Molecular Gas in a Gravitationally Lensed Galaxy Group at $z = 2.9$

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Abstract

Most molecular gas studies of $z > 2.5$ galaxies are of intrinsically bright objects, despite the galaxy population being primarily normal galaxies with less extreme star formation rates. Observations of normal galaxies at high redshift provide a more representative view of galaxy evolution and star formation, but such observations are challenging to obtain. In this work, we present Atacama Large Millimeter/submillimeter Array $^{12}$CO(1 – 2) observations of a submillimeter selected galaxy group at $z = 2.9$, resulting in spectroscopic confirmation of seven images from four member galaxies. These galaxies are strongly lensed by the MS 0451.6-0305 foreground cluster at $z = 0.55$, allowing us to probe the molecular gas content on levels of $10^{9} – 10^{10} M_{\odot}$. Four detected galaxies have molecular gas masses of $(0.2 – 13.1) \times 10^{10} M_{\odot}$, and the nondetected galaxies have inferred molecular gas masses of <8.0 $\times$ 10$^{10} M_{\odot}$. We compare these new data to a compilation of 546 galaxies up to $z = 5.3$, and find that depletion times decrease with increasing redshift. We then compare the depletion times of galaxies in overdense environments with the field, finding that the depletion time evolution is steeper for galaxies in overdense environments than for those in the field. More molecular gas measurements of normal galaxies in overdense environments at higher redshifts ($z > 2.5$) are needed to verify the environmental dependence of star formation and gas depletion.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); High-redshift galaxies (734); High-redshift galaxy clusters (207); Star formation (1569); Strong gravitational lensing (1643)

Supporting material: figure sets

1. Introduction

Molecular gas is the fuel for star formation and is consequently a key parameter in determining how galaxies evolve. Although we have a deep understanding of the galaxy populations of today (see the review by Blanton & Moustakas 2009), observations of distant galaxies are important for us to infer how galaxies formed and evolved (Tacconi et al. 2020). A crucial cosmic epoch is the peak of cosmic star formation (Shapley 2011; Madau & Dickinson 2014).

High-redshift galaxies have historically been difficult to detect, relative to local galaxies, due to their distance. As such, detections of molecular gas in high-z star-forming galaxies are heavily biased toward the most extremely star-forming galaxies, which harbor copious amounts of molecular gas (e.g., Walter et al. 2004; Carilli et al. 2010; Riechers et al. 2010a; Danielson et al. 2011; Combes et al. 2012; Spilker et al. 2015; Miller et al. 2018; Tadaki et al. 2018; Ciesla et al. 2020; Spingola et al. 2020).

The vast majority of galaxies are not as strongly star forming as submillimeter galaxies (SMGs; Madau & Dickinson 2014). It is thus vital to characterize the molecular gas of distant normal galaxies in order to understand the representative mode of star formation. Significant progress toward this goal has been made since the advent of the Atacama Large Millimeter/submillimeter Array (ALMA), whose sensitivity has enabled studies that probe faint carbon monoxide (CO) emissions (a common tracer for molecular gas) in distant galaxies (e.g., review by Hodge & da Cunha 2020). However, obtaining CO detections of normal galaxies at $z > 2$ remains a challenge.

To date, only a few galaxy clusters with molecular gas mass measurements have spectroscopic confirmations, with the majority of them at $z < 2.5$ (Noble et al. 2017; Rudnick et al. 2017; Hayashi et al. 2018). These cluster galaxies also present a range of results on the gas content, with gas fractions ($f_{\text{gas}} = M_{\text{gas}}/(M_{\text{gas}} + M_{\text{s}})$), where $M_{\text{gas}}$ is the gas mass and $M_{\text{s}}$ is the stellar mass) and depletion times ($t_{\text{depl}} = M_{\text{gas}}/\text{SFR}$, where SFR is the star formation rate) varying by over an order of magnitude. In contrast, protoclusters discovered at $z > 4$ all contain massive starburst galaxies totaling SFRs of over 6000 $M_{\odot}$ yr$^{-1}$ in the entire protocluster (Miller et al. 2018; Oteo et al. 2018), which may suggest that $z = 2$–4 is a time of transition in the star formation of galaxy protoclusters.

A relevant and ongoing discussion relating to molecular gas in high-redshift galaxies is the environmental dependence of molecular gas properties like the gas fraction and depletion time. Generally, a high-density environment means that a
higher molecular gas content, and thus star formation, would be expected (Schmidt 1959). However, the dense environment also promotes more interactions between galaxies and facilitates processes such as ram pressure stripping and strangulation, which would reduce a galaxy’s gas content during their infall toward the cluster center (Mo et al. 2010). Some studies find evidence of higher molecular gas fractions in clusters than field-scaling relations (Noble et al. 2017; Hayashi et al. 2018; Gómez-Guijarro et al. 2019; Tadaki et al. 2019, for galaxies with stellar mass $10.5 < \log(M_*/M_\odot) < 11.0$). On the other hand, there is also evidence for similar molecular gas fractions between coeval cluster and field galaxies (Dannerbauer et al. 2017; Lee et al. 2017; Stach et al. 2017), and for the presence of massive galaxies, primarily near the center of clusters, which contain extremely low molecular gas fractions (Wang et al. 2018; Zavala et al. 2019). This molecular gas deficiency is attributed to quenching mechanisms that inhibit gas accretion or cooling; alternatively, the molecular gas may have been rapidly consumed or expelled (Man & Belli 2018, and references therein). However, most of these studies on the molecular gas content of cluster galaxies have been limited to $z < 2.5$ (Tacconi et al. 2020). Obtaining higher redshift observations of protocluster galaxies would shed light on the impact of an overdense environment on molecular gas, and how that evolves with time. The use of strong gravitational lensing makes it possible to detect galaxies that are otherwise too faint for spectroscopic follow-up. Previous studies have found success using lensing as a tool to probe galaxies with relatively low SFRs ($< 1000 M_\odot$ yr$^{-1}$), which are considered to be normal at $z > 2$ (Saintonge et al. 2013; Dessauges-Zavadsky et al. 2015, 2017).

In this paper, we present $^{12}$CO(J = 3 → 2) observations of a group of interacting normal star-forming galaxies at $z \approx 2.9$ in a giant submillimeter arc (Borys et al. 2004) lensed by the MS 0451.6-0305 foreground cluster (MacKenzie et al. 2014). The group is composed of nine sources, labeled Gals. 1–9 as in MacKenzie et al. (2014). We note that Gal. 9 is a foreground galaxy, and do not present an analysis of its CO content in this work. The total SFR, as derived from far-infrared (FIR) luminosity, of $450 \pm 50 M_\odot$ yr$^{-1}$ for the entire group is far lower than the SFR of known protoclusters at comparable redshifts; the protoclusters in Oteo et al. (2018), Miller et al. (2018), Wang et al. (2018), Gómez-Guijarro et al. (2019), and Zavala et al. (2019) have SFRs that range from $1400 M_\odot$ yr$^{-1}$ to over $6000 M_\odot$ yr$^{-1}$. Several of the background submillimeter sources in the group are multiply imaged due to the lensing, and have been observed at optical and radio wavelengths (Borys et al. 2004; Berciano Alba et al. 2007, 2010; Zitrin et al. 2010; Jauzac et al. 2020).

The environment, redshift, and SFR of the lensed sources make them valuable for investigating star formation in early protocluster galaxies. Using data from ALMA, we examine the molecular gas content of the sources and compare our results to a compilation of high-redshift galaxies. Using this compiled sample, we also discuss the impact of the environment and the redshift evolution of the depletion time, an important quantity in the discussion of molecular gas underpinning the future star formation potential of galaxies.

The layout of this paper is as follows. In Section 2, we describe the observations and data reduction. In Section 3, we analyze the CO observations and describe the calculation of molecular gas masses of the sources. In Section 4, we discuss our findings in the context of high-redshift galaxy evolution, compare the gas properties of our sources against a compilation of primarily CO-detected high-redshift galaxies, and consider the uncertainties in our results. A summary of this paper is presented in Section 5.

