SUB-MILLIMETER TELESCOPE CO (2–1) OBSERVATIONS OF NEARBY STAR-FORMING GALAXIES

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ABSTRACT

We present CO J = 2–1 observations toward 32 nearby gas-rich star-forming galaxies selected from the ALFALFA and Wide-field Infrared Survey Explorer (WISE) catalogs, using the Sub-millimeter Telescope (SMT). Our sample is selected to be dominated by intermediate-M∗ galaxies. The scaling relations between molecular gas, atomic gas, and galactic properties (stellar mass, NUV − r, and WISE color W3 − W2) are examined and discussed. Our results show the following. (1) In the galaxies with stellar mass M∗ < 1010 M⊙, the H2 fraction (fH2 ≡ MHI/M∗) is significantly higher than that of more massive galaxies, while the H2 gas fraction (fH2 ≡ MHI/M∗) remains nearly unchanged. (2) Compared to fHI, fH2 correlates better with both M∗ and NUV − r. (3) A new parameter, WISE color W3 − W2 (12–4.6 μm), is introduced, which is similar to NUV − r in tracing star formation activity, and we find that W3 − W2 has a tighter anti-correlation with log fHI than the anti-correlation of (NUV − r) − fHI. (4) MHI/M∗, and (W3 − W2) − fHI. This indicates that W3 − W2 can trace the H2 fraction in galaxies. For the gas ratio MHI/M∗, only in the intermediate-M∗ galaxies it appears to depend on M∗ and NUV − r. We find a tight correlation between the molecular gas mass MHI, and 12 μm (W3) luminosities (L12μm), and the slope is close to unity (1.03 ± 0.06) for the SMT sample. This correlation may reflect that the cold gas and dust are well mixed on a global galactic scale. Using the all-sky 12 μm (W3) data available in WISE, this correlation can be used to estimate CO flux for molecular gas observations and can even predict H2 mass for star-forming galaxies.

Key words: galaxies: evolution – galaxies: ISM – infrared: galaxies – ISM: molecules – radio lines: galaxies

1. INTRODUCTION

In all star-forming systems, from Galactic molecular clouds to high-redshift galaxies, cold atomic and molecular gases (H1 and H2) are the raw material that form stars and drive the evolution of galaxies. Understanding of the relationships between cold gas and global properties of galaxies, such as star formation activities, has been greatly improved thanks to recent multi-wavelength advances. For example, galaxies show strongly bimodal distributions in their integrated colors, which indicates two modes in the history of galaxy evolution: young galaxies with active star formation in the “blue cloud” appeared to rapidly evolve into the “red sequence” populated by quiescent galaxies with little star formation (Kennicutt & Evans 2012). This transition must be preceded by the transformation from H1 to H2, the assembly of molecular clouds, and star formation therein (Krumholz 2013; Schruba et al. 2011).

Star-forming galaxies were found to fall on the main sequence (MS) in the relation between stellar mass and star formation rate (SFR; Daddi et al. 2007), and recent studies have found that the scatter in the MS is remarkably small at different redshifts, implying that the majority of star-forming galaxies are “normal” galaxies lying along the relation (Gru et al. 2013; Rodighiero et al. 2011). Particularly, intermediate-mass (or low-mass) galaxies M∗ < 1010 M⊙ are still not well understood. Their numbers dominate galaxy populations, and many of them are cold interstellar medium (ISM) dominated and have lower-than-solar metallicities. As a result, their star formation properties are distinct from massive galaxies. Low-mass galaxies were found to be more gas rich and inefficient in transforming their gas into stars (Blanton & Moustakas 2009), but they may dominate the present star-forming galaxy populations rather than massive galaxies (the downsizing effect), and may help us understand high-z galaxies since the physical conditions in low-mass systems such as high gas ratio and low metallicity resemble those in the early universe.

Recent studies have found a steep decline of cosmic SFR density between z = 1 and 0, and peaks at z ~ 1–2 (Bouwens et al. 2011; Carilli & Walter 2013), and this evolution appears to be strongly regulated by the evolution of cold gas content, of which the most important parameters are gas fraction fgas (MHI/M∗, and MHI/M∗, sometimes Mgas/M(H2 + Mgas)) and gas phase ratio rgas (MHI/MH2). fgas and rgas have been found to increase significantly toward high redshift, and the pronounced evolution of fgas seems to resemble the evolution of SFR (Combes et al. 2013), implying its important role in determining the star formation history. Moreover, Tacconi et al. (2013) shows a trend of increasing fgas with decreasing stellar mass (see also Saintonge et al. 2011a), implying that the cosmic gas density could be higher than current derived values (Carilli & Walter 2013). Although representing MS star-forming galaxies, the sample by Tacconi et al. (2013) was limited to the high-mass end of galaxy distribution, and studies on low- to intermediate-stellar mass galaxies would provide a crucial constraint on the cosmic gas content as well as star formation history. In this context, the study of nearby galaxies of intermediate-stellar mass can provide a benchmark of high-z studies. In existing CO surveys, galaxies beyond our immediate vicinity are almost entirely dominated by massive systems (COLD GASS; Saintonge et al. 2011a) and/or luminous infrared galaxies (LIRGs; Genzel et al. 2010), while surveys of intermediate-mass galaxies are limited by distance (HERACLES; Leroy et al. 2009) or environment.
(Analysis of the Interstellar Medium of Isolated Galaxies (AMIGA); Liskenfeld et al. 2011). This stands in sharp contrast to surveys of other wavelengths (e.g., Sloan Digital Sky Survey (SDSS) in optical or Galaxy Evolution Explorer (GALEX) in UV), where homogeneous samples of ordinary (and many low-mass) galaxies out to distances of hundreds of Mpc are available.

Atomic gas (neutral hydrogen) is traced by the H I 21 cm hyperfine transition line (Haynes et al. 2011) and molecular gas (mainly H2) mass can be traced by carbon monoxide, typically 12CO(J = 1→0) (Young & Scoville 1991; Saintonge et al. 2011a; Liskenfeld et al. 2011) and 12CO(J = 2→1) (Leroy et al. 2013). Surveys toward very nearby galaxies such as SINGS (Kennicutt et al. 2003) and THINGS (Walter et al. 2008) have conducted detailed analyses for spiral disks of galaxies, while there are also surveys with larger sample of greater distances (>100 Mpc, e.g., the COLD GASS; Saintonge et al. 2011a, 2011b), which mainly focus on global scaling relations. Much recent effort has been devoted to the study of the correlation between molecular gas tracers (CO, HCN, HCO+ and CS, etc.) and star formation in nearby galaxies, both individually and as a function of Hubble type (Zhang et al. 2014; Gao & Solomon 2004; Calzetti et al. 2007; Kennicutt et al. 2009; Bigiel et al. 2011). On global scales (>1 kpc) H I and H2 appear to depend on other galactic physical properties, and such scaling relations can help to understand better the role of cold gas in the histories of galaxy evolution and star formation.

The Arecibo ALFALFA survey (a 40, Giovanelli et al. 2005) scanned a large area of the sky and aimed to study the HI content of normal galaxies out to ∼250 Mpc (Haynes et al. 2011). Thus far, it covers ∼3000 deg2 of the sky and contains more than 15,000 galaxies, and it is characterized by a maximum overlap with the coverage of both the SDSS and GALEX. Compared to the optical–selected sample, this HI–selected sample represents a less evolved galaxy population, in which a transition in star formation properties is found at around M * ∼ 109.5 M⊙. Below this mass, galactic star formation is found to be strongly regulated by H I mass rather than stellar mass (Huang et al. 2012). Thus a survey of molecular gas in the intermediate-mass galaxies selected from the ALFALFA sample would provide a key missing link between star formation and global gas content (H2 + H I) in these galaxies.

