The AT-LESS CO(1-0) survey of submillimetre galaxies in the Extended Chandra Deep Field South: First results on cold molecular gas in galaxies at z \sim 2

Minh T. Huynh, ^{1,2}★ B.H.C. Emonts, ³ A.E. Kimball, ^{4,5} N. Seymour, ⁶ Ian Smail, ⁷ A.M. Swinbank ⁷ W.N. Brandt, ^{8,9,10} C.M. Casey, ¹¹ S.C. Chapman, ¹² H. Dannerbauer, ^{13,14} J.A. Hodge, ¹⁵ R.J. Ivison, ^{16,17} E. Schinnerer, ¹⁸ A.P. Thomson, ⁷ P. van der Werf, ¹⁵ J.L. Wardlow ⁷

- ¹ International Centre for Radio Astronomy Research, M468, University of Western Australia, Crawley, WA 6009, Australia
- ² CSIRO Astronomy and Space Science, 26 Dick Perry Avenue, Kensington WA 6151, Australia
- ³ Centro de Astrobiología (INTA-CSIC), Ctra de Torrejón a Ajalvir, km 4, E-28850 Torrejón de Ardoz, Madrid, Spain
- ⁴ CSIRO Astronomy and Space Science, PO Box 76, Epping, NSW, 1710, Australia
- ⁵ National Radio Astronomy Observatory, 1003 Lopezville Rd, Socorro, NM, 87801, USA
- ⁶ International Centre for Radio Astronomy Research, Curtin University, Bentley, WA 6102, Australia
- Centre for Extragalactic Astronomy, Department of Physics, Durham University, South Road, Durham DH1 3LE UK
- Bepartment of Astronomy and Astrophysics, 525 Davey Lab, The Pennsylvania State University, University Park, PA 16802, USA
- ⁹ Institute for Gravitation and the Cosmos, The Pennsylvania State University, University Park, PA 16802, USA
- Department of Physics, The Pennsylvania State University, University Park, PA 16802, USA
- 11 Department of Astronomy, the University of Texas at Austin, 2515 Speedway Blvd, Stop C1400, Austin, TX 78712, USA
- ² Dalhousie University, Halifax, Nova Scotia B3H 3J5, Canada
- ¹³ Instituto de Astrofísica de Canarias (IAC), E-38205 La Laguna, Tenerife, Spain
- ¹⁴ Universidad de La Laguna, Dpto. Astrofísica, E-38206 La Laguna, Tenerife, Spain
- ¹⁵ Leiden Observatory, Leiden University, PO Box 9513, NL-2300 RA Leiden, the Netherlands
- ⁶ European Southern Observatory, Karl-Schwarzschild-Str. 2, D-85748 Garching bei München, Germany
- ¹⁷ Institute for Astronomy, University of Edinburgh, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK
- ¹⁸ Max-Planck-Institut für Astronomie, Königstuhl 17, D-69117 Heidelberg, Germany

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ABSTRACT

We present the first results from our on-going Australia Telescope Compact Array survey of ¹²CO(1-0) in ALMA-identified submillimetre galaxies in the Extended Chandra Deep Field South. Strong detections of ¹²CO(1-0) emission from two submillimetre galaxies, ALESS 122.1 (z=2.0232) and ALESS 67.1 (z=2.1230), were obtained. We estimate gas masses of $M_{\rm gas}\sim 1.3\times 10^{11}~\rm M_{\odot}$ and $M_{\rm gas}\sim 1.0\times 10^{11} \rm M_{\odot}$ for ALESS 122.1 and ALESS 67.1, respectively, adopting $\alpha_{\rm CO}=1.0$. Dynamical mass estimates from the kinematics of the $^{12}{\rm CO}(1\text{-}0)$ line yields $M_{\rm dyn}\sin^2 i=(2.1\pm 1.1)\times 10^{11}~\rm M_{\odot}$ and (3.2) \pm 0.9) $\times 10^{11}$ M_{\odot} for ALESS 122.1 and ALESS 67.1, respectively. This is consistent with the total baryonic mass estimates of these two systems. We examine star formation efficiency using the $L_{\rm FIR}$ versus $L'_{\rm CO(1-0)}$ relation for samples of local ULIRGs and LIRGs, and more distant star-forming galaxies, with ¹²CO(1-0) detections. We find some evidence of a shallower slope for ULIRGs and SMGs compared to less luminous systems, but a larger sample is required for definite conclusions. We determine gas-todust ratios of 170 ± 30 and 140 ± 30 for ALESS 122.1 and ALESS 67.1, respectively, showing ALESS 122.1 has an unusually large gas reservoir. By combining the 38.1 GHz continuum detection of ALESS 122.1 with 1.4 and 5.5 GHz data, we estimate that the free-free contribution to radio emission at 38.1 GHz is 34 \pm 17 μ Jy, yielding a star formation rate (1400 \pm 700 M_{\odot} yr⁻¹) consistent with that from the infrared luminosity.

Key words: galaxies: evolution – submillimetre: galaxies – radio lines: galaxies

1 INTRODUCTION

Since their initial discovery, submillimeter galaxies (SMGs) have become an important element of our understanding of cosmic galaxy formation and evolution (e.g. Blain et al. 2002; Casey et al. 2014). Selected in the rest-frame farinfrared (FIR), SMGs contain significant masses of cold dust (Casey et al. 2012) and large reservoirs of molecular gas ($\gtrsim 10^{10}$ M_☉; e.g. Bothwell et al. 2013). These luminous galaxies have median redshifts of $z \sim 2-3$ (Chapman et al. 2005; Wardlow et al. 2011; Smolčić et al. 2012; Simpson et al. 2014), and extreme far-infrared (FIR) luminosities $L_{FIR} > 10^{12} L_{\odot}$ implying large star formation rates of ~ 100 – $1000~M_{\odot}~yr^{-1}$ (e.g. Blain et al. 2002). The peak of star formation in the Universe also occurred at $z \sim$ 2 – 3 (Hopkins & Beacom 2006; Madau & Dickinson 2014) and ultraluminous infrared galaxies (ULIRGs) are responsible for roughly half of the cosmic infrared luminosity density at those redshifts (Magnelli et al. 2013; Gruppioni et al. 2013), suggesting SMGs play a vital role in galaxy evolution.

Since the extreme star formation rates of local ULIRGs are believed to be driven by major mergers, it has also been asserted that SMGs at high redshift have similar evolutionary histories (e.g. Engel et al. 2010; Chen et al. 2015). However, secular origins have also been proposed for SMGs, one justification being that there are not enough mergers in some simulations to account for the number of observed SMGs (e.g. Hopkins & Hernquist 2010; Hayward et al. 2013). Cosmological hydrodynamic simulations are now able to reproduce some SMG properties, such as stellar masses and molecular gas fractions, without a major merger (e.g. Davé et al. 2010; Narayanan et al. 2015), but they in general can not reproduce the highest SFRs seen in SMGs or match the properties of descendants at $z \sim 0$. Moreover, the SMG population appears to be diverse and so large observational samples are necessary to capture this diversity and test the models.