Throughout this paper, we assume a Kroupa (2001) initial mass function (IMF), a flat Lambda cold dark matter cosmology, a Hubble constant of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, and a density of nonrelativistic matter at $z = 0$ of $\Omega_M = 0.3$, in units of the critical density. At $z = 2.9$, 1″ corresponds to 7.78 kpc.

2. Observations

2.1. ALMA

Observations of MS 0451.6-0305 were performed with the ALMA 12 m array under the project code 2017.1.00616.S (PI: Allison Man). The 41 antennas were arranged in a compact configuration with baselines ranging from 14–783 m. The total on-source integration time was 64.08 minutes over two consecutive execution blocks on 2018 March 12–13. The precipitable water vapor during the observations was about 2.94–3.19 mm, J0423-0120 was used as a flux and bandpass calibrator, while J0501-0159 was used for phase calibration. The pointings were centered on Gal. 1b following the MacKenzie et al. (2014) naming convention. We used ALMA Band 3 in a mixed spectral setup to target the $^{12}$CO(J = 3 → 2) transition ($v_{\text{rest}} = 345.796$ GHz) at $z \approx 2.9$, the redshift of the lensed group. A spectral window was centered on 88.136 GHz covering a bandwidth of 1.875 GHz with 240 channels. The native channel width is thus 26.6 km s$^{-1}$.

The data were calibrated with the Common Astronomy Software Package (CASA version 5.4.0; McMullin et al. 2007) with pipeline version 42030. The data cube was imaged with natural weighting to optimize the signal-to-noise ratio with pipeline version 42030. The on-source integration time was 64.08 minutes over two consecutive execution blocks on 2018 March 12–13. The precipitable water vapor during the observations was about 2.94–3.19 mm, J0423-0120 was used as a flux and bandpass calibrator, while J0501-0159 was used for phase calibration. The pointings were centered on Gal. 1b following the MacKenzie et al. (2014) naming convention. We used ALMA Band 3 in a mixed spectral setup to target the $^{12}$CO(J = 3 → 2) transition ($v_{\text{rest}} = 345.796$ GHz) at $z \approx 2.9$, the redshift of the lensed group. A spectral window was centered on 88.136 GHz covering a bandwidth of 1.875 GHz with 240 channels. The native channel width is thus 26.6 km s$^{-1}$.

The data were calibrated with the Common Astronomy Software Package (CASA version 5.4.0; McMullin et al. 2007) with pipeline version 42030. The data cube was imaged with natural weighting to optimize the signal-to-noise ratio (S/N) of compact sources. The resulting synthesized beam is $1.81'' \times 1.28''$ corresponding to $14.08 \times 9.96$ kpc at $z = 2.9$, with a position angle of $-64.3^\circ$. We further bin the cube with the CLEAN task (Högbohm 1974) to a channel width of 100 km s$^{-1}$ to improve the S/N. The moment maps in Figure 1 are created with the non-primary-beam corrected cube, and the spectra are extracted from the primary-beam corrected cube. We measure different noises for each source, as the sources are spread out over the field of view.

2.2. HST

Hubble Space Telescope (HST) wide-field imaging observations of MS 0451.6-0305 are available in six optical or near-infrared (NIR) filters (Egami et al. 2010; Jauzac et al. 2020). The main purposes of using HST images for this work is to create an RGB image (Figure 1) and to identify the source positions for spectral extraction (Section 3.2). For these purposes, we use the deepest optical image (F814W) taken with the Advanced Camera for Surveys (ACS), and the two NIR images (F110W and F160W) taken with the Wide-Field Camera 3 (WFC3). Three epochs of ACS/F814W images are available (program IDs: 9836, 10493, 11591) for a total exposure time of 11438 s. The WFC3 F110 and F160W images each has exposure time of 2612s and 2412s, respectively (program ID: 11591). The individual exposures were retrieved from the Mikulski Archive for Space Telescopes website. For

11 https://archive.stsci.edu
each visit (i.e., a set of exposures of a target taken with an instrument and filter combination at each epoch), the absolute astrometry is aligned to stars in the Gaia DR2 catalog (Gaia Collaboration et al. 2018). The alignment of the HST images is done with seven Gaia DR2 stars within the HST footprint, six of which are matched to better than 20 mas. We have also compared the positional offsets of stars in the Pan-STARRS catalog PS1 (Chambers et al. 2016), which has a higher source density but lower astrometric precision than Gaia. For the 55 stars from Pan-STARRS PS1, the residual offset is 43 mas. Both of these values are smaller than the 60 mas size of one HST pixel. Standard imaging calibration procedure were applied with the grizli analysis software (Brammer 2019). The exposures per filter are combined into a mosaic and drizzled onto a common pixel scale of 0.06".

Figure 1. The central figure is a composite color image created using HST F160W, F110W, and F814W filters as the red, green, and blue channels, respectively. Overplotted in blue is the critical line of the lens model. The moment zero maps are created from the −200 to 200 km s$^{-1}$ channels of the non-primary-beam corrected cubes. The optimized extraction regions are indicated in the corresponding moment zero maps by the dotted black line. The solid white contours start from 2σ and go up in 2σ increments, and the dotted contours start from −2σ and go in 2σ increments, where σ is the rms noise. The ellipses in the bottom-left corners are the ALMA beam, which has FWHM major and minor axis sizes of 1.810" and 1.275" respectively, and a position angle of −64.3°. The spectra are extracted by spatially integrating the primary-beam corrected cube within the optimized extraction regions in all channels in the spectral window. Also included are cutouts of the HST image with the contour corresponding to the CO extraction aperture overlaid in white. Each cutout measures 6" × 6", corresponding to roughly 46 × 46 kpc on the image plane at z = 2.9. In each cutout, the up direction is north and the left direction is east.
### 3. Analysis and Results

#### 3.1. SFRs

The SFRs used in this paper are obtained from MacKenzie et al. (2014), who employed a forward-modeling approach in combination with Markov Chain Monte Carlo methods to simultaneously deblend and fit spectral energy distributions (SEDs) to the source galaxies whose emissions are blended together in a giant submillimeter arc. They made use of 450 μm and 850 μm data from the Submillimetre Common-User Bolometer Array-2, as well as Herschel Spectral and Photometric Imaging Receiver and Photodetecting Array Camera and Spectrometer data. The locations of HST candidate counterparts are used as priors for the source of submillimeter emissions during the SED fitting. By integrating the resulting SEDs, they obtain intrinsic FIR luminosities, which were converted to SFRs with the relation

$$\text{SFR} = 1.49 \times 10^{-10} \ M_\odot \ yr^{-1} L_{\text{FIR}} \ L_\odot^{-1}$$

from Murphy et al. (2011) with the assumption that UV radiation is completely absorbed by dust and reradiated at longer wavelengths. We refer the reader to MacKenzie et al. (2014) for a more detailed description of the procedures.

#### 3.2. Spectrum Extraction

High-redshift galaxies can have slight offsets between their optical/NIR and submillimeter positions due to different astrometry reference systems or intrinsic offsets between stars and gas. In our data, we note offsets in the locations of the HST peaks and the corresponding ALMA peaks. We explore reasons for the observed offsets in Section 4.4 and argue that the offsets are intrinsic, rather than astrometric.

We recalculate the HST locations by first creating an HST RGB image with the F160W, F110W, and F814W filters as the red, green, and blue channels, respectively. The galaxy is resolved into multiple substructures in the HST image. We then use a combination of cropping and brightness masking to isolate each source as best as possible before applying the same method to the RGB composites created using the F160W, F110W, and F814W filters as the red, green, and blue channels, respectively. ALMA source positions are determined by applying the same method to the −200 to 200 km s$^{-1}$ moment zero maps of the detected sources.

