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A blind CO detection of a distant red galaxy in the HS1700+64 protocluster

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ABSTRACT

We report the blind detection of ^{12}CO emission from a distant red galaxy, HS1700.DRG55. We have used the IRAM Plateau de Bure Interferometer WideX, with its 3.6 GHz of instantaneous dual-polarization bandwidth, to target ^{12}CO(3–2) from galaxies lying in the protocluster at $z = 2.300$ in the field HS1700+64. If indeed this line in DRG55 is ^{12}CO(3–2), its detection at 104.9 GHz indicates $z_{\rm CO} = 2.296$. None of the other eight known $z \sim 2.30$ protocluster galaxies lying within the primary beam (PB) are detected in ^{12}CO, although the limits are $\sim 2\times$ worse towards the edge of the PB where several lie. The optical/near-IR magnitudes of DRG55 ($R_{\rm AB} > 27$, $K_{\rm AB} = 22.3$) mean that optical spectroscopic redshifts are difficult with 10-m-class telescopes, but near-IR redshifts would be feasible. The 24-µm-implied star formation rate (210 M$_\odot$ yr^{-1}), stellar mass ($\sim 10^{11}$ M$_\odot$) and ^{12}CO line luminosity (3.6×10^{10} K km s^{-1} pc^2) are comparable to other *normal* ^{12}CO-detected star-forming galaxies in the literature, although the galaxy is some $\sim$2 mag ($\sim 6\times$) fainter in the rest-frame UV than ^{12}CO-detected galaxies at $z > 2$. The detection of DRG55 in ^{12}CO complements three other ^{12}CO detected UV-bright galaxies in this protocluster from previous studies, and suggests that many optically faint galaxies in the protocluster may host substantial molecular gas reservoirs, and a full blind census of ^{12}CO in this overdense environment is warranted.

Key words: ISM: molecules – galaxies: clusters: general – galaxies: high-redshift – galaxies: starburst.

1 INTRODUCTION

Massive galaxy clusters at $z > 1$ show a reversal in the star-formation density relation such that there is an enhancement of activity in the highest density regions (e.g. Elbaz et al. 2007, 2011), with observations revealing increasing levels of activity even in the cluster cores (Cooper et al. 2008; Chapman et al. 2009; Hilton et al. 2010; Tran et al. 2010; Smail et al. 2014). By contrast, the gas properties of galaxies in distant clusters remain poorly constrained, despite the fact that they may well elucidate the mechanisms for the increasing SFRs in cores of massive clusters. Studies of the molecular medium in distant galaxies provide key diagnostics about the evolutionary state of galaxies in the high-redshift universe. To date, over 200 high-redshift galaxies have been detected in ^{12}CO emission, the main tracer for molecular gas (e.g. Bothwell et al. 2013; Tacconi et al. 2013). Essentially all these detections were obtained by targeted observations of galaxies that have been pre-selected through their star-forming properties, e.g. ultraviolet (UV) or far-infrared (FIR) emission. However, the gas supplies, SF efficiencies and starburst modes (merger driven versus quiescent disc) may vary strongly as a function of their local density, and comparing the ^{12}CO properties of galaxies in protoclusters to the field should elucidate the stronger evolution seen in overdense regions.

In this Letter, we describe a blind 3 mm survey for redshifted ^{12}CO(3–2) molecular gas from $z \sim 2.30$ galaxies in HS1700+64, a protocluster with a redshift-space galaxy overdensity of $\delta_g^z \sim 7$ and an estimated matter overdensity which indicates that it will virialize

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by $z \sim 0$ with a mass scale of a rich galaxy cluster, $\sim 14 \times 10^{15}$ M$_\odot$ (Steidel et al. 2005). Low-J ^{12}CO transitions are collisionally excited by H_2 at low temperatures providing a good census of the star-forming gas in a range of galaxy types/luminosities (e.g. Ivison et al. 2011; Riechers et al. 2011; Harris et al. 2012). In the Tacconi et al. (2013) study of ^{12}CO(3–2) in *normal* star-forming galaxies, 6 of the 19 targets lying at $z > 2$ are in this HS1700+64 field, with 4 identified to UV-bright protocluster members at $z \sim 2.3$, providing a reference sample for our study. The 3 mm band provides a reasonably large field of view on the IRAM-Plateau de Bure Interferometer [PdBI; ∼50 arcsec primary beam (PB), ∼0.4 Mpc diameter at $z = 2.3$], with the strong clustering of galaxies in angular scales and along the line of sight effectively increasing the number of galaxies observed within a single pointing with the PdBI (see also Tadaki et al. 2014). We use cosmological parameters $\Omega_m = 0.3$, $\Lambda_0 = 0.7$ and $H_0 = 70$ km s^{-1} Mpc^{-1} throughout this Letter; at $z = 2.30$, this corresponds to an angular scale of 7.9 kpc arcsec^{-1}.

2 OBSERVATIONS

We have obtained an observation centred at 100.4 GHz in the 3 mm window performed at PdBI at a pointing centre: RA = 17^{h} 01^{m} 17^{s}.62, Dec. = +64° 14′ 38″.0 (J2000.0), designed to perform a blind census of ^{12}CO(3–2) near the $z = 2.300$ protocluster core, and specifically targeted a bright submillimetre galaxy (SMG) thought to potentially lie at $z = 2.31$ given its location 2 arcsec from an extended complex of UV-luminous star-forming galaxies (the SMG turned out to have $z = 2.82$ – Chapman et al., in preparation). The galaxy DRG55 described in this Letter lies 9.1 arcsec from the pointing centre. Observations were obtained on 2014 April 13 and 14, over two tracks (project S04CK) in D configuration, using the five-antenna sub-array. We used the PdBI WideX correlator covering frequency range of 3.6 GHz (102.1–105.7 GHz), corresponding to redshifts $2.271 < z < 2.387$ in the ^{12}CO(3–2) line. Flux calibration used 3C273 and 3C345, and the quasar B1749+096 was used as a phase and amplitude calibrator.

We resampled the data cubes in 60 km s^{-1} channels, and imaged them using the GILDAS suite MAPPING using natural weighting.

The beam size is 6.6 arcsec × 4.1 arcsec, PA = 61.7 deg (∼30 × 45 kpc at $z = 2.3$). The final cube corresponds to 3.34 h on source. To obtain flux measurements, we deconvolved the visibilities using the CLEAN task with natural weighting, and applied the corresponding PB correction.

The data have an rms of 0.6 mJy beam^{-1} in 50 MHz channels, corresponding to a 3.5σ limit in ^{12}CO of 0.4 Jy km s^{-1} or $L_{\rm lim} = 1.8 \times 10^{10}$ K km s^{-1} pc^2 at $z \sim 2.30$ (assuming a typical line width of 300 km s^{-1}, 0.38 mJy rms and an average PB correction of 0.72). This is comparable with faint ^{12}CO detections reported from 3 mm observations at these redshifts (e.g. Bothwell et al. 2013; Tacconi et al. 2013).

Submillimeter Array (SMA) interferometric imaging observations at 870 µm were also taken in this field, using both compact and extended configurations. The SMA ∼35 arcsec PB at this wavelength encompasses both the original targeted SMG and the 9 arcsec offset position of DRG55, where the PB correction is 15 per cent. The combined map reaches an rms of 1.0 mJy at phase centre (Chapman et al., in preparation) with a resolution of ∼1 arcsec. The Submillimetre Common-User Bolometer Array-2 (SCUBA-2) map of this field, reaching the confusion limit with an rms at 850 µm of 0.5 mJy, is also described elsewhere (Chapman et al., in preparation).

2.1 The four archival protocluster PdBI pointings

Archival observations of ^{12}CO emitters by Tacconi et al. (2013) observed four Lyman-break galaxies (LBGs) lying within the protocluster at $z = 2.3$ using the old-generation receivers [giving velocity coverage of ∼2000 km s^{-1}, detecting three of them robustly in ^{12}CO(3–2)]. Despite the arguments in Tacconi et al. (2013) for these being *normal* star-forming galaxies, all four actually have AGN-like near-IR spectra (from [N II]/Hα; Erb, Bogosavljevic & Steidel 2011), while MD174 is clearly an AGN even in its UV spectrum. A SCUBA-2 850 µm survey of these CO-observed galaxies (Beanlands et al., in preparation) shows that on average these sources have $S_{850\,\mu\rm m} = 1.4$ mJy, although a few (in fields other than HS1700+64) have substantially higher $S_{850\,\mu\rm m} \sim 4$ mJy.

As we detect DRG55 in ^{12}CO within 1000 km s^{-1} of our targeted $z = 2.305$, there is some hope that the Tacconi PdBI observations might uncover additional protocluster sources offset from the targeted LBG. We retrieved the Tacconi et al. data cubes from the archive and searched for blind ^{12}CO detections offset from the targeted galaxies. We confirm their three of four ^{12}CO detections of the BX galaxies, but do not find any additional ^{12}CO sources to depths similar to our present study. In addition, there are no known optical galaxies with redshifts in the ^{12}CO range in any of these four pointings (summary in Table 1), although two lie very near the frequency band edge in the MD69 and MD174 pointings.

3 RESULTS

Our PdBI observations cover the ^{12}CO(3–2) line emission from nine galaxies (listed in Table 1) near the protocluster core that either have an optical spectroscopic redshift in the range $2.28 < z < 2.38$ (five galaxies) or appear luminous at 24 µm and have colours consistent with $z \sim 2.3$ [three distant red galaxies (DRGs) and an SMG]. They allow for initial exploration of the diversity of gas-rich galaxies in the protocluster, and to quantify the potential missing sources.

This field represents a particularly overdense sub-region of the protocluster, tripling the average overdensity over 20 arcmin^2 and lying ∼1.5 arcmin from the optically defined protocluster core.

Since the frequency of the ^{12}CO(3–2) line emission could be slightly offset from the frequency implied by the optical redshifts, we searched for a ^{12}CO emission peak in the spectra along the line of sight. Only DRG55 shows a clear line detection (although the SMG at pointing centre is detected >5σ in 3 mm continuum at 0.380 ± 0.075 mJy). When we stack the seven non-detections, we do not find any significant line emission, but set an improved limit of $L_{\rm lim,\,3\sigma} = 0.8 \times 10^{10}$ K km s^{-1} pc^2 on their average ^{12}CO(3–2), the average expected emission from a 100 M$_\odot$ yr^{-1} starburst (fig. 2 in Tacconi et al. 2013).

An optimal extraction of DRG55 was found by summing channels from 104.76 to 105.15 GHz (∼1100 km s^{-1}), showing a 4.8σ detection of 1.1 ± 0.2 mJy at the position of DRG55 (Fig. 1), coincident (to 0.2 arcsec) with a 160 µJy 24 µm source. There are no other peaks in the channel map this strong: the next two are 3.5σ and 2.8σ. The extracted 1D spectrum shows a well-detected ^{12}CO(3–2) line peaking at ∼2 mJy (Fig. 1) with a continuum rms = 0.23 mJy, and a line flux of 1.14 ± 0.31 Jy km s^{-1}, and an implied line luminosity of 3.6 × 10^{10} K km^{-1} pc^2. The total molecular gas mass of 3.2 × 10^{11} M$_\odot$ is derived, corrected for helium (1.36), a 'Galactic' CO–H_2 conversion factor $\alpha = 4.36$, a CO(1–0)/CO(3–2) ratio of 2 and systematic uncertainty 50 per cent. A Gaussian fit to the line suggests a peak frequency of 104.9 GHz, and $z_{\rm CO} = 2.296$, near the central protocluster redshift of $z = 2.300$ (Steidel et al. 2005).

Table 1. CO-targeted galaxies within the PB of our survey (upper entries), and summary of Tacconi et al. (2013) ^{12}CO-observed BX galaxies in the same protocluster (lower entries). Submm fluxes are either 850 μm from SCUBA-2, with the ∼0.5 mJy rms listed, or 870 μm from SMA follow-up (where the SCUBA-2 map cannot be used to set useful limits due to the bright SMG). Molecular gas mass, corrected for helium, a 'Galactic' CO–H_2 conversion factor, $\alpha = 4.36$ and a CO(1–0)/CO(3–2) ratio of 2. The last four galaxies were selected by the LBG colour criteria (although all four actually have AGN-like near-IR spectra), with 850 μm fluxes from Beanlands et al. (in preparation). The DRG55 redshift is obtained solely from ^{12}CO(3–2).

ID	RA/Dec. (J2000) ($^{\mathrm{h\,m\,s}}$/° ′ ″)	Rad. (arcsec)	z	$S_{850\,\mu\mathrm{m}}$ (mJy)	$S_{24\,\mu\mathrm{m}}$ (μJy)	SFR ($\mathrm{M_\odot\,yr^{-1}}$)	M^* ($\times10^{10}\,\mathrm{M_\odot}$)	M_g ($\times10^{11}\,\mathrm{M_\odot}$)
BX951	17 01 17.90 +64 14 40.5	2.9	2.308	<3	<10	<13	3.8	<1
DRG55	17 01 19.37 +64 14 37.7	9.1	2.296	<3	160.1 ± 5.0	210	9.8	3.2
BX917	17 01 16.15 +64 14 19.6	20.1	2.304	<3	110.9 ± 5.0	146	4.5	<2
DRG71	17 01 16.49 +64 14 15.4	22.3	∼2.3 ± 0.2	<3	<10	<13	2.0	<2
DRG53	17 01 21.06 +64 14 22.3	23.3	∼2.3 ± 0.2	1.7 ± 0.5	604 ± 5.0	793	75.7	<2
BX950	17 01 14.19 +64 14 40.4	25.2	2.311	<3	<10	<13	1.3	<2
DRG73	17 01 21.75 +64 14 36.0	25.4	∼2.3 ± 0.2	<3	<10	<13	<0.9	<2
BX913	17 01 21.61 +64 14 18.2	29.2	2.291	2.1 ± 0.5	30.2 ± 5.0	40	4.0	<2
MD103[a]	17 01 00.25 +64 11 55.3		2.315	<1.5	164.2 ± 5.0	216	6.6	<1.1
MD174[b]	17 00 54.58 +64 16 24.5		2.344	1.7 ± 0.5	1116.5 ± 5.0	1466	24.0	1.7
MD69[c]	17 00 47.65 +64 09 44.5		2.288	1.8 ± 0.5	256.8 ± 5.0	337	19.0	0.96
MD94[d]	17 00 42.06 +64 11 24.0		2.340	1.3 ± 0.5	57.3 ± 5.0	75	15.0	3.3

Notes. [a]MD103 is listed as undetected in ^{12}CO(3–2) in Tacconi et al. (2013), consistent with our analysis. All other known LBGs in the PB are at $z \sim 2.75$.
[b]MD174 is a strong AGN from UV/near-IR spectra. Another galaxy, BX1156 $z = 2.285$, lies just beyond $z = 2.327$–2.357 covered by PdBI. A bright $S_{850\,\mu\mathrm{m}} = 7$ mJy SMG lies within the PB, but no lines are detected: we conclude that it is not in the covered redshift range, but could still be in protocluster.
[c]Another galaxy, BX505 $z = 2.309$, is just beyond (545 km s^{-1}) the $z = 2.273$–2.303 probed by PdBI. The galaxy is undetected in ^{12}CO at band edge.
[d]All other known galaxies with spectroscopic redshifts falling in the PB lie outside the redshift range $z = 2.325$–2.355.

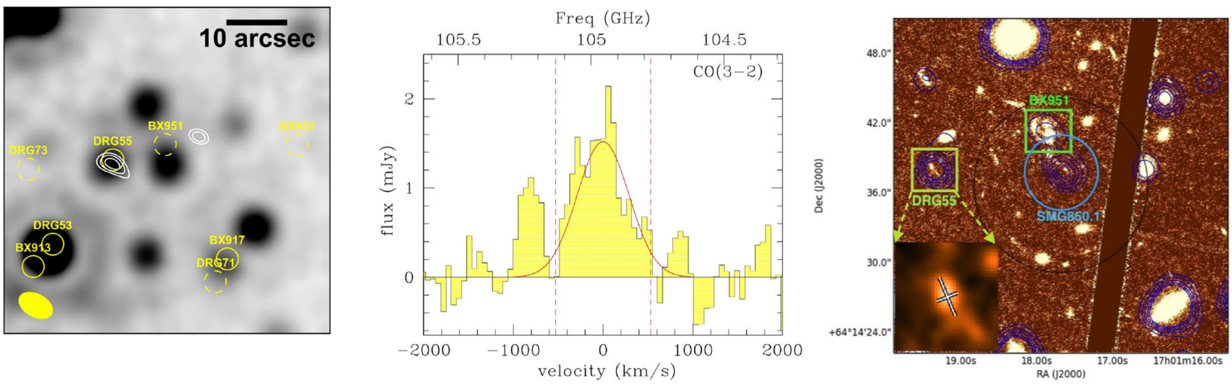

Figure 1. Left: a *Spitzer*-MIPS 24 μm image with the ^{12}CO channel map at $z \sim 2.30$ from the HS1700+64 PdBI pointing overlaid, constructed by summing channels from 104.76 to 105.15 GHz (∼1100 km s^{-1}), showing a 4.8σ detection of 1.1 ± 0.2 mJy at the position of DRG55 (contours), coincident with a 160 μJy 24 μm source. The primary beam of PdBI (48 arcsec) is larger than the field shown. Middle: the extracted 1D spectrum shows a well-detected CO(3–2) line with a continuum rms = 0.23 mJy. A Gaussian fit to the line suggests $z_{\mathrm{CO}} = 2.296$. The velocity limits of the channel map (left) are shown as dashed lines. Right: an *HST* ACS *F*814*W* image (details in Peter et al. 2007) centred on the PdBI observation. The DRG55 is identified, along with a UV-luminous BX galaxy and an $S_{850\,\mu\mathrm{m}} = 19.1$ mJy SMG. Blue contours show IRAC 4.5 μm emission. DRG55 is identified with a faint galaxy with *tadpole* morphology, also shown in the 1.5 arcsec field inset with a Gaussian fit to the galaxy of FWHM 0.7 arcsec × 0.4 arcsec.

While the SCUBA-2 map cannot easily place a limit on the 850 μm emission due to the bright SMG 10 arcsec away, it shows no detection at 450 μm (7 ± 6 mJy) where the beam is 7 arcsec. The SMA map shows an 850 μm emission at the position of DRG55 of 2.5 ± 1.1 mJy or <3.3 mJy (3σ). DRG55 is essentially undetected in optical ground-based imagery ($R \sim 27$, $g > 27.3$, $U > 27.2$, 3σ). In a *Hubble Space Telescope* (*HST*) ACS *F*814*W* image (details in Peter et al. 2007), DRG55 is identified with a faint $I_{\mathrm{AB}} = 26.0$ galaxy with *tadpole* morphology (Fig. 1), and is well detected in near/mid-IR ($J_{\mathrm{AB}} = 23.92$, $K_{\mathrm{AB}} = 22.30$, IRAC-*ch*2$_{\mathrm{AB}} = 21.9$).

Our constraint on the FIR emission is really grounded by the S(24 μm) = 0.16 ± 0.01 mJy point, and the $S_{850\,\mu\mathrm{m}} < 3$ mJy limit. However, the 24 μm point sits at the peak of the 7.7 μm polycyclic aromatic hydrocarbon line, and as such is also subject to systematic uncertainty. None the less, from IRAC through submm wavelengths, the Spectral Energy Distribution (SED) is remarkably similar to the Swinbank et al. (2014) composite SMG SED from ALESS (Fig. 2), from which we derive an $L_{\mathrm{FIR}} = 2.1 \times 10^{12}$ L$_\odot$ and an SFR ∼ 210 M$_\odot$ yr^{-1} (Kennicutt 1998, Chabrier initial mass function). The peak in the SED at IRAC 4.5 μm suggests that there is no obvious AGN, and the 24 μm emission may therefore be SF powered, contrasted with the AGN-like galaxies hosting the other three known ^{12}CO sources in the protocluster (as described in Section 2.1).

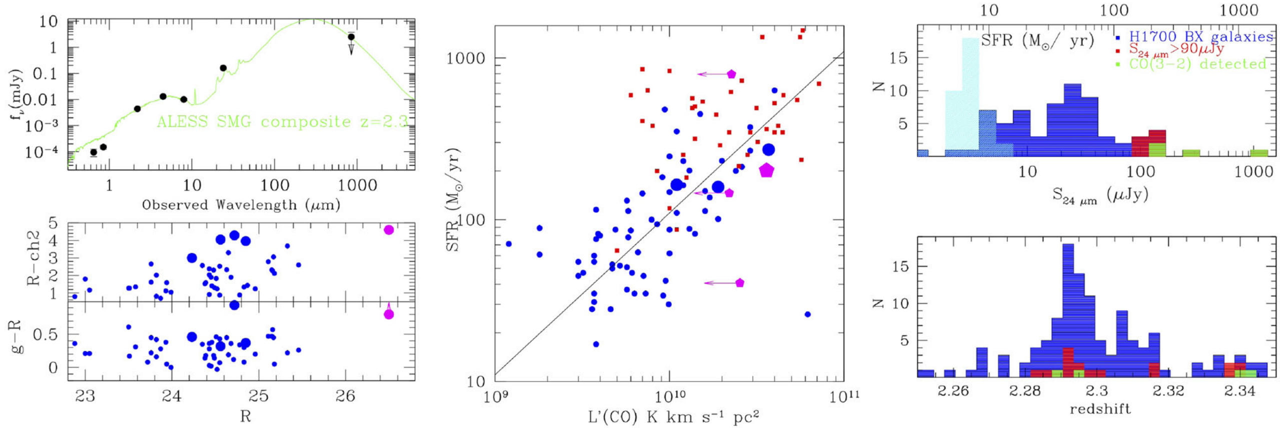

Figure 2. Left top: multiwavelength SED of HS1700.DRG55, compared to the ALMA ALESS SMG composite (Swinbank et al. 2014) scaled to a 2 mJy 850 μm source at $z = 2.3$. DRG55 is remarkably similar to the source, but optically fainter shortwards of 1 μm. Left bottom: comparison of the optical/IR colours of DRG55 (red symbol) with spectroscopically confirmed UV-selected galaxies in the same field from Shapley et al. (2005), emphasizing the redness of the source relative to typical UV galaxies. The Tacconi et al. (2013) CO-detected BX galaxies are also highlighted with larger circles. Middle: SFR versus L'(CO) for various literature galaxies compared with DRG55 (blue circles – Tacconi et al. 2013; red squares – Bothwell et al. 2013). The solid magenta pentagons show L'(CO) for the 24-μm-brightest galaxies in our survey, with limits at 3σ. DRG55 is nominally overluminous in ^{12}CO compared to other ultraluminous galaxies, but similar to other Tacconi et al. (2013) LBGs lying in the protocluster (larger blue circles). Right top: the 24 μm fluxes of all protocluster galaxies with spectroscopic redshifts, with inferred SFR labelled on top axis. The brightest 24 μm sub-sample and those that are detected in CO(3–2) are highlighted. For $S_{24\,\mu m} < 10$ μJy (2σ limit of the *Spitzer*-MIPS map), we have estimated the 24 μm fluxes from the UV-derived SFR (cyan shading). Right bottom: histogram of the protocluster galaxies, with the same sub-populations highlighted. The 24-μm-bright and CO-detected sub-samples appear to span a larger range in redshifts than the overall cluster population.

