et al. [58] and Kauffmann et al. [55], or using the P1P2 BPT diagram following Ji & Yan [52]. The [S II]-based BPT ([O III]/Hβ versus [S II]/Hα) classifies galaxies or regions into H ii, Low-Ionization Nuclear Emission Line Regions (LINERs), and Seyfert [59]. In some cases, shocks can appear even in star-forming regions of BPT diagrams [2]. Typically, H ii emission-dominated galaxies or regions exhibit emission primarily from massive young stars, while AGN-dominant regions are driven by AGN photoionization or shocks, and composite components result from a mixture of star formation, shock excitation, and/or AGN activity [60].

Theoretical models consider metallicity as a controlling parameter in H2 formation [41, 62, 87], which is supported by observations in nearby galaxies. Rmol and gas metallicity are tightly correlated [15] because metallicity serves as an indicator of dust content, which facilitates H i-H2 conversion as a catalyst [62]. At a given stellar mass, a high star formation rate (SFR) is associated with low metallicity [28, 39] but high fractions of both atomic and molecular gas [96]. Thus, the complex effects of gas content and metallicity on atomic-to-molecular gas conversion are non-trivial. The influence of metallicity distribution on the H i-H2 transition remains unknown, making further studies critical to reveal the connection between gas conversion and metallicity.

Detailed investigation of this field requires high-resolution optical integral field unit (IFU) data and cold gas data with large sample sizes. The Mapping Nearby Galaxies at APO (MaNGA, [1, 19]) survey and nearby cold gas surveys provide spatially resolved metallicity and gas content information for nearby galaxies. The MaNGA project utilizes IFU spectroscopy to map the detailed composition and kinematic structures of 10,010 nearby galaxies. H i follow-up (H i-MaNGA: [76, 111]) collects 3,669 unique H i observations from GBT and Arecibo. Moreover, the ALMA MaNGA Quenching & Star-Formation Survey (ALMaQUEST) utilizes high-resolution spatially resolved optical spectroscopy from MaNGA and 12CO (J = 1-0) follow-up observations with ALMA in the C43-2 configuration to study stellar and gas properties on the same physical scales [70, 71]. The IFU and CO observations of MaNGA and ALMA have a beam size of 2.5 (1 1 kpc) with 0.02 z 0.05 and a field of view of 50 . For galaxies with MaNGA IFU, CO, and H i data, we can investigate the relation between gas conversion and optical diagnostics. However, the ALMaQUEST survey lacks complete and homogeneous H i observations.

In this paper, we present new observations of H i global spectra for 37 galaxies in the ALMaQUEST survey using the Five-hundred-meter Aperture Spherical Telescope (FAST, [81], [68]). To build a large sample for statistical analysis, we match the MaNGA survey with ALMaQUEST, the CO follow-up of the GALEX Arecibo SDSS survey (xCOLD GASS: [95, 97]), the APEX Low-redshift Legacy Survey for MOlecular Gas (ALLSMOG: [16, 25]), and "JCMT dust and gas In Nearby Galaxies Legacy Exploration" (JINGLE: [32, 98]) surveys to investigate the dependence of Rmol on gas distribution and metallicity. In Section 2, we introduce the sample properties and cross-match results. The H i data processing and spectral measurements are presented in Section 3. We investigate the dependence of molecular-to-atomic gas ratio in Section 4. The main results are summarized in Section 5. This work adopts the following parameters for a ΛCDM cosmology: $\Omega m = 0.315$, $\Omega\Lambda = 0.685$, and $H0 = 67.4$ km s−1 Mpc−1 [86]. We adopt a Chabrier initial mass function (IMF, [24]) to uniformly derive SFRs and stellar masses.

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2 The Sample

We compile a sample of galaxies with atomic and molecular gas measurements from H i and CO surveys to construct a comprehensive sample for investigating the atomic-to-molecular gas conversion (H i-H2). The molecular gas in nearby galaxies has been extensively studied through various large observational programs such as the ALMaQUEST survey [70, 71], xCOLD GASS [95, 97], ALLSMOG [16, 25], and the JINGLE survey [32, 98]. The xCOLD GASS sample covers a stellar mass range of $10^{9.0-10}${11}.5 M with a redshift of 0.01–0.05 and includes star-forming, green valley, and quenched galaxies. The H i surveys primarily consist of xGASS [22, 23] and H i-MaNGA [76, 111], which combines new GBT observations with existing data from the Arecibo Legacy Fast ALFA (ALFALFA) survey [48, 49]. We collect the H i and CO data of our sample galaxies from the datasets listed above.

2.1 The ALMaQUEST and Supplementary Samples

We obtained FAST H i spectral line observations for 37 galaxies selected from 51 galaxies in the ALMaQUEST survey [71] and supplemented with 2 galaxies (MaNGA 8439-6102 and MaNGA 8250-6104) from Gao et al. [44]. These 51 galaxies include 46 published systems in the original ALMaQUEST Survey and 5 additional galaxies from the extended ALMaQUEST merger sample [115], the latter of which are either not covered by previous H i observations or have a detection with signal-to-noise ratio (S/N) less than 3. The two galaxies included in Gao et al. exhibit a gas-rich nature in their molecular phase (CO 2-1) and are actively star-forming. Their stellar masses and redshifts fall within similar ranges ($10.0 < \log M /M < 11.5$, z 0.04) compared to the ALMaQUEST sample. We also include these two systems in our analysis.

These 37 galaxies were not included in H i-MaNGA data release 1 [76] but fall within the declination range of $-14°$ to $+66°$. This selected sample (referred to as the ALMaQUEST sample in this paper) consists of galaxies with a stellar mass range of 10.0 log (M$*$/M) 11.5 and a redshift range of 0.02 z 0.13. This sample primarily consists of galaxies in the green valley, star-forming main sequence, and star-burst categories [40, 70–72]. We adopt values of stellar masses and SFRs using the Chabrier IMF instead of the Salpeter IMF used in previous work by utilizing the conversion of Madau & Dickinson [73].