### Table 1

| Gal ID | R.A. J2000 | R.A. Err. (arcsec) | Decl. J2000 | Decl. Err. (arcsec) | R.A. J2000 | R.A. Err. (arcsec) | Decl. J2000 | Decl. Err. (arcsec) |
|--------|------------|--------------------|-------------|--------------------|------------|--------------------|-------------|--------------------|
| 1.a    | 04$^h$ 54$^m$ 13.415$^s$ | 0.014 | −3$^\circ$ 00' 42.708$''$ | 0.028 | ... | ... | ... | ... |
| 1.b    | 04 54 12.643 | 0.035 | −03 01 16.210 | 0.034 | ... | ... | ... | ... |
| 1.c    | 04 54 12.161 | 0.016 | −03 01 21.161 | 0.016 | ... | ... | ... | ... |
| 2.a    | 04 54 13.142 | 0.009 | −03 00 38.114 | 0.012 | ... | ... | ... | ... |
| 2.b    | 04 54 12.565 | 0.011 | −03 01 11.661 | 0.011 | 04$^h$ 54$^m$ 12.537$^s$ | 0.181 | −03 01 12.508$''$ | 0.181 |
| 2.c    | 04 54 11.777 | 0.042 | −03 01 19.872 | 0.020 | 04 54 11.841 | 0.182 | −03 01 19.688 | 0.181 |
| 3.a    | 04 54 13.033 | 0.009 | −03 00 38.943 | 0.015 | ... | ... | ... | ... |
| 3.b    | 04 54 12.670 | 0.026 | −03 01 08.755 | 0.037 | ... | ... | ... | ... |
| 3.c    | 04 54 11.452 | 0.016 | −03 01 21.404 | 0.016 | ... | ... | ... | ... |
| 4.a    | 04 54 12.812 | 0.009 | −03 00 38.957 | 0.011 | ... | ... | ... | ... |
| 4.b    | ... | ... | ... | ... | ... | ... | ... | ... |
| 4.c    | 04 54 11.020 | 0.014 | −03 01 22.074 | 0.015 | ... | ... | ... | ... |
| 5.a    | 04 54 12.793 | 0.018 | −03 00 44.066 | 0.024 | 04 54 12.807 | 0.195 | −03 00 44.083 | 0.199 |
| 5.b    | 04 54 12.665 | 0.061 | −03 01 01.168 | 0.044 | 04 54 12.690 | 0.183 | −03 01 01.726 | 0.183 |
| 5.c    | 04 54 10.911 | 0.040 | −03 01 24.290 | 0.019 | ... | ... | ... | ... |
| 6.a    | ... | ... | ... | ... | ... | ... | ... | ... |
| 6.b    | ... | ... | ... | ... | ... | ... | ... | ... |
| 6.c    | ... | ... | ... | ... | ... | ... | ... | ... |
| 7.a    | ... | ... | ... | ... | 04 54 12.934 | 0.183 | −03 00 55.158 | 0.182 |
| 7.b    | ... | ... | ... | ... | ... | ... | ... | ... |
| 7.c    | 04 54 11.105 | 0.012 | −03 01 26.296 | 0.006 | ... | ... | ... | ... |
| 8      | 04 54 10.542 | 0.029 | −03 01 27.061 | 0.019 | 04 54 10.577 | 0.182 | −03 01 27.319 | 0.181 |

Notes. The positions of the sources on the HST image are determined by using a least-squares fitting algorithm to fit a 2D Gaussian to HST cutouts where the sources are isolated as best as possible. The uncertainties are the errors on the estimated means (i.e., not the standard deviations) of the fitted Gaussians. The HST images are RGB composites created using the F160W, F110W, and F814W filters as the red, green, and blue channels, respectively. ALMA source positions are determined by applying the same method to the −200 to 200 km s$^{-1}$ moment zero maps of the detected sources.

- Calculated with Equations 7–9 from Schinnerer et al. (2010).
- The source is obscured by a foreground cluster galaxy (MacKenzie et al. 2014).
- The diffuse structure of the source makes it difficult to determine an HST position.
- Positions are only provided for detected galaxies. A position for Gal. 7.b is not provided as its shape is highly irregular and somewhat diffuse.

High-redshift galaxies can have slight offsets between their optical/NIR and submillimeter positions due to different astrometry reference systems or intrinsic offsets between stars and gas. In our data, we note offsets in the locations of the HST peaks and the corresponding ALMA peaks. The galaxies are isolated as best as possible before applying the same method to the −200 to 200 km s$^{-1}$ moment zero maps of the detected sources.
### Table 2
Star-gas Offset for Detected Galaxies

| Gal. ID | Offset (arcsec) | Position Angle (deg, east of north) | Offset (arcsec) | Position Angle (deg, east of north) |
|---------|-----------------|------------------------------------|-----------------|------------------------------------|
|         | Image plane     | Source plane                        |                 |                                    |
| 2.b     | 0.96±0.18       | 207±10                             | 0.25±0.11       | 98±11                              |
| 2.c     | 0.99±0.18       | 78±12                              | 0.25±0.12       | 93±18                              |
| 5.a     | 0.30±0.17       | 104±24                             | 0.14±0.11       | 95±27                              |
| 5.b     | 0.70±0.20       | 146±15                             | 0.25±0.07       | 80±12                              |
| 8       | 0.61±0.17       | 117±18                             | 0.33±0.14       | 128±27                             |

#### Note
The offsets and position angles are calculated from the HST locations to the ALMA locations (as given in Table 1). The estimates are obtained by perturbing the positions of each HST and ALMA pair with Gaussian noise with standard deviation equal to the position uncertainties 1000 times, calculating the offset and position angle each time, and then taking the median of the sampling distribution. The uncertainties on these estimates are difference between the median and the 16th and 84th percentile values from the sampling distributions.

best-fit Gaussians are also reported in Table 1. The offset between the HST and ALMA peaks for detected galaxies, where the CO emission is detected and both locations are unambiguous, are given in Table 2.

For each galaxy with reported offsets, both the HST and ALMA positions are passed through the MacKenzie et al. (2014) lens model along with their uncertainties to obtain corresponding positions and uncertainties on the source plane. From these source plane positions, we are able to calculate the offset and position angle on the source plane. These offsets also reported in Table 2, range from 0.14″–0.33″ and are statistically significant for all five sources.

Because of the HST-ALMA offsets, we do not extract spectra using apertures centered on the HST positions. Rather, we adopt the following procedure to identify the optimal extraction apertures for the $^{12}$CO($J = 3 \rightarrow 2$) spectra of each galaxy. We note that the nondetected galaxies have a different extraction procedure described later in the subsection.

For each source, we use an initial $6'' \times 6''$ extraction to create a velocity-integrated flux map (also known as moment zero map) centered at the HST position. This is done by integrating the velocity channels ranging from $-200$ to $+200$ km s$^{-1}$ around the peak of the $^{12}$CO($J = 3 \rightarrow 2$) emission as identified from the 1D spectrum, which is calculated by spatially integrating the same extraction. Contours of the local rms noise are also calculated and overplotted. This noise is calculated by fitting a 1D Gaussian to a histogram of a mirrored version of the negative flux values in a $60'' \times 60''$ moment zero map centered at the source. Examples of moment zero maps and contours are shown in Figure 1. Moment zero maps for all the galaxies are given in the figure set in Appendix B; an example of one of these figures is provided in Figure 5.

The contours are used to optimize the extraction region from which we obtain the spectra. We use these contours to perform a masking procedure, which we repeat at 0.2σ increments from 0σ–5σ, where σ is the rms noise as calculated previously. First, the primary contour corresponding to a given noise level (e.g., 2σ) is selected and used to indicate the spatial extent of the CO emission in the original cube. Note that there may be multiple disjoint contours at this noise level; only the primary contour which encloses the pixel with the maximum integrated flux is selected. The spectrum is then calculated by integrating the flux over the region within the contour in all channels in the spectral window. The S/N of this spectrum is defined as the flux in the peak channel over the rms flux of the spectrum with the peak channel removed.

Through this iterative process, we define an optimal extraction region (i.e., contour level) that maximizes the S/N of the spectrum. In Figure 1, the optimal extraction region of each source is given by the dashed black line in the moment zero maps, and by the (same) white line in the HST cutouts. We note that this procedure is robust with respect to the initial extraction—regardless of the initial cube position or size (given that the source is entirely contained within the cube), the optimal region will be extracted.