A Gaussian fit to the ^{12}CO line of full width at half-maximum (FWHM) $= 680 \pm 141$ km s^{-1}, together with a size of 0.35 arcsec (half-light radius) in the *HST F*814*W* image, implies a dynamical mass of 3.7×10^{11} M$_{\odot}$, assuming a virial mass indicator. The *J*, *K* and IRAC 4.5 μm luminosities suggest a stellar mass of $\sim 1 \times 10^{11}$ M$_{\odot}$. The dynamical constraint thus sets a limit to the gas mass of $<2.7 \times 10^{11}$ M$_{\odot}$. Another approach is to estimate the gas fraction as $m_{gas}/(m_{stars} + m_{gas})$, suggesting a very gas rich system of $f_{gas} \sim 80$ per cent with $\alpha_{CO} = 4.36$, although the stellar mass is uncertain with systematic error of a factor of 2 (e.g. Hainline et al. 2011). For high-z SMGs, an ~50 per cent gas fraction was estimated (Bothwell et al. 2013), but using a lower $\alpha = 1$–2. If we adopt similarly low α_{CO}, f_{gas} is ~50 per cent for DRG55, in line with the ULIRGs from Bothwell et al. (2013).

To search for any additional protocluster members which may not be associated with known optical galaxies, we also performed a blind search for significant emission line peaks in the PdBI data cube, lying within the PB. We performed the search making use of the AIPS task SERCH, which uses a Gaussian kernel to convolve the data cube along the frequency axis with an expected input line width, and reports all channels and pixels having a signal-to-noise ratio over the specified limit. We experimented with Gaussian kernel line widths, from ~260 to 520 km s^{-1}. We found no peaks at $>5\sigma$ ranging over 10 000 km s^{-1} in velocity space. At $>4\sigma$, we find an additional three candidate lines ranging from 4.4σ to 4.7σ, but all with velocity offsets >2000 km s^{-1} from $z = 2.300$, and with distances from the pointing centre of 10.2–24.3 arcsec. None of these lie within <2 arcsec of any IRAC 4.5 μm sources, and may be spurious lines, but in any case are distant enough in velocity to be outliers from the protocluster.

4 DISCUSSION AND CONCLUSIONS

The detection of DRG55 in ^{12}CO complements three other ^{12}CO-detected UV-bright galaxies in this protocluster from Tacconi et al. (2013), suggesting that many optically faint galaxies in the protocluster may host substantial molecular gas reservoirs, and a full blind census of ^{12}CO in this overdense environment is warranted. To assess how many additional ^{12}CO-bright sources might be found in this region, we look first at the likely size of such a protocluster (the pieces which end up within the central 1 Mpc at $z \sim 0$), for example Chiang, Overzier & Gebhardt (2013) predict 5–10 comoving Mpc. While we have targeted an overdense sub-region within the protocluster, our PdBI survey size is of only 0.5 Mpc in diameter. While the full protocluster may well extend over 100–200 times the area, less than ~one tenth will be as overdense as this DRG55 sub-region (already three times the average core density). We thus might expect that in a blind survey in this protocluster, we would uncover 10–20 such ^{12}CO(3–2) emitters. Under the assumption that Tacconi et al. (2013) fairly sampled the top end of the UV-bright luminosity function in the protocluster (Fig. 2), a similar number (~20) of UV-bright galaxies with $L'(\mathrm{CO}) > 1 \times 10^{10}$ K km s^{-1} pc^2 should reside in the full extent of the protocluster.

A colour–luminosity plot (Fig. 2) for the protocluster population is used to compare DRG55 with the Tacconi et al. (2013) galaxies and the general $z \sim 2.3$ UV population. DRG55 is certainly significantly fainter and redder, and suggests that there may well be other gas-rich members of the protocluster that are not accounted for by the UV-bright census. We learn that the Tacconi et al. galaxies are amongst the reddest in the population, but that DRG55 still separates significantly in optical properties despite having a similar ^{12}CO mass. DRG55 is one of 72 near-IR selected objects in the surrounding 9 arcmin × 9 arcmin field, satisfying the $(J-K_s)_{vega} > 2.3$ criteria advocated by Franx et al. (2003) for selecting $z > 2$ red galaxies.

DRG55 is significantly fainter in the rest-UV than typical LBG-selected objects, but its near-IR properties are not particularly unusual.

It is one of only two DRGs in the 9 arcmin field that is also flagged as an Hα narrow-band candidate (which was designed to probe the protocluster redshift; Erb et al. 2014), setting some limit on the number of additional objects with similar near-IR-bright properties that could be found within the $z \sim 2.3$ structure. Its Hα+[N II] flux is 8×10^{-17} erg s^{-1} cm^{-2} Hz^{-1} (relatively easy to reach with near-IR spectroscopy), corresponding to an SFR of $\sim$15 M$_{\odot}$ yr^{-1} before applying an extinction correction (a factor 14 to match the SFR$_{24\,\mu\mathrm{m}}$).