To investigate the dependence of H i-H2 conversion, we also compile a set of galaxies with similar properties to the ALMaQUEST sample. In addition to the ALMaQUEST survey, galaxies with both H i and CO observations are mainly from the xCOLD GASS, ALLSMOG, and JINGLE surveys. Sample galaxies selected from these surveys have relatively uniform sample selection criteria, consistent global H i and CO profiles, and a large sample size that covers a stellar mass range of 9.0 log (M$*$/M) $\leq$ 11.5. Among these surveys, the xCOLD GASS survey provides both accessible H i and CO spectra.

We adopt a constant CO(1-0) to H2 conversion factor: αCO = 4.35 M (K km s$-$1 pc^2)$-$1 following Bolatto et al. [14] and references therein. Our sample has an oxygen abundance 12+log (O/H) 8.4 (see details in Section 4.4), thus the value of αCO does not depend on galaxy metallicity [14, 103]. For galaxies in the ALLSMOG and JINGLE surveys that only have CO(2-1) observations, we convert the intrinsic brightness temperature luminosity LCO(2$-$1) to LCO(1$-$0) by assuming a ratio of r21 = LCO(2$-$1)/LCO(1$-$0) = 0.8 as suggested by Cicone et al. [25] for nearby normal star-forming galaxies, and recent spatially resolved studies from Leroy et al. [67] also give similar but slightly lower values. We investigate the dependence of cold gas conversion on galaxy ionization states

(Section 4.3) and metallicity (Section 4.4).

2.2 Sample Definitions

In the following discussions, we refer to galaxies with both published H i and CO spectra as the "HICO-Spec" sample. This sample comprises galaxies with H i and CO observations (with at least one detection in H i or CO) from the ALMaQUEST and xCOLD GASS samples. After removing 2 duplicate galaxies, the HICO-Spec sample contains 412 galaxies with both H i and CO observations, of which 310 galaxies have detections in both H i and CO. In Section 4.2, we investigate the dependence of H i-H2 conversion on integrated profile shape and asymmetry using this sample.

[Figure 1: see original paper]

On the other hand, we refer to the "HICO-MaNGA" sample as the cross-match result of the cold gas surveys (ALMaQUEST, xCOLD GASS, ALLSMOG, and JINGLE) and the MaNGA survey [99, 100]. During the cross-matching process, we utilize TOPCAT [114] and require a maximum projected optical position separation of 3 and a velocity separation of 500 km s−1. We compile the sources in the cold gas catalogs and remove 4 duplicated galaxies, resulting in a total of 390 galaxies with both H i and CO detections. We cross-match these 390 galaxies with the MaNGA catalog of 10,010 unique galaxies by their positions and redshifts. This step yields 32 galaxies from xCOLD GASS, 7 galaxies from ALLSMOG, 38 galaxies from ALMaQUEST, and 17 galaxies from the JINGLE survey. Thus, the HICO-MaNGA sample consists of 94 galaxies with both H i and CO detection as well as optical IFU data from MaNGA. Figure 1 shows the sample distribution in the space of log SFR vs. log M∗ for the HICO-Spec and HICO-MaNGA samples. The sample size of HICO-Spec is slightly larger than that in Saintonge et al. [95]. The galaxy number of the HICO-MaNGA sample is 10% of the xCOLD GASS survey [23], but all galaxies in the HICO-MaNGA sample have MaNGA IFU observations. Meanwhile, our sample covers a similar dynamical range in stellar mass and SFR compared to the star-forming galaxies in the MaNGA survey.

2.3 FAST H i Observations

In addition to existing H i observations from GBT and Arecibo, we obtained FAST H i spectral line observations for the ALMaQUEST and Supplementary Samples. The observation is designed to reach a detection threshold of log MH i/M∗ 1% following the strategy of GASS and xGASS [22, 23]. In 2020, we conducted the initial H i follow-up observation using FAST (PI: Zheng, project code: PT2020_{0102}). We performed additional observations on two galaxies (MaNGA 7977-12705, MaNGA 8077-6104) that were previously detected by H i-MaNGA (GBT) to verify the calibration procedure. It should be noted that a portion of the data was affected by strong radio frequency interference (RFI), primarily caused by the refrigerating dewar in the compressor. However, this issue has been partially resolved in 2021 [128]. Taking into account the data obtained in 2020, we adjusted our observation strategy and proposed a new FAST observation in 2022 led by PI Zheng (project code: PT2022_{0091}). The observations were conducted using the entire wide band of 500 MHz, employing the on-off mode and the 19-beam receiver at the L band (1.05–1.45 GHz). Each beam has a size of 2.9 and a sampling time of approximately 0.1 seconds. During each second, the 10 K (high CAL) noise diode is on for the first 0.1 seconds and off in the remaining 0.9 seconds. The spectrum encompasses 65,536 channels and has a spectral resolution of 7.6 kHz (1.6 km s—1) for dual-polarization observations. The separation between the center of beam M01 and one of the outer beams M14 is 11.6 .

In each cycle of observation, the central beam M01 points on the source and the outer beam M14 points away from the source in the "source on" mode. Conversely, beam M14 points on the source and beam M01 points away from the source in the "source off" mode. The switching time between source on and source off modes is 30 seconds. Besides the switching or overhead time, the observation beam keeps pointing on the source, effectively doubling the integration time compared to observations without simultaneous on-off pointing. Previous studies [134, 137] have also employed the use of other beams as off-target points to save observation time.