Each source was inspected to ensure that there were no false signals due to contributions from nearby sources. Sources with S/N > 3 as obtained by the described method were classified as a detection. The spectra of the detections, alongside the moment zero maps and HST composite thumbnails, are shown in Figure 1. Integrated spectra for all galaxies can be found in the figure set in Appendix C; an example of an integrated spectrum is given in Figure 6. The velocities of each spectrum are relative to the redshift of the respective galaxy as given in Table 3. The displayed spectra are the ones with the highest S/N over the different extraction regions for each source.

For the nondetected galaxies with S/N < 3 as calculated using the above procedure, we instead use a 1.5″ radius circular aperture centered at the HST location to extract a subcube. The sources were assumed to be unresolved, and the spectra were calculated at the pixel position that had the maximum flux density on the $-200$ to $200$ km s$^{-1}$ moment zero map.

For each of the galaxies (both detections and nondetections), we also checked to make sure that the contribution from the continuum was negligible. The $-200$ to $200$ km s$^{-1}$ channels of each spectrum were masked out, and the mean and rms noise of the resulting line-free spectrum were calculated. In each case, the mean was consistent with zero (i.e., the absolute value of the mean was less than the rms noise), indicating that the continuum emission is insignificant. We also create a continuum image with the remaining three spectral windows where no spectral line emission is expected. None of the sources were detected in this continuum at S/N > 5. The mean continuum noise at the location of the sources is 0.018 mJy, and an upper limit of 3σ = 0.054 mJy would be less than 10% of the maximum flux density in each spectra (i.e., the flux density in the channel with the peak of the line). Continuum images are shown in Appendix E; an example is shown in Figure 8.

#### 3.3. Molecular Gas Mass

For the detected galaxies with S/N > 3, each spectrum was fit with a 1D Gaussian model in order to obtain the $^{12}$CO($J = 3 \rightarrow 2$) line flux, which was then used to calculate the molecular gas mass. In order to quantify the uncertainty in the measurement, a Monte Carlo simulation was performed. Each spectrum was perturbed with Gaussian noise, centered at the observed intensity and with a standard deviation equal to the rms noise of the signal. We then fit a Gaussian function to each of the 500 simulated spectra to obtain a distribution of best-fitting parameters.

The FWHM for a Gaussian is related to its standard deviation σ by FWHM = 2√2 ln 2σ, and the line flux

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### Table 3
Molecular Gas Properties of Galaxy Images

| Gal ID | FWHM (km s\(^{-1}\)) | \(S_{\text{CO}(3-2)}\) (Jy km s\(^{-1}\)) | Rms \((\times 10^{-4} \text{ Jy beam}^{-1})\) | \(z^a\) | \(L_{\text{CO}(3-2)}^b\) \((\times 10^{10} \text{ K km s}^{-1} \text{ pc}^2)\) | Amplification\(^d\) | Delensed \(M_{\text{gas}}\) \((\times 10^{10} \text{ M}_\odot)\) | Delensed SFR\(^d\) \((\text{M}_\odot \text{ yr}^{-1})\) | \(t_{\text{age}}\) (Gyr) |
|--------|-----------------------|----------------------------------|-------------------------|------|----------------------------------|------------------|-------------------------|-------------------------|-------------------------|
| 2.b    | 260 ± 49              | 0.305 ± 0.038                    | 1.3                     | 2.9211 ± 0.0005                | 1.3 ± 0.2            | 8.1 ± 0.4                | 1.4 ± 0.2                | 99 ± 9                   | 0.14 ± 0.02             |
| 2.c    | 650 ± 131             | 0.248 ± 0.071                    | 1.0                     | 2.922 ± 0.003                  | 1.0 ± 0.3            | 6.1 ± 0.1                | 1.5 ± 0.4                | 99 ± 9                   | 0.15 ± 0.04             |
| 5.a    | 446 ± 264             | 0.503 ± 0.150                    | 3.2                     | 2.919 ± 0.001                  | 2.1 ± 0.6            | 5.3 ± 0.1                | 3.4 ± 1.0                | <35                     | <0.98                   |
| 5.b    | 712 ± 171             | 0.438 ± 0.088                    | 2.0                     | 2.923 ± 0.002                  | 1.8 ± 0.4            | 6.4 ± 0.1                | 2.5 ± 0.5                | <35                     | <0.71                   |
| 7.a    | 982 ± 890             | 0.155 ± 0.064                    | 1.0                     | 2.910 ± 0.006                  | 0.6 ± 0.3            | 33.0 ± 2.0               | 0.2 ± 0.1                | 11 ± 2                   | 0.15 ± 0.07             |
| 7.b    | 513 ± 487             | 0.278 ± 0.090                    | 1.6                     | 2.916 ± 0.001                  | 1.2 ± 0.4            | 45.0 ± 3.0               | 0.2 ± 0.1                | 11 ± 2                   | 0.20 ± 0.08             |
| 8      | 273 ± 34              | 0.633 ± 0.069                    | 2.6                     | 2.9065 ± 0.0002                | 2.6 ± 0.3            | 1.73 ± 0.04              | 13.1 ± 1.5               | 290 ± 40                 | 0.45 ± 0.08             |

#### Notes
- Table of values for the detections (top portion of the table) and nondetections (bottom portion). The delensed gas masses and SFRs are lensing-corrected values. The rest of the data are observed values. Unless otherwise specified, values given with uncertainties are the means and standard deviations from Monte Carlo simulations. Upper limits are 3σ upper limits.
- Redshifts for the detections are calculated from the CO detections. Redshifts for the nondetections are redshifts derived from the lensing model of MacKenzie et al. (2014) unless otherwise specified.
- Median \(z^a\) derived from VLT/X-SHOOTER spectrum of Gal.1.b (Man et al. 2021). The quoted lower and upper uncertainties are the differences between the median and the 16th and 84th percentiles, respectively.
- This is a spectroscopic redshift from Borys et al. (2004), derived from interstellar absorption lines.
- From MacKenzie et al. (2014) unless otherwise specified.
- Median SFR of Gal. 1.b from Man et al. (2021), adjusted to magnification \(\mu = 20\) from MacKenzie et al. (2014). The quoted lower and upper uncertainties are the differences between the median and the 16th and 84th percentiles, respectively.
The conversion of the 12CO(J = 3 → 2) transition ratio of k, where k is the peak intensity of the curve. The reported values and uncertainties for the peak frequency, FWHM line width, and flux in Table 3 are the means and standard deviations, respectively, of the Monte Carlo realizations.

For galaxies without a strongly detected 12CO(J = 3 → 2) emission, we derive upper limits on the line flux by assuming a boxcar line profile. The width of the profile was taken to be 400 km s$^{-1}$, which is slightly low relative to the median detection profile width of 512 km s$^{-1}$. The height of the profile was set at 3σ, where σ is the rms noise of the 1D spectrum. The resulting 3σ upper limits on the line fluxes for the nondetections are provided in Table 3.

We measure spectroscopic redshifts from the 12CO(J = 3 → 2), z_{CO}, which are more reliable than—but largely consistent with—the redshifts provided in MacKenzie et al. (2014) based on lensing predictions. Knowing that the rest frequency of the 12CO(J = 3 → 2) transition is ν_{rest} ≈ 345.796 GHz (Carilli & Walter 2013), we apply the equation ν_{obs} = ν_{rest} / (1 + z).

The intrinsic line luminosity L_{CO} is calculated using the following equation from Solomon et al. (1992), which has been modified to include the lensing magnification:

$$L'_{CO} = \frac{c^2 S_{CO} \Delta v}{2k} \frac{D_l^2}{\mu^2 \sigma_{obs}^2 (1+z)^3},$$

where k = 1.381 × 10^{-23} J K^{-1} is the Boltzmann constant, μ is the magnification of the object (with μ = 1 for unlensed sources and μ > 1 for lensed sources), D_{l} is the luminosity distance in megaparsecs, and ν_{obs} is the observed frequency of the emission in gigahertz.

This 12CO(J = 3 → 2) luminosity was converted to an equivalent 12CO(J = 1 → 0) luminosity with an assumed rotational transition ratio of L_{CO(3-2)} / L_{CO(1-0)} = 0.5 (Tacconi et al. 2013). The 12CO(J = 1 → 0) luminosity was then used to derive the molecular gas mass. We adopt a conversion factor of α_{CO} = 4.36 M_{⊙} (K km s^{-1} pc^{2})^{-1}, which accounts for the mass contribution from helium, following convention for Milky Way-like galaxies (Bolatto et al. 2013). See Section 4.5 for further discussion of the selection and uncertainty of the spectral line energy distribution (SLED) and the α_{CO} conversion factor. All of the resulting values are presented in Table 3. Note that the luminosity as defined above gives the intrinsic luminosity, whereas the values reported in Table 3 are observed (i.e., lensed) luminosities.

Since the sources are gravitationally lensed, we need to take into account the amplification factor for each image due to the lensing in order to calculate the delensed (intrinsic) molecular gas mass of each source. Although the amplification factor is given with respect to the flux density, all of the calculations necessary to go from flux density to the gas mass are linear in the relevant variables. Thus, we can directly apply the amplification factor to calculate the delensed gas mass.

We are aware of the revised lens model for the foreground cluster presented in Jauzac et al. (2020), which would impact both the SFR and the molecular gas mass. For consistency in the magnification factors used for M_{gas} and SFR and to ensure that the depletion times are not affected by magnification, we choose to use the original magnifications as given in MacKenzie et al. (2014). We note that although both M_{gas} and SFR are based on luminosities (L_{CO} and infrared luminosity L_{IR}, respectively), the scaling due to the change in magnification may not be equal between the two. This is due to the offsets between the CO emission and the SFR tracers, as described in Section 3.2. The different regions may be magnified differently by the foreground cluster, and thus one luminosity may be magnified more strongly than the other. We do not consider the effects of differential lensing in our analysis.

3.4. Spectrum Stacking

Each galaxy in the group, apart from Gal. 8, has three multiple images. We stack the spectra from the three multiple images in an attempt to increase the S/N. Each of the spectra are normalized by their respective magnifications (MacKenzie et al. 2014) so that the more strongly lensed sources do not inadvertently contribute more to the stacked result. In order to reduce the importance of noisier spectra, the stacking was done with an inverse-variance weighting (where the variances are also corrected for magnification), according to Equation 3:

$$S_i = \frac{1}{\sum_{i=1}^{3} \frac{1}{\text{Var}(S_i)}} \frac{1}{3} \sum_{i=1}^{3} \frac{1}{\text{Var}(S_i)} S_i,$$

where the index i = 1, 2, 3 corresponds to the “a”, “b”, and “c” multiple images, respectively. S_i is the i-th delensed spectrum (i.e., S_i = s_i / μ_i, where s_i is the i-th observed spectrum), Var(S_i) is the variance of the i-th delensed spectrum, and S_i is the stacked spectrum. The first term in the equation is a normalization term to ensure that the weights sum to 1.

For Galas. 2, 5, and 7, the stacking procedure increased the S/N over the maximum S/N of the constituent spectra (e.g., max S/N among Galas. 2.a, 2.b, and 2.c) by only a marginal amount. Furthermore, stacking the nondetected galaxies where none of the constituent sources were detected did not bring them over the S/N > 3 threshold.

As with the constituent sources, the stacked spectra are classified as a detection if S/N > 3, and the Gaussian fits are used to calculate the flux. Otherwise, a boxcar profile is used to estimate an upper limit for the flux in the same procedure as described in Section 3.3. The resulting gas properties derived from the stacked spectra are presented in Table 4.

4. Discussion

4.1. Star Formation in High-redshift Galaxies

The molecular gas and the SFR are in essence the amount of fuel available to a galaxy and the galaxy’s fuel consumption rate. The ratio between the two quantities provides an estimate for the molecular gas depletion time, which is the time that a galaxy will take to consume all of its currently available fuel at its present SFR, assuming there are no other causes of net change in the molecular gas mass.

Figure 2 shows the SFR as a function of molecular gas mass for the galaxies from this work, as well as from a compiled sample of over 500 galaxies, the majority of which are CO detected. This compilation is presented in Table 5 in Appendix A. The compilation includes normal galaxies and starbursts in various environments up to z = 5.3. The emphasis lies on the high-redshift (using z > 1 as the cutoff) normal galaxy population where the sources in this work belong. The only included study that does not target CO emission is Zavala et al. (2019), which presents dust continuum observations. However, this study provides a useful and relatively large sample of high-redshift normal protocluster galaxies as a point
Table 4
Properties of Stacked Galaxy Images

| Gal. ID | FWHM (km s \(^{-1}\)) | \(S_{\text{CO}(1-0)}\Delta v\) (mJy km s \(^{-1}\)) | Rms \((\times 10^{-4} \text{ Jy beam})\) | \(z_{\text{CO}}\) | \(L'_{\text{CO}(1-0)}\) \((\times 10^8 \text{ K km s}^{-1} \text{ pc}^2)\) | Delensed \(M_{\text{gas}}\) \((\times 10^8 \text{ M}_\odot)\) | Distance \(t_{\text{depl}}\) (Gyr) |
|---------|------------------------|---------------------------------|------------------|-------------|---------------------------|------------------|------------------|
| Detections |
| 2 | 279 \(\pm\) 33 | 37.705 \(\pm\) 3.625 | 0.13 | 2.9210 \(\pm\) 0.0004 | 1.58 \(\pm\) 0.15 | 1.36 \(\pm\) 0.13 | 0.14 \(\pm\) 0.01 |
| 5 | 694 \(\pm\) 143 | 83.385 \(\pm\) 12.426 | 0.34 | 2.921 \(\pm\) 0.001 | 3.50 \(\pm\) 0.52 | 3.01 \(\pm\) 0.45 | \(<0.86\) |
| 7 | 379 \(\pm\) 362 | 4.317 \(\pm\) 0.975 | 0.02 | 2.915 \(\pm\) 0.001 | 0.18 \(\pm\) 0.04 | 0.16 \(\pm\) 0.04 | 0.14 \(\pm\) 0.03 |
| Nondetections |
| 1 | \(\ldots\) | \(<9.429\) | 0.08 | \(\ldots\) | \(<0.39\) | \(<0.34\) | \(\ldots\) |
| 3 | \(\ldots\) | \(<50.107\) | 0.42 | \(\ldots\) | \(<2.12\) | \(<1.82\) | \(\ldots\) |
| 4 | \(\ldots\) | \(<33.357\) | 0.28 | \(\ldots\) | \(<1.41\) | \(<1.21\) | \(\ldots\) |
| 6 | \(\ldots\) | \(<35.120\) | 0.29 | \(\ldots\) | \(<1.47\) | \(<1.26\) | \(<0.24\) |

Notes. Properties derived from the stacked spectra. Values are all delensed/intrinsic values as the constituent spectra (e.g., Gals. 2.a, 2.b, and 2.c) have all been divided by their respective amplifications before the stacking procedure. Stacking was done with a inverse-variance weighted sum. The top section of the table provides values for the galaxies where two or more of the multiple images were detected in \(^{12}\)CO(J = 3 \(\rightarrow\) 2). In these cases, the flux of the stacked spectrum was calculated with a Gaussian fitting procedure as described in Section 3.3. The rest of the galaxies’ fluxes are calculated using a boxcar profile, also described in Section 3.3. The reported upper limits for these galaxies are \(3\sigma\) upper limits.

