Jansky Very Large Array Detections of CO(1–0) Emission in H I-absorption-selected Galaxies at \( z \gtrsim 2 \)

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Abstract

We report a Karl G. Jansky Very Large Array search for redshifted CO(1–0) emission from three H I-absorption-selected galaxies at \( z \approx 2 \), identified earlier in their CO(3–2) or CO(4–3) emission. We detect CO(1–0) emission from DLA B1228-113 at \( z \approx 2.1933 \) and DLA J0918+1636 at \( z \approx 2.5848 \); these are the first detections of CO(1–0) emission in high-z H I-selected galaxies. We obtain high molecular gas masses, \( M_{\text{mol}} \approx 10^{11} \times (\alpha_{\text{CO}}/4.36) M_\odot \), for the two objects with CO(1–0) detections, which are a factor of \( \approx 1.5–2 \) lower than earlier estimates. We determine the excitation of the mid-J CO rotational levels relative to the \( J = 1 \) level, \( r_{J1} \), in H I-selected galaxies for the first time, obtaining \( r_{11} = 1.00 \pm 0.20 \) and \( r_{11} = 1.03 \pm 0.23 \) for DLA J0918+1636, and \( r_{11} = 0.86 \pm 0.21 \) for DLA B1228-113. These values are consistent with thermal excitation of the \( J = 3 \) and \( J = 4 \) levels. The excitation of the \( J = 3 \) level in the H I-selected galaxies is similar to that seen in massive main-sequence and submillimeter galaxies at \( z \gtrsim 2 \), but higher than that in main-sequence galaxies at \( z \approx 1.5 \); the higher excitation of the galaxies at \( z \gtrsim 2 \) is likely to be due to their higher star formation rate (SFR) surface density. We use Hubble Space Telescope Wide Field Camera 3 imaging to detect the rest-frame near-ultraviolet (NUV) emission of DLA B1228-113, obtaining an NUV SFR of \( 4.44 \pm 0.47 M_\odot \, \text{yr}^{-1} \), significantly lower than that obtained from the total infrared luminosity, indicating significant dust extinction in the \( z \approx 2.1933 \) galaxy.

Unified Astronomy Thesaurus concepts: High-redshift galaxies (734); CO line emission (262); Damped Lyman-alpha systems (349)

1. Introduction

The highest H I column density absorption systems in quasar (QSO) spectra, the damped Ly\( \alpha \) absorbers (DLAs), arise from gas associated with high-redshift galaxies (e.g., Wolfe et al. 2005). Such absorbers provide a route to identifying high-z galaxies without the luminosity bias that afflicts galaxy samples selected directly via their emission. Understanding the nature of these H I-absorption-selected galaxies is critical for an unbiased understanding of galaxy evolution. Unfortunately, the proximity of the faint foreground galaxy to the bright background QSO has meant that, despite many studies, it has been difficult to even identify, let alone characterize, the high-z H I-selected galaxies via optical imaging and spectroscopy (e.g., Fumagalli et al. 2015; Krogager et al. 2017).

Recently, the Atacama Large Millimeter/submillimeter Array (ALMA) has opened new windows on H I-selected galaxies via their redshifted [CII] 158\( \mu \)m and CO emission. Besides the characterization of H I-selected galaxies at intermediate redshifts, \( z \approx 0.6 \) (e.g., Kanekar et al. 2018; Möller et al. 2018; Klitsch et al. 2019; Péroux et al. 2019), this has resulted in the identification of more than a dozen such galaxies at \( z \approx 2 \) (Fynbo et al. 2018; Kanekar et al. 2020; Neeleman et al. 2018) and \( z \approx 4 \) (Neeleman et al. 2017, 2019). Perhaps the most remarkable results from these studies are the large impact parameters to the QSO sight line of the galaxies at \( z \approx 4 \) (Neeleman et al. 2017, 2019), the high molecular gas masses of the galaxies at \( z \approx 2 \) (Kanekar et al. 2020), and the identification of a cold, dusty, rotating disk at \( z \approx 4.26 \) (Neeleman et al. 2020). Multiwavelength observations are now under way to obtain a detailed understanding of these galaxies, by characterizing their stellar and gas properties, star formation activity, etc. (e.g., Prochaska et al. 2019; Kaur et al. 2021; Klitsch et al. 2022).