We process the FAST data to obtain the final global spectra. To mitigate the effects of RFI, we remove values with a deviation from the median value larger than 1.5σ per channel in each observation cycle. This pre-processing step was necessary for the FAST data from 2020. We then interpolate the remaining FAST raw data using the values of the nearest neighbors to supplement data points. We calibrate the flux intensity using data from the on-off noise diode and apply aperture efficiency correction taking the beam, frequency, and position into consideration [53, 54]. Then the data from the first two polarizations are averaged to derive the preliminary spectrum.

To remove the standing wave, we fit a sine function after masking the RFI and the velocity range of the potential emission line signal. If the removal of the standing wave did not decrease the noise level of a specific spectrum, we did not adopt the standing wave subtraction. Subsequently, a polynomial of order 1–3 was used to fit the spectrum and flatten the baseline. The degree of polynomial order is determined by selecting the degree with the minimum Bayesian Information Criterion (BIC, [107]), which balances the goodness of the fit (reduced chi-square) with the number of parameters in the polynomial fitting. We convert the frequency to heliocentric velocity using the optical velocity convention and performing the Doppler correction. For each source, we stack the spectrum of each cycle (at least two cycles for each galaxy using M01 on and M14 on) by weighting the spectrum according to its noise level [18, 42].

We observed 37 galaxies with a total observation time of 45 hours, which includes the source on, source off, and overhead time. The integration time for each galaxy ranges from 2 minutes to 1 hour. Table 1 provides the basic information and observation details for these galaxies. For an RFI-masked and baseline-subtracted profile, we search for the emission line signal by rebinning the spectra to a channel width of 20 km s−1. The noise level of the spectrum (σspec) is the standard deviation obtained from the best-fit half-Gaussian fitting to the negative values of all flux intensities within a range of $±500*kms*−1*aroundtheopticalcentralvelocity.Iftherebinnedspectrumcontainsatleastthreechannelswithfluxintensitiesg* it is considered a detection; otherwise, it is classified as a non-detection. The FAST H i spectral quality is listed in Column (9) of Table 1.

The new FAST observation yields 27 detections, 1 absorption signal, and 2 non-detections, and all these spectra are public. Among the 53 galaxies in the ALMaQUEST sample, we have acquired 42 emission line signals, 1 absorption signal, 7 non-detections, and 3 RFI-contaminated ones by combining the data from H i-MaNGA [76, 111] and new FAST observations. There is no useful signal for MaNGA 8082-12704, MaNGA 8623-6104, and MaNGA 7975-6104 due to heavy RFI contamination, and thus they were excluded from further discussion. The distribution of ALMaQUEST detection and non-detection of H i signal is shown in Figure 1. Approximately half of the non-detections are massive green-valley galaxies with log M_* > 10.8, which may suggest that galaxy quenching is due to gas depletion.

3.1 FAST H i Spectra

The final results of FAST observations are shown as blue profiles in Figures 2 and 3, which include emission, absorption, and non-detection cases. To align with the spectra obtained from Arecibo and GBT, we rebin the spectra to a channel width of 6 km s−1. The measurement of spectral noise level σ (in units of mJy per channel) follows the same approach as σspec, but with a narrower channel width ΔV 6.4 km s−1.

The black profiles in Figure 2 are observations from the H i-MaNGA survey. The comparison of the blue and black global profiles in Figure 2 demonstrates excellent consistency between the FAST and archival (Arecibo and GBT) spectra, though the new data exhibit a relatively lower noise level. While the H i-MaNGA data indicate a non-detection for MaNGA 8155-6101, the FAST data reveal a high S/N H i absorption signal by reducing the noise level by half, which was submerged in the noise in the GBT spectrum (we will return to a discussion of this absorption signal in Section 3.3). The discrepancy in spectra between FAST and GBT demonstrates the capability of FAST in detecting new signals. Regarding MaNGA 8084-6103, the new FAST observation further constrains the upper limit of the H i mass to $M_{\mathrm{H\,I,lim}} = 10^{8.5}$ M , which is 1.1 dex deeper than that of H i-MaNGA. The upper limit of H i mass is calculated by assuming a line width of 200 km s−1 and a 3σ detection following H i-MaNGA [76, 111]. The upper limits for the H i mass are calculated as $M_{\mathrm{H\,I,lim}}/M = 2.356 \times 10^{5} \times (D_L/\mathrm{Mpc})^{2} \times (3\sigma/\mathrm{mJy}) \times (\Delta V/\mathrm{km\ s^{-1}}) \times (3\sigma/1000\ \mathrm{mJy})$

Jy km s−1. Due to the inclusion of the emission at 8200–8600 km s−1, our H i mass upper limit exceeds that of H i-MaNGA. The H i mass upper limits of 7 non-detections are shown in Table 3. Additionally, the H i profile of MaNGA 8728-3701 from H i-MaNGA is classified as a non-detection, while the strong H i emission at 8400–8600 km s−1 originates from its companion, MaNGA 8728-12701. The new FAST data provide further confirmation that the weak emission around 8300 km s−1 may be from MaNGA 8728-3701 and give a conservative H i mass upper limit of 10^9.3 M .

[Figure 2: see original paper]

[Figure 3: see original paper]

3.2 Measurements of Global Profiles

The H i emission line spectra of the new FAST supplements and xCOLD GASS datasets are uniformly measured using the curve-of-growth method [131, 133]. This method defines the profile center as the flux-intensity weighted velocity and constructs the curve of growth by accumulating flux intensities from the center to both sides, then quantifies the total flux, line width, asymmetry, and profile shape. We remove two galaxies–MaNGA 8728-3701 and MaNGA 8155-6101–from Section 4 due to contamination from companions and absorption signals.

The total flux F (in units of Jy km s−1) is determined as the median value of the flat part of the growth curve. The line width is defined as the velocity width that encloses a characteristic fraction of the total flux. For instance, line widths V25 and V85 correspond to the velocity widths enclosing 25% and 85% of the total flux, respectively. The profile asymmetry is quantified as the ratio of the integrated fluxes for the two sides ($AF \geq 1.0$) and the ratio of the slopes of the rising part of the curve of growth for the two sides ($AC \geq 1.0$). We quantify the emission line profile shape as the degree of concentration of the line profile CV and the integrated area between the normalized curve of growth and the diagonal line of unity K. With increasing CV or K, the profile transitions from a double-horned profile to a single-peaked profile. The S/N of a spectrum is calculated as $S/N = 1000F/\sigma$, where σ is the noise level in mJy.

We apply a second-order polynomial correction to account for systematic bias in the total flux, line width, profile asymmetry, and profile shape when the spectrum has an S/N below 40 following Yu et al. [133]. The H i mass is calculated as MH i = 2.356 × 10^5 DL^2 F M [91], where DL is the luminosity distance in Mpc. The FAST beam roughly corresponds to a physical scale of 200 kpc, which is sufficient to cover all H i emissions within the host galaxy; thus, aperture correction is not necessary for our targets. The final measured parameters of all detections obtained from our H i spectra are presented in Table 2.

The H i mass upper limits of the ALMaQUEST sample cover a range of 10^8.2

to 10ˆ9.8 M (Table 3), which correspond to a gas fraction log MH i/M$*$ of 0.5-10% with a median value of 2%. The two H i non-detections from FAST further constrain the atomic-to-stellar mass ratio to 0.5%, which is consistent with our expectations of 1%. The noise level of our new FAST observation is 3-7 times better than that from GBT or Arecibo, due to the large dish size and thus high sensitivity of FAST compared to GBT, and significantly longer integration times relative to the ALFALFA survey.

3.3 H i Absorption in MaNGA 8155-6101

Remarkably, MaNGA 8155-6101 has a 6σ H i absorption signal (Figure 4). MaNGA 8155-6101 is a merging galaxy system with a companion CGCG 391-011 at a velocity difference of 360 km s−1 and a projected physical separation of 30 kpc (44). To investigate the absorption feature, we follow Wolfe & Burbidge [125] and Allison et al. [3], and determine the H i column density from the absorption line signal as NH i = 1.823 × 10ˆ{18} Tspin τ(V)dV 1.823 × 10ˆ{18} Tspin τobs(V)dV, where τ(V) is the optical depth at a given velocity V, τobs(V) is the observed optical depth (panel e of Figure 4), Tspin is the mean harmonic spin temperature of the gas, and f is the covering factor of H i absorption. The H i spin temperature ranges from 10 to 1000 K based on analyses of H i emission and absorption profiles toward individual clouds located in front of Galactic and extragalactic radio continuum sources [50, 77, 80, 108]. The covering factor f varies from 0.1 to 1 [27] for galaxies with z 1, and we often assume it to be 1 due to lack of information [78]. We adopt Tspin = 100 K and f = 1 following Carilli et al. [21]. This results in an H i column density of 5.5 × 10ˆ{20} cm−2, which is within the typical range of $10^{\{19\}\text{-}10}$\{21\} cm−2 [80]. However, given the uncertainty in the spin temperature and the covering fraction, the uncertainty of H i column density could be one or two orders of magnitude.

The center of the absorption signal is precisely consistent with the optical central velocity of MaNGA 8155-6101, while the emission line signal on the blue-shifted side suggests a potential association with the neighboring companion, CGCG 391-011. Based on spatially resolved stellar kinematics, MaNGA 8155-6101 has a regular rotation pattern and high velocity dispersion within one effective radius (Panel c of Figure 4). However, the ionized gas kinematics traced by Hα emission shows significant perturbation. The CO emission line profile is quite extended with a line width 600 km s−1, even though the S/N is low [71]. The broad CO line width is rare considering there are only two galaxies with CO line widths larger than 600 km s−1 among 333 detections in the xCOLD GASS sample [97], which may suggest that the CO in the two interacting galaxies is perturbed and mixed. Therefore, the molecular gas in MaNGA 8155-6101 is potentially perturbed, either by AGN or galaxy interaction. Furthermore, its SFR, specific star formation rate (sSFR), and star formation efficiency are typical for a massive quenched galaxy with a molecular gas fraction of 1% [71]. Thorp et al. [115] found that central bursts of star formation in mergers require centralized enhancements in gas fraction; thus, the broad CO line width and normal SFR in MaNGA 8155-6101 may suggest that gas is distributed extensively and thus fails to fuel central starburst activities.

We employ three types of BPT diagrams ([N II], P1P2, and [S II]) to classify the ionization state based on the spatially resolved IFU data from MaNGA. MaNGA 8155-6101 is classified as an AGN host based on BPT diagrams (panels i–n of Figure 4), and the fraction of AGN or Seyfert pixels decreases from 100% to 50% with the transition from [N II], P1P2, to [S II] BPT diagrams. The high ionization states are likely due to perturbations fueling an AGN or driving shocks [60].

The possible overall scenario is that galaxy interaction disturbs the gas distribution in the galaxy outskirts and then results in gas inflow and turbulent motion, which in turn triggers the AGN [46, 112, 121] within MaNGA 8155-6101. To gain further insights into the gas distribution and kinematics under the effects of merger and AGN, future spatially resolved H i observations may provide valuable details of the gas kinematics in the circum-galactic medium, intergalactic medium, and around the central black hole.

[Figure 4: see original paper]

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4 Atomic-to-Molecular Gas Conversion

The atomic-to-molecular gas conversion is predominantly facilitated in regions with high mid-plane pressure, weak ultraviolet radiation fields, and high metallicity, which holds both theoretically [41, 62] and observationally [66]. Intriguingly, a weak correlation between MH i and MH2 in nearby galaxies suggests that the physical conditions governing the atomic-to-molecular gas conversion are non-trivial [23, 95]. To further constrain the conditions that influence gas conversion, we carefully scrutinize whether the molecular-to-atomic gas ratio (Rmol log MH2/MH i) depends on various physical properties.