*Note that the units are in millijansky per kilometer per second rather than jansky per kilometer per second as in Table 3.*

Figure 2: SFR as a function of molecular gas mass, plotted in log-log scale. All SFRs have been scaled to a Kroupa (2001) IMF. A compilation of literature measurements listed in Table 5 is separated into three galaxy populations as labeled. These are shown as contours corresponding to levels of constant density (in the probabilistic sense). The contours shown here are at 20%, 40%, 60%, and 80%, indicating the probability mass below/outside the contour. The darker inner contours indicate the parameter space that a larger number of galaxies occupy. Galaxies from this work are plotted separately; detections are plotted with gray-face colors, and nondetections are plotted as rings. The ring color indicates the source galaxy as given by the legend in the lower-right corner. For all galaxies except for Gal. 8, there are three points, one for each of the multiple images. Diagonal gray lines indicate constant depletion time \(t_{\text{depl}} = M_{\text{gas}} / \text{SFR}\) as annotated in gray text.

of comparison. For starbursts where the IR luminosity was given instead of the SFR, Equation 4 from Kennicutt (1998) was used to calculate the SFR (Ivison et al. 2011; Papadopoulos et al. 2012; Combes et al. 2013; Magdis et al. 2014; Herrero-Illana et al. 2019). All SFRs are scaled to a Kroupa (2001) IMF following the conversion factors provided in Madau & Dickinson (2014)—to convert from a Salpeter IMF, multiply by 0.67, and to convert from a Chabrier IMF, multiply by 0.67/0.63.

In Figure 2, we separate the compilation into three populations: \(z < 1\) normal galaxies, \(z < 1\) starbursts, and \(z > 1\) galaxies. We do not distinguish between normal galaxies and starbursts for the \(z > 1\) population as there is not as clear of a distinction between the two populations.

We find that most of the galaxies from this work lie on the lower end, both in terms of SFR and \(M_{\text{gas}}\) of the region of the plot that is most densely populated by other \(z > 1\) galaxies—clustered around the 1 Gyr line, with \(M_{\text{gas}} > 10^{10} \text{ M}_\odot\). However, most of the detections have depletion times closer to 0.1–0.5 Gyr (see Table 3). The shorter depletion times of these galaxies indicate that they may quench before \(z = 2.4\), which is roughly 0.5 Gyr after \(z = 2.9\). By \(z = 2\), 1 Gyr will have elapsed, and most of the sources will have depleted their molecular gas reservoirs.

The outlier of most interest is Gal. 7 because its SFR and gas mass are lower than the bulk of the other \(z > 1\) galaxies by an order of magnitude. It is the source at the highest magnification, with the “b” image being magnified by a factor of 45 \(\pm\) 3, and without lensing, more telescope time than is practical would be required in order to achieve the same S/N as in the presented spectrum. We also note that all of our limits are upper limits, and the true location of the undetected galaxies in the \(M_{\text{gas}} - \text{SFR}\) parameter space is toward the position of Gal. 7, with lower masses and SFRs than other high-redshift detections.

There is a span of two orders of magnitude in the SFRs of the galaxies in this work, ranging from \(3.8_{-0.98}^{+0.98} \text{ M}_\odot\text{ yr}^{-1}\) for Gal. 1 (Man et al. 2021) to \(290_{-90}^{+90} \text{ M}_\odot\text{ yr}^{-1}\) for Gal. 8 (MacKenzie et al. 2014). This is comparable to what is observed by Zavala et al. (2019), who find SFRs from as low as \(6_{-3}^{+2.5} \text{ M}_\odot\text{ yr}^{-1}\) to as high as \(612_{-200}^{+280} \text{ M}_\odot\text{ yr}^{-1}\) in \(z \approx 2.1\) and \(z \approx 2.5\) protocluster galaxies. Although sensitivity and selection bias play a large role at high redshifts (e.g., selections based on narrow-band filters bias against galaxies with low star...
formation activity, and due to the $M_\star$–SFR relation for typical galaxies, against low-mass galaxies (Muldrew et al. 2015), the few confirmed protocluster galaxies at $z > 3$ with CO detections form stars much more vigorously than the galaxies in this work. For example, the protoclusters from Miller et al. (2018) and Oteo et al. (2018) have total SFRs exceeding 6000 $M_\odot$ yr$^{-1}$.

The large range of SFRs at $z = 1$–3—and possibly at even higher redshifts, but there are too few detections to say with certainty—suggest that protocluster galaxies are quenched during the $z = 1$–3 period. During this period, we concurrently see starburst galaxies with high SFRs and post-starburst galaxies with nearly no star formation. It is possible that the quenching of protocluster galaxies is aided by the dense environments—promoting more interactions, which could lead to quenching (Lotz et al. 2013)—in which these galaxies reside. If indeed galaxies in dense environments are more rapidly quenched than field galaxies, a high fraction of quiescent galaxies would be observed in dense environments at $z < 1$. Existing studies on the impact of the environment on quenching support this (Cooper et al. 2007; Wang et al. 2018; Strazzullo et al. 2019; Castignani et al. 2020). Preferential quenching in dense environments would also mean that the more strongly star-forming galaxies would be in the field at later cosmic epochs. This is supported by the inversion in the density–SFR relation at $z \approx 1$, showing that locally, galaxies with high SFRs are preferentially found in isolated environments (Dressler 1980; Gomez et al. 2003; Cooper et al. 2007; Elbaz et al. 2007; Tran et al. 2010; Popesso et al. 2015a, 2015b).

4.2. Dependence of Depletion Time on Redshift

Figure 3 shows the redshift evolution of the depletion time, distinguished by the environment. The data are from compiled galaxies in Table 5, where studies are marked as overdense if they provide measurements of (proto-)cluster galaxies. The blue line is the fit to galaxies in overdense environments, and the blue shading is the 1σ confidence interval on that fit. The fit and uncertainty are calculated from the sample means and the standard errors of the line parameters as determined by the Levenberg–Marquardt algorithm for 10,000 bootstrapped samples (Levenberg 1944; Efron 1979). Also plotted in yellow for comparison is the field-scaling relation for CO measurements from Tacconi et al. (2018). The depletion time here is given by $\log(t_{\text{depl}}) = (0.06 \pm 0.03) - (0.44 \pm 0.13) \log(1+z) - (0.43 \pm 0.03) \log(M_\star) + (0.17 \pm 0.04) (\log(M_\star - 10.7)$. This scaling relation is for CO measurements, and is informed by 667 galaxies. The normalization factors we assume for this relation are $\delta M_\star = 1$ and $\delta M_\star = 10.7$, where $\delta M_\star = 10\text{SFR}/s\text{SFR}(M_\star, z, M_\star)$ is the offset from the star formation main sequence (MS). These are chosen so that the relation is only dependent on redshift. Although the depletion time depends on main-sequence offset and stellar mass (the $C_O$ and $D_O$ coefficients in Tacconi et al. 2018), we do not consider these factors due to a lack of adequate data for accurate measurements.

Looking at the evolution of the depletion time of galaxies, the fit suggests that high-redshift galaxies have shorter depletion times than lower redshift galaxies. For galaxies in overdense environments, the slope of the best-fit line is $t_{\text{depl}} \propto \left(1 + z\right)^{-1.37 \pm 0.26}$. We note here that there may be biases against long depletion times observationally and/or in the sample we have compiled, which cannot be accounted for in the line fitting. We compare this to the Tacconi et al. (2018) field relation of $t_{\text{depl}} \propto (1+z)^{-0.44 \pm 0.13}$, which is less steep, suggesting that while depletion time decreases with increasing redshift for all galaxies, the evolution is stronger for galaxies in overdense environments. Darvish et al. (2018) also investigated the redshift evolution of depletion time for galaxies in various environmental densities up to $z \approx 3.5$ and found that the depletion time decreases with increasing redshift. However, they did not find evidence for a dependence of the redshift-depletion time relation on environmental density.

