The Circumgalactic Medium of Submillimeter Galaxies. II. Unobscured QSOs within Dusty Starbursts and QSO Sightlines with Impact Parameters below 100 kpc

Hai Fu1, Jacob Isbell1, Caitlin M. Casey2, Asantha Cooray3, J. Xavier Prochaska4, Nick Scoville5, and Alan Stockton6

1 Department of Physics & Astronomy, University of Iowa, Iowa City, IA 52242, USA
2 Department of Astronomy, University of Texas at Austin, 2515 Speedway Boulevard, Stop C1400, Austin, TX 78712, USA
3 Department of Physics and Astronomy, University of California, Irvine, CA 92697, USA
4 Department of Astronomy and Astrophysics, UCO/Lick Observatory, University of California, 1156 High Street, Santa Cruz, CA 95064, USA
5 California Institute of Technology, MC 249-17, 1200 East California Boulevard, Pasadena, CA 91125, USA
6 Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, Honolulu, HI 96822, USA

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Abstract

We present Atacama Large Millimeter/submillimeter Array (ALMA) 870 μm observations of 29 bright Herschel sources near high-redshift QSOs. The observations confirm that 20 of the Herschel sources are submillimeter-bright galaxies (SMGs) and identify 16 new SMG–QSO pairs that are useful to studies of the circumgalactic medium (CGM) of SMGs. Eight out of the 20 SMGs are blends of multiple 870 μm sources. The angular separations for six of the Herschel-QSO pairs are less than 10″, comparable to the sizes of the Herschel beam and the ALMA primary beam. We find that four of these six “pairs” are actually QSOs hosted by SMGs. No additional submillimeter companions are detected around these QSOs, and the rest-frame ultraviolet spectra of the QSOs show no evidence of significant reddening. Black hole accretion and star formation contribute almost equally in bolometric luminosity in these galaxies. The SMGs hosting QSOs show similar source sizes, dust surface densities, and star formation rate surface densities to those of other SMGs in the sample. We find that the black holes are growing ∼3× faster than the galaxies when compared to the present-day black hole/galaxy mass ratio, suggesting a QSO duty cycle of ≤30% in SMGs at z ∼ 3. The remaining two Herschel-detected QSOs are undetected at 870 μm, but each has an SMG “companion” only 9″ and 12″ away (71 and 95 kpc at z = 3). They could be either merging or projected pairs. If the former, they would represent a rare class of “wet–dry” mergers. If the latter, the QSOs would, for the first time, probe the CGM of SMGs at impact parameters below 100 kpc.

Key words: galaxies: starburst – quasars: supermassive black holes

1. Introduction

QSOs are among the first high-redshift galaxies that were shown to have luminous thermal (sub)millimeter emission (Isaak et al. 1994; McMahon et al. 1994). Systematic single-dish observations, mostly carried out with the Institut de Radioastronomie Millimétrique (IRAM) 30 m telescope and the James Clerk Maxwell Telescope (JCMT), have found that about 1/3 of optically selected QSOs at z > 1 show (sub) millimeter continuum at millijansky levels (e.g., Carilli et al. 2001; Omont et al. 2001, 2003; Priddey et al. 2003). Their brightness is comparable to the submillimeter-bright galaxies (SMGs; e.g., Smail et al. 1997), which are JCMT-unresolved sources with 850 μm flux densities above 2–3 mJy. The detection fraction is significantly above that predicted by chance superposition, implying that the QSOs are physically associated with the (sub)millimeter sources. The (sub)millimeter emission indicates rest-frame far-infrared (IR) luminosities on the order of 10^13 L_⊙. Detection of molecular gas in these submillimeter-bright QSOs (see Carilli & Walter 2013, for a review) indicates that the far-IR luminosities are powered by intense star formation with star formation rates (SFRs) of ∼1000 M_⊙ yr^-1. However, the spatial resolution of the single-dish observations at (sub)millimeter wavelengths is limited: e.g., the FWHM beam is 10″6 for the IRAM 30 m at 1.2 mm and 13″8 for the JCMT at 850 μm. Thus, optically selected QSOs detected in single-dish (sub)millimeter observations may be a mixed population. High-resolution interferometer observations have found examples for the following four categories: (1) SMG–QSO composite galaxy—QSOs hosted by dusty starbursts (e.g., Guilloteau et al. 1999; Wang et al. 2013; Wilott et al. 2013; Trakhtenbrot et al. 2017); (2) gas-rich mergers—SMG–QSO composite galaxies interacting with nearby dusty starbursts (e.g., Omont et al. