Total Molecular Gas Masses of Planck – Herschel Selected Strongly Lensed Hyper Luminous Infrared Galaxies

K. C. Harrington1,2, M. S. Yun3, B. Magnelli2, D.T. Frayer4, A. Karim2, A. Weiß1, D. Riechers5, E. F. Jiménez-Andrade1,2, D. Berman3, J. Lowenthal6, and F. Bertoldi2

1 Max-Planck-Institut für Radioastronomie, Auf dem Hügel 69, 53121 Bonn, Germany
2 Argelander Institut für Astronomie, Auf dem Hügel 71, 53121 Bonn, Germany
3 Department of Astronomy, University of Massachusetts, 619E Lederle Grad Research Tower, 710 N. Pleasant Street, Amherst, MA 01003, USA
4 Green Bank Observatory, 155 Observatory Rd., Green Bank, West Virginia 24944, USA
5 Department of Astronomy, Cornell University, Space Sciences Building, Ithaca, NY 14853, USA
6 Department of Astronomy, Smith College, Northampton, MA 01063, USA

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ABSTRACT

We report the detection of CO(1 – 0) line emission from seven Planck and Herschel selected hyper luminous (LIR(8–1000μm) > 1013L⊙) infrared galaxies with the Green Bank Telescope (GBT). CO(1 – 0) measurements are a vital tool to trace the bulk molecular gas mass across all redshifts. Our results place tight constraints on the total gas content of these most apparently luminous high-z star-forming galaxies (apparent IR luminosities of LIR > 1013–14L⊙), while we confirm their predetermined redshifts measured using the Large Millimeter Telescope, LMT (zCO = 1.33 – 3.26). The CO(1 – 0) lines show similar profiles as compared to Jup = 2 – 4 transitions previously observed with the LMT. We report enhanced infrared to CO line luminosity ratios of < LIR/LCO(1–0) >= 110 ± 22 L⊙(K km s⁻¹ pc⁻²)⁻¹ compared to normal star-forming galaxies, yet similar to those of well-studied IR-luminous galaxies at high-z. We find average brightness temperature ratios of < r21 >= 0.93 (2 sources), < r31 >= 0.34 (5 sources), and < r41 >= 0.18 (1 source). The r31 and r41 values are roughly half the average values for SMGs. We estimate the total gas mass content as μM_H2 = (0.9 – 27.2) × 10¹¹(αCO/0.8)M⊙, where μ is the magnification factor and αCO is the CO line luminosity to molecular hydrogen gas mass conversion factor. The rapid gas depletion times, < τappl >= 80 Myr, reveal vigorous starburst activity, and contrast the Gyr depletion timescales observed in local, normal star-forming galaxies.

Key words: galaxies: high-redshift – galaxies: starburst – submillimeter: galaxies – galaxies: ISM – gravitational lensing: strong

1 INTRODUCTION

Most of the stars in the local universe formed out of tremendous cool gas reservoirs (Mgas ≈ 10¹⁰⁻¹¹M⊙, T ≈ 10 – 100 K) in the interstellar medium (ISM) of high redshift (1 < z < 3.5) galaxies with intense star-formation (SF) (Carilli & Walter 2013; Madau and Dickinson, 2014).

Massive, dusty star forming galaxies at high-z (DSFGs; M_dust ≈ 10⁸–⁹M⊙) are typically gas-rich galaxies selected via their bright observed (sub)-mm fluxes (also known as SMGs). The rest-frame far-IR (FIR)-mm luminosity associated with the thermal dust emission (Elstathion et al. 2000; Johnson et al. 2013) (re-radiated far-UV radiation) traces the total star-formation (SF) activity, while the extreme star-formation rates (SFRs) in these IR luminous galaxies are likely due to a sustained supply of cool gas from the intergalactic medium (IGM). The dense molecular ingredients of the ISM thereby limits the timescale for extended starburst (SB) activity, with short-lived SB episodes of 10⁸-10⁹’s of Myr. These are believed to often include gas-rich mergers that induce star formation via tidal torques, which drive gas infall and subsequent collapse (Hernquist 1992). The most active SB galaxies at z > 2 contribute key insights into galaxy evolution and structure formation, as their mas-
sive gas reservoirs play a key role in the bulk stellar mass growth in their ISM environments, and as a result are believed to be the progenitors to massive elliptical/spheroidal galaxies and clusters at low-z (Casey et al. 2014).

The SMG population can be accounted for by major or minor-merger dominated starbursts (Baugh et al. 2005; Swinbank et al. 2008) in some semi-analytic models. Others suggest that the observed population is a heterogeneous mix of early and late stage major mergers and blending of passive star-forming disc galaxies. The brightest SMGs are likely early-stage mergers, exchanging a significant amount of molecular material for continued star formation (Hayward et al. 2012; Narayanan et al. 2015). SMGs typically have high gas mass fractions, $M_{\text{gas}}/M_*$, up to 80% (Carilli & Walter 2013).

CO line measurements are vital for directly probing the fuel for these star-forming galaxies, i.e. the total molecular gas mass, at the peak of the co-moving SFR density ($z \sim 2 - 3$). The gas accretion history of growing dark matter (DM) halos in cosmological simulations (Kereš et al. 2005) agrees well with the observed evolution of the CO luminosity function, as Decarli et al. (2016a) find a peak redshift for CO luminous galaxies at $z \sim 2$, comparable to the peak of the co-moving star formation rate density.

The CO ($J = 1 \rightarrow 0$) transition accounts for both the dense and most diffuse molecular gas, and has traditionally been calibrated to trace the bulk $H_2$ gas mass (via collisional excitation with the $H_2$ gas). The observed CO line luminosity, $L_{\text{CO}}$, to $H_2$ mass conversion factor, $\alpha_{\text{CO}}$, (Carilli & Walter 2013; Bolatto et al. 2013), is calibrated to this transition, making observations of CO($1 \rightarrow 0$) important for determining the total $H_2$ mass content at high-$z$.

The number of high-$z$ sources with galaxy integrated CO($1 \rightarrow 0$) detections is sparse (see Scoville et al. 2017; Carilli & Walter 2013), although it is accumulating (e.g. Carilli et al. 2002; Hainline et al. 2006; Riechers et al. 2011; Harris et al. 2012; Thomson et al. 2012; Riechers et al. 2013; Fu et al. 2013; Aravena et al. 2013; Sharon et al. 2016; Decarli et al. 2016a,b; Huynh et al. 2017), with approximately 60 to date. Resolved imaging of this lowest rotational transition of CO (e.g. Riechers et al. 2011; Lestrade et al. 2011) in high-$z$ SMGs indicates that the total molecular gas can extend up to 30 kpc for merging systems. Only the most active star forming sources with apparent $L_{\text{IR}} \geq 10^{12.5-14}L_\odot$ at $z > 1$ can be observed at this fundamental CO rotational transition. These apparent luminosities are often due to strong lensing. The strong lensing effect (usually with magnification factor, $\mu = 10 - 30X$) (e.g. Bussmann et al. 2013, 2015; Geach et al. 2015; Spilker et al. 2016) yields shorter integration times to provide secure detections of the molecular gas in both strongly lensed, intrinsically bright and faint, but highly magnified, normal star-forming systems.

The far-IR/sub-mm $Herschel$ Astrophysical Terahertz Large Area Survey (H-ATLAS) (Eales et al. 2010) and the Herschel Multi-tiered Extragalactic Survey (HerMES) (Oliver et al. 2012), together covering about 650deg$^2$, and the 2500 deg$^2$ South Pole Telescope (SPT; Carlstrom et al. 2011) have paved the way forward in discovering a rare population of gravitationally lensed DSFGs (e.g. Negrello et al. 2010; Planck Collaboration et al. 2011; Wardlow et al. 2013; Vieira et al. 2013; Weiß et al. 2013; Negrello et al. 2017), as well as an intrinsically bright, unlensed population. Cañameras et al. (2015) and Harrington et al. (2016) have exploited the all-sky sensitivity of Planck to find the most luminous high redshift galaxies currently known in the Planck era – all of which are gravitationally lensed (also Herranz et al. 2013; Fu et al. 2012; Combes et al. 2012).

Here we present galaxy integrated, CO($1 \rightarrow 0$) measurements of seven $z > 1$ galaxies using the Green Bank Telescope (GBT). This is a pilot study for a larger program to identify a large sample of extremely luminous high-$z$ SMGs identified by the all-sky Planck survey. In our original pilot study leading to the sample in this work, our goal was to identify sources that have the probability to be gravitationally lensed given their high flux densities in the 3 SPIRE bands of 250, 350, 500μm (e.g. the $S_{250}$ or $S_{350} \gtrsim 100$ mJy Negrello et al. 2010; Ivison et al. 2011). We have previously obtained one $J_{\mu m} = 2 - 4$ transition for all seven of the sources presented in this study using the Redshift Search Receiver (RSR) on the LMT. The majority of these sources have apparent $\mu_{\text{IR}} > 10^{14.0-14.5}L_\odot$ making them some of the most luminous sources currently known (Harrington et al. 2016; Cañameras et al. 2015). Our goals in this study are to confirm the LMT CO redshift, measure the CO($1 \rightarrow 0$) line emission to constrain our estimate of the $H_2$ masses and begin analysing the CO spectral line energy distributions (CO SLEDs). In § 2 we review our sample selection and previous observations described in detail in Harrington et al. (2016), and in § 3 we outline our CO($1 \rightarrow 0$) observations using the VERSatile GBT Astronomical Spectrometer (VEGAS) instrument on the GBT. Measured and derived gas properties using the CO($1 \rightarrow 0$) line emission and supplementary LMT CO data is found in § 4, followed by a discussion in § 5. Finally, we conclude our study in § 6. We adopt a $\Lambda$ CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ with $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ throughout this paper.

2 SAMPLE

In a search for the most extreme, and thus rare, star-forming galaxies at $z > 1$, we exploit the full-sky sub-mm coverage offered by the the Planck Catalog of Compact Sources (PCCS). The highest frequency observed by Planck (857 GHz / 350 μm) contains a dataset of ~24,000 point source objects (Planck Collaboration XXVIII 2014). From this dataset we limit our searches to point sources at Galactic latitude $b > 30^\circ$ to minimize the Galactic source contamination. This filtered sample is then cross-correlated with the combined catalogs of three Herschel large area surveys: Herschel Multi-tiered Extragalactic Survey (HerMES, Oliver et al. 2012), Herschel Stripe 82 Survey (HerS-82, Viero et al. 2014), and the dedicated Planck follow-up Herschel DDT “Must-Do” Programme: “The Herschel and Planck All-Sky Source Snapshot Legacy Survey”. The details of our selection method can be found in Harrington et al. (2016) for the Planck - Herschel counterparts with $S_{350} \gtrsim 100$mJy in our initial follow-up during the Early Science Campaign 2 for the LMT. In brief, we cross-matched Planck-Herschel counterparts within 150". In total there were 350 Herschel counterparts to 56 Planck sources within 150". The higher spatial resolution of Herschel allowed us to pinpoint the position of the Planck point sources, enabling follow up studies.

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For 8/11 galaxies observed with the LMT we detected a single, compact source using the Atacama Compact Array (ACA). We utilise GBT observations to derive apparent \( \mu_{95} > 10^{14.0–14.5} L_\odot \) at \( z_{\text{g}} = 1.33 – 3.26 \) (see Table 2). The current sample in this GBT study consists of observations of only seven of the original eight targets.

3 GBT OBSERVATIONS

Based on our GBT spectroscopy, two of our sources have redshifted CO(1–0) (i.e. rest-frame 115.27 GHz) line emission in the range of the Q band receiver (38.2–49.8 GHz) on the GBT. The other two sources fall within the K\(_\alpha\) band receiver (26.0–40 GHz). We used the low-resolution 1500 MHz bandwidth mode of the backend spectrometer, VEGAS. The raw channel resolution corresponds to 1.465 MHz, or \( \sim 16 \text{ km s}^{-1} \) in K\(_\alpha\) band, using 1024 channels. Observations between February and March, 2016, took place in typical weather conditions. For both Q and K\(_\alpha\) band observations, we used a SubBeamNull procedure, noding the 8m GBT sub-reflector every 6 seconds between each receiver feed for an integration time of four minutes. In most cases, this 4 minute procedure was repeated back-to-back for up to an hour to achieve the ON source integration times presented in Table 1. The atmosphere becomes highly variable at the frequencies within the expected full-width at half maximum (FWHM) of the emission. The width of the high-pass filter was at least twice the ripples in the overall baseline without removing the line. As the high-pass filter removes the low-frequency ripples, and not the mid-frequency baseline ripples, we then fit and remove a baseline (\( n_{\text{poly}} = 2 – 3 \)) to the emission free regions of the spectra. The resulting spectra can be seen in Fig. 1. We adopt a 30% total uncertainty given a 15-20% flux calibration error, typical 5-10% pointing/focus drifts and atmospheric losses and a conservative 10-15% for the baseline removal due to the variations across the bandpass at the observed frequencies.

4 RESULTS: CO (1 – 0) LINE PROPERTIES

We detect CO(1–0) at \( S_{\text{peak}}/n_{\text{channel}} > 7 \) from each of our seven targets at the expected redshifts. We first derive the observed central frequency by fitting a single Gaussian to the CO(1–0) line emission, confirming the exact redshifts of these Planck-Herschel identified galaxies, which had previously been derived using only one CO line from the LMT (Tab. 2). The spectroscopic redshifts span from 1.33 < \( z \) < 3.26. Our new GBT measurements further support our previous redshift determinations from the combination of panchromatic photometry (WISE-11 and 22 \( \mu \)m, Herschel SPIRE 250, 350, and 500 \( \mu \)m, Atacama 1.1mm and NVSS/FIRST radio) and single CO line observations (see Appendix A of [Harrington et al. 2016]).

We find that the CO(1–0) lines show nearly identical profiles and widths as the \( J_{\text{up}} = 2 - 4 \) CO lines, with FWHM = [375–740 km s\(^{-1}\)] (see Fig. 1). It is unlikely that there is a significant amount of gas that excites the CO(1–0) but not, e.g. the CO(3–2). Therefore, the similar line emission FWHM and line profiles suggests that both transitions are tracing co-spatial volumes.

We calculated the line luminosity, \( L'_{\text{CO}(1–0)} \), using Eq. (3) by Solomon et al. (1997),

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

with \( S_{\text{CO}} \Delta V \) in Jy km s\(^{-1}\), \( J_{\text{obs}} \) in GHz, and \( D_L \) in Mpc (see Table 3). Since the CO lines are not exactly Gaussian, we also integrated the spectra within \( \pm 1500 \text{ km s}^{-1} \) to compute \( S_{\text{CO}} \Delta V \). The corresponding Gaussian derived values of \( S_{\text{CO}} \Delta V \) are the same within 1-sigma. Some of the measured apparent \( L'_{\text{CO}} \) are amongst the brightest, if not the brightest, for all \( z > 1 \) QSO, SMG, LBG, including the SPT DSFGs (Aravena et al. 2016), as well as \( z < 1 \) ULIRGs, nearby spirals, and low-z starburst galaxies (Carilli & Walter 2013). These bright apparent luminosities suggest that our galaxies have been strongly magnified.

5 DISCUSSION

5.1 CO Spectral Line Energy Distributions (SLEDs)

In Fig 2 we plot the ratio of the line integrated intensity of the higher-J CO \( S_{\text{CO}} \Delta V \) to our CO(1–0) \( S_{\text{CO}} \Delta V \). All of our galaxies show sub-thermalised excitation conditions. Up to \( J \leq 3 \), we find these values to be consistent with both the lower end of the SMG excitation distribution (Bothwell et al. 2013; Carilli & Walter 2013) and the upper end of the MW (Fitsen et al. 1999). The uncertainty of the MW measurements and the physical intrinsic SMG dispersion overlap for \( J \leq 4 \). Without higher-J CO lines, where SMGs and the MW differ strongly, it is a challenge to disentangle which of these two ISM conditions dominate our galaxies.
Table 1. Sources and GBT Observations Summary

| Source ID   | RA        | DEC       | \(\mu L_{1R}^1\) | GBT RX   | Dates       | Int. Time (On-Source) | < \(T_{\text{sys}}\) > |
|-------------|-----------|-----------|------------------|----------|-------------|-----------------------|----------------------|
|             | J2000     | J2000     | (10^{14} L_{\odot}) |          |             |                       |                      |
| PJ142823.9  | 14h28m23.9s | +35d26m20s | 0.19 \(\pm\) 0.04 | Q        | 2/12/2/19   | 936                   | 100                  |
| PJ160722.6  | 16h07m22.6s | +73d47m03s | 0.14 \(\pm\) 0.03 | Q        | 2/12/2/19   | 216                   | 75                   |
| PJ105353.0  | 10h53m53.0s | +05d56m21s | 2.9 \(\pm\) 0.4   | K_a      | 3/30        | 336                   | 100                  |
| PJ112714.5  | 11h27m14.5s | +42d36m01s | 1.1 \(\pm\) 0.2   | K_a      | 3/30        | 84                    | 40                   |
| PJ120207.6  | 12h02m07.6s | +53d34m39s | 1.4 \(\pm\) 0.3   | K_a      | 3/30        | 80                    | 40                   |
| PJ132302.9  | 13h23m02.9s | +55d36m01s | 1.2 \(\pm\) 0.2   | K_a      | 3/30        | 96                    | 40                   |
| PJ160917.8  | 16h09m17.8s | +60d45m20s | 2.0 \(\pm\) 0.4   | K_a      | 3/26        | 92                    | 35                   |

[1] Q band receiver frequency coverage: 38.2 – 49.8GHz. [2] K_a band receiver frequency coverage: 26.0 – 40GHz. [3] \(\mu L_{1R}^1\) is the far-infrared luminosity integrated between 8-1000 \(\mu\)m.

Figure 1. The RSR CO spectra (yellow) for all 7 galaxies (Harrington et al. 2016) are scaled by \(J_{21}\) and overlaid (red) onto the GBT CO spectra (yellow) in this study. The comparable line widths and spectral features are coincident. PJ160918 has both its CO(4 – 3) and (3 – 2) lines compared to the (1 – 0) line emission.

We parametrized these CO SLEDs in terms of brightness temperature, or CO line luminosity, ratios,

\[ r_{\text{up},1} = \frac{T_B(J_{\text{upper}} > 1)}{T_B(1-0)} = \frac{L'_{CO}(J_{\text{upper}} > 1)}{L'_{CO}(1-0)} \]

For two sources with only \(r_{21}\) we found \(< r_{21} > = 0.92\), while the remaining five sources have \(< r_{31} > = 0.34\). Finally, for the one source with a CO(4 – 3) line observation, we found \(r_{41} = 0.18\), similar to what has been reported in Hainline et al. (2006) for an SMG of similar redshift (i.e. \(z \sim 3.3 – 3.5\)). As noted in (Frayer et al. 2011), there is a wide-range in the observed \(r_{31} = 0.1 – 1\) in the local starburst population. The fact that our galaxies fall in the lower end of the SMG excitation distribution, while being some of the most luminous sources currently known, suggests that they may not be exceptional SMGs, but more strongly magnified sources.

In Harrington et al. (2016) we showed that all of these sources fall within the parameter space for SF powered luminosity (rather than AGN) in a mid-IR to far-IR color-color diagnostic plot (Kirkpatrick et al. 2013). Using their CO SLED we can further rule out the presence of a powerful QSO in our galaxies, as typical QSO host galaxies with powerful AGN activity often exhibit thermalised line ratios out to CO(4 – 3) (e.g Riechers et al. 2006; Weiss et al. 2007). However, we caution that most QSO hosts with a good coverage in the CO SLED are strongly lensed objects selected in the optical/NIR. This may result in a bias towards the excitation conditions within the central region. Sharon et al. (2016) show there is a statistical similarity between the \(r_{31}\) values reported for SMGs and AGN in their sample. However, the line ratios in their sample have a global average (AGN and SMG) 3 times higher for \(r_{31}\) (in fact close to thermalised: \(< r_{31} > = 0.9\)) as compared to our
Figure 2. Here we plot the velocity-integrated line intensity ratios of $J_{up}/J_{1-0}$, normalised to the CO($1-0$) derived integrated flux for the current sample. Our seven galaxies (red diamonds) are within the spread for average SMGs (Bothwell et al. 2013) (yellow), and can be compared to the low-z (U)LIRG population (Papadopoulos et al. 2012) (blue), and the Milky Way center (Fixsen et al. 1999) (gray). All regions contain the dispersion between the 25th and 75th percentile of the distribution of the CO($1-0$) normalised integrated flux. Yellow stars show the average QSO values out to $J=6$ (Carilli & Walter 2013).

sources. This suggests that their sample might consist of hybrid SMG/AGN galaxies. Our CO SLEDs are currently limited out to $J=3$ or 4, therefore we cannot rule out the presence of an AGN.

5.2 Ratio of IR Luminosity to CO Line Luminosity

The observable $\mu L_{IR}/\mu L_{CO(1-0)}$ ratio serves as a proxy for SF efficiency (SFE), and stands independent of the unknown magnification factor ¹. The integrated IR emission (8-1000µm) reflects the bulk star-forming activity, while the CO line luminosity indicates the amount of gas supplying the ongoing star formation.

Using the value of this ratio we place our sample in the context of SB versus typical star-forming galaxies at different $z$, IR and CO line luminosity (Fig 3; e.g. Genzel et al. 2010). We measure the $\mu L_{IR}/\mu L_{CO(1-0)}$ ratio as $(58-170) L_\odot/(Kkms^{-1}pc^2)$, with $<110 \pm 22 > L_\odot/K km s^{-1}pc^{-2}$ (see Fig 3). The average value of our galaxies is closer to $140 L_\odot/(Kkms^{-1}pc^2)$ observed in SB galaxies, rather than $30 L_\odot/(Kkms^{-1}pc^2)$ observed in typical star-forming galaxies (Solomon & Vanden Bout 2005; Genzel et al. 2010; Frayer et al. 2011). From this we conclude that the $L_{IR}/L_{CO(1-0)}$ values obtained for this subset of Planck-Herschel sources have enhanced ratios with respect to typical star-forming galaxies, as expected from their large apparent $L_{IR}$ (Cañameras et al. 2015; Harrington et al. 2016).

We note that our sample exhibits slightly lower ratios on average compared to both the highly excited system, HFLS-3 ($z \sim 6$ Riechers et al. 2013), as well as the lensed SPT DSFGs (Aravena et al. 2016) (Fig 3). Roughly half of the strongly lensed, dusty Herschel galaxies (Harris et al. 2012) are consistent with our sample and lie within the yellow shaded region for SB systems. In contrast, more than half of the SPT sources have excess $L_{IR}$-to-$L_{CO(1-0)}$ Aravena et al. (2016), although the dispersion is similar for both H-ATLAS and SPT samples. Our seven Planck-Herschel sample are unusual as they lack a similar dispersion. This may reflect the ability of the all-sky sub-mm sensitivy and coverage of

¹ We assume, without high angular resolution imaging of the two luminosity sources, that the CO($1-0$) emitting region and the pervasive dust content are on average co-spatial.
the Planck survey in detecting the rare galaxies that are, on average, more strongly lensed than the similarly selected H-ATLAS sample.

While the SPT lensed galaxies are a similar population at high-z with comparable LIR, due to different selection methods (350 µm versus mm), the average redshift of their sample is significantly shifted towards a higher value compared to our sample: < z > = 3.9 and < z >= 2.3, respectively. At such a high redshift, z ~ 4, a MW type galaxy would be subject to non-negligible dust heating due to the CMB (da Cunha et al. 2013), and may contribute to the higher LIR-to-L′_{CO(1−0)} values observed in the SPT sample. At z ~ 4, the CMB temperature is also a sufficient background to radiatively excite the cool reservoirs of CO, particularly the J = 1 → 0 ground state rotational transition, resulting in a dimming of the observed CO line emission. Because (sub)-mm flux measurements are made against the CMB, the contrast in the CO (1−0) line integrated intensity via collisional excitation (typically with H_2 molecules), compared with the radiatively excited CO gas from the CMB background becomes more severe beyond z = 4. About 80% of the CO (1−0) emission can be recovered against the CMB at z = 2 – 3, but only 50-60% just beyond z = 4 if there would be a gas kinetic temperature of 40 K (da Cunha et al. 2013).

We caution that the effects of the CMB alone cannot account for the differences observed in these luminosity-luminosity ratios, as the H-ATLAS and SPT sample have a similar spread in their L_{IR}-to-L′_{CO(1−0)} values. The similar redshift range of the 12 H-ATLAS sample compared to the sample of 7 Planck-Herschel galaxies in this study reveals that the CMB effects cannot explain this offset. The excitation conditions of a multi-phase, multiple gas component ISM are also expected to change for each galaxy. One would expect that the density and kinetic temperature of the CO (1−0) emitting gas (and the gradients across the galaxy) to factor into the total attenuation of the CO (1−0) line emission (Tunnard & Greve 2016, 2017) and any self-shielding. As the intense star-forming conditions during the redshifts indicated in these three samples (SPT, H-ATLAS, Planck-Herschel) will give rise to a dynamic set of ISM conditions, these varying gas excitation conditions will therefore have non-negligible effects in the observed L_{IR}-to-L′_{CO(1−0)} values.

### 5.3 Total gas mass from L′_{CO(1−0)}

CO is the second most abundant molecule in the ISM after the highly abundant molecular hydrogen, H_2, and the CO (1−0) line emission is the most direct proxy for H_2 as it traces even the most diffuse gas. Our galaxy integrated CO (1−0) line luminosity is converted to a total molecular gas mass assuming an α_{CO} conversion factor (see review by Bolatto et al. 2013). It is common to use a standard U/LIRG conversion, i.e. α_{CO} = 0.8, for star bursting SMG/DSFGs at high-z, although we reference a standard
Here we present the $L_{\text{IR}}/L'_{\text{CO}(1-0)}$ ratios of our sample compared with known, lensed Herschel and SPT DSFGs (Harris et al. 2012; Aravena et al. 2016), the highly excited HFLS-3 (Riechers et al. 2013) and the median for all SMGs (125 ± 50 $L_\odot/(K\text{km}s^{-1}pc^{-2})$) compiled in the literature by Frayer et al. (2011) (shaded yellow). We plot 2σ boundaries taken from Genzel et al. (2010) for starburst (140 $L_\odot/(K\text{km}s^{-1}pc^{-2})$) and typical star-forming galaxies (30 $L_\odot/(K\text{km}s^{-1}pc^{-2})$). The average for our seven targets in this study is 110 ± 22 $L_\odot/(K\text{km}s^{-1}pc^{-2})$.

Galactic value in Table 3. The similarity of the $L_{\text{IR}}/L'_{\text{CO}(1-0)}$ ratios observed in our sample and those of local ULIRGs seems to further support the use of a starburst-like $\alpha_{\text{CO}}$ conversion factor, even if the centrally compact, concentrated nuclei in local ULIRGs may not be representative of the entire ISM environments in our galaxies. We found $\mu M_H = (0.9 - 27.4) \times 10^{11} M_\odot (\alpha_{\text{CO}}/0.8)$, which are amongst the largest apparent gas contents measured at high-z, even if a lensed magnification of an order of magnitude is taken into account (see Carilli & Walter 2013).