4.3. Dependence of Depletion Time on Environmental Density

In line with other studies, we find that galaxies in overdense environments at $z < 2$ have depletion times that are roughly consistent with (Noble et al. 2017; Rudnick et al. 2017; Darvish et al. 2018) the depletion times of coeval field galaxies, as determined by field-scaling relations (from Tacconi et al. 2013, 2018 or Genzel et al. 2015). This is in spite of the fact that high-redshift cluster galaxies have similar or larger gas fractions compared to coeval field galaxies (Noble et al. 2017; Hayashi et al. 2018), suggesting that galaxies in overdense environments are less efficient at converting gas into stars. We also note that the stellar mass is likely an important factor in the efficacy of these environmental processes. From the fit shown in Figure 3 (which includes many starburst galaxies), galaxies in overdense environments seem to have shorter depletion times than field galaxies at $z > 2.5$. However, this fit is informed by mostly $z < 2.5$ galaxies, many of which are starbursts. If we analyze the small subset of CO-detected galaxies at $z > 2.5$ with normal SFRs, this becomes unclear. In the Tacconi et al. (2018) sample, only four detections belong to this subset: one nonlensed Lyman break galaxy from Magdis et al. (2012) (M23), and three lensed galaxies from Saintonge et al. (2013) (cB58, 8:00 arc, and Eye). The mean depletion time for these four galaxies is $0.21 \pm 0.04$ Gyr. From the compilation, there are 23 galaxies with normal SFRs in overdense environments with known depletion times—19 from Tadaki et al. (2019) and Wang et al. (2018), and five from this work (Gals. 2.b, 2.c, 7.a, 7.b, and 8). The mean depletion time for these 23 galaxies is longer, at $1.14 \pm 0.14$ Gyr. Based on this very small sample, it would seem then, that even at high redshifts, the depletion times of galaxies in overdense environments are longer than those of galaxies in field environments.

The primary problem preventing consensus in this discussion is the scarcity of CO-detected galaxies at $z > 2.5$ with normal SFRs, both in the field and in overdense environments. Current studies of molecular gas at high redshift, particularly those with CO measurements, are primarily composed of massive starbursts (e.g., Riechers et al. 2010a; Bothwell et al. 2013; Miller et al. 2018; Oteo et al. 2018). More observations of high-redshift normal galaxies are needed in order to better constrain the relationship between redshift and depletion time, and to identify the impact of the environment on that relationship.

4.4. Star-gas Offset

We find HST-ALMA spatial offsets of 0.14″–0.33″ on the source plane, corresponding to 1.1–2.6 kpc at $z = 2.9$. Such offsets are not particularly surprising given the conditions of our sources, and have also been observed in other high-redshift galaxies (Carilli et al. 2010; Daddi et al. 2010; Hodge et al. 2010).
we assume normalization factors of
plotted in log-log scale. The blue line and shading indicate the line of best
corresponding 1
I

Depletion time
Figure 3.

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rather, the offset would be of a similar magnitude and direction in all the sources.

4.5. Systematic Uncertainties in the Gas Mass

The measurement of the molecular gas mass relies on two factors, both of which carry significant systematic uncertainties. The first is the ratio between the strengths of the different CO rotational transitions, or the CO SLED. The 12CO(J = 3 → 2) transition requires more energy to be excited than the ground-state transition, and thus it traces denser clumps of gas with higher temperatures (Riechers et al. 2007). A conversion factor r_{3−2/1−0} = \frac{L_{\text{CO}(3−2)}}{L_{\text{CO}(1−0)}} needs to be used in order to infer the 12CO(J = 1 → 0) luminosity. However, a wide range of values have been adopted in literature, ranging from 0.4–1.15 in z ≈ 2.5 galaxies (Ivison et al. 2011; Gómez-Guijarro et al. 2019). This conversion factor is also increasingly impacted by the cosmic microwave background (CMB) at high redshifts (da Cunha et al. 2013); the elevated CMB in the early universe reduces the brightness contrast of CO line emissions against background emissions (Zhang et al. 2016). Across all redshifts, the value most commonly adopted or calculated by the studies in our compilation targeting that transition is 0.5. This is the value we use for our calculations.

The second major uncertainty is the CO-to-H2 conversion factor, α_{CO}. This conversion factor is dependent on many physical properties like the metallicity and the pressure of the interstellar medium (ISM; Genzel et al. 2012; Carilli & Walter 2013; Dessauges-Zavadsky et al. 2017). This is particularly problematic at high redshifts and in low-mass galaxies where there is a rapid metallicity evolution (Tan et al. 2013). Even within the Milky Way and nearby spirals where resolved observations are easier to obtain and ISM properties are better understood, α_{CO} is not certain, with Bolatto et al. (2013) finding a factor of 2 scatter. For extragalactic sources, it is much more difficult to determine α_{CO}. For Milky Way–like galaxies, a value of α_{CO} = 4.36 M_\odot (K km s\(^{-1}\) pc\(^2\)\(^{-1}\)) is commonly used, and for (U)LIRGs and SMGs, α_{CO} = 0.8 is commonly used (Downes & Solomon 1998; Dessauges-Zavadsky et al. 2015; Noble et al. 2019). If metallicity measurements are available, it may be beneficial to adopt a CO line intensity and metallicity dependent α_{CO} factor from the best-fitting function in Narayanan et al. (2012) rather than the conventional bimodal α_{CO} values, as this has been shown to significantly reduce scatter in star formation relations.

Together, the CO SLED and α_{CO} factors introduce close to an order of magnitude in systematic uncertainty into the M_{gas} and t_{depl} derived in this work.

4.6. Future Prospects

Future observations of these sources and other lensed high-redshift galaxies could take many avenues. Future instruments like the Next Generation Very Large Array and ALMA Band 1 will enable large, multi-transition CO surveys of more representative galaxies at z > 2, which would open up the possibility to model the CO SLED (e.g., Narayanan & Krumholz 2014). Higher spatial resolution observations would allow for viral mass estimates that could be used to independently constrain α_{CO}, and to reconstruct the gas distribution on the source plane (e.g., Brewer & Lewis 2006; Riechers et al. 2007; Vegetti & Koopmans 2009; Spingola et al. 2020).
It is conceivable that the overdense environment is more conducive to mergers and active galactic nuclei (AGNs) activity. Radio counterparts to some of the sources in this work have been identified by Berciano Alba et al. (2010) (e.g., “RJ Bright” near Gal 1.b and the three multiple images of the “E” system near the three multiple images of Gals. 5 and 6). These could be indications of the existence of potential mergers and/or AGN in the galaxies. We examined the spectra for broader CO components, but the ALMA data at hand are not sufficiently deep to identify signatures of AGN-driven molecular gas outflows. Future investigations into the presence of AGN could shed light on its impact on star formation in protocluster galaxies.

Follow-up rest-frame optical imaging could also aim to provide information about the stellar mass of the galaxies of this z = 2.9 group. That would allow for the calculation of gas fractions in these galaxies, which could lead to further understanding of the impact of the environment on molecular gas. Stellar masses could also be used to compare the sources to the star formation main sequence, allowing for a more comprehensive understanding of star formation in these galaxies.

5. Conclusions

In this paper, we have presented a study of a gravitationally lensed group of galaxies at z = 2.9. With a compact ALMA configuration, we target the $^{12}\text{CO}(J = 3 \rightarrow 2)$ emission line and spectroscopically confirm the redshifts of seven images of four members. These molecular gas mass measurements represent the highest redshift CO detections in dense environments for galaxies that are not undergoing extreme starburst. We compile a diverse sample of over 500 galaxies up to z = 5.3 in order to place our results in context. We find that the galaxies in this work are consistent in molecular gas mass and SFR with the high-redshift (z > 1) normal population from our compilation.

The inferred molecular gas masses of our detections span a range of $(0.2-13.1) \times 10^{10} M_\odot$.

We also investigated the impact of the environment on the depletion time of galaxies. The sources in this work are among the highest redshift CO-detected galaxies with normal SFRs in an overdense environment, and extend the discussion about the impact of the environment beyond $z = 2.5$. At the same time, our results highlight the challenge of constraining molecular gas relations for normal galaxies at high redshift due to the scarcity of observations. We find that at high redshifts, galaxies tend to have shorter depletion times than those at low redshifts, and that this depletion time evolution is steeper for galaxies in overdense environments than for field galaxies. At $z > 2.5$, we find tentative evidence that those in overdense environments have shorter depletion times than coeval field galaxies, but this does not seem to hold when considering only CO-detected galaxies with normal SFRs. The lack of CO detections of normal galaxies at $z > 2.5$ makes it difficult to conclusively determine the impact of the environment on the depletion time. Further investigation into cluster evolution will be needed in order to fully understand how early galaxies in dense environments evolve.