In this paper, we describe our Sub-millimeter Telescope (SMT) sample in Section 2.8. The SMT observation and results are presented in Section 3. We present our calculations of molecular gas mass for the SMT sample in Section 3.1, as well as the stellar mass calculations for both the SMT sample and the AMIGA sample. The main results are presented in Section 4. In Section 4.1, the different samples are compared, in Sections 4.2 and 4.3 we discuss the scaling relations of the gas fraction (Mgas/M *) and gas ratio (MHI/MH2), and in Section 4.4 the correlation between molecular gas and WISE infrared properties is discussed. Throughout this work, we assume the cosmological parameters (Ωm = 0.3, ΩΛ = 0.7, Ho = 70), which are consistent with the Wilkinson Microwave Anisotropy Probe third-year results in combination with other data (Spergel et al. 2007).

2. THE SAMPLE
2.1. The SMT Sample

To obtain a representative sample of nearby galaxies selected based on gas content and to explore their infrared properties, we begin from the most up-to-date ALFALFA survey catalog and look for counterparts in the WISE all-sky catalog to construct the parent sample. Compared to optical-selected samples, the ALFALFA is an H I–selected sample and thus represents a less evolved galaxy population.

The Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) Catalog provides all-sky image data in four infrared bands (3.4, 4.6, 12, and 22 μm), with an angular resolution of 6′.1, 6′.4, 6′.5, and 12′/0, respectively. WISE achieved 5σ point-source sensitivities of better than 0.08, 0.11, 1, and 6 mJy, respectively, in unconfused regions on the ecliptic in the four bands.

First, we cross-matched the ALFALFA α.40 catalog with the WISE all-sky catalog, and selected galaxies based on the following criteria: (1) signal-to-noise ratio (S/N) ≥ 5 for the W1 (3.4 μm), W2 (4.6 μm), and W3 (12 μm) bands of WISE, and S/N ≥ 3 for W4 (22 μm). Because W4 is much less sensitive than other bands, and we are not using W4 in our analysis, we lower the requirement for the W4 band. (2) An object is defined as being the same object in both catalogs if the difference between its coordinates in the WISE catalog and the ALFALFA catalog is ≤ 3′. We obtained 5434 ALFALFA–WISE counterparts as a parent sample.

Second, based on this parent sample, we limited the distance of the sample to be in the range of 20–165 Mpc, and required that galaxies are covered by the GALEX Medium Image Survey (exposure time >1500 s).

Third, we selected infrared bright (W3 ≤ 10 and W4 ≤ 8) galaxies to ensure a high detection probability within a realistic integration time. The stellar masses of the sample, which were obtained from the MPA-JHU catalog,7 were then selected to be distributed in the range of 109–1011 M⊙. Therefore we obtained 115 galaxies as candidates for observation. For these galaxies, we visually checked the optical images of these galaxies from SDSS to exclude those obvious interacting or merger systems, to ensure that the SMT telescope only obtained CO emission from the target galaxies. We used the W3 magnitude and H I linewidth to estimate the CO flux of the sample, and observed those relatively strong sources.

From this ALFALFA–WISE parent sample, 30 galaxies were selected and two other LIRGs were added for comparison. Hence there are 32 galaxies in the final SMT sample. Although the selection might bias the sample to gas-rich and/or infrared bright galaxies, these galaxies still span a range of more fundamental parameters, such as MHI , M HI , and M *, and most of them have stellar masses < 1010 M⊙, so that this sample can still fulfill our goal of focusing on intermediate-M * galaxies. We list the general information of the SMT sample in Table 1.

2.2. Literature CO 1–0 Data

Since a few molecular gas surveys were recently conducted, we combined our SMT sample, which was selected from the ALFALFA–WISE parent sample, with these surveys, so that we can compare the properties and/or relations of different galaxies.

COLD GASS (CO Legacy Database for the GASS; Saintonge et al. 2011a; Catinella et al. 2012) is a molecular gas survey in nearby massive (M * ≥ 1010 M⊙) galaxies. By measuring CO 1–0 with the IRAM 30 m telescope, they have provided the MHI for 366 galaxies, 194 of which were treated as secure CO 1–0 detections (S/N ≥ 5).

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8 The SMT is operated by the Arizona Radio Observatory (ARO), Steward Observatory, University of Arizona.

9 http://www.mpa-garching.mpg.de/SDSS/
AMIGA is another galaxy survey in nearby isolated galaxies, which aimed to address the environmental effects on the cold gas content of galaxies. Lisenfeld et al. (2011) has provided CO 1–0 data for 273 AMIGA galaxies, which deviates from its value in DR7 ($z_{\text{test}} = 13.1^{\text{mag}}$) as other galaxies’ $z$-band magnitudes, which are all brighter than 16$^{\text{mag}}$. After inspecting the SDSS images of AGCNr 4584, we found that the photometric position of this galaxy has been shifted in DR9 (and DR8) but is not in the galactic nucleus, which may be the reason for the abnormal photometry. Thus for AGCNr 4584, we adopt its data from DR7 instead of DR9.

We also searched in the GALEX GR6/7 catalog and found GALEX counterparts for 27 SMT galaxies and 223 AMIGA–CO galaxies. For the AMIGA–CO sample, 9% SDSS counterparts and 28% GALEX counterparts have angular separation larger than 3′, but we performed a visual inspection and ensured that they are the genuine counterparts and are not contaminated by nearby galaxies. In fact, since the AMIGA sample are all isolated galaxies, mismatch and/or contamination is not likely for nearly all the AMIGA–CO galaxies. The NUV magnitudes are corrected for Galactic extinction following Wyder et al. (2007).

3. SMT OBSERVATION AND DATA REDUCTION

In order to construct a multi-wavelength data set for comprehensive analysis and comparison with the COLD GASS and AMIGA–CO, we have collected SDSS and GALEX data for both the SMT sample and the AMIGA–CO sample.

The newest SDSS data release SDSS-III DR9 (hereafter DR9), have provided more valuable images and photometric measurements in the $ugriz$ bands. We run a query with our SMT sample and the AMIGA–CO sample in DR9, and obtained photometric magnitudes ($ugriz$, extinction corrected) and morphological parameters (R90 and R50) for 30 SMT galaxies and 186 AMIGA–CO galaxies. Since extended sources are probably “deblended” in the SDSS photometry process (Huang et al. 2012), we check the SDSS flags for each galaxy to make sure that they are the “brightest child” photometric object extracted from the galaxy.

The SMT observations were carried out in 2012 December. We spent 59 hr in total, including ~40% overhead, to observe CO 2–1 ($\nu_{\text{rest}} = 230.538$ GHz) toward 32 galaxies. We used the Forbes Filter Bank system, which provides 1 MHz per channel and 1024 channels in total, corresponding to a velocity coverage of 1300 km s$^{-1}$ bandwidth for each polarization. During the observations the typical system temperature was less than 300 K. Each galaxy was integrated until CO 2–1 was detected or three hours integration time was reached. Beam Switch mode with a 2′ throw was used and pointing and focus were checked every 1.5 hr using DR 21. Saturn was used for flux calibration. The half-power beamwidth (HPBW) of the SMT at this frequency is about 3′.