Molecular gas studies of SMGs provide unique insight into the physical properties of these systems. Molecular line observations provide information on the kinematics of the galaxy (i.e. turbulent versus ordered rotating discs), as well as dynamical and gas mass estimates. Radio emission produced by the rotational transition of carbon monoxide (12CO) is one of the most accessible tracers of cold molecular gas in galaxies (Carilli & Walter 2013). However only a few tens of unlensed SMGs at $z \gtrsim 1.5$ have been detected in CO (e.g. Carilli & Walter 2013) and most are of high J (J > 2) transitions. The high-CO transitions trace dense and thermally excited gas in the starburst/AGN regions, while only the lowest CO transitions fully reveal the more widely distributed reservoirs of less dense, sub-thermally excited gas (e.g. Papadopoulos & Allen 2000; Papadopoulos et al. 2001; Carilli et al. 2010; Ivison et al. 2011). The ground transition CO(1-0) is least affected by the excitation conditions of the gas and therefore provides the most robust estimates of overall molecular gas content and the broadest tracer of the dynamics of the system.

To study the molecular gas content of SMGs we have initiated a survey of CO(1-0) with the the Australia Telescope Compact Array (ATCA). We describe the SMG sample and the ATCA observations in Section 2. The results of the observations are presented in Section 3. In Section 4 we discuss the molecular gas masses, dynamical masses, star

formation efficiency and dust-to-gas ratios of the observed systems. The standard $\Lambda\text{-}CDM$ cosmological parameters of $\Omega_M=0.29,~\Omega_{\Lambda}=0.71,$ and a Hubble constant of 70 km s^{-1} Mpc $^{-1}$ are adopted throughout this paper.

2 OBSERVATIONS AND DATA REDUCTION

2.1 Our ALESS SMG Sample

Our sample is selected from the ALMA study of 99 submillimeter sources from the ALMA LABOCA Extended Chandra Deep Field South (ECDFS) Submillimeter Survey (ALESS, Weiß et al. 2009; Hodge et al. 2013). ALESS is an ALMA Cycle 0 survey at 870 μ m to follow up 122 of the original 126 submm sources detected by the LABOCA ECDFS Submillimeter Survey (LESS, Weiß et al. 2009). The excellent angular resolution and sensitivity of ALMA (~1.5 arcsec and about 3 times deeper than LESS) resulted in a sample of 99 statistically reliable SMGs (Hodge et al. 2013). This large ALMA-identified SMG sample is free of the biases and misidentifications which have affected previous SMG studies.

The ECDFS (RA = 03h32m28s, Dec = $-27^{\circ}48'30''$) is one of the best-studied extragalactic survey fields available, allowing for secure identification of counterparts at other wavelengths. A spectroscopic survey of the original LESS SMGs was performed as part of a VLT Large Programme with the FOcal Reducer and low dispersion Spectrograph (FORS2) and VIsible MultiObject Spectrograph (VIMOS) during 2009 - 2012 (Danielson et al. 2016, submitted). To supplement the Large Programme, and target ALMA-identified ALESS SMGs which differed from the original LESS counterparts, observations were also obtained on XSHOOTER on the VLT, Gemini Near-Infrared Spectrograph (GNIRS) on Gemini South, the Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE) on Keck I, and DEep Imaging Multi-Object Spectrograph (DEIMOS) on Keck II. This extensive spectroscopic campaign has provided secure redshifts for 51/99 ALESS SMGs (Danielson et al. 2016, submitted). Herschel SPIRE imaging was deblended by combining the ALMA, Spitzer Multiband Imaging Photometer (MIPS) 24 μm and radio catalogue priors, to determine far-infrared properties, including dust masses, total infrared luminosities and star formation rates of the individual SMGs (Swinbank et al. 2014).

Our initial sample consists of nine ALESS SMGs at 1.5 < z < 2.5, where CO(1-0) is detectable in the Australia Telescope Compact Array (ATCA) 7mm band, with the best quality optical spectra from Danielson et al. (2016). These nine SMGs have secure redshifts with multiple emission or absorption features identified in the optical spectra. Pilot ATCA observations were granted in the OCT2015 semester in which we targeted two ALESS SMGs: ALESS 122.1 and ALESS 67.1. These two targets were chosen as they are the most infrared luminous SMGs out of the nine, and hence most likely to have detectable molecular gas reservoirs.

2.2 ATCA Observations and Data Reduction

Observations of ALESS122.1 and ALESS67.1 were performed on the Australia Telescope Compact Array (ATCA),

using the Compact Array Broadband Backend (CABB; Wilson et al. 2011), in August and September 2015. The array was in the standard compact hybrid configurations H75 and H168 for ALESS 122.1 and ALESS 67.1, resulting in maximum baselines of 89m and 192m, respectively, discarding the outer 6th antenna. The hybrid configurations, consisting of two antennas along the northern spur, allow good (u, v) coverage to be obtained for integrations less than the full 12 hour synthesis. Our observations consisted of ~ 8 hour runs to ensure the source elevation is greater than ~ 30 degrees. We obtained total integration times of 38 and 31 hours on-source for ALESS122.1 and ALESS67.1, respectively. The weather was good to average, with atmospheric path length rms variations generally in the range of 50 to 400 μ m, as measured on the 230m baseline ATCA Seeing Monitor (Middelberg et al. 2006). The 7mm receiver was centred at the expected frequency of the ¹²CO(1-0) line emission $(\nu_{\text{rest}} = 115.2712 \text{ GHz})$ given their spectroscopic redshifts, i.e. $38.129~\mathrm{GHz}$ for ALESS122.1 and $36.910~\mathrm{GHz}$ for ALESS67.1 GHz. The 2GHz bandwidth of CABB results in a velocity coverage of approximately 15,000 km s⁻¹.

Following Emonts et al. (2011), a bandpass calibration scan was acquired at the beginning and end of each 8 hour night; however we found that the bandpass scan in the beginning of the night is sufficient for good bandpass calibration and the second scan is thus a backup. Phase and amplitude calibration information was acquired with 2 minute scans on PKS 0346–279 every 15 minutes and pointing checks performed on the same source every hour. For flux calibration we observed Uranus at a time when it was close to the same elevation as our targets; this occurred around 00:30 LST and at an elevation of ~ 50 degrees. The uncertainty in the flux density calibration using the standard MIRIAD model of Uranus is estimated to be 30% (Emonts et al. 2011), but can be as little as 20% when following this scheme and in good conditions.

The data were calibrated, mapped and analysed using the standard MIRIAD (Sault & Killeen 1999) and KARMA (Gooch 1996) packages. The synthesized beam from natural weighting is 14.4×10.6 arcsec and 7.0×4.6 arcsec for ALESS 122.1 and ALESS 67.1, respectively. The resultant noise in the single 1 MHz (\sim 8 km s⁻¹) channels is ~ 0.40 mJy beam⁻¹ for both the ALESS122.1 and ALESS 67.1 cubes, consistent with other comparable 7mm ATCA/CABB studies (e.g. Coppin et al. 2010; Emonts et al. 2014; Huynh et al. 2014; Emonts et al. 2015).

3 RESULTS

The visibilities were re-sampled to produce cubes with velocity resolutions of 200, 300, 400 and 600 km s⁻¹ and each cube was examined for an emission line at the expected redshift and centered near the ALMA position. We identify a line at the ALMA position and spectroscopic redshift in the cubes for both sources at more than 8σ significance, and across multiple channels for 200 and 300 km s⁻¹ binning. The 200 km s⁻¹ binned spectra have similar sensitivities (0.079 mJy/beam) and the CO peaks are detected at ~12 σ and ~8 σ significance in the brightest channel for ALESS 122.1 and ALESS 67.1, respectively (see Figure 1). The CO emis-

Table 1. Observed and derived properties of ALESS122.1 and ALESS67.1

	ALESS122.1	ALESS67.1
RA _{CO(1-0)} (J2000)	03:31:39.53	03:32:43.20
$Dec_{CO(1-0)}$ (J2000)	-27:41:19.6	-27:55:14.8
$z_{ m spec}$	2.0232	2.1230
ZCO(1-0)	2.0238 ± 0.0003	2.1228 ± 0.0004
$L_{\rm FIR}^{a} \ (10^{12} L_{\odot})$	$6.3^{+0.4}_{-0.5}$	$5.3^{+0.7}_{-1.3}$
$SFR^b (M_{\odot} yr^{-1})$	940^{+60}_{-80}	790^{+100}_{-190}
$M_{\rm dust}^{a} \ (10^{8} M_{\odot})$	7.9 ± 0.9	7.1 ± 0.6
Dust temperature ^{a} (K)	32	31
$peak_{CO(1-0)}$ (mJy)	0.86 ± 0.06	0.58 ± 0.07
$FWHM_{CO(1-0)} (km s^{-1})$	700 ± 60	710 ± 90
CO(1-0) line center (km s ⁻¹)	45 ± 30	-31 ± 40
$I_{\text{CO}(1-0)} \text{ (Jy km s}^{-1}\text{)}$	0.64 ± 0.07	0.44 ± 0.08
$L'_{\rm CO(1-0)}~(10^{10}~{\rm K~km~s^{-1}~pc^2})$	13 ± 2	9.9 ± 1.8
$M({\rm H_2}) (10^{10} {\rm M_{\odot}})^c$	13 ± 2	9.9 ± 1.8
S _{7mm continuum} (μJy)	60 ± 10	48 ± 11

a from Swinbank et al. (2014)

sion is coincident with the ALMA submillimeter source and has a clear IRAC counterpart (Figure 2).

Gaussian fits were performed on the 200 km s⁻¹ cube to obtain $^{12}\mathrm{CO}(1\text{-}0)$ line parameters, which are summarised in Table 1. The CO(1-0) spectrum for ALESS122.1 has a significant fitted continuum of $70\pm20\,\mu\mathrm{Jy}$, which is subtracted from the spectra in Figure 1. The CO(1-0) line for ALESS 122.1 then has a fitted peak of 0.86 ± 0.06 mJy, a FWHM of 700 ± 60 km s⁻¹. The CO(1-0) line for ALESS 67.1 has a fitted peak of 0.58 ± 0.07 mJy and a FWHM of 710 ± 90 km s⁻¹. Both lines are consistent with having a zero velocity offset with respect to the optical spectroscopic redshift. Integrating the best fit Gaussian yields a line luminosity of 0.64 ± 0.07 and 0.44 ± 0.08 Jy km s⁻¹ for ALESS 122.1 and ALESS67.1, respectively. These values do not include the flux calibration uncertainties, which are about 20–30% (Emonts et al. 2011).

Continuum images were also made from the full CABB 2 GHz bandwidth for each SMG. The central 200 channels were flagged to remove any CO(1-0) flux, and natural weighting used to achieve the highest sensitivity. Both SMGs are detected in the continuum images as point sources, with ALESS 122.1 having a 38.1 GHz flux density of 60 \pm 10 $\mu\rm{Jy}$ and ALESS 67.1 having a 36.9 GHz flux density of 48 \pm 11 $\mu\rm{Jy}$.

4 ANALYSIS AND DISCUSSION

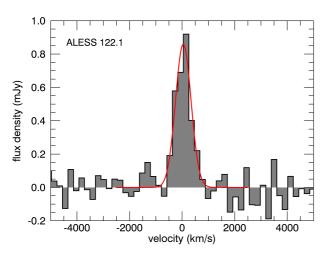
4.1 Molecular Gas Masses

CO detections provide a tool for deriving the masses of the molecular gas reservoirs of these systems. This is important as the reservoir of molecular gas is the raw material from which new stars will be formed, thus giving an indication of the final mass of these systems post the starburst phase (modulo gas falling into or being ejected from the system). The ground transition of CO(1-0) is particularly powerful as no assumption of a brightness ratio, or gas spectral line en-

 $[^]b$ using $L_{\rm FIR}$ conversion from Kennicutt and Evans (2012)

^c Adopting $\alpha_{\rm CO} = 1$

4 M. T. Huynh et al.



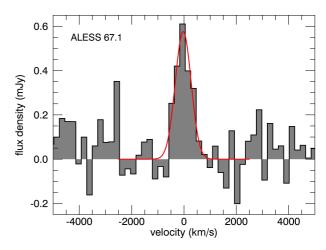
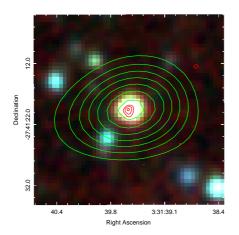


Figure 1. The CO(1-0) spectrum for ALESS 122.1 (left, continuum subtracted) and ALESS 67.1 (right), binned to 200 km s⁻¹ resolution. The best fit Gaussian is shown as a red line. The CO emission peaks at $\gtrsim 8\sigma$ significance with this binning with both lines well-fit by single Gaussians at this resolution.



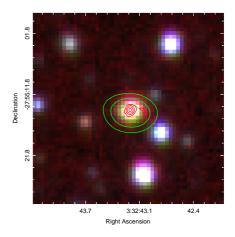


Figure 2. False-colour images made from *Spitzer* Infrared Array Camera (IRAC) images of Damen et al. (2011)¹ for ALESS 122.1(left) and ALESS 67.1 (right). Green contours indicate the CO(1-0) emission from the 600 km s⁻¹ cube at 3, 5, 7 ... × σ . The red contours are from the ALMA 870 μ m continuum map (Hodge et al. 2013) at 3, 5, 7 ... × σ . The postage stamp images are 30 × 30 arcsec.

ergy distribution (SLED), is required to convert down from a higher J transition.

Following the method of Solomon & Vanden Bout (2005), we find ALESS 122.1 has a line luminosity of $L'_{CO(1-0)}$ = (1.3 \pm 0.2) \times $10^{11}~\rm K~km~s^{-1}~pc^{2}$ and ALESS67.1 has a line luminosity of $L'_{\rm CO(1-0)}=(9.9\,\pm\,1.8)\times10^{10}~\rm K~km~s^{-1}~pc^{2}$ (Table 1). A CO-to- H_2 conversion factor, α_{CO} , is then required to convert the line luminosity to a total molecular gas mass, $M(H_2)$. At $z \sim 0$ disc galaxies such as the Milky Way have relatively large values of $\alpha_{\rm CO} \sim 3-5$, while a smaller value of $\alpha_{\rm CO} = 0.8$ is believed to be appropriate for local ULIRGs (e.g. Downes & Solomon 1998), and this has been widely used for high redshift SMGs. However there is some evidence that the local ULIRG value of $\alpha_{CO} = 0.8$ leads to under-estimated gas masses (Bothwell et al. 2010) and at least one SMG is known to have a large $\alpha \sim 2$ (Swinbank et al. 2011; Danielson et al. 2011). Given the uncertainty in the conversion factor we adopt $\alpha_{CO} = 1$, following Bothwell et al. (2013), and derive molecular gas masses, $M(H_2)$, of $(1.3 \pm 0.2) \times 10^{11} M_{\odot}$ and $(9.9 \pm 1.8) \times 10^{10} \text{ M}_{\odot} \text{ for ALESS } 122.1 \text{ and ALESS } 67.1,$ respectively. The mean gas mass for a representative sample of $z\sim 2$ SMGs from $J\gtrsim 3$ observations has been found to be $(3.2\pm 2.1)\times 10^{10}$ M $_{\odot}$ (Bothwell et al. 2013). The high-J transitions used in the earlier work may explain some of the discrepancy, but nevertheless ALESS 122.1 and ALESS 67.1 appear to have relatively large gas masses compared to the general SMG population. This is not unexpected as they were selected to have large IR luminosities.

4.2 CO Line Kinematics and Dynamical Masses

The kinematics of the CO line traces the gravitational potential well in the system. Previous studies have found very broad CO emission lines from SMGs, but are typically from $J \gtrsim 3$ transition lines. Bothwell et al. (2013) find a mean FWHM of 510 \pm 80 km s⁻¹ for their sample of SMGs. A greater mean FWHM of 780 km s⁻¹ was found for a more infrared-luminous subset of those SMGs (Greve et al. 2005).

¹ https://irsa.ipac.caltech.edu/data/SPITZER/SIMPLE/

More infrared-luminous sources could potentially have a greater dynamical mass, and therefore a larger CO line FWHM. The CO line FWHMs of ALESS 122.1 and ALESS 67.1 are \sim 700 km s⁻¹, which are larger than most of the Bothwell et al. (2013) SMG sample, but in line with what is expected from the more infrared-luminous SMGs. The measured CO(1-0) linewidth may also be relatively large due to the J=1-0 transition being more spatially extended than higher J transitions (e.g. Ivison et al. 2011; Emonts et al. 2015).

The width of the CO line from the SMGs allows an estimation of the galaxy dynamical masses, given a spatial extent of the system and an assumption about the dynamical structure. Following Solomon & Vanden Bout (2005), the dynamical mass of the system can be estimated using $M_{\rm dyn} \sin^2 i = 233.5 V^2 R$, where R is the radius of the molecular disk or half the separation between components in a merger model, measured in parsec, and V is the FWHM of the CO line or half the separation in velocity of the component CO lines in a merger model, measured in km s⁻¹. The HST images (Rix et al. 2004) show various clumps that indicate ALESS 122.1 and ALESS 67.1 could be mergers (Figure 3). Taking the merger model and R to be ≤ 0.5 arcsec (4.2 kpc at z = 2), which is the approximate separation of the clumps in HST optical counterparts (Figure 3), the dynamical mass, $M_{\rm dyn} \sin^2 i$, is $\lesssim 5 \times 10^{11} {\rm M}_{\odot}$ for both ALESS 122.1 and ALESS67.1.

However, the HST image does not reveal whether or not the systems contain a gaseous disc. In the presence of a gas-disc, the dynamical mass can be estimated from the CO line kinematics, by comparing the spatial offset between the redshifted and blueshifted components of the CO line. This was determined by making 300 km s^{-1} wide channel maps centred at -300 to 0 km s⁻¹ and 0 to +300 km s⁻¹ (Figure 3). The centroid of the CO emission was determined for the maps, and we derive a spatial offset between the redshifted and blueshifted emission of 1.2 \pm 0.6 arcsec (10.2 \pm 5.1 kpc) and 1.8 ± 0.5 arcsec (15.2 ± 4.2 kpc) for ALESS122.1 and ALESS67.1, respectively. This is comparable to CO(1-0) sizes observed in other SMGs by Ivison et al. (2011). Assuming this spatial offset represents rotating gas, then the dynamical mass $M_{\rm dyn} \sin^2 i = (2.1 \pm 1.1) \times 10^{11} \rm M_{\odot}$ and (3.2) \pm 0.9) $\times 10^{11}$ M_{\odot} for ALESS 122.1 and ALESS 67.1, respectively. These estimates are consistent with the dynamical masses derived from using the CO line FWHM and optical size from HST imaging. For a rotating model, Bothwell et al. (2013) found their sample of SMGs to have a median dynamical mass of $(1.6 \pm 0.3) \times 10^{10} R M_{\odot}$, where radius R is in kpc. Using the measured spatial offsets of 10 and 15 kpc for R, the dynamical masses of ALESS 122.1 and ALESS 67.1 are consistent with the median dynamical mass of their SMG

The total baryonic mass can be calculated by combining the gas and stellar mass estimates for the SMGs. The stellar masses of ALESS 122.1 and ALESS 67.1 have been estimated by Simpson et al. (2014), who used absolute restframe H-band magnitudes from best fit SEDs to multi-band photometry and a model mass-to-light ratio. They estimate ALESS 122.1 has a stellar mass of 5.2×10^{10} M_{\odot} and ALESS 67.1 has a stellar mass of 4.4×10^{10} M_{\odot}. These estimates are uncertain by a factor of at least a few, due to the difficulty in distinguishing between different model star for-

mation histories to predict an accurate mass-to-light ratio (Hainline et al. 2011). Nevertheless, this suggests the total baryonic mass of the system, $M_{\rm bary} = M_{\rm H_2} + M_{\rm stars}$, is then $(1.9 \pm 1.1) \times 10^{11} \ {\rm M_{\odot}}$ and $(1.4 \pm 0.9) \times 10^{11} \ {\rm M_{\odot}}$ for ALESS 122.1 and ALESS 67.1, respectively, where the uncertainties for the stellar mass estimate is assumed to be a factor of two. These mass estimates are consistent with the derived dynamical masses, given the uncertainties involved. Given these total baryonic mass estimates, ALESS 122.1 and ALESS 67.1 have gas mass fractions of ~70%, which, although large, have been been observed in other gasdominated SMGs (e.g. Bothwell et al. 2013) and $z \sim 2$ UV-selected massive star forming galaxies (Tacconi et al. 2010).

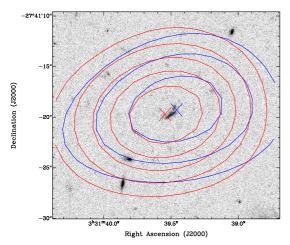
4.3 Star Formation Efficiency

The detection of CO(1-0) provides an opportunity to examine the efficiency with which the molecular gas is being converted into stars in these systems. Star formation efficiency is commonly defined as SFR/ $M(H_2)$, the inverse of the gas depletion time scale. A useful approach is to investigate the star formation efficiency by comparing the two observable quantities, total infrared luminosity $L_{\rm FIR}$ and line luminosity $L'_{\rm CO(1-0)}$. Using these observables instead negates any offsets in SFR/ $M(H_2)$ that may be introduced by the application of an inappropriate CO-to-H₂ conversion factor $\alpha_{\rm CO}$. The slope of the $L_{\rm FIR}-L'_{\rm CO(1-0)}$ relation describes the relationship between the infrared luminosity due to star formation and the total gas content of the system. It is thus a basic observational form of the Kennicutt-Schmidt (K-S) relation between the gas reservoir and the SFR of a system.

The original form of the K-S relation was established using H_I and CO(1-0) measurements of galaxies in the local universe (Schmidt 1959; Kennicutt 1989, 1998) and the SFR density was found to be related to gas surface density by a power law, $\Sigma_{\rm SFR} \propto \Sigma_{\rm gas}^N$, with the slope $N=1.4\pm0.15$ (Kennicutt 1998). Using the COLD GASS sample of about 350 local massive galaxies, Saintonge et al. (2012) find a global K-S relation of $N=1.18\pm0.24$. At higher redshifts ($z\sim1-3$) Genzel et al. (2010) suggested that "normal" star forming galaxies show a K-S relation of $N=1.17\pm0.09$ and SMGs show a similar slope of $N=1.1\pm0.2$ but offset by 1 dex above the "normal" star forming galaxies. Their result comes from high-J (mostly J=3) transitions of CO, however, and different $\alpha_{\rm CO}$ are adopted for the different populations included in their study.

The 'integrated' K-S relation, as opposed to the original 'surface density' K-S relation, is also observed, but assumes the star formation (e.g. as measured by the far-infrared), has the same spatial extent as the molecular gas. In the $L_{\rm FIR}$ and $L'_{\rm CO(1-0)}$ plane "normal" star forming galaxies show a slope² of 1.15 ± 0.12 and SMGs have a similar slope but offset on average by a factor of four above the relation for "normal" star forming galaxies (Genzel et al. 2010). Since the $L'_{\rm CO(1-0)}$ luminosities of the "normal" star forming galaxies extended into the bright SMG regime ($\gtrsim 10^{10}$ K km s⁻¹ pc²) Genzel et al. (2010) argued this is evidence that the merging population (ULIRGs and SMGs) are offset from the "normal" z=0 disc galaxy population, rather than a

² Here slope is a, where $L_{\text{FIR}} \propto L'_{\text{CO}(1-0)}{}^{a}$



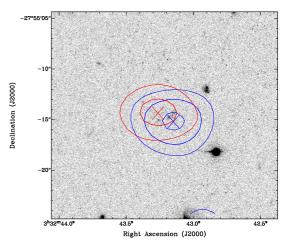


Figure 3. The CO(1-0) velocity structure of ALESS 122.1 (left) and ALESS 67.1 (right), overlaid on HST z band (F850LP) images from Rix et al. $(2004)^3$. Both optical counterparts are clumpy or complex in the rest-frame UV, indicating either structured dust or a possible merging system. Blue contours indicate the CO(1-0) emission integrated from -300 to 0 km s⁻¹ at 3, 5, 7 ... × σ . Red contours indicate the CO(1-0) emission integrated from 0 to +300 km s⁻¹ at 3, 5, 7 ... × σ . Red and blue crosses mark the centroid of the blueshifted and redshifted emission, respectively. The images are 20 × 20 arcsec.

change of slope occurring at high luminosities. More recent work on (local) ULIRGs and SMGs found a $L_{\rm FIR}$ - $L'_{\rm CO(1-0)}$ relation slope of 1.20 ± 0.09 for the populations combined, and 1.27 ± 0.08 and 1.08 ± 0.14 for the ULIRG and SMG populations, respectively (Bothwell et al. 2013). These studies relied on J=2 or higher transitions of CO converted to CO(1-0), introducing systematic uncertainties in the relation. Ivison et al. (2011) used mostly CO(1-0) transitions and fully self-consistent $L_{\rm FIR}$ measurements to find a shallower slope of 0.65 ± 0.13 for SMGs, suggesting high transitions of CO may artificially steepen the slope.