For the \( z \approx 2 \) H I-selected galaxies, the high inferred molecular gas masses, \( M_{\text{mol}} \approx (1.3 - 20.7) \times 10^{10} M_\odot \) (Kanekar et al. 2020), were obtained from the CO(3–2) or CO(4–3) mid-\( J \) rotational transitions. These estimates are based on two critical assumptions, subthermal excitation of the CO \( J = 3 \) or \( J = 4 \) levels relative to the \( J = 1 \) level, and the value of the CO-to-H\(_2\) conversion factor, \( \alpha_{\text{CO}} \) (e.g., Tacconi et al. 2020). Direct observations of the CO(1–0) line are critical to remove the first of these assumptions, and obtain more accurate molecular gas mass estimates. Combining the CO(1–0) line luminosity with the luminosity in the higher-\( J \) CO lines also allows one to determine the CO excitation and thus probe physical conditions in the molecular gas (e.g., Carilli & Walter 2013). Indeed, studies in the local universe have shown that the CO excitation is related to the value of \( \alpha_{\text{CO}} \); high-excitation galaxies like ultraluminous infrared galaxies (ULIRGs) and QSO hosts have lower \( \alpha_{\text{CO}} \) values \( \approx 1.0 M_\odot/\text{(K km s}^{-1}\text{pc}^{-2}) \) than low-excitation objects like the Milky Way and nearby disk galaxies \( \approx 4.3 M_\odot/\text{(K km s}^{-1}\text{pc}^{-2}) \); e.g., Bolatto et al. 2013.

At high redshifts, CO(1–0) studies have so far only been carried out in bright, emission-selected galaxies, mostly QSO...
hosts, submillimeter galaxies (SMGs), lensed galaxies, and massive main-sequence galaxies (e.g., Aravena et al. 2014; Bolatto et al. 2015; Sharon et al. 2016; Riechers et al. 2020). In this Letter, we report the first detections of redshifted CO(1–0) emission from H I-selected galaxies at $z \approx 2$, obtained with the Karl G. Jansky Very Large Array (JVLA). We also report Hubble Space Telescope (HST) Wide Field Camera 3 (WFC3) imaging of the rest-frame near-ultraviolet (NUV) continuum emission for one of the H I-selected galaxies, which shows that the object is a dusty galaxy.

2. Observations, Data Analysis, and Results

2.1. JVLA Observations and Data Analysis

We used the JVLA Ka-band receivers in the D-array to search for redshifted CO(1–0) emission from the H I-selected galaxies at $z \approx 1.9615$ toward QSO B0551-366, $z \approx 2.1933$ toward PKS B1228-113, and $z \approx 2.5848$ toward QSO J0918+1636 in 2019 November and December (Proposal ID: VLA/19B-271; PI: N. Kanekar). The three galaxies (hereafter DLA B0551-366, DLA B1228-113, and DLA J0918+1636) had been earlier detected with ALMA in their CO(4–3) or CO(3–2) emissions (Neeleman et al. 2018; Fynbo et al. 2018; Kanekar et al. 2020).

The JVLA observations used the WIDAR correlator in 8-bit mode, with two 1 GHz intermediate-frequency (IF) bands, one covering the redshifted CO line frequency for the target galaxy, and two polarizations. Each IF band was divided into eight 128 MHz digital subbands, with each subband further divided into 512 and 128 channels, for line and off-line subbands, respectively. This yielded a velocity coverage of $\approx 800–955$ km s$^{-1}$ for the subband covering the redshifted CO line frequency, albeit with lower sensitivity at the subband edges, and a raw velocity resolution of $\approx 2$ km s$^{-1}$. Observations of the targets were interleaved with runs on nearby phase calibrators every 5 minutes; in addition, a standard flux calibrator was observed once in each session. The on-source times were 2.1–5.8 hr for the three galaxies.