4.1 Stellar Mass Distribution and Star Formation

We investigate the dependence of Rmol on M∗, µ∗, NUV−r color, and sSFR in Figure 5 using the HICO-MaNGA sample in comparison with the HICO-Spec sample. Galaxies with at least one detection in H i or CO are shown. The NUV−r color is obtained from the NASA-Sloan Atlas (NSA) catalog [10], and its typical uncertainty is 0.2 dex [126]. The p-value and Kendall' s τ coefficient indicate that Rmol is correlated with µ∗, less tightly but still correlated with M∗ and NUV−r color, and not related to the sSFR. The best-fit linear relations in panels (a–c) of Figure 5 are derived from orthogonal distance regression. The typical uncertainty of H i and CO detection is 0.1 dex for log MH i and 0.2 dex for log MH2 for our sample. While fitting the linear relations, we assume a typical uncertainty of 0.2 dex for log MH i and 0.4 dex for log MH2 for these non-detections. The uncertainties of p-value and Kendall' s τ coefficient are obtained by bootstrap realizations, which consider the uncertainties of both x and y axes.

The HICO-Spec sample has Rmol ranging from -1.9 to 0.8 with a median value of -0.7 [23]. The values of Rmol for our sample cover a similar range. The HICO-MaNGA sample shows a trend consistent with that of HICO-Spec and xCOLD GASS: Rmol increases monotonically with increasing M∗, µ∗, and NUV−r color [15, 16, 23, 94, 95] with a scatter of 0.5 dex.

The positive relation between M∗ and Rmol is consistent with literature studies. The typical value of the logarithmic molecular-to-atomic gas ratio Rmol is 0.6 for S0/Sa galaxies and -0.6 for Sd/Sm galaxies [93, 116, 129], which decreases statistically from Sa to irregular galaxies (high mass to low mass, [15, 130]). This weak relation holds true for both constant αCO and luminosity-dependent αCO [16]. Hydrodynamical and semi-analytical simulations have also successfully reproduced this relation [64, 87]. Therefore, the efficiency of atomic-to-molecular gas conversion varies across different types of galaxies.

We consider that the dependence of Rmol on µ∗ is primarily due to the regulation of mid-plane pressure [41], which is within expectation for a spatially resolved view: Rmol (µg + µ∗vg/v∗)^0.8 [62], assuming a thin disk of uniform gas and stars in balance [11]. Here, µg is the gas surface density, and vg and v∗ are the vertical velocity dispersions of the gas and stellar components, respectively. In a spatially resolved view, the molecular-to-atomic gas surface density ratio is tightly proportional to µ∗ observationally [66]. These results support the scenario that atomic gas in high-density regions is more easily converted to molecular gas. This is also consistent with the observation that massive early-type galaxies have higher values of Rmol than late-type galaxies [15, 94].

However, the HICO-MaNGA sample exhibits a steeper slope between Rmol and µ∗ compared to that of the HICO-Spec or xCOLD GASS sample. The reason may be that the HICO-MaNGA sample (1) mainly consists of star-forming galaxies, and (2) has log µ∗ < 8.7 M kpc−2. In bulge-dominated cases with high stellar mass surface densities µ∗ > 10^8.7 M kpc−2, the cold gas reservoir can be efficiently converted to stars. Below this µ∗ threshold, higher detection rates are found in both molecular and atomic gas measurements [22, 95]. As galaxies become more bulge-dominated, both the atomic and molecular gas fractions decrease significantly, as do their detection rates [95]. The flattening of the relations between µ∗ and Rmol for the xCOLD GASS sample is evident above the characteristic threshold of log µ∗ 8.7 M kpc−2, which is mainly due to cold gas depletion in mostly quiescent, early-type galaxies [94]. The HICO-MaNGA sample is mainly composed of star-forming galaxies and is not depleted in cold gas; thus, the flattened trend is not observed.

We investigate the relation between Rmol and star formation activity in the bottom panels of Figure 5, which show a weak and no relation, respectively.

NUV−r color is an indicator of star formation history or sSFR in galaxies [126]. Saintonge et al. [95] also showed that Rmol is an increasing function of NUV−r, but this relation may be a direct result of the strong relation between atomic gas fraction and NUV−r [22, 23, 136]. The NUV−r color is sensitive to star formation within several hundred Myr [65], but sSFR is more sensitive to star formation over longer timescales (several Gyr) because it quantifies the current star formation activity relative to the existing stellar mass. Therefore, the tighter relation between Rmol and NUV−r color compared with that of sSFR may suggest that gas conversion is related to star formation on relatively short timescales.

The HICO-MaNGA and xCOLD GASS samples show no relation between Rmol and sSFR (panel d of Figure 5). The weak relation is consistent with results based on 18 detections out of 33 galaxies from the ALMaQUEST sample using H i-MaNGA data release 1 [71]. From late-type to spiral galaxies (sSFR   10ˆ−10 yrˆ−1), the value of Rmol increases slowly and then becomes constant in spirals [15]. The global sSFR is related to the atomic gas fraction (e.g., [35, 51, 138]) and molecular gas fraction [15] with large scatters. For galaxies on the star-forming main sequence, variations in Rmol are mainly influenced by their H i reservoirs [23], but star formation activity relies more on H2 content [57]. In addition to the total gas content, the central concentration of cold gas within the optical disk may be more directly related to star formation [122, 132], especially when there is an abundant gas reservoir. Our results suggest that the global conversion from H i to H2 does not significantly influence the global sSFR in non-starburst galaxies.