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Appendix A
Compilation

Table 5 presents studies of molecular gas from the literature. The total sample of 546 galaxies includes galaxies in both the local and early universe. In each row, the minimum and maximum redshift, gas mass, SFR, and depletion time of the galaxies in the given study are provided. The studies are ordered by maximum redshift.

| Reference                          | Overdense | Starburst | Objects | Redshift Range | Gas Mass Range ($\times 10^{10} M_\odot$) | SFR Range ($M_\odot$ yr$^{-1}$) | Depletion Time Range (Gyr) |
|------------------------------------|-----------|-----------|---------|----------------|------------------------------------------|---------------------------------|--------------------------|
| Cicone et al. (2017)               | No        | No        | 97      | 0.011–0.029    | 0.005–1.046                              | 0–13                            | 0.004–3.238               |
| Herrero-Illana et al. (2019)       | No        | Yes       | 53      | 0.011–0.088    | 0.090–3.017                              | 20–450                         | 0.016–0.183               |
| Papadopoulos et al. (2012)         | No        | Yes       | 70      | 0.003–0.100    | 0.005–1.392                              | 15–286                         | 0.007–1.684               |
| Cybulski et al. (2016)             | Yes       | No        | 8       | 0.187–0.208    | 0.92–1.84                               | 3–44                           | 0.412–4.325               |
| Geach et al. (2011)                | Yes       | No        | 5       | 0.380–0.396    | 1.38–5.06                               | 37–66                          | 0.371–0.806               |
| Magdis et al. (2014)               | No        | Yes       | 9       | 0.216–0.436    | 0.52–1.56                               | 71–898                         | 0.014–0.107               |
| Combes et al. (2013)               | No        | Yes       | 39      | 0.607–0.996    | 0.08–3.36                               | 201–5535                       | 0.001–0.050               |
| Hayashi et al. (2018)              | Yes       | No        | 17      | 1.445–1.471    | 2.7–10.7                               | 3–154                          | 0.443–10.030              |
| Stach et al. (2017)                | Yes       | Yes       | 6       | 1.450–1.472    | 1.0–2.4                                | 43–149                         | 0.067–0.414               |
| Daddi et al. (2010, 2015)          | No        | Yes       | 6       | 1.414–1.600    | 4.2–12.0                               | 66–425                         | 0.282–0.703               |
| Rudnick et al. (2017)              | Yes       | No        | 2       | 1.624–1.629    | 3.31–11.22                              | 12–165                         | 0.678–2.595               |
| Noble et al. (2017, 2019)          | Yes       | No        | 17      | 1.596–1.635    | 1.7–25.5                               | 3–230                          | 0.248–31.970              |
| Dannerbauer et al. (2017)          | Yes       | No        | 1       | 2.148         | 18.0                                   | 372                            | 0.484                    |
| Tacconi et al. (2013)              | No        | No        | 53      | 1.002–2.434    | 1.1–35.0                               | 18–670                         | 0.146–5.436               |
| Ivison et al. (2011)               | No        | Yes       | 5       | 2.201–2.487    | 2.5–9.8                                | 568–1430                       | 0.029–0.130               |
| Lee et al. (2017)                  | Yes       | No        | 7       | 2.478–2.487    | 3.14–18.52                             | 69–440                         | 0.079–3.699               |
| Zavala et al. (2019)               | Yes       | No        | 67      | 2.085–2.513    | 1.5–37.3                               | 3–670                          | 0.022–5.955               |
| Wang et al. (2018)                 | Yes       | No        | 14      | 2.494–2.515    | 1.4–55.0                               | 14–796                         | 0.200–6.170               |
| Tadaki et al. (2019)               | Yes       | No        | 16      | 2.144–2.529    | 5.75–34.67                             | 38–496                         | 0.211–6.521               |
| Gómez-Guijarro et al. (2019)       | Yes       | Yes       | 11      | 2.171–2.602    | 6.61–109.65                            | 106–1808                       | 0.236–1.525               |
| Riechers et al. (2010b)            | No        | No        | 2       | 2.730–3.070    | 0.046–0.093                            | 27–149                         | 0.006–0.017               |
| Coppin et al. (2007)               | No        | No        | 1       | 3.074         | 0.24                                   | 25                             | 0.095                    |
| Saintonge et al. (2013)            | No        | No        | 10      | 1.411–3.074    | 0.56–40.74                             | 19–647                         | 0.119–1.024               |
| Spingola et al. (2020)             | No        | Yes       | 2       | 2.059–3.200    | 25.0–34.0                             | 415–542                        | 0.461–0.820               |
| Dessauges-Zavadsky et al. (2015, 2017)  | No        | No        | 7       | 1.585–3.631    | 0.3–7.4                                | 10–81                          | 0.076–1.254               |
| Oteo et al. (2018)                 | Yes       | Yes       | 4       | 4.000–4.000    | 10.8–26.2                             | 200–1224                       | 0.214–0.539               |
| Carilli et al. (2010)              | Yes       | Yes       | 1       | 4.050         | 16.0                                   | 3190                           | 0.050                    |
| Tan et al. (2013)                  | No        | No        | 2       | 3.216–4.058    | 16.0–18.0                             | 181–330                        | 0.485–0.996               |
| Miller et al. (2018)              | Yes       | Yes       | 14      | 4.300–4.300    | 1.0–12.0                              | 68–1304                        | 0.063–0.254               |
| Riechers et al. (2010a)            | Yes       | Yes       | 1       | 5.298         | 5.3                                   | 1914                           | 0.028                    |

Notes. All galaxies are CO-detected except for Zavala et al. (2019). All SFRs have been scaled to the Kroupa (2001) IMF following the factors given in Madau & Dickinson (2014).

* SFRs for these studies are calculated from the IR luminosity using the Kennicutt (1998) relation.

* Source galaxies are gravitationally lensed.
Appendix B

Moment Zero Maps

Figure 5 shows an example of a moment zero map. The full figure set containing moment zero maps for all galaxies (22 images) is available in the online version.

Figure 5. Moment zero map of Gal. 8 centered on the HST position. The image is created from the $-200$ to $200$ km s$^{-1}$ channels of the non-primary-beam corrected data cubes, and measures $6'' \times 6''$. The solid white contours start from $2\sigma$ and go up in $2\sigma$ increments, and the dotted contours start from $-2\sigma$ and go in $2\sigma$ increments, where $\sigma$ is the rms noise. The ellipses in the bottom-left corners are the ALMA beam, which has FWHM major and minor axis sizes of $1.810''$ and $1.275''$, respectively, and a position angle of $-64.3^\circ$. The optimized extraction regions are indicated by the dotted black line. The full figure set with the moment zero maps for all galaxies (22 images) is provided in the online version of the paper.

Appendix C

Integrated Spectra

Figure 6 shows an example of an integrated spectrum. The full figure set containing spectra for all galaxies (22 images) is available in the online version.

Figure 6. Integrated spectrum of Gal. 8, created by spatially integrating the primary-beam corrected cube in all channels in the spectral window. The integration region is determined by the optimal extraction region (see Section 3.2 for details).

Appendix D

Moment One Maps

Figure 7 shows an example of a moment one map. The full figure set containing moment one maps for the detected galaxies (seven images) is available in the online version.

Figure 7. Moment one map of Gal. 8, as created from a data cube masked to only retain the optimal extraction region (see Section 3.2 for details) in the $-200$ to $200$ km s$^{-1}$ channels of the non-primary-beam corrected cubes. The velocities are given relative to the systemic velocity of the source.

Appendix E

Continuum Images

Figure 8 shows an example of a continuum image. The full figure set containing continuum images for all galaxies (22 images) is available in the online version.

Figure 8. Continuum image of Gal. 8, centered on the HST position and measuring $6'' \times 6''$. The continuum image is created with the three spectral windows where no spectral line emission is expected. The contours indicate the rms noise, with the solid contours starting at $1\sigma$ and increasing in $2\sigma$ increments, and the dashed contours starting at $-1\sigma$ and decreasing in $2\sigma$ increments.

(13)