The data were reduced with the c1as package of the g1das package. Poor scans and bad channels were flagged, and a three-degree polynomial baseline was fitted to subtract the unstable baseline from each spectrum. The rms noise level of each averaged spectrum of the sample target was obtained at a velocity resolution of 11–21 km s$^{-1}$, based on the linewidth of each galaxy.
The velocity-integrated intensities of CO 2–1 are calculated using

\[ I = \int_{\Delta V} T_{mb} dv, \]  

where \( T_{mb} \) is the main beam brightness temperature, and \( \Delta V \) is the velocity range used to integrate the intensity. Molecular line intensity in antenna temperature \( T^*_a \) is converted to main beam temperature \( T_{mb} \) using \( T_{mb} = \eta_{eff} T^*_a \), where the efficiency factor \( \eta_{eff} = F_{eff}/B_{tot} = 77\% \) (\( F_{eff} \): forward efficiency; \( B_{tot} \): beam efficiency) was measured in the flux calibration. The peak \( T_{mb} \) of the sample is in the range between about 3 and 80 mK. The basic measured results of the SMT sample, including their rms, linewidth, and integrated intensities, are listed in Table 2.

The CO 2–1 spectra of the 32 galaxies obtained by SMT are shown in Figure 7 in the Appendix. Only one galaxy AGCnr 171860 was a non-detection, and the 3 \( \sigma \) of its CO integrated intensity and a rms noise level of the smoothed spectra.

### 3.1. Calculation of \( M_{H_2} \) and \( M_\ast \)

The total molecular gas of a galaxy is computed using

\[ M_{H_2} = \alpha_{CO} L'_{CO}, \]

and the CO line luminosity is calculated following Solomon et al. (1997):

\[ L'_{CO} = 3.25 \times 10^7 S_{CO} \Delta V v_{obs}^2 D_L^2 (1 + z)^{-3}, \]

where the CO line intensity \( S_{CO} \Delta V \) is in units of Jy km s\(^{-1}\), the observing frequency \( v_{obs} \) is in GHz, the luminosity distance \( D_L \) is in Mpc, and \( L'_{CO} \) is in K km s\(^{-1}\) pc\(^2\).

We adopt a CO 2–1/CO 1–0 line ratio (R21) of 0.7, and a CO(1–0)-to-H\(_2\) conversion factor of \( \alpha_{CO} = 4.35 M_\odot \) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\), equivalent to \( X_{CO} = 2 \times 10^{20} \) cm\(^{-2}\) (K km s\(^{-1}\))\(^{-1}\), which are consistent with those used in COLD GASS and AMIGA–CO, as well as recent studies of resolved star-forming regions in nearby galaxies (Leroy et al. 2013). For more detail about R21 and \( \alpha_{CO} \) in nearby galaxies, we refer the readers to Leroy et al. (2013) and Sandstrom et al. (2013). All the molecular gas masses in this paper include a factor of 1.36 correcting for the presence of heavy elements (mostly helium). Although the \( M_{H_2} \) could not be directly compared with that derived from CO 1–0, the HERACLES survey (Leroy et al. 2013; Sandstrom et al. 2013) has demonstrated that CO 2–1 is robustly able to trace global molecular gas.

The mean error brought by the line measurements itself is about 10%, and other error sources include calibration errors (flux, pointing), missing CO flux due to the finite dish aperture, and the uncertainty of \( \alpha_{CO} \). Bolatto et al. (2013) summarized an uncertainty of \( \pm 0.3 \) dex (a factor of two) for \( \alpha_{CO} \) in the disks of normal, solar metallicity star-forming galaxies. Therefore the total error on \( M_{H_2} \) is about 0.4 dex. We do not adopt an aperture correction for this SMT sample, since the angular sizes of the galaxies were carefully selected so that the SMT beam could effectively cover the CO emission region (their half-light radii are listed in Table 1), as the CO-emitting size is generally proportional to the optical size of disk galaxies (Lisenfeld et al. 2011).

We calculate the stellar masses with the spectrum energy distribution (SED) fitting code kcorrect (ver. 4.2; Blanton & Roweis 2007). Provided a set of photometric data (in our case ugriz magnitudes), this code returns stellar masses fitted from galaxy templates that are based on stellar population synthesis models (Bruzual & Charlot 2003) using the Chabrier (2003) stellar initial mass function. For consistency we used this method to recalculate \( M_\ast \) for those SMT galaxies and the AMIGA–CO sample that have available SDSS DR9 data, and the results of the SMT sample are consistent with those provided by the JHU-MPA catalog. The COLD GASS survey has provided \( M_\ast \), 101985, 241492, 242440. It is unlikely that the H\(_2\) and H\(_i\) are spatially inconsistent, so instead we suggest that such offsets between \( V_{H_2} \) and \( V_{CO} \) at least partially result from observational uncertainties.

Figure 7 also shows that, for some SMT galaxies, especially those with large linewidths, their CO 2–1 spectra exhibit some structures, such as offset peaks and/or multiple peaks (e.g., AGCnr 463, 1629, 9172, 10384). Although we do not have spatially resolved CO images for these galaxies, their spectra do reflect the clumpy distribution of \( M_{H_2} \), in late-type galaxies, and the offset CO peaks suggest that \( M_{H_2} \) may be located in circumnuclear regions and/or spiral arms in the form of giant molecular clouds, which is consistent with that revealed by imaging surveys (e.g., Rahman et al. 2012).
data. $M_{H_1}$, $M_*$ of the SMT sample are listed in Table 2. The stellar mass for the 186 AMIGA–CO galaxies will be available online at the VizieR Web site.

4. RESULTS AND DISCUSSION

4.1. Sample Comparison

Among all kinds of galactic parameters, stellar mass ($M_*$) is the most fundamental and important one. The history of galaxy evolution is accompanied by the formation of stars from molecular gas and the accumulation of stars. Therefore, $M_*$ is the first parameter discussed in the following sections along with $H_1$ and $H_2$ . We use NUV $− r$ as an indicator of star formation activity, as it is well correlated with the specific star formation rate ($sSFR$). The third parameter used in our analysis is WISE color $W3 − W2$, which is similar to NUV $− r$ but less affected by dust attenuation.

First of all, we compare our SMT sample with the AMIGA and COLD GASS samples to explore their difference in physical properties. Figure 1 shows the distributions of their stellar masses ($M_*$), concentration indices ($R_{90}/R_{50}$) and NUV $− r$. Comparing all galaxies from the three samples and including those undetected in CO, we find a few differences between the samples. First, the SMT sample is very similar to the AMIGA especially in $M_*$ and $R_{90}/R_{50}$ distributions, although its NUV $− r$ colors are slightly bluer than that of AMIGA on average, and AMIGA included a small portion of galaxies with red NUV $− r$ colors. Second, the COLD GASS galaxies show properties that are distinct from the SMT and AMIGA samples, in that they are not only more massive ($M_* \geq 10^{10}\,M_\odot$), but also tend to be more bulge dominated (higher $R_{90}/R_{50}$ values) and redder in NUV $− r$. However, if we only compare those galaxies with secure CO detections (thicker histograms in Figure 1), the differences between the three samples become less prominent, since most of the undetected galaxies are red and budge dominated. The NUV $− r$ distribution shows that COLD GASS contained some red galaxies, which are probably in accordance with those in the middle panel that have high $R_{90}/R_{50}$ values. These undetected galaxies should be early-type massive galaxies that have a predominant stellar bulge, and should be quiescent in star formation since they contain little molecular gas.

Figure 2 shows the normalized distributions of $M_{H_1}$ and $M_{H_1}$ of the three samples. It is interesting to see that although they share a common distribution in $M_{H_1}$, their $M_{H_1}$ distributions are different. The highest $M_{H_1}$ in each sample is similarly

Figure 1. Normalized distributions of stellar mass $M_*$, concentration indices $R_{90}/R_{50}$, and NUV $− r$ color of the three samples used in this paper. Blue dotted histograms represent the COLD GASS survey of massive galaxies ($M_* \geq 10^{10}\,M_\odot$). Red solid and green dashed histograms represent the SMT and AMIGA–CO samples, respectively. The histograms of thin lines denote the entire sample, while thicker histograms denote only those galaxies with secure CO detections ($S/N \geq 5$). For clarity, in the first panel SMT and COLD GASS samples are slightly offset with respect to the AMIGA sample.

Figure 2. Normalized distributions of molecular gas masses ($M_{H_1}$) and atomic gas masses ($M_{H_1}$) of the three samples used in this paper. Blue histograms represent the COLD GASS survey of massive galaxies ($M_* \geq 10^{10}\,M_\odot$). Red solid and green dashed histograms represent our SMT sample and the AMIGA sample, respectively. COLD GASS has a narrower $M_{H_1}$ distribution, and the three samples are similar in $M_{H_1}$ distribution at $\sim 10^{10.2}\,M_\odot$, but the COLD GASS galaxies have a higher mean $M_{H_1}$ and a narrower $M_{H_1}$ distribution. Looking into the samples and we found that, among all the galaxies studied in this paper, only seven galaxies with $M_{H_1} < 10^{8.5}\,M_\odot$ are massive galaxies ($M_* \geq 10^{10}\,M_\odot$). So the reason we do not see low $M_{H_1}$ ($<10^{8.4}\,M_\odot$) in the COLD GASS sample is because $M_*$ is proportional to $M_{H_1}$, and those galaxies with low $M_{H_1}$ are most likely low-$M_*$ galaxies that were missed by the COLD GASS sample, and such galaxies can only be studied when samples are extended down to the low-$M_*$ regime. On the other hand, the lower panel of Figure 2 shows that, although the three samples have different $M_*$ distributions, they appear to show similar $M_{H_1}$ distributions. As a consequence, our SMT sample and the AMIGA–CO sample span a wider $M_{H_1}$ range than the COLD GASS did, and such a difference will play a role in our analysis of the $M_{H_1}/M_{H_1}$ ratios (Section 4.3).

4.1.1. WISE Color Diagram

The WISE all-sky near-to-middle infrared catalog with high sensitivity provides large and homogenous samples for
exploring the relationship between gas (H$_2$ and H$_1$) and the infrared emission of galaxies. Here we compare the infrared properties of the three samples derived from the WISE catalog.

In Figure 3, we plot the color–color diagram (W1 – W2 as a function of W2 – W3) for the whole combined sample, including those sources with only tentative or non-detection of CO. With the annotation of different kinds of sources on the diagram (see Wright et al. 2010), it is obvious that those galaxies without significant CO detection are more likely ellipticals, and they tend to have “bluer” W2 – W3 colors (W2 – W3 $\lesssim$ 2). In contrast, for galaxies detected in CO, there is a good consistency in WISE colors of massive galaxies and intermediate-$/M_*$ galaxies, in that they are confined in a quite small area on the diagram. The CO-detected galaxies tend to be “redder” in W2 – W3 color, and such a difference resembles that in the NUV – $r$ color (Figure 1). The W2 – W3 color has been suggested to be a useful star-forming indicator (Donoso et al. 2012), in the context that the W4 band is much less sensitive compared to the other bands, so W4 data would not be available for as many galaxies as the other three bands. In fact, we found that the detection rate of CO has good correspondence with the W3 S/N, i.e., for both COLD GASS and AMIGA–CO. Among those galaxies with CO S/N $\geq$ 5, only two sources have W3 S/N $<$ 10.

In the COLD GASS sample, three galaxies can be classified as active galactic nuclei (AGNs), based on the WISE color criteria, W1 – W2 $> 0.8$, which has been demonstrated to be capable of selecting strong AGN QSOs (Yan et al. 2013). Moreover, eight COLD GASS galaxies were classified as ULIRGs (two of them are also AGNs based on the W1 – W2 criteria), and this diagram shows that these AGN ULIRGs have nearly the reddest IR colors among the whole combined sample, since their IR SED peaks toward longer wavelength due to the contribution of hot dust emission originated from an AGN or intense starburst. Because the IR emission in AGN host galaxies is severely contaminated, and deviates from normal galaxies whose IR emission is mainly contributed by stellar populations, we exclude these AGNs in the discussion of the relation between molecular gas and IR luminosities.

4.2. Gas Fraction Scaling Relations

In Figure 4, we plot the scaling relations between gas fraction $M_{gas}/M_*$ (in this paper it refers to $f_{H_2}$ $\equiv M_{H_2}/M_*$ and $f_{H_1}$ $\equiv M_{H_1}/M_*$) and several galactic properties, $M_*$, NUV – $r$, and W3 – W2 colors, for our SMT sample, the AMIGA–CO sample, and the COLD GASS sample. Compared to AMIGA and COLD GASS, our SMT observations have provided a well-selected sample that extends to the lower stellar mass regime. To explore the relationship between WISE infrared color and gas fractions, and to compare the infrared color with NUV – $r$, we use the color W3 – W2 so that it is consistent with the optical color NUV – $r$, in the sense that galaxies with greater W3 – W2 values correspond to “red,” indicating that the emission is dominated by the old stellar population, while “blue” indicates that the emission is dominated by young stars arising from ongoing star formation. Note the difference from the traditional form W2 – W3 used in Figure 3 and the literature (e.g., Donoso et al. 2012). The Spearman correlation coefficients are shown on each panels.

In Figure 4(a1) we plot $f_{H_2}$ as a function of $M_*$, and in Figure 4(a2) $f_{H_1}$ as a function of $M_*$ (in log–log scale). Combining the different samples allows the relation between $f_{H_2}$ and $M_*$ to be explored in the range between $M_* \sim 10^8 M_\odot$ and $10^{11.5} M_\odot$. These two panels show two major differences between $f_{H_2}$ and $f_{H_1}$. First, $f_{H_1}$ obviously increases with decreasing $M_*$, and in the low-$M_*$ end $f_{H_1}$ can reach as high as almost 10, while $f_{H_2}$ is always lower than unity. In the massive galaxies $f_{H_1}$ significantly decreases with increasing $M_*$, but in low to intermediate $M_*$ galaxies the mean $f_{H_2}$ seems unchanged (see the following paragraph). Such a difference indicates that in low-mass systems, most of the gas mass is in the form of H$_1$, while $M_{H_2}$ is always less than the $M_*$. Second, log $f_{H_1}$ anti-correlates much better with log $M_*$ than does log $f_{H_2}$. In the stellar mass range between about $10^8 M_\odot$ and $10^9 M_\odot$, $f_{H_2}$ decreases with increasing $M_*$ with a universal slope and the correlation is quite prominent ($r_s = -0.72$ for the entire sample), while in Figure 4(a1) the scatter is larger, and the Spearman coefficient is lower ($r_s = -0.48$). It is intriguing to notice that the scatter of the COLD GASS sample in panels (a1) and (a2) are quite similar, and the two figures are mainly different in the low to intermediate $M_*$ galaxies, which may imply that the properties of cold gas content change quickly in galaxies of intermediate $M_*$, likely accompanying the transitions from H$_1$ to H$_2$.

To check the mean relations for the intermediate-$M_*$ sample in Figures 4(a1) and (a2), we also plot the bin-averaged log $f_{H_1}$ and log $f_{H_2}$ (magenta squares), with nearly the same amount of sources in each $M_*$ bin. It is interesting that the averaged $f_{H_1}$ in low-mass galaxies ($M_* < 10^{10} M_\odot$) seem unchanged, while the decreasing trend of the averaged $f_{H_2}$ with increasing $M_*$ is more prominent, with much smaller scatter. The results of COLD GASS survey showed that the trend of decreasing $f_{H_1}$ with increasing $M_*$ becomes steeper at $M_* > 10^{10.5} M_\odot$ (Tacconi et al. 2013 and references therein), and in our work the mean $f_{H_1}$ at $M_* \sim 10^{10} M_\odot$ is similar to that given by the COLD GASS (7%). The trend of increasing $f_{H_2}$ with decreasing $M_*$ is able to be extended down to $M_* \sim 10^8 M_\odot$, and thus we confirm that the trend becomes much shallower in lower mass galaxies. It is interesting that our result is not only consistent with that of the COLD GASS, but also agrees with the scenario predicted by semi-analytical models (Fu et al. 2012) that the $f_{H_2}$ in low-mass galaxies ($M_* < 10^{10.2} M_\odot$) do not differ much.

![Figure 3](image-url)
Figure 4. Scaling relations of gas fraction ($M_{H_2}/M_*$ and $M_{H_1}/M_*$) as a function of $M_*$, NUV – $r$, and W3 – W2 (12–4.6 μm), respectively. Red circles, green crosses, and blue dots represent our SMT sample, AMIGA–CO, and COLD GASS, respectively. Dark gray triangles and light gray open arrows show gas fraction upper limits of COLD GASS and AMIGA, respectively. Gray solid lines are the linear fitting of the SMT and AMIGA–CO combined sample, with the Spearman correlation coefficient $r_{S1}$ shown in each panel. Blue dashed lines are the linear fitting for the COLD GASS sample, with the Spearman correlation coefficient $r_{S2}$ shown in each panel. Only secure detections (S/N ≥ 5) are included in the fitting. In panels (a1) and (a2) the averaged log $M_{H_2}/M_*$ and log $M_{H_1}/M_*$ along with their scatters are shown with magenta squares, each bin having same the number of galaxies. While log $M_{H_1}/M_*$ is obviously higher in lower mass galaxies, the trend of increasing log $M_{H_2}/M_*$ with decreased $M_*$ is very weak.

Figure 5. Scaling relations of the gas ratio ($M_{H_2}/M_{H_1}$) as a function of $M_*$, and NUV – $r$ and W3 – W2, respectively. Red circles, green crosses, and blue dots represent our SMT sample, AMIGA–CO, and COLD GASS, respectively. The Spearman correlation coefficient $r_{S1}$ in each panel are for the SMT and AMIGA–CO combined sample, and $r_{S2}$ are for the COLD GASS massive sample. Since most of the galaxies in these plots are normal galaxies, it is natural to see a similarity in their moderate $f_{H_2}$, because high $f_{H_2}$ is likely to occur in LIRGs and/or starburst systems. Panel (a2) shows that our SMT sample selected from the ALFALFA catalog seems to follow the same relation between $f_{H_1}$ and $M_*$ as the other galaxies, although Huang et al. (2012) have demonstrated that the ALFALFA population is generally more gas-rich than other samples such as the GASS. The very high-$f_{H_1}$ in low-$M_*$ galaxies indicates that these systems had little integrated past star formation, and they have been very inefficient in converting their gas into stars (Huang et al. 2012; Blanton & Moustakas 2009). Because their H1 is more abundant than H2 (see Figure 5 and following discussions), we speculate that they were mainly inefficient in the process of converting H1 to H2 and forming molecular clouds.

In Figures 4(b1) and (b2), we explore how $f_{H_2}$ and $f_{H_1}$ relate to the NUV – $r$ color, respectively. Since UV emission originates from young stars and $r$-band emission is mainly contributed by old stars, NUV – $r$ is strongly correlated with $sSFR$ (Huang et al. 2012), and hence is a good tracer of star-forming activities. It is natural to see in panels (b1) and (b2) that $f_{H_2}$ and $f_{H_1}$ both depend on NUV – $r$, and that $f_{gas}$ is...
obviously higher in blue galaxies. First of all, compared with Saintonge et al. (2011a), we have provided in panel (b1) more low-\( M_\ast \) galaxies that are bluer in NUV \(-\) r. Although in low-mass galaxies the dust-to-gas ratio is suggested to be less due to their lower gas-phase metallicities (Blanton & Moustakas 2009), we do not see any significant difference between the samples in the relation between \( f_{H_2} \) and NUV \(-\) r. With respect to the red end, Saintonge et al. (2011a) have found that in COLD GASS galaxies the CO detection rates significantly dropped at NUV \(-\) r \(\gtrsim 5\), which implied a \( f_{H_2} \) threshold and very little \( H_2 \) content in those red and quiescent systems. Second, we show in Figure 4(b2) that in the bluest star-forming galaxies, the decreasing trend of \( f_{H_2} \) with NUV \(-\) r is steeper than that in the red galaxies, which are mostly massive. This is consistent with the result of Catinella et al. (2012) that H\( i \)-rich galaxies deviate from the mean relation defined by galaxies with “normal” H\( i \) content, and the reason for this deviation and the scatter might be the scenario that the UV emission in red galaxies is contributed by more evolved stellar populations, and their UV emission might not be well associated with H\( i \). Another reason of the non-linearity was some of the galaxies with very low gas fractions were missed in the GASS survey (Catinella et al. 2012), and panel (b2) shows that our sample provides more galaxies with higher \( f_{H_2} \), thus the non-linearity is more obvious. Third, it is interesting that log \( f_{H_2} \) correlates with NUV \(-\) r better than log \( f_{H_1} \). It is probably because \( H_2 \) resides in the central region of galaxies, where UV emission is easily absorbed due to dense dust content, while on the other hand H\( i \) dominates the outskirt of galactic disks, where most of the UV emission can be observed (Saintonge et al. 2011a).

To address this issue, in Figures 4(c1) and (c2) we plot \( f_{H_1} \) and \( f_{H_2} \) as a function of WISE infrared color W3 \(-\) W2, which is another color parameter but it is much less affected by dust attenuation than NUV \(-\) r or other optical colors. The W2 (4.6 \(\mu\)m) near-infrared band is a good tracer of stellar mass, and W3 (12 \(\mu\)m) mid-infrared band covers the 11.3 \(\mu\)m polycyclic aromatic hydrocarbon (PAH) and can also be contributed by the dust continuum emission at 12 \(\mu\)m. NUV \(-\) r has been widely used to indicate galactic star formation activities and classify galaxies into blue cloud or red sequence, and W2 \(-\) W3 color has also been suggested to be a good star formation indicator (Donoso et al. 2012). Here we compare their relations with \( f_{H_1} \) and \( f_{H_2} \). Panel (c1) shows a clear correlation between \( f_{H_1} \) and W3 \(-\) W2, and the dependence of \( f_{H_2} \) on W3 \(-\) W2 (\( r_s = -0.74 \)) is much stronger than that on NUV \(-\) r. Panel (c1) also shows that, most of the sources without positive CO detection are red in W3 \(-\) W2, and none of the galaxies with W3 \(-\) W2 \(> -1\) were detected. These “red” galaxies seem to lie above the relation defined by those “blue” galaxies, which might indicate that the \( f_{H_2} \) upper limits of the red galaxies were probably overestimated, which is consistent with that suggested by Saintonge et al. (2011a), where by stacking the undetected spectra they found a mean \( f_{H_2} \) less than 0.16\%. Figure 4(c1) allows us to confirm that the scatter between \( f_{H_1} \) and NUV \(-\) r is mainly caused by dust attenuation, and by introducing the new infrared color W3 \(-\) W2, we show that \( f_{H_1} \) has a better correlation with W3 \(-\) W2. Since the samples used in this work are mostly star-forming galaxies, their 12 \(\mu\)m emission is contributed by both PAH and dust continuum, which originate from current star-forming activities, while their W2 (4.6 \(\mu\)m) emission is mainly contributed by stellar components. In addition, the mass of their star-forming gas (dense molecular gas) should be proportional to the overall gas content traced by CO, and therefore we can see this strong correlation between \( f_{H_1} \) and W3 \(-\) W2.

Then, in Figure 4(c2), we plot log \( f_{H_2} \) as a function of W3 \(-\) W2, and the result shows that the COLD GASS sample appears to be distinct from the other two samples, and only in the COLD GASS sample does log \( f_{H_2} \) have a weak dependence on W3 \(-\) W2, whereas the scatter in the other two samples is much larger. There are some galaxies that tend to be redder than the mean relation (magenta squares), and compared to panel (a2) it is obvious that those offset sources are mainly low-mass galaxies. This may indicate the large diversity of star formation efficiencies in these low-\( M_\ast \) systems. On the one hand, as already mentioned above, there is a large amount of H\( i \) in some of the low-\( M_\ast \) systems but they have been inefficient in converting their H\( i \) into \( H_2 \) and stars, and since infrared emission originates from dust that mixes with both atomic and molecular gas (Bohlin et al. 1978), we do not see a good correlation between \( f_{H_1} \) and W3 \(-\) W2 in low-\( M_\ast \) galaxies. On the other hand, in massive galaxies, they have more consistent star formation efficiencies and consume the gas constantly; thus, we see a correlation between \( f_{H_2} \) and infrared color. Another possible explanation for the deviation of those high-\( f_{H_2} \) galaxies in panel (c2) is that in low-\( M_\ast \) galaxies there might be little PAH emission due to their low metallicities, and compared to massive galaxies more abundant in PAH, the W3 emission of low-mass systems would be contributed less by the 11.3 \(\mu\m) PAH, so they are prone to be redder.

In summary, the correlations between \( f_{gas} \) and the two colors, NUV \(-\) r and W3 \(-\) W2, are consistent with a galaxy evolution picture that low-mass galaxies are more gas rich and especially abundant in H\( i \), but they are more inefficient in converting their H\( i \) into \( H_2 \) molecular clouds than stars; in massive galaxies the star-forming efficiency is more consistent and there is less molecular gas since it has been consumed in forming stars, while the overall decreased gas amount causes a drop in the overall gas density, and reduces the rate of transforming H\( i \) into \( H_2 \), with a certain amount of gas remaining in the form of H\( i \), and some of the H\( i \) can be either replenished or accreted from the environment recently, if not expelled by the interaction between nearby galaxies.

### 4.3. H\( _2 \)-to-H\( i \) Gas Ratio

In the previous section, we discuss how the gas fractions \( f_{H_2} \) and \( f_{H_1} \) depend on galactic properties. It is also worth exploring the scaling relations between \( M_{H_2}/M_{H_1} \) and global physical parameters, because the relationship between \( H_2 \) and \( H_1 \) in galaxies is a fundamental question, yet how this relation is affected or regulated by other galactic properties is still unclear. As already discussed in Young & Scoville (1991) and recently in the AMIGA survey (Lisenfeld et al. 2011), the ratio of \( M_{H_2}/M_{H_1} \) declines in late-type galaxies because of more H\( i \) content in late-type galaxies than early-type galaxies (such as S0 and Sa Hubble types). Saintonge et al. (2011a) also found that log \( M_{H_2}/M_{H_1} \) decreases with increasing \( R_90/R_50 \), but the \( M_{H_2}/M_{H_1} \) ratio has quite a large scatter in different galaxies, although \( M_{H_2} \) is proportional to \( M_{H_1} \) as expected (Saintonge et al. 2011a).

In Figure 5, we plot the scaling relations between gas ratio (log \( M_{H_2}/M_{H_1} \)) and the same parameters used in Figure 4, \( M_* \), NUV \(-\) r, and W3 \(-\) W2. The plots show that the dependence of log \( M_{H_2}/M_{H_1} \) on these parameters is quite weak, and in the COLD GASS massive sample the scatter is large, characteristics that were already found in Saintonge et al. (2011a) and can be explained by the large scatter of log \( f_{H_2} \) and log \( f_{H_1} \) in
Figure 4. However, it is interesting to see in panels (a) and (b) that for our SMT galaxies, log $M_{\text{HI}}/M_{\text{H}_2}$ appears to correlate with log $M_*$ ($r_s = 0.4$) and NUV $- r$ ($r_s = 0.43$), although the color of the SMT sample tends to be blue (NUV $- r < 4$). The $M_{\text{HI}}/M_{\text{H}_2}$ ratio tends to be higher in more massive and/or relatively redder galaxies of the SMT sample. We do not find any significant correlation between log $M_{\text{HI}}/M_{\text{H}_2}$ and W3 $- W2$, which should be the result from the large scatter and the non-linear relation between $f_{\text{HI}}$ and W3 $- W2$. The $M_{\text{HI}}/M_{\text{H}_2}$ in the SMT sample are in the range of about 0.02–4.7, and only in the two LIRGs are their $M_{\text{HI}}/M_{\text{H}_2}$ greater than unity, indicating more $H_2$ than $H_1$, but in all the other normal galaxies the $M_{\text{HI}}$ is heavier than $M_{\text{H}_2}$. The trend in Figure 5 confirms what was suggested in the SINGS survey that $M_{\text{HI}}/M_{\text{H}_2}$ declined at lower $M_*$ (Blanton & Moustakas 2009). Also, $M_{\text{HI}}/M_{\text{H}_2}$ seems to increase in moderate NUV $- r$ color, due to the decreasing $f_{\text{HI}}$ in red galaxies that is shown in Figure 4(a2).

Considering Figure 5 with Figure 4 together, we speculate that, as $M_{\text{HI}}/M_{\text{H}_2}$ increases as increasing $M_*$ in lower $M_*$ galaxies, it is an implication of the dependence of $H_1$-to-$H_2$ transition on the $M_*$ cumulation in galaxies. In the history of galaxy evolution, consuming gas to form stars is accompanied by the accretion of surrounding diffuse gas that is mainly in atomic form ($H_1$), and star formation is also accompanied by the transformation from $H_1$ into $H_2$ (Krumholz 2013). In the early (young) stage, there was enough $H_1$ to be converted into $H_2$ than molecular clouds, wherein stars formed and the $M_{\text{HI}}/M_*$ fraction remained at a certain level (intermediate-$M_*$ in Figure 4(a1)); in a later stage, when a galaxy becomes more massive (in $M_*$) its sSFR (NUV $- r$) increases, and then its $H_1$ probably becomes deficient (Figure 4(a2)) as most of the $H_1$ was transformed into molecular clouds, and then the stellar mass kept growing but molecular gas fraction would decrease (massive galaxies in Figure 4(a1)). Despite the large scatter in our plots, this scenario of the evolution of $H_1$, $H_2$, and $M_*$ is a possible explanation of the plausible turnover of $f_{\text{HI}}$ at $M_* \sim 10^{10} M_\odot$. We should note two major sources of the large scatter in these relations: one is the different star-forming history and environment of different galaxies, and the other is the larger uncertainty of $\alpha_{\text{CO}}$, especially in different kinds of galaxies, which brings in large scatter in the conversion from CO flux to $M_{\text{HI}}$. Whereas COLD GASS used a different $\alpha_{\text{CO}}$ for the 12 ULIRGs (1.0 $M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$), the $M_{\text{HI}}$ of all the other galaxies in the combined sample was calculated based on a universal $\alpha_{\text{CO}}$. We do not discuss the details of the calibration of $\alpha_{\text{CO}}$ in different kinds of galaxies, such as nearby normal galaxies, dwarfs, or LIRGs, as other studies have been focusing on this topic (e.g., see Bolatto et al. 2013; Sandstrom et al. 2013). Therefore the large scatter we see in these scaling relations is largely intrinsic and thus might not be reduced easily at this stage.

4.4. The Relationship between $M_{\text{HI}}$ and 12 $\mu$m

The tight anti-correlation shown in Figure 4(c1) implies that $M_{\text{HI}}$ might be well correlated with 12 $\mu$m emission, since $M_*$ can be traced by the 4.6 $\mu$m (W2). In this section, we discuss the relation between molecular gas mass $M_{\text{H}_2}$, and the WISE 12 $\mu$m emission. Donoso et al. (2012) has found that 12 $\mu$m is a good tracer of star formation especially in galaxies, so to relate 12 $\mu$m with $M_{\text{HI}}$ is essentially the same question as the traditional Kennicutt–Schmidt (K-S) law, which related the SFR surface density ($\Sigma_{\text{SFR}}$) and gas surface density ($\Sigma_{\text{gas}}$) and has been one of the most important topics in astrophysics (Kennicutt 1998; Schmidt 1963; Kennicutt & Evans 2012). We will not go into detail on this complicate topic in this paper. Instead, we only discuss how $L_{12\mu m}$ relates to $M_{\text{H}_2}$, and to what extend can we use $L_{12\mu m}$ to trace $M_{\text{H}_2}$, at least for certain types of galaxies. Although the W4 band (22 $\mu$m) of WISE suffers from relatively poor sensitivity and sparse resolution, the W3 band data still have potential for the study of star formation in galaxies.

In Figure 6, molecular masses $M_{\text{HI}}$ are plotted as a function of $W3$ (12 $\mu$m) luminosities $L_{12\mu m}$. Including in panel (a) only those galaxies with high S/N in both CO 1–0 detection and W3 magnitude (S/N $\geq 5$), we find that log $M_{\text{HI}}$ is strongly correlated with log $L_{12\mu m}$ in all the samples. There are a few AGNs and (U)LIRGs of the COLD GASS sample (red and orange squares in panel (a)) that significantly deviate from the mean relation, which is probably because their near-to-mid infrared emission
is enhanced by the warmer dust temperature due to AGNs and/or intense starbursts. We excluded these AGNs and (U)LIRGs in the fitting, and panel (a) shows that the COLD GASS sample has a smaller scatter compared to the AMIGA–CO. This might be a result from the difference in the angular sizes of galaxies of the two samples. Since the COLD GASS limited the galaxy distance to being larger than 100 Mpc, galaxies that are too large for the observations are effectively excluded, and the aperture effect did not induce significant scatter in this plot, although some of the galaxies might still be larger than both the IRAM 30 m beam and the WISE aperture. On the other hand, the AMIGA sample suffers from the aperture effect because of the smaller distances of galaxies and different instruments used in the CO observations. First, the AMIGA included very nearby galaxies as close as a few Mpc, and since the WISE W3 band photometry was performed with finite apertures (the maximal aperture adopted is ∼25″), the data for those very nearby galaxies only covered a small portion of the galaxy, and hence larger uncertainties in both their CO and 12 μm fluxes, which were very likely underestimated. Second, the AMIGA compiled the CO sample with data from different telescopes with different HPBW (21″ for the IRAM 30 m, and 45″ for the FCRAO 14 m, respectively), and the W3 photometry aperture is much smaller than the HPBW of the 14 m telescope so the W3 data were actually collected from smaller spatial regions than that of the CO data thus W3 emission was very likely underestimated.

In panel (a), we plot the AMIGA galaxies with different symbols according to the telescopes they were observed with, IRAM 30 m (green crosses), or FCRAO 14 m (green circles). Also the plot shows that the aperture effect causes most of the AMIGA galaxies that were observed with the 14 m telescope to be weaker in $L_{12\mu m}$, because the relatively small W3 aperture underestimated their $L_{12\mu m}$, and some AMIGA galaxies that were observed with the 30 m galaxies tend to have smaller $M_{H_2}$ because the small beam of the 30 m telescope underestimated their CO fluxes. These two aspects of the AMIGA–CO sample together caused large scatter in panel (a), but the overall correlation between log $M_{H_2}$ (derived from CO 1–0) and log $L_{12\mu m}$ is still quite strong (Spearman coefficient $r_s = 0.90$). A least-squares linear fit for Figure 6(a) yields

$$\log M_{H_2}(CO_{1-0}) = (0.88 \pm 0.03)\log L_{12\mu m} + (1.49 \pm 0.27)$$

with a correlation coefficient of $r = 0.88$.

Figure 6(b) shows the same plot for the SMT sample, whose $M_{H_2}$ was converted from the CO 2–1 data. The correlation turns out to be even stronger than that in panel (a). Although the sample size is smaller than the CO 1–0 sample shown in panel (a), our sample selection has excluded those galaxies that are interacting systems or are too extended for observation, and the result shows that such criteria effectively alleviate the aperture effect (see the Appendix for more discussion). A least-squares linear fit for Figure 6(b) yields

$$\log M_{H_2}(CO_{2-1}) = (1.03 \pm 0.06)\log L_{12\mu m} + (-0.12 \pm 0.48)$$

with a correlation coefficient of $r = 0.96 (r_s = 0.94)$. It is intriguing that the slope is very close to unity, suggesting that the $M_{H_2}$ traced by CO 2–1 is nearly proportional to $L_{12\mu m}$. This slope is slightly larger than that derived from CO 1–0 in panel (a), which can be contributed by two effects. The first effect might be the influence of the aperture effect. As mentioned above some galaxies in the CO 1–0 sample in panel (a) were too extended and the measurements of their $M_{H_2}$ and/or $L_{12\mu m}$ has large uncertainties, which might affect the fitted slope, while the SMT CO 2–1 sample suffers much less from the aperture effect since they were carefully selected. The second effect is probably the difference between the two CO transitions. Observations in nearby galaxies have provided a mean CO 2–1 to CO 1–0 line ratio $R_{21} = 0.7$ (Leroy et al. 2013), and CO 2–1 has been demonstrated to be a reliable $M_{H_2}$ tracer. However, the excitation condition in different galaxies would induce scatter in $R_{21}$, especially in galaxies with different star-forming activities. In more active star-forming galaxies, the $H_2$ is more abundant and the gas temperature is higher so the CO line would tend to be saturated, hence a higher $R_{21}$, while in quiescent galaxies if the temperature is very low (∼8 K) the CO 2–1 would be less excited and $R_{21}$ lower, thus their $M_{H_2}$ is possibly underestimated with CO 2–1. Therefore, this effect can cause the slope in Figure 6(b) to be higher, and we consider this the major influence.

This correlation resembles the K–S law, in which SFR can be calculated using total infrared luminosity $L_{IR}$, which is usually integrated from 12 μm to 100 μm IRAS data. So the correlation between $M_{H_2}$ and $L_{12\mu m}$ is anticipated, since in star-forming galaxies their infrared spectral energy is dominated by young stellar populations (Donoso et al. 2012). Moreover, the W3 band is very sensitive to PAH emission at 11.3 μm and amorphous silicate absorption (10 μm) in nearby star-forming galaxies (Wright et al. 2010). The 11.3 μm PAH emission was found to be spatially well correlated with CO emission in high-resolution observation toward nearby star-forming galaxies (Wilson et al. 2000), and Figure 6 shows a consistent relation on the global scale. Clemens et al. (2013) also suggested that the dust mass in a galaxy is proportional to its ISM content in general. One might expect that the WISE W4 band would improve this relation as 24 μm should trace star formation better than other near- or mid-infrared bands, but substituting W4 for W3 in Figure 6(b) does not improve the correlation, and shows larger scatter. We believe this is due to the fact that compared to the other three bands, the WISE W4 band suffers from much poorer sensitivity, sparser resolution, and sometimes saturated images, thus for the study of extragalactic subjects that require sensitive and accurate photometric measurements, W4 is not as useful as the other three bands.