The Hα line excess also means that the ^{12}CO redshift is almost certainly $z = 2.296$.

DRG55 is not detected in deep Lyman α images of the field reaching $<1 \times 10^{-17}$ erg s^{-1} cm^{-2} Hz^{-1} (Erb et al. 2011; Steidel et al. 2011). We also put DRG55 in the context of other photometrically studied populations, specifically the 'dust-obscured' galaxies with high $f_{24\,\mu\mathrm{m}}/f_R > 1000$ (e.g. Dey et al. 2008; Penner et al. 2012), for which DRG55 qualifies, although galaxies selected in this way are a mixture of dusty star formers and obscured AGN. ^{12}CO observations exist only for few rather luminous similar sources (Yan et al. 2010). Interesting ^{12}CO-detected (though more luminous) comparison objects may also be obscured SMGs such as SMM14009 (Weiss et al. 2009) or SMMJ00266+1708 (Sharon et al. 2015), and several from Chapman et al. (2005).

A targeted search for ^{12}CO in the protocluster around faint DRGs identified to 24 or 850 µm sources, with photo-z's consistent with $z \sim 2.30$ (but too faint for optical spectroscopy), might quickly increase the total number of known ultraluminous cluster members.

We next turn to a discussion of DRG55 versus other ^{12}CO-detected sources, plotting L'(CO)–SFR for the high-z population (Fig. 2). DRG55 is somewhat overluminous in ^{12}CO for its SFR compared to SMGs from Bothwell et al. (2013), as are two of the Tacconi et al. (2013) protocluster ^{12}CO sources, suggesting a low efficiency of SF. Our survey limit is sufficient to detect the average relation for an SFR $\sim$ 200 M$_{\odot}$ yr^{-1}, but can only detect overluminous ^{12}CO emitters at lower SFRs. Fig. 2 also highlights the 24 µm properties of all known protocluster galaxies, revealing that DRG55 has a similarly high IR luminosity to the Tacconi et al. (2013) galaxies (although one of their sources is a clear outlier with $S_{24\,\mu\mathrm{m}} \sim 1$ mJy). To date, the only truly blank field, blind high-J CO survey conducted is that of Decarli et al. (2014) who found two secure CO detections in a deep PdBI scan of the *Hubble Deep Field*-North (their ID.03 and ID.19), which they identified with star-forming galaxies at $z = 1.784$ and 2.047. They found these galaxies to have colours consistent with the BzK galaxies (Daddi et al. 2008), although with specific SFRs below the locus of $z \sim 2$ main-sequence galaxies. They show relatively bright ^{12}CO emission compared with galaxies of similar dust continuum luminosity [but still within the observed scatter of the L_{IR}–L'(CO) relation].

Finally, we assess the redshift and spatial distribution of DRG55 relative to the other known ^{12}CO emitters in the protocluster. Of note is that the ^{12}CO-detected galaxies comprise the four brightest 24 µm sources known to be in the protocluster, with estimated SFRs (24 µm) ranging from 200 to 1100 M$_{\odot}$ yr^{-1} (Fig. 2). There are of course many potential dust-obscured SMGs lying in the protocluster, yet to be identified. None of the SCUBA-2 sources in this field have spectroscopic redshifts, but many have robust DRG counterparts which have colours consistent with those lying in the protocluster. The redshifts of these four ^{12}CO emitters divide into two redshift groups, also mirrored by the eight brightest 24 µm emitters known in the protocluster (Fig. 2). One group is in the central protocluster 'spike', with the second group in a knot of more receding objects, which might represent a gas-rich group falling in and being lit up. However, this background 'group' does not cluster spatially within the 9 arcmin field, and may be more *sheet*-like. These eight galaxies have a much broader dispersion than the protocluster redshift distribution, and may indicate environmental triggering of the most luminous population.

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