We also compare our CO-based gas mass to the ISM gas mass estimates using the empirical calibration from measured rest-frame dust continuum (e.g. Scoville et al. 2016, 2017). Using our AzTEC 1.1mm photometry ($\nu_{\text{obs}} = 272$ GHz → rest-frame 250-470μm), we compute the ISM mass using Eq. 14 of Scoville et al. (2017). The ISM masses we report scatter predictably around the values obtained from a ULIRG or Galactic conversion factor, suggesting that the value for $\alpha_{\text{CO}}$ varies intrinsically from galaxy to galaxy. Later in § 5.5 we will revisit this empirical calibration to compare the CO line luminosity to the specific luminosity at rest-frame 850μm.

### 5.4 Gas Depletion Time Scales

The amount of time for a galaxy to consume its total molecular gas, given its current galaxy integrated star formation rate, is its so-called depletion time, or gas consumption time scale, $\tau_{\text{depl}} = \mu M_H / \mu SFR$. This inverse SFE reflects the nature of the SF activity of a galaxy, and is a measure that stands independent of the magnification factor in the same way for the $L_{\text{IR}}$-to-CO$(1-0)$ line luminosity ratios above.

To derive our SFR estimates we used the integrated 8-1000μm SED and the empirical calibration (Kennicutt 1998) to convert $L_{\text{IR}}$ to SFR – adopting a Kroupa IMF. The values we obtain are, uncorrected for magnification amplification, $\sim 1500 - 30700 M_\odot/\text{yr}$ (Harrington et al. 2016). Combined with the CO-based gas masses reported in § 5.3, this suggests a depletion time scale of $\tau_{\text{depl}} \sim 80$ Myr. These actively evolving galaxies represent a special mode of rapid starburst activity. This is consistent with short gas depletion times observed on the order of $\tau_{\text{depl}} = 10 - 100$ Myr (e.g. Genzel et al. 2015; Béthermin et al. 2016; Aravena et al. 2016; Scoville et al. 2016), and also with typical galaxy-galaxy crossing time ($\sim 100$ Myr; (Scoville et al. 2016)). The rapid $\tau_{\text{depl}}$ in
these galaxies at high-$z$ rival the $\tau_{\text{dep}} = 2.2$ Gyr timescales for normal star-forming galaxies at $z = 0$ (Leroy et al. 2013).

### 5.5 Global Gas to Dust Comparison

The ratio of measured $L'_{\text{CO}(1-0)}$ to rest-frame specific luminosity at 850$\mu$m serves as a foundation for converting the optically thin Rayleigh-Jeans dust continuum, observed in the (sub)-mm, into total ISM mass (Scoville et al. 2014, 2016, 2017). To infer the rest-frame 850$\mu$m of our galaxies, and thus to compare them to the empirical relation, we use the far-IR SED model fit procedure described by Harrington et al. (2016), fitting the Herschel SPIRE 250-500$\mu$m and AzTEC 1.1mm photometry with a modified blackbody (Eq. 14 Yun & Carilli 2002) (Fig. 4). Several of $z \sim 2$-3 galaxies lie above the empirical calibration obtained by Scoville et al. (2017), in Scoville et al. (2017) the SED analyses was redone using the published sub-mm photometry and CO$(1-0)$ line emission for the 30 normal low-$z$ star-forming galaxies (Dale et al. 2012; Young et al. 1995), 12 low-$z$ ULIRGs (Mentuch Cooper et al. 2012; Chu et al. 2017; Sanders et al. 1989, 1991; Solomon et al. 1997), and 30 SMGs (Greve et al. 2003; Harris et al. 2010; Ivison et al. 2011; Carilli et al. 2011; Harris et al. 2012; Riechers et al. 2011; Lestrade et al. 2011; Thomson et al. 2012; Ivison et al. 2013; Fu et al. 2013; Aravena et al. 2013; Thomson et al. 2015), and lensed SPT galaxies (Aravena et al. 2016) with global measurements of CO$(1-0)$ – or CO$(2-1)$ for some SPT sources, where we used $r_{21} = 0.9$ when applicable. We overplot the best fit linear relation from Scoville et al. (2017): $L'_{\text{CO}(1-0)} = 3.02 \times 10^{-21} L_{\nu850}$.