With new CO(1-0) detections of SMGs and BzKs over the last few years, and now our work, we can make a relatively unbiased comparison to local samples. In Figure 4 we show L_{FIR} and $L'_{\text{CO}(1-0)}$, populated with local ULIRGs from Solomon et al. (1997) and Chung et al. (2009) and local LIRGs from Papadopoulos et al. (2012). For "normal" star forming galaxies at $z \sim 2$ we include eight BzK galaxies with published CO detections (Daddi et al. 2010; Aravena et al. 2010, 2012), all but three in CO(1-0). Three BzKs have only CO(2-1) detections, which Daddi et al. (2010) correct to $L'_{\text{CO}(1-0)}$ adopting $r_{21}=0.84.$ This is also the median r_{21} ratio found by Bothwell et al. (2013), so we include the Daddi et al. (2010) CO(2-1) detections with the corrected $L'_{\text{CO}(1-0)}$. SMGs with CO(1-0) detections come from Greve et al. (2003), Ivison et al. (2011), Swinbank et al. (2011), and Harris et al. (2012). Because of the small number of SMGs detected in CO(1-0) (21 including this work) we add seven Bothwell et al. (2013) SMGs with CO(2-1) detections, where $L'_{\text{CO}(1-0)}$ is derived using $r_{21}=0.84$. Care was taken in the compilation to use a consistent definition of $L_{\rm FIR}$ across the samples. In the literature, total infrared luminosity L_{FIR} is usually the luminosity across 8 - 1000 μ m, but in some cases, especially IRAS samples, authors have given the luminosity across $42.5 - 122.5 \mu m$. In these cases (Solomon et al. 1997; Chung et al. 2009) we convert the quoted infrared luminosity to $L(8-1000 \mu m)$ using a factor of 1.9, consistent with typical infrared SEDs (e.g. Helou et al. 1988; Chary & Elbaz 2001).

A linear relation of the form $\log L_{\text{FIR}} = a \log L'_{\text{CO}(1-0)} + b$ was fit with chi-square minimisation, using the MPFITEXY routine (Williams et al. 2010) to take into account errors in both coordinates. The slopes, a, were determined for the various samples, and we report these in the legend of Figure 4. The local ULIRGs and SMGs have consistent slopes of $a = 0.67 \pm 0.13$ and $a = 0.61 \pm 0.13$, respectively. The more normal star forming galaxy samples, local LIRGs and BzKs, show marginally steeper slopes of $a = 0.84 \pm 0.09$ and $a = 0.87 \pm 0.61$, but the BzK slope is highly uncertain due to the small number of sources in that sample and the limited luminosity range spanned. The combined BzK and LIRG sample exhibits a slope of $a = 0.88 \pm 0.08$, which is steeper than the ULIRG and SMG combined slope of $a = 0.52 \pm 0.05$ at about the 2σ significance level. While a larger sample of SMGs and BzKs with well determined line luminosities $L'_{\text{CO}(1-0)}$ is required to definitively say that ULIRGs and SMGs populate a different sequence in the K-S relation to the more normal LIRGs and BzKs, this work does hint that there may be a difference in their SF modes. We stress that our analysis is free of the biases from high JCO transitions which has been present in earlier work (e.g. Greve et al. 2005; Daddi et al. 2010; Genzel et al. 2010). By using the CO(1-0) transition (and CO(2-1) for a small number of sources) we remove the uncertainties in the line luminosity introduced by excitation conditions of the gas.

The total infrared luminosities of ALESS 122.1 and ALESS 67.1 (Swinbank et al. 2014) correspond to star formation rates (SFR) of 940^{+60}_{-80} and 790^{+100}_{-190} M_{\odot} yr⁻¹, respectively, using the infrared conversion from Kennicutt & Evans (2012). The gas depletion timescales, $M(\rm H_2)/\rm SFR$, are 140 \pm 30 and 130 \pm 40 Myr, which are similar to other SMGs at $z \sim 2$ (e.g. Bothwell et al. 2013). Assuming little further gas infall from the surrounding environment and 100% efficiency in converting the gas to stars, the star formation is effectively shut off at $z \sim 2$ and this galaxy would appear as a 'red and dead' elliptical by $z \sim 1.5$ (1 Gyr after gas depletion). The estimated total baryonic masses (> 1× 10^{11} M_{\odot}) and timescales involved are consis-

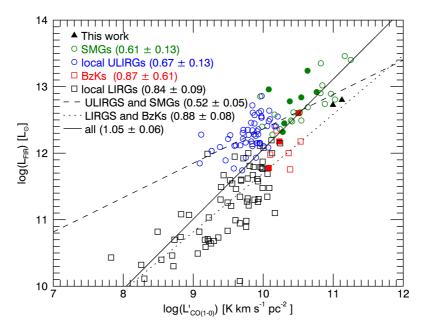


Figure 4. L_{FIR} vs $L'_{\text{CO}(1-0)}$ for SMGs, local (U)LIRGs and BzK galaxies. All sources but three BzKs (filled squares) and seven SMGs (filled circles) have robust CO(1-0) measurements. The filled squares and circles mark sources with CO(2-1) detections which are converted to CO(1-0) using $r_{21} = 0.84$. Linear relations are fitted to the local ULIRGs plus SMGs (dashed) and local LIRGs plus BzK galaxies (dotted), as well as all the samples combined (solid). The numbers in brackets indicate the best fit slope for the different populations.

tent with these SMGs being progenitors of today's massive ellipticals, which has been the consensus in the literature for some time (e.g. Lilly et al. 1999; Simpson et al. 2014).

4.4 Dust to Gas Mass Ratios

As early as the 1980s it was suggested that the emission from dust could be used to measure the mass of the ISM in a galaxy (Hildebrand 1983). Dust mass estimates can be determined from the infrared-submm luminosity on the Rayleigh-Jeans tail of the dust SED, and then an appropriate gas-to-dust ratio can be applied to derive the total mass of the molecular ISM (Eales et al. 2012; Scoville et al. 2014). Herschel surveys have catalogued hundreds of thousands of galaxies (e.g. Herschel-ATLAS, Eales et al. 2010; Valiante et al. 2016) in the far-infrared, and SCUBA2 has detected thousands of galaxies in the submm (SCUBA2 Cosmology Legacy Survey, Geach et al. 2016). Individual CO measurements cannot feasibly be made for all of these galaxies, but dust mass estimates provide a potential avenue for crudely estimating total gas masses for very large samples of galaxies.

The Milky Way has a gas-to-dust ratio of $\delta_{\rm GDR} \sim 130$ (Jenkins 2004), while the *Spitzer* Infrared Nearby Galaxy Survey (SINGS) of 13 local star forming galaxies have $\delta_{\rm GDR} = 130 \pm 20$ (Draine et al. 2007). Combining the CO-derived gas measurements from Bothwell et al. (2013) and dust mass estimates from far-infrared SEDs by Magnelli et al. (2012), the average $\delta_{\rm GDR}$ for SMGs is estimated to be 90 \pm 25 (Swinbank et al. 2014). Combining the dust mass estimates of ALESS 122.1 and ALESS 67.1 from Swinbank et al.

(2014) with our CO(1-0) gas mass estimates results in gasto-dust ratios $\delta_{\rm GDR} = 170 \pm 30$ and 140 ± 30 , respectively. This suggests ALESS 122.1 has an unusually large gas-to-dust ratio, probably due to its extremely large gas reservoir.