[Figure 5: see original paper]

4.2 Cold Gas Distribution

Although spatially resolved H i and CO are not simultaneously available for galaxies with large sample sizes (e.g., [66, 135]), the asymmetry and relative concentration of cold gas can be inferred from their global profiles [131, 132]. Meanwhile, spatially resolved gas asymmetry is reflected in asymmetry parameters derived from the global profile [89]. A double-horned profile with a deep central trough may suggest a centrally depressed H i distribution [92]; thus, the global profile encodes the gas spatial distribution.

We investigate the dependence of Rmol on the H i profile asymmetry AF,HI and profile shape KHI for galaxies with H i detection in the xCOLD GASS and HICO-Spec samples (Figure 6). Our analyses indicate a weak or no relation between Rmol and the atomic gas distribution, inferred from either asymmetry AF,HI or profile shape KHI. The p-value for Rmol versus AF,HI is slightly larger than 0.05, thus their relation is not significant. The p-value for Rmol versus KHI is significantly smaller than 0.05, which suggests that gas conversion may be related to the H i profile shape K.

Asymmetric features in the distribution and kinematics of H i can be attributed to either internal perturbations, such as stellar feedback [26] and AGN feedback [79], or external perturbations, such as accretion [102], stripping [123], and merging [13]. We caution that the profile asymmetry of massive mergers is not higher than that of control galaxies after correcting for the effects of S/N [139]. Based on high-resolution, spatially resolved H i distributions in nearby galaxies, Reynolds et al. [89] argued that gas-removal mechanisms, such as tidal interactions and ram-pressure stripping, are the most probable mechanisms for generating asymmetric H i distributions. The weak relation between Rmol and H i asymmetry may suggest that gas-removal mechanisms do not significantly influence the H i-to-H2 conversion.

Panel (b) of Figure 6 demonstrates that galaxies with higher Rmol tend to exhibit more single-peaked H i profiles in our study, suggesting that H i is relatively more centrally concentrated within the optical disk. Perturbations may drive H i inflow [34, 37, 105] and promote atomic-to-molecular gas conversion [110]. However, we note that the inclination angle, stellar mass, optical concentration, and gas mass cannot be well controlled in this work as done in Yu, Ho, & Wang [132] to better infer relative gas concentration within the optical disk for nearby galaxies due to the limited sample size. H i profile shape asymmetry AC,HI shows similar results as AF,HI, and profile concentration CV,HI also demonstrates comparable trends to KHI. Therefore, the H i distribution does not significantly regulate the atomic-to-molecular gas conversion.

[Figure 6: see original paper]

Figure 7 illustrates the trends of Rmol as a function of CO profile asymmetry AF,CO and profile shape KCO. The uncertainty of CO profile asymmetry is high because there are many marginal detections with low S/N. As in Figure 6, the dependence of Rmol on CO distribution is weak or nonexistent, with p = 0.131 for Rmol versus AF,CO and p = 0.031 for Rmol versus KCO. The CO redistribution or asymmetry can be caused by AGN activity [25, 113] or bar structures [109]; thus, gas conversion does not influence the molecular gas distribution.

Even though the trend is as weak as that of H i, it is noteworthy that the trends in CO are opposite to those in H i. The contrasting trends suggest that the distribution and kinematics of H i and CO in galaxies are not identical, which is consistent with previous findings by comparing global profiles of H i and CO [30, 90]. The spatially resolved H i and CO asymmetry is weakly correlated for galaxies in the Virgo cluster but shows a stronger correlation for galaxies strongly perturbed by environmental effects [90]. Specifically, H i disks tend to be more fragile and extended (e.g., [31]), while CO is more centrally concentrated within the optical disk. Using global profiles in the xCOLD GASS survey, we find no correlation between the global profile asymmetry and shape of H i and CO, which indicates that the distribution of atomic and molecular gas in nearby galaxies is not tightly linked. A comprehensive analysis of global H i and CO profiles will be fully investigated in an upcoming paper.

[Figure 7: see original paper]

4.3 Ionization States

We investigate the dependence of the atomic gas fraction log (MH i/M∗) and molecular gas fraction log (MH2/M∗) on the fraction of different ionization states for the HICO-MaNGA sample employing the P1P2 BPT diagram (panels a and b of Figure 8). We find that the H ii region fractions monotonically decline to 50% with decreasing atomic gas fraction. A similar trend is observed for the molecular gas fraction. As the fraction of atomic or molecular gas increases, the proportion of H ii regions in galaxies increases from 40% to 100%. Galaxies with log (MH i/M∗) ≥ -0.8 tend to have H ii region fractions greater than or equal to 80% (panel a of Figure 8). Thus, the most gas-rich galaxies are predominantly star-forming. A similar trend appears in the molecular gas fraction. These trends are consistent across the three types of BPT diagrams: nearly identical results for the [N II] and P1P2 BPT diagrams, whereas the [S II] BPT diagram exhibits a lower fraction of composite regions ($ 20 $5%).

To disentangle the dependence of log (MH i/M∗) and log (MH2/M∗) on M∗, we investigate the relations of the vertical offsets with respect to the median trends as a function of M∗ and the fractions of three components (panels c and d of Figure 8). With increasing Δlog (MH i/M∗) and Δlog (MH2/M∗), the fraction of emissions from H ii regions increases monotonically, similar to the trends shown in panels (a) and (b). Therefore, the positively correlated trend indicates that an abundant cold gas reservoir, both atomic and molecular, promotes widespread star formation within galaxies.