All data were analyzed in the Astronomical Image Processing System package (“classic” AIPS; Greisen 2003), using standard procedures. After identifying and editing out malfunctioning antennas and any data affected by systematic errors, we used the calibrator data to determine the antenna-based complex gains and bandpass shapes. The gains and bandpasses were applied to the data for each target, and the calibrated target visibilities then split out into a new data set.

Table 1

| DLA         | $z_{\text{QSO}}$ | $z_{\text{abs}}$ | $z_{\text{gal}}$ | $\nu_{\text{obs}}$ (GHz) | $\nu_{\text{int}}$ ($\times 10^8$) | $\sigma_{\text{rms}}$ (Jy beam$^{-1}$) | $S_{\text{CO}}$ (Jy km s$^{-1}$) | $L_{\text{CO}}$ (10$^4$ K km s$^{-1}$ pc$^2$) | $M_{\text{mol}}$ (10$^4$ M$_\odot$) |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| B0551-366   | 2.317           | 1.9622          | 1.9615          | 38.92           | 5.8 $\times$ 1.6 | 99              | $<0.057$         | $<1.14$          | $<5.0$          |
| B1228-113   | 3.528           | 2.1929          | 2.1933          | 36.10           | 3.1 $\times$ 2.0 | 94              | 0.094 $\pm$ 0.023 | 2.29 $\pm$ 0.56 | 10.0 $\pm$ 2.4  |
| J0918+1636  | 3.096           | 2.5832          | 2.5848          | 32.15           | 2.8 $\times$ 2.3 | 57              | 0.082 $\pm$ 0.016 | 2.65 $\pm$ 0.51 | 11.5 $\pm$ 2.2  |

Note. The columns are (1) the galaxy name; (2) the QSO redshift; (3) the absorption redshift, $z_{\text{abs}}$; (4) the galaxy redshift, $z_{\text{gal}}$, from the higher-$J$ CO lines; (5) the redshifted CO(1–0) line frequency, in GHz; (6) the synthesized beam, in $\times 10^8$; (7) the rms noise, in Jy beam$^{-1}$, at a velocity resolution of 100 km s$^{-1}$; (8) the integrated CO line flux density, in Jy km s$^{-1}$; (9) the CO(1–0) line luminosity, $L_{\text{CO}}$; and (10) the molecular gas mass, $M_{\text{mol}}$ assuming $\alpha_{\text{CO}} = 4.36$, $M_{\text{mol}}$ (K km s$^{-1}$ pc$^{-2}$). For the CO(1–0) nondetection in B0551-366, the last three columns list the 3$\sigma$ upper limits on $S_{\text{CO}}$ dV, $L_{\text{CO}}$, and $M_{\text{mol}}$ for an assumed line FWHM of 300 km s$^{-1}$ (Kanekar et al. 2020).

For each target, the central channels of each subband of this data set were averaged together, and the resulting data sets were imaged to search for any continuum emission in each field. Although continuum emission was detected from two QSOs, only PKS B1228-113 was found to have a sufficient flux density for self-calibration. The self-calibration for PKS B1228-113 followed a standard iterative procedure, with multiple rounds of imaging and phase-only self-calibration, followed by amplitude-and-phase self-calibration and data editing, until neither the image nor the residual visibilities showed any improvement on further self-calibration. The improved complex gains for DLA B1228-113 were applied to the multichannel data to produce the final calibrated data set for this field.