The significance of this correlation between 12 μm emission and $M_{H_2}$ is that it indicates the potential application of W3 data in the prediction of molecular gas content of galaxies, which would be useful considering that WISE provides an all-sky catalog for galaxies and it is much more sensitive than IRAS, whose infrared catalog has been widely used in observations to predict CO flux. Although the ALFALFA catalog will have H1 data for up to ∼30,000 galaxies, large CO surveys today such as COLD GASS have only measured hundreds of galaxies because of current technical restrictions, and CO surveys toward galaxies are still needed for investigating the molecular gas scaling relations. WISE W3 data can provide CO flux estimation for observations, and can even provide $M_{H_2}$ prediction for the sake of statistics. Our results demonstrate that such predictions should be reliable at least for nearby star-forming galaxies selected from the ALFALFA–WISE matched sample. It should be noted that the sample used in our discussion are mainly star-forming galaxies, and careful treatment is still needed to verify whether this method of using $L_{12\mu m}$ to trace $M_{H_2}$ can be applied to other kinds of galaxies, such as early-type galaxies, as 12 μm PAH emission can also originate from old stellar population, and in those galaxies without significant star-forming activities,
the 12 $\mu$m emission will be likely dominated by such old stars. We also caution that PAH is not an unambiguous tracer of star formation and such correlation might actually reflect that these galaxies share similar properties at 12 $\mu$m, which is contributed by both dust continuum and PAH emission. It would be interesting to study the behaviors of W3 emission in a variety of galaxy samples. Further verification of this technique and its usage in the study of gas scaling relations in such a large sample will be addressed in future work.

5. SUMMARY

We selected a sample of 32 gas-rich normal star-forming galaxies from the ALFALFA–WISE matched sample, which span a stellar mass range $\sim 10^8$–$10^9$ $M_\odot$, and carried out CO 2–1 observations with the SMT 10 m telescope. We obtained a high CO 2–1 detection rate and only one galaxy without significant CO detection (see Figure 7). The calculated $M_{H_2}$ and $M_*$ are presented in Table 2.

CO 1–0 data are compiled from other galaxies surveys, the COLD GASS and AMIGA, and we use them along with our SMT sample to explore the gas scaling relations with $f_{W_1}$ and $f_{H_1}$. The AMIGA–CO sample has similar properties to our SMT sample, in the sense that they share common $M_*$, $R_{90}/R_{50}$, and NUV $- r$ distributions (Figure 1), so combining the SMT sample with the AMIGA–CO sample allows us to improve the sample size of low- to intermediate-$M_*$ galaxies ($M_* < 10^{10} M_\odot$), and can be compared with the COLD GASS massive sample ($M_* > 10^{10} M_\odot$). Since we include a number of galaxies of low $M_*$, the dynamical range in plotting the relation between $f_{W_1}$ and $M_*$ as well as other galactic properties is enhanced compared to the COLD GASS. Our main results include the following.

1. Bin-averaged $f_{W_1}$ and $f_{H_1}$ are derived for the whole sample, which shows that $f_{H_1}$ obviously increases in galaxies of lower $M_*$, while $f_{W_1}$ almost remains unchanged in low- to intermediate-$M_*$ galaxies ($M_* < 10^{10} M_\odot$). This result is consistent with that of COLD GASS at similar $M_*$ ($\sim 10^{10} M_\odot$), but we are able to extend it to lower $M_*$ regime. We also introduce a new parameter $W_3$ and $W_2$ and compare the scaling relations between $f_{gas}$ and two colors, NUV $-r$ and $W_3$ $-W_2$, which are all star-forming indicators (Figure 4). Our results show that while NUV $- r$ is anti-correlated with log $f_{H_1}$, $W_3$ $-W_2$ has a tighter anti-correlation with log $f_{H_1}$ than log $f_{W_1}$.

2. The gas ratio (log $M_{H_2}/M_{W_1}$) scaling relations are also explored, and they all show large scatter (Figure 5). This can be attributed to the scatter in the $f_{H_1}$, and/or $f_{W_1}$, scaling relations. Only in the SMT sample do we see correlations between log $M_{H_2}/M_{W_1}$ and log $M_*$ as well as NUV $- r$, namely, that more massive and/or redder galaxies have higher $M_{H_2}/M_{W_1}$.

3. We compare the relation between $M_{H_2}$ and infrared properties derived from the WISE catalog, and find an excellent correlation between log $M_{H_2}$ and log $L_{12\mu m}$, the 12 $\mu$m luminosity. The slope of the linear fittings of our SMT CO 2–1 sample is very close to unity (1.03 ± 0.06), while the slope in the CO 1–0 sample is slightly shallower (slope = 0.88 ± 0.03). Considering that WISE has provided all-sky data with high sensitivity and has significant overlap with the ALFALFA H_1 catalog, one can use this relation to predict CO flux for observations, or even estimate $M_{H_2}$ for a large amount of galaxies, at least for the ALFALFA–WISE matched sample, which is dominated by gas-rich star-forming galaxies. Note that this method might not be used in galaxies dominated by old stellar populations, since a significant part of the 12 $\mu$m emission would originate from old stars and thus no longer only trace young stars, which are tightly correlated with molecular gas.

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APPENDIX A

APERTURE EFFECT

Our study is affected by aperture effect from both the radio telescopes and WISE. On the one hand, the single-dish telescopes (IRAM 30 m, FCRAO 14 m, and SMT 10 m) mentioned above all have a finite aperture size (HPBW) and can only cover a portion of the CO emission from a galaxy observed if its angular size is significantly larger than the beam size of the dish. Thus for the majority of the sources, especially...
Figure 7. CO 2–1 spectra of the SMT sample (1). Source names from the ALFALFA are denoted in the upper left corner of each panel. The Gaussian profiles are only for reference but not used in the flux calculations.
Figure 7. (Continued)
those observed with the 30 m telescope whose HPBW was only 22" at 115 GHz, an aperture correction from the observed CO flux to total CO flux was necessary. In the latest COLD GASS data release and the AMIGA sample, they both assume that the radial distribution of CO and molecular gas is exponential, and for the CO scale length \( r_s \) correlates well with the optical radius at the 25 mag isophote, \( r_s = 0.2 r_{25} \). Thus the correction from the observed CO flux to the total flux based on this model can be calculated. The technical details of the aperture correlation method can be found in Lisenfeld et al. (2011) and Saintonge et al. (2012).

On the other hand, the standard photometry pipeline of WISE adopted a series of circular apertures to measure the magnitudes of a galaxy, and the maximum aperture size used is 24.75′. Thus, for some large galaxies their W3 will suffer from the same aperture issue, so the study of the relation between molecular gas and W3 relies on improved accurate photometry. However, since the angular sizes of the galaxies in our selected SMT sample is relatively suitable for both WISE and the SMT beam (33′ at 230 GHz) and could be effectively covered, we did not adopt this aperture correction for this sample, and Figure 6(b) already shows a very robust correlation. There is no deviation from the fitted line, and we confirmed that its enhanced overall fitting results even when it is included in the sample for statistics.

**APPENDIX B**

**SMT CO 2–1 SPECTRA**

Figure 7 shows the CO 2–1 spectra obtained by the SMT. The blue lines are Gaussian fitting for reference, which are not used in the CO flux calculations.

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