The monochromatic submm flux density has been explored as a probe of gas mass. It potentially provides a simple and effective estimate of both the dust and gas mass content of a galaxy. *Planck* measurements of the submillimeter emission from Milky Way regions yields a Galactic constant of proportionality between 850 $\mu \rm m$ luminosity and ISM mass of $\alpha = L_{850}/M_{\rm ISM} = 0.79 \times 10^{20}~\rm erg~s^{-1}~Hz^{-1}~M_{\odot}^{-1},$ while an empirical calibration using 12 local ULIRGs and SINGS survey galaxies yields $\alpha = 1.0 \pm 0.2 \times 10^{20}~\rm erg~s^{-1}~Hz^{-1}~M_{\odot}^{-1}$ (Scoville et al. 2014). We convert the measured ALMA 870 $\mu \rm m$ continuum flux densities of ALESS 122.1 and ALESS 67.1 (Hodge et al. 2013) to 870 $\mu \rm m$ restframe luminosities following

$$L_{870} = 4\pi D^2 (1+z) S_{870} K_{\text{corr}},$$

where L_{870} is the luminosity in W Hz⁻¹, D is the comoving distance, S_{870} is the observed flux density at 870 μ m, and $K_{\rm corr}$ is the K-correction which is given by

$$K_{\rm corr} = \left(\frac{\nu_{\rm obs}}{\nu_{\rm obs(1+z)}}\right)^{3+\beta} \frac{e^{h\nu_{\rm obs(1+z)}/kT}-1}{e^{h\nu_{\rm obs}/kT}-1},$$

where $\nu_{\rm obs}$ is the observed ALMA frequency (350 GHz), $\nu_{\rm obs(1+z)}$ is the rest-frame frequency, T is the dust SED effective temperature, and β is the dust emissivity index. We use temperatures of 32K and 31 K for ALESS 122.1 and ALESS 67.1, respectively, which have been determined from the detailed far-infrared SED fitting of Swinbank et al. (2014). The emissivity index β can range from 1.5 to 2.0, but for consistency with Scoville et al. (2014) we take $\beta=1.8$. We thus find $L_{850}=(1.0\pm0.1)\times10^{31}~{\rm erg~s^{-1}~Hz^{-1}}$ for ALESS 122.1 and $L_{850}=(1.3\pm0.1)\times10^{31}~{\rm erg~s^{-1}~Hz^{-1}}$ for ALESS 67.1.

³ https://archive.stsci.edu/prepds/gems/

This corresponds to monochromatic $850\mu m$ luminosity to mass ratios of (0.75 ± 0.11) and $(1.3\pm0.3)\times10^{20}$ erg s⁻¹ Hz⁻¹ M_{\odot}⁻¹ for ALESS 122.1 and ALESS 67.1, respectively, using our measured CO molecular gas masses. This is consistent with the result from Scoville et al. (2014) given that the uncertainty in the luminosity-to-mass ratios includes only the flux uncertainties for the CO and ALMA measurements. The luminosity-to-mass ratio given by Scoville et al. (2014) includes HI masses, which we do not include here, and that will also add some uncertainty to the ratio.

4.5 Radio Thermal Free-Free Emission and the Star Formation Rate

Most radio measures of star formation use non-thermal radio synchrotron radiation (e.g. Haarsma et al. 2000; Seymour et al. 2008), which is emitted by cosmic ray electrons propagating through a galaxy's magnetic field after being initially accelerated by core-collapse supernovae. This synchrotron emission is a complex tracer of star formation and is potentially affected by the inverse-Compton losses against the CMB, which scales as $(1+z)^4$. The thermal freefree radio emission from ionized HII regions traces the massive young stars ($>5M_{\odot}$) which are capable of photoionizing the ISM. As such, it is a more direct tracer of the star formation rate of a galaxy than synchrotron radio emission, and has the same advantage of being a dust-unbiased indicator. The thermal fraction at GHz frequencies for a typical star forming galaxy is ≤10% but thermal emission dominates by about 30 GHz (Condon 1992).

ALESS 122.1 is detected at 1.4 GHz (Miller et al. 2013) and 5.5 GHz (Huynh et al. 2015), with flux densities of 202.6 \pm 14.1 and 71 \pm 9 μ Jy, respectively. Combined with our high frequency 38.1 GHz continuum detection, we can make an estimate of the the amount of radio free-free emission in ALESS 122.1. The free-free luminosity is derived by fitting the radio SED with a fixed contribution from dust, thermal free-free radio emission with a fixed slope of $\alpha = -0.1$ (S \propto ν^{α}), and a non-thermal synchrotron radio component with a fixed slope of $\alpha = -0.8$. The dust contribution is determined from a grey body SED $(S \propto B(v,T)v^{\beta})$, where B(v,T) is the Planck blackbody and β is the emissivity index. We set the blackbody function to a temperature of 32K, as determined by Swinbank et al. (2014) for ALESS 122.1, and adopt β = 1.5. The free-free and synchrotron radio components are then allowed to scale to fit the 3 radio continuum data points. The resulting best-fit decomposition of the ALESS 122.1 SED, shown in Figure 5, has a reduced χ^2 value of ~ 2 , indicating a reasonable fit.

The contributions to $S_{38.1 \rm GHz}$ from dust, free-free and synchrotron radio emission are presented in Table 2. Using Condon (1992), we determine SFR ($M > 5 \rm M_{\odot}$) = 440 ± 220 $\rm M_{\odot}$ yr⁻¹ from the fitted radio free-free emission. Using an IMF similar to Kennicutt & Evans (2012), we account for stars with $1 < M < 5 \rm M_{\odot}$ using a Salpeter IMF and low mass stars (0.1 < $M < 1 \rm M_{\odot}$) with a shallower Kroupa IMF, to find a radio free-free total SFR of 1400 ± 700 $\rm M_{\odot}$ yr⁻¹. This is consistent with SFR of 940^{+60}_{-80} $\rm M_{\odot}$ yr⁻¹ derived from the infrared luminosity, showing that radio free-free emission has the potential to be a powerful measure of galaxy SFRs. The fitted thermal fraction of the radio emission from ALESS 122.1 is $73 \pm 37\%$, $47 \pm 23\%$ and $26 \pm 13\%$ at 38.1, 5.5 and 1.4 GHz,

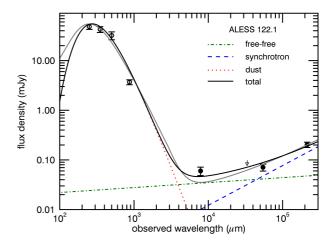


Figure 5. The far-infrared to radio SED of ALESS 122.1. We plot Herschel and ALMA far-infrared and submm datapoints (open circles), and the 1.4 GHz (Miller et al. 2013), 5.5 GHz (Huynh et al. 2015) and 38.1 GHz (this work) radio data (fill circle). The downward arrow denotes the 9.0 GHz 4σ limit (Huynh et al. in prep). The thermal dust emission component with a temperature of 32K is shown as a red dotted line. The radio free-free (green dot-dashed line) and synchrotron (blue dashed line) components are scaled to produce a best fit to the radio data (solid circles). The black solid line marks the total of all 3 components. For comparison, the best fit SED of Swinbank et al. 2014 is also shown (solid grey line).