Next, for each target, the task UVSUB was used to subtract out all continuum emission from the calibrated visibilities. The residual multichannel visibility data sets were then imaged in the Common Astronomy Software Applications package (CAS A version 5.6; McMullin et al. 2007), using natural weighting in the barycentric frame, to produce spectral cubes at velocity resolutions of 50–100 km s$^{-1}$. The FWHM of the JVLA synthesized beams is $\approx 1\prime\!\!\!\!\prime 6–5\prime\!\!\!\!\prime 8$ for the three targets, larger than the size of the ALMA CO emission (Kanekar et al. 2020); we hence do not expect any of the CO(1–0) emission to be resolved out in the JVLA images. For each galaxy, a CO(1–0) emission spectrum was extracted by taking a cut through its cube at the location of the ALMA CO emission. Finally, in the case of DLA B1228-113 and DLA J0918+1636, which showed detections of CO(1–0) emission at $>4\sigma$ significance, we also made images of the CO emission, at velocity resolutions matched to the line FWHMs. The observational details and results are summarized in Table 1.

2.2. HST Observations and Data Analysis

The HST WFC3 observations of DLA B1228-113 were carried out in late 2019 (PID: 15882; PI: Kanekar), using the F105W filter to cover the rest-frame NUV stellar continuum from the $z \approx 2.1933$ galaxy. A single orbit was obtained, using a WIDE-7 dither pattern increased by a factor of 3 over the pattern described in the Instrument Science Report (ISR 2016-14; Anderson 2016), in order to obtain cleaner images by dithering over the size of the IR blobs.

The data were calibrated using the new IR filter-dependent sky flats (WFC3 ISR 2021-01; Mack et al. 2021). Image mosaics were made using AstroDrizzle (Hack et al. 2020), drizzling to a scale of $0\prime\!\!\!\!\prime 0.06$ pixel$^{-1}$. TweakReg was used to astrometrically align the image to the GAIA DR2 catalog (Gaia Collaboration et al. 2018), yielding an absolute astrometric
The effective angular resolution of the ALMA sky is 3.3 arcsec, based on a Gaussian point-spread function (PSF) of the quasar.

2.3. Results

Our JVLA observations yielded detections of CO(1–0) emission at >4σ significance from the H i-selected galaxies at \( z \approx 2.1933 \) toward PKS B1228-113 and \( z \approx 2.5848 \) toward QSO J0918+1636. We also obtained an upper limit to the CO(1–0) line luminosity for the \( z \approx 1.9615 \) galaxy toward QSO B0551-366. Figure 1 shows the JVLA CO(1–0) spectra of the three H i-selected galaxies, while Figure 2 shows the CO(1–0) images of DLA B1228-113 and DLA J0918+1636 (in red contours), overlaid on the ALMA CO(3–2) images (white contours), and the HST WFC3 images (in color; Fynbo et al. 2018, this work) of the two fields. For DLA B1228-113 and DLA J0918+1636, the detected CO(1–0) emission agrees in both position and velocity with the ALMA CO(3–2) emission.

The measured velocity-integrated CO(1–0) line flux densities and inferred CO line luminosities for the three galaxies are listed in Table 1. Here, the 3σ upper limits for DLA B0551-366 assume that the CO(1–0) emission has an FWHM of 300 km s\(^{-1}\), equal to that of the CO(4–3) emission (Kanekar et al. 2020). The CO(1–0) line luminosities yield molecular gas masses of \( (10.0 \pm 2.4) \times 10^{10} M_\odot \) (DLA B1228-113), \( (11.5 \pm 2.2) \times (\alpha_{\text{CO}}/4.36) \times 10^{10} M_\odot \) (DLA J0918+1636), and \( < 5.0 \times (\alpha_{\text{CO}}/4.36) \times 10^{10} M_\odot \) (3σ limit; DLA B0551-366), where we have assumed \( \alpha_{\text{CO}} = 4.36 M_\odot (\text{K km s}^{-1}\text{pc}^2)^{-1} \) (Bolatto et al. 2013; Tacconi et al. 2020).