We investigate how the molecular-to-atomic gas ratio (Rmol) and galaxy ionization states influence each other (Figure 9). All galaxies in HICO-MaNGA have Hα equivalent widths larger than 1 Å, both within the field of view and within one effective radius; thus, none of them is an emission line-less galaxy [7]. We adopt the mask of each emission line and require the S/N of each spaxel to be higher than 10 to minimize the effects of noise [124]. Three galaxies (MaNGA 8655-12705, MaNGA 12700-12702, and MaNGA 12769-6104) have numbers of spaxels smaller than 100 after adopting the S/N threshold, which may lead to high uncertainties in the fraction of different components; thus, we remove them from the following discussion.

With increasing Rmol from −1 to 0, the H ii region fractions slightly decrease from 100% to 80% (panel a of Figure 9). The decreasing fraction of H ii regions may be caused by the decreasing cold gas fraction (see Figure 8). Because the decreasing trend has a large scatter and BPT classification is a mixed effect of metallicity and ionization states, we divide the HICO-MaNGA sample into three Rmol bins with equal galaxy numbers and investigate their distribution in the P1P2 BPT diagram (panels b–d in Figure 9). The galaxy ionization state increases with increasing P1 parameter, and the metallicity decreases with increasing P2 parameter [52]. With increasing Rmol, P2 decreases significantly and P1 evolves into two branches.

From Rmol ≤ -0.75 to Rmol > -0.75, the fraction of composite regions increases by 3-6%. Efficient atomic-to-molecular gas conversion will promote star formation and enhance stellar feedback. The increase in composite regions may be the mixed effect of star formation, shock excitation, and/or AGN activity [60]. On the other hand, the values of P1 decrease significantly with increasing Rmol, but the regions are still classified as H ii-dominated emission. The P2 values are anti-correlated with galaxy metallicity; thus, higher values of Rmol correspond to higher galaxy metallicity. More research is vital to reveal the detailed physical mechanisms behind the bilateral evolution of P1.

The efficiency of atomic-to-molecular gas conversion has been found to decrease monotonically with increasing galactic radius [66]; thus, we evaluate the dependence of global Rmol on the fraction of different ionization states within a given galactic radius range in our samples. We divide spatially resolved BPT diagrams (see the example in Figure 4) into two or three radius ranges: R $\leq$ 0.5Re, 0.5Re $<$ R $\leq$ 1.5Re, and 1.5Re $<$ R $\leq$ 2.5Re, where Re is the effective radius of each galaxy. The results in Figure 10 show that with increasing galaxy radius, the fraction of non-star-forming regions decreases from 20% to 2%. It is worth noting that more than 80% of our sample have an AGN fraction below 5% in their BPT diagrams, and more than half of our sample have a fraction of the combination of AGN and composite regions lower than 10%; thus, our sample exhibits a low fraction of non-star-forming regions. The non-star-forming emission could be mainly caused by AGN or shock activity [60]. The HICO-MaNGA sample contains 15 galaxies with a weighted AGN and composite fraction higher than 15%, which tend to be AGN hosts [127]. However, only one galaxy, MaNGA 7977-9101, has a typical Hα velocity dispersion higher than 150 km/s, which could be caused by galactic wind shocks or AGN feedback [29, 60]. Thus, it is difficult to distinguish the main physical drivers for the decrease in the fraction of star-forming regions with increasing Rmol using the current data.

We specifically examined 5 galaxies characterized by a high molecular-to-atomic gas ratio and a low fraction of H ii regions (Rmol ≥ -0.3 and the fraction of H ii regions $<$ 50%): GASS 4030, GASS 11071, MaNGA 8081-12703, MaNGA 9194-3702, and MaNGA 8655-3701. These galaxies exhibit distinct characteristics: a bright Hα core and an old stellar population (high values of Dn4000) surrounding the Hα core. Their main disks show significant AGN or composite emission. This can be seen in Figure 11, where we show the optical images, Dn4000, Hα, and BPT diagrams of MaNGA 8655-3701: a typical galaxy among these outliers. Both the stellar and Hα components display a rotation pattern, and its bright central core has high velocity dispersion. The relative distribution of H i and H2 may be offset because there is a significant difference between their global profiles. Consequently, we find that a high global value of Rmol is not necessarily linked to a high fraction of H ii regions. They are separate processes within the baryon cycle in certain cases. The decline in H ii region fraction at high molecular-to-atomic ratios can be mainly attributed to high velocity dispersion (see the Hα velocity field in Figure 11) in the intermediate region ($0.5\mathrm{Re} < \mathrm{R} \leq 1.5\mathrm{Re}$) and extended cold gas distribution. These factors hinder the connection between H i, H2, and star formation. A similar effect is found that intensive star formation may promote gas velocity dispersion, but non-axisymmetrical torques can prevent the gas from being gravitationally unstable [61].

[Figure 8: see original paper]

[Figure 9: see original paper]

[Figure 10: see original paper]

[Figure 11: see original paper]

4.4 Metallicity

Metallicity acts as a catalyst in the process of converting H i to H2 gas, which enhances gas conversion [41, 62]. Gas metallicity serves as a direct indicator of dust content [33], and efficient H2 formation occurs on the surfaces of dust grains [45]. Thus, metallicity plays a positive role in gas conversion. Boselli et al. [15] collected optical emission lines and utilized the O3N2 calibration following Pettini & Pagel [84]. Their results indicated a correlation between Rmol and the oxygen abundance 12+log (O/H) globally. However, concerns about non-uniformly measured oxygen abundance due to limitations in data quality could affect the conclusions.