The highest value of $L_{\text{CO}}/L_{850}$ for some SPT sources, where we used $r_{21} = 0.9$. To compare our measured $L'_{\text{CO}(1-0)}$ to rest-frame $L_{\nu}(353\text{GHz}/850\mu\text{m})$ in our sample to the low-$z$ star-forming galaxies (Dale et al. 2012; Young et al. 1995), local ULIRGs (Mentuch Cooper et al. 2012; Chu et al. 2017; Sanders et al. 1989, 1991; Solomon et al. 1997), $z \sim 2$ SMGs (Greve et al. 2003; Harris et al. 2010; Ivison et al. 2011; Harris et al. 2012; Riechers et al. 2011; Lestrade et al. 2011; Thomson et al. 2012; Ivison et al. 2013; Fu et al. 2013; Aravena et al. 2013; Thomson et al. 2015), and lensed SPT galaxies (Aravena et al. 2016) with global measurements of CO$(1-0)$ – or CO$(2-1)$ for some SPT sources, where we used $r_{21} = 0.9$ when applicable. We overplot the best fit linear relation from Scoville et al. (2017): $L'_{\text{CO}(1-0)} = 3.02 \times 10^{-21} L_{\nu850}$.

The SMG/DSFG population predominantly falls below the 1:1 relation, making our small sample the first to populate the upper envelope—which corresponds to a higher amount of observed CO gas per unit 850$\mu$m dust emission. The highest value of $L_{\text{CO}}/L_{850}$ observed in the SMG population compiled by Scoville et al. (2017) is the 350$\mu$m selected source in Ivison et al. (2011). Two of our galaxies are above the observed scatter, while three of our galaxies exhibit extreme CO luminosities compared to their rest-frame dust luminosity. A larger sample is undoubtedly required to further unveil if, as suggested by our sample, there is a larger intrinsic scatter at high-$z$, particularly at log($L'_{\text{CO}(1-0)}$) > 10.5 K km s$^{-1}$ pc$^2$ and log($L_{850}$) > 31.5 ergs$^{-1}$ Hz$^{-1}$. To compare to the SPT-DSFGs with $J \leq 2$ CO line detections (Aravena et al. 2016), we take their 18 galaxies with consistent sampling of 0.25-1.4mm photometry, similar to our 0.25-1.1mm data, and fit their FIR-mm SEDs as described above. Those SPT galaxies with only CO$(2-1)$ were converted to $L'_{\text{CO}(1-0)}$ using an $r_{21} = 0.9$.

The relatively high $L_{\text{CO}}/L_{850}$ ratios observed in our
galaxies indicate larger gas-to-dust mass (GDMR) ratios than observed in previous samples (Fig. 4). Converting the AzTEC 1.1mm continuum measurement into dust mass, assuming $T_d = 25K$, we found GDMRs in the range [40-200] using the CO-based gas mass ($\alpha_{CO} = 0.8$), compared with the average GDMR of $\sim 230$ from the 1.1mm derived ISM mass (Scoville et al. 2017). This range is both consistent, though slightly larger, than observed in local galaxies with solar metallicities (Leroy et al. 2011; Draine et al. 2007). Assuming instead a Galactic abundance, we would infer extremely high GDMRs (up to 1100), only observed in local, greatly metal-poor dwarf galaxies, e.g., the blue compact dwarf, I Zwicky 18, with 1/50 solar metallicity (Annibali et al. 2015). The assumption of $\alpha_{CO}$, as well as the choice of dust temperature in the ISM mass calculations ultimately determines the derived GDMRs.

6 CONCLUSIONS

Using VEGAS on the GBT, we have successfully measured the CO(1 – 0) line emission for seven of the most gas-rich SMGs/DSFGs studied to date. The key results of this study can be summarised as:

- We have confirmed the previously determined spectroscopic redshifts reported by Harrington et al. (2016)
- The linewidths/profiles for the low-J RSR and CO(1 – 0) VEGAS measurements are nearly identical; therefore, the emitting regions are likely co-spatial, with <FWHM> = 590 km s$^{-1}$
- The CO SLEDs of the galaxies in our sample are indicative of a gas component with sub-thermal excitation conditions: CO line luminosity ratios of $< r_21 > = 0.92$ (2 sources), $< r_{31} > = 0.34$ (5 sources), and $r_{41} = 0.18$ (1 source)
- We find enhanced $L_{NH}/L_{CO(1–0)}$ ratios with respect to normal star-forming systems, as we report an average value of $110 \pm 22 L_\odot/(K$ km s$^{-1}$ pc$^2$), comparable to the median of other well studied SMGs.

With the CO(1 – 0) line emission we place tight constraints on the total molecular gas mass, and allow future CO SLED analyses to benefit from having the fundamental rotational transition observed. The large gas masses obtained are $\mu M_{HI} = (0.9–27) \times 10^{11}(\alpha_{CO} / 0.8) M_\odot$. The average gas depletion time we find is $\tau_{depl} \sim 80$ Myr. These extremely luminous IR galaxies (with $L_{IR} \geq 10^{13–14} L_\odot$) exhibit rapid depletion timescales, and we are likely capturing this light from a relatively short-lived starburst episode.

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