Both DLA J0918+1636 and DLA B1228-113 are detected in HST rest-frame NUV imaging. The HST images of DLA J0918+1636 are presented and described in Fynbo et al. (2018), and yield a half-light radius of 0.30 J. P. U. Fynbo 2021, private communication). In the case of DLA B1228-113, the rest-frame NUV emission is detected in our HST WFC3 F105W image (see Figure 2(A)), at R.A. = 12\(^{h}\)30\(^{m}\)55\(^{s}\)44, decl. = -11°39′ 05″87, at an offset of \( \approx 0.9 \) (\( \approx 7.7 \) kpc) from the CO(3–2)
The columns are (1) the galaxy name; (2) the galaxy redshift, \( z_{\text{gal}} \); (3) the ratio \( r_{\text{J1}} \); (4) the ratio \( r_{\text{J1}} \); (5) the ratio \( r_{\text{J1}} \); (6) the ratio \( r_{\text{J1}} \); and (7) references for the higher-J CO studies: (1) Kanekar et al. (2020); (2) Klitsch et al. (2022); (3) Neelam (2018); (4) Fynbo et al. (2018).

Table 2

| DLA         | \( z_{\text{gal}} \) | \( r_{\text{J1}} \) | \( r_{\text{J1}} \) | \( r_{\text{J1}} \) | \( r_{\text{J1}} \) | Refs. |
|-------------|-----------------|-----------------|-----------------|-----------------|-----------------|------|
| B0551-366   | 1.9615          | ...             | >0.48           | >0.24           | >0.07           | 1,2  |
| B1228-113   | 2.1933          | 0.86 ± 0.21     | ...             | ...             | 0.18 ± 0.05     | 1-3  |
| J0918+1636  | 2.8488          | 1.00 ± 0.20     | 1.03 ± 0.23     | 0.39 ± 0.09     | ...             | 2,4  |

Our JVLA CO(1–0) measurements allow us, for the first time, to determine the excitation of the mid-J rotational levels relative to the \( J = 1 \) level in H I-selected galaxies. Table 2 lists the values of \( r_{\text{J1}} \) and \( r_{\text{J1}} \), for \( J = 3 \)–6, combining our measured CO(1–0) line luminosities with the luminosities of the higher-J lines (Kanekar et al. 2020; Klitsch et al. 2022).

Studies of high-redshift galaxies typically assume subthermal excitation of the mid-J rotational levels, with \( r_{\text{J1}} \) ≈ 0.55 and \( r_{\text{J1}} \) ≈ 0.42 (e.g., Tacconi et al. 2020). Remarkably, we find that DLA J0918+1636 has values of \( r_{\text{J1}} \) = 1.00 ± 0.20 and \( r_{\text{J1}} \) = 1.03 ± 0.23, consistent with thermal excitation of the \( J = 3 \) and \( J = 4 \) levels. We note that Klitsch et al. (2022) had earlier measured \( r_{\text{J1}} = 1.03 \) in DLA J0918+1636, suggesting that the \( J = 4 \) and \( J = 3 \) levels are likely to show thermal excitation. Similarly, the value of \( r_{\text{J1}} = 0.86 ± 0.21 \) in DLA B1228-113 is consistent with thermal excitation, while the CO(1–0) nondetection in DLA B0551-366 yields the lower limit \( r_{\text{J1}} > 0.48 \), higher than the canonical value of 0.42 (Tacconi et al. 2020). We thus find direct evidence that the mid-J rotational levels of massive H I-selected galaxies at \( z > 2 \) show relatively high excitation (see also Klitsch et al. 2022).