Table 2. Radio SED fitting results for ALESS 122.1

$S_{38.1 ext{GHz,total}} \ (\mu ext{Jy})$	$S_{38.1 ext{GHz,ff}} \ (\mu ext{Jy})$	$S_{38.1 ext{GHz,synch}} \ (\mu ext{Jy})$	$S_{38.1 ext{GHz,dust}} \ (\mu ext{Jy})$
46 ± 14	34 ± 17	10 ± 3	2.7 (fixed)

respectively, i.e. 115, 16.6 and 4.2 GHz restframe. This is consistent with the thermal fraction found in M82 (Condon 1992) and some z < 0.5 ULIRGs (Galvin et al. 2016). This result is from fitting to only three radio data points, and has a large uncertainty, but it shows the potential of radio free-free emission in measuring the star formation rates of galaxies at these redshifts. A caveat however is that an X-Ray stacking analysis by Wang et al. (2013) found that ALESS 122.1 is likely to contain an AGN. An additional flat spectrum AGN component can not be ruled out with the current radio data.

Note that the same analysis cannot be performed on ALESS 67.1 because it does not have a 5.5 GHz detection.

5 CONCLUSIONS

We have presented the first results from an ATCA 12 CO(1-0) survey of cold molecular gas from ALMA-detected SMGs in the ECDFS.

In this first phase we targeted two SMGS at $z\sim 2$. The main results from this work are:

(i) We detect strong CO(1-0) emission from ALESS 122.1 and ALESS 67.1, which lie at z=2.0232 and z=2.1230, respectively. The CO line redshift is consistent with the optical

spectroscopic redshift in both cases. The CO emission lines have FWHM > 700 km s⁻¹, which is as expected for more infrared-luminous SMGs. The CO(1-0) luminosities are (13 \pm 2) and (9.9 \pm 1.8) \times 10¹⁰ K km s⁻¹ pc², which correspond to molecular gas masses of 13 and 9.9 \times 10¹⁰ M_{\odot}, for a conversion factor of $\alpha=1.0$.

(ii) Assuming the CO(1-0) emitting region of ALESS 122.1 and ALESS 67.1 be constrained by the HST high resolution optical counterpart, we use the optical source sizes (<0.5 arcsec, or 4.2 kpc at z=2) and the measured CO linewidths to estimate dynamical masses of $M_{\rm dyn} \sin^2 i \lesssim 5 \times 10^{11} \ {\rm M}_{\odot}$ for ALESS 122.1 and ALESS67.1. The spatial offset between the redshifted and blueshifted components of the CO line gives a consistent dynamical mass of $M_{\rm dyn} \sin^2 i = (2.1 \pm 1.1) \times 10^{11} \ {\rm M}_{\odot}$ and $(3.2 \pm 0.9) \times 10^{11} \ {\rm M}_{\odot}$ for ALESS 122.1 and ALESS 67.1, respectively, within 10–15 kpc. These dynamical masses are similar to the median dynamical masses of typical SMGs (Bothwell et al. 2013).

The stellar masses were combined with the gas mass to derive total baryonic masses of $(1.9 \pm 1.1) \times 10^{11} \mathrm{~M_\odot}$ and $(1.4 \pm 0.9) \times 10^{11} \mathrm{~M_\odot}$ for ALESS 122.1 and ALESS 67.1, respectively. This implies a gas mass fraction greater than 70%

- (iii) We examine the star formation efficiency of SMGs using the observed $L_{\rm FIR}$ and $L'_{\rm CO(1-0)}$ luminosities. We find that ULIRGs and SMGs have a similar slope in $L_{\rm FIR}$ vs $L'_{\rm CO(1-0)}$. Together the ULIRG and SMG population show a slope of 0.60 ± 0.08 , while LIRGs and BzKs show a slightly steeper relation with slope = 0.86 ± 0.08 . A larger sample with more high redshift CO(1-0) detections is required to definitely conclude that there is a difference in the slope for these populations, but this is some evidence that there is a difference in the SF modes of LIRGS and BzKs versus more extreme ULIRGs and SMGs.
- (iv) We derive gas-to-dust ratios $\delta_{\rm GDR}=170\pm30$ and $\delta_{\rm GDR}=140\pm30$ for ALESS 122.1 and ALESS 67.1, respectively. ALESS 122.1 appears to have an unusually large gas-to-dust ratio, due to its large inferred gas reservoir. We convert the ALMA submm continuum flux densities to luminosities and find monochromatic 850 μ m luminosity to mass ratios, $L_{850}/M_{\rm gas}$, of (0.75 \pm 0.11) and (1.3 \pm 0.3) \times 10²⁰ erg s⁻¹ Hz⁻¹ M_{\odot}⁻¹ for ALESS 122.1 and ALESS 67.1, respectively, using our measured CO molecular gas masses.
- (v) The 38.1 GHz continuum detection of ALESS 122.1 was combined with literature radio data at 1.4 and 5.5 GHz to estimate the free-free radio emission. We find free-free emission makes up $73 \pm 37\%$ of the radio emission at 38.1 GHz (115 GHz restframe). Converting the free-free emission to SFR yields a SFR of $1400 \pm 700~M_{\odot}~yr^{-1}$, consistent with the SFR derived from total infrared luminosity. An AGN contribution to the radio emission can not be ruled out, however. Further sensitive high frequency radio observations between 10 and 100 GHz (restframe) would provide better constraints on free-free radio emission.

CO(1-0) detections are important as the J=1 transition removes uncertainties in the estimated line luminosities introduced by excitation conditions of the molecular gas. Our work has no biases from high J CO transitions, which has hampered earlier work, and illustrates the importance of ATCA observations at these frequencies (7mm band, 30 – 50 GHz).

The remaining SMGs in the ALESS sample will be targeted with ATCA in the near future as part of our ongoing survey of CO(1-0) from SMGs at $z \sim 2$. The ALESS sample of SMGs is also being followed-up with ALMA for higher J CO lines and other molecular line tracers of gas such as [CII] and [NII]. The combination of the J=1 transition CO observations from ATCA with the ALMA observations will reveal the gas excitation conditions and other properties, such as metallicity, in SMGs, shedding even more light on the physical conditions of molecular gas in high redshift galaxies.

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