To address this, we re-investigate the dependence of Rmol on the oxygen abundance 12 + log(O/H) using data from the MaNGA IFU. The oxygen abundance and its slope are taken from Sánchez et al. [101], which is determined using the O3N2 ([O III]/Hβ)/([N II]/Hα) calibration discussed above [84] for star-forming regions classified by the [N II] BPT diagrams with EW(Hα) > 3 Å. The slope of the oxygen abundance is derived from the fitting results obtained between 0.5 and 2.0 Re. As shown in Figure 12, the conversion from atomic to molecular gas is enhanced with increasing oxygen abundance at both central regions and at one effective radius. The oxygen abundance calibrated by the O3N2 index is widely used in the high-metallicity regime at solar and super-solar metallicities [74, 84], where [N II] saturates. The oxygen abundance based on the R23 ([O II]+[O III]/Hβ) and N2 [N II]/Hα calibration [101] returns similar results. Thus, metallicity plays a positive role in gas conversion.

Compared to the central metallicity, the metallicity at one effective radius shows a stronger relation with global Rmol. This suggests that gas conversion predominantly occurs within the optical disk, even though the central region exhibits higher conversion efficiency. We also find that the xCOLD GASS sample shows a positive relation between Rmol and global gas-phase metallicity.

Our data show a weak or no positive relation between Rmol and the slope of the oxygen abundance: p = 0.112 and τ = 0.11. Positive slopes of oxygen abundance are likely the result of gas accretion [118], which dilutes metallicity. However, the gradient of oxygen abundance is slightly dependent on stellar mass [8, 119, 120], although EAGLE simulations show no clear trend between them [117]. The physical drivers of the observed metallicity gradients are complicated, including radial variations in SFR [85, 106], gas motions [82, 88], and IMF [47, 75]. Therefore, the lack of correlation between Rmol and the oxygen abundance gradient does not necessarily rule out the effects of gas accretion.

The Kendall' s τ coefficient for global Rmol versus the oxygen abundance at one effective radius is higher than other relations in Figures 5, 6, 7, and 12. Among the dependencies studied in this work, metallicity within the optical disk may be the most important factor regulating the H i-to-H2 conversion in galaxies, which is consistent with literature studies [36, 45].

[Figure 12: see original paper]

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5 Summary

The atomic-to-molecular gas conversion is an important step in the galaxy baryon cycle. We obtained H i spectral line observations with FAST for the ALMaQUEST sample. We derived 42 emission lines, 1 absorption line, and 8 non-detections after combining data from Arecibo and GBT. Our FAST observations have a noise level of approximately 0.2 mJy with a velocity resolution of 6 km s−1, which is much better than that of H i-MaNGA. Thanks to the high sensitivity of FAST, the H i detection rate is 80%, rendering it an ideal instrument for extragalactic H i research.

Additionally, we compile H i and CO spectra or data from the xCOLD GASS, ALLSMOG, and JINGLE surveys to construct two samples: HICO-Spec and HICO-MaNGA, which contain around 300 and 100 galaxies, respectively. The HICO-MaNGA sample has H i, CO, and optical IFU observations. This sample is predominantly composed of star-forming galaxies with a stellar mass range of $10^{9.0\text{-}10}${11}.5 M and a redshift range of 0.02 z 0.06. We analyzed the H i and CO spectra using our recently developed "curve of growth" method [131, 133] to measure parameters such as total flux F, profile asymmetry AF, and profile shape K.

The main results are briefly summarized as follows:

- The molecular-to-atomic gas ratio Rmol is positively related to M∗, μ∗, and NUV−r color, but shows no discernible relation with sSFR. In contrast to the results of Saintonge & Catinella [94], our sample does not show a flattened trend in the relation between μ∗ and Rmol. This difference may be attributed to the star-forming nature of our sample and low stellar mass surface density (log μ∗ < 8.7 M kpc−2). Gas conversion depends on mid-plane pressure, which is primarily proportional to surface density, assuming a thin disk with uniform gas and star distribution [11].

- The relationship between Rmol and the distribution of H i and CO is weak when the gas distribution is inferred from the asymmetry and shape of their global profiles. Galaxies exhibiting higher H i asymmetry or more single-peaked H i profiles tend to have higher values of Rmol, while the opposite trend is observed for CO. Because the relation is weak, we cannot draw definitive conclusions regarding the relationship between cold gas distribution and H i-to-H2 conversion.

- With increasing Rmol, the fraction of H ii regions decreases within 1.5Re, likely due to the influence of shocks. We determine the spatially resolved ionization states using the BPT diagram introduced by Ji & Yan [52] and examine the dependence of Rmol on the fractions of different regions. The fraction of H ii regions increases with increasing atomic and molecular gas fraction, which remains evident after controlling for the effects of stellar mass. Consequently, cold gas reservoirs enhance star formation within galaxies.

- However, the fraction of H ii regions decreases with increasing Rmol. This decrease is related to the decreasing cold gas fraction. With increasing Rmol, the metallicity increases and the ionization states diverge. The fraction of composite regions increases by 2%, which may be due to stellar feedback. Therefore, a high molecular-to-atomic gas ratio does not necessarily lead to a high fraction of H ii regions, as this is also regulated by galaxy kinematics and gas distribution.

- Furthermore, galaxies with higher oxygen abundance 12 + log (O/H) tend to have higher values of Rmol, indicating that metallicity acts as a catalyst enhancing atomic-to-molecular gas conversion. The oxygen abundance at Re proves to be more critical than the central oxygen abundance or oxygen abundance gradients. The slope of oxygen abundance is not tightly related to global Rmol, which may suggest that gas accretion does not significantly promote atomic-to-molecular gas conversion.

In summary, the atomic-to-molecular gas conversion mainly depends on stellar mass surface density and metallicity. The most efficient atomic-to-molecular gas conversion occurs in massive or metal-rich galaxies. Over longer timescales, feedback mechanisms may play a role in galaxy ionization states, thereby influencing gas conversion. To gain deeper insights, multi-wavelength observations of stars, ionized gas, atomic gas, molecular gas, and dust with similar resolutions are needed to further constrain the atomic-to-molecular gas conversion in nearby galaxies.

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Conflict of interest: The authors declare that they have no conflict of interest.

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