Figure 3 plots the \( r_{\text{J1}} \) values of the three H I-selected galaxies (red symbols) against the upper rotational level quantum number, \( J \). The dashed horizontal line at \( r_{\text{J1}} = 1 \) indicates thermal excitation of the rotational levels. The figure also includes data for the inner disk of the Milky Way (gray diamonds; Fixsen et al. 1999), three main-sequence (BzK)
galaxies at $z \approx 1.5$ (green crosses; Aravena et al. 2014; Daddi et al. 2015), five main-sequence galaxies at $z > 2$ (blue pentagons; Riechers et al. 2010; Bolatto et al. 2015; Brinch et al. 2019; Boogaard et al. 2020; Henríquez-Brocal et al. 2021), and a large sample of SMGs at $z > 2$ (inverted black triangles; Sharon et al. 2016; Calistro Rivera et al. 2018; Birkin et al. 2021). The gray diamonds indicate the CO SLED of the inner disk of the Milky Way (Fixsen et al. 1999).

Figure 3 shows that the three HI-selected galaxies have CO SLEDs consistent with those of massive main-sequence galaxies at $z > 2$. The excitation of the mid-J rotational levels of the HI-selected galaxies is clearly higher than that of both the inner disk of the Milky Way and main-sequence galaxies at $z \approx 1.5$. Further, the roughly thermal excitation of the $J = 3$ and $J = 4$ levels in DLA J0918+1636 (and of the $J = 3$ level in DLA B1228-113) is consistent with the excitation of the same levels in the main-sequence galaxy BX610 (Bolatto et al. 2015; Brinch et al. 2019). It is interesting that the excitation in DLA J0918+1636 drops sharply in the $J = 5$ rotational level, with $r_31 \approx 0.39$, well below thermal.

Figure 4(A) plots $r_{31}$ versus redshift for DLA B1228-113, DLA J0918+1636, and the above samples of SMGs at $z > 2$, and main-sequence galaxies at $z \approx 1.5$ and $z > 2$. Here, the individual $r_{31}$ values are plotted for the main-sequence galaxies (e.g., Riechers et al. 2010; Daddi et al. 2015; Bolatto et al. 2015; Brisbin et al. 2019; Henríquez-Brocal et al. 2021; Boogaard et al. 2020) and the median value for the SMGs (Sharon et al. 2016). Interestingly, we find evidence that all galaxies at $z > 2$ show higher excitation of the $J = 3$ level than main-sequence galaxies at $z \approx 1.5$, by a factor of $\approx 1.5-2$. This is consistent with the result from the ALMA Spectroscopic Survey in the Hubble Ultra Deep Field (ASPECS), that galaxies at $z \geq 2$ have an intrinsically higher CO excitation than those at $z < 2$ (Boogaard et al. 2020). As noted by the latter authors, the likely cause of the higher CO excitation is the higher SFR surface density $\Sigma_{SFR}$ in higher-$z$ galaxies (e.g., Shibuya et al. 2015): simulations have found that the CO excitation is closely linked to the SFR surface density, with a higher excitation obtained for higher values of $\Sigma_{SFR}$ (Narayanan & Krumholz 2014; Bournaud et al. 2015). Figure 4(B) plots $r_{31}$ versus SFR surface density for our HI-selected galaxies and the main-sequence galaxies$^8$ of the left panel. It is clear that the SFR surface densities of the HI-selected galaxies and the $z > 2$ main-sequence galaxies are higher by factors of $\approx 10$ than those of the main-sequence galaxies at $z \approx 1.5$, consistent with the higher CO excitation of the higher-$z$ sample.

3.3. Stellar Properties of DLA B1228-113

Finally, our SFR estimate of $4.44 \pm 0.47 M_{\odot}$ year$^{-1}$ for the $z \approx 2.1933$ HI-selected galaxy DLA B1228-113 from its rest-frame NUV continuum is consistent with the estimate of $\approx 3.9 M_{\odot}$ year$^{-1}$ from the H$\alpha$ line (Neenam et al. 2018). The total SFR, estimated from both the total infrared luminosity and fits to the broadband SED, is far higher than the above estimates, $\approx (87 - 100) M_{\odot}$ year$^{-1}$ (Neenam et al. 2018; Klutsch et al. 2022), implying a high dust extinction. Figure 2(A) shows that the rest-frame NUV emission detected in the HST WFC3 image is offset from the peak of the ALMA CO(3–2) emission, by $\approx 8$ kpc. Combined with the very large CO(3–2) line FWHM ($\approx 600$ km s$^{-1}$; Neenam et al. 2018), this suggests that the CO emission may arise from two merging galaxies, one of which has a high extinction and is hence not visible in the HST WFC3 image. High angular resolution CO mapping studies would be of much interest to directly probe this issue. Finally, we cannot formally rule out the possibility that the detected NUV emission arises from an interloper at a different redshift; if so, this would imply an even higher dust extinction for the $z \approx 2.1933$ HI-selected galaxy.

4. Summary

We report JVLA detections of CO(1–0) emission in two HI-selected galaxies at $z \approx 2.1933$ and $z \approx 2.5848$, and an upper limit to the CO(1–0) line luminosity in a third HI-selected galaxy at $z \approx 1.9615$. These are the first detections of CO(1–0) emission in HI-selected galaxies at high redshifts, $z \gtrsim 2$, allowing us to directly estimate the molecular gas mass of the galaxies without assumptions about their CO excitation. We obtain molecular gas masses $\approx 1.5-2$ times lower than earlier estimates based on the mid-J CO lines. We find thermal excitation of the $J = 3$ and $J = 4$ rotational levels in the $z = 2.5848$ galaxy DLA J0918+1636, and near-thermal

$^8$ The $\Sigma_{SFR}$ values for the main-sequence galaxies are from Tacconi et al. (2013) and Boogaard et al. (2020).
excitation of the \( J=3 \) level in the \( z=2.1933 \) galaxy DLA B1228-113. In both cases, the CO excitation of the mid-\( J \)-rotational levels is higher than that typically assumed for main-sequence galaxies at \( z \approx 2 \). We also find evidence for higher excitation of the \( J=3 \) level in H\textsc{i}-selected galaxies, main-sequence galaxies, and SMGs at \( z \gtrsim 2 \) than in main-sequence galaxies at \( z \approx 1.5 \). This appears to arise due to a higher SFR surface density in the former types of galaxies. Finally, we used HST WFC3 imaging to detect rest-frame NUV emission from the \( z \approx 2.1933 \) galaxy DLA B1228-113, obtaining an NUV SFR of \( 4.44 \pm 0.47 \, M_\odot \, \text{yr}^{-1} \). This is a factor of \( \approx 20 \) lower than the SFR estimated from the total infrared luminosity or from SED fitting, confirming that the object is a highly dusty galaxy. The stellar NUV emission appears slightly offset from the ALMA CO(3–2) emission, suggesting that the CO and NUV emission may arise from a pair of merging galaxies, one of which is highly obscured and hence not detected in its stellar emission.

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**Figure 4.** The ratio of the CO(3–2) line luminosity to the CO(1–0) line luminosity (\( r_{31} \)), plotted as a function of (A) redshift and (B) SFR surface density, for the H\textsc{i}-selected galaxies of this work (red symbols), BzK galaxies at \( z \approx 1.5 \) (green crosses; Daddi et al. 2015), and main-sequence galaxies at \( z > 2 \) (blue pentagons; Riechers et al. 2010; Brisbin et al. 2019; Boogaard et al. 2020; Henríquez-Brocal et al. 2021). The left panel also shows the median \( r_{31} \) value for submillimeter galaxies at \( z > 2 \) (inverted black triangles; Sharon et al. 2016). The dashed horizontal line in both panels indicates \( r_{31} = 1 \), for thermal excitation.

**Software:** DrizzlePac (Hack et al. 2020), CASA (\textsc{v}5.6; McMullin et al. 2007), AIPS (Greisen 2003), ASTROPHY (Astropy Collaboration et al. 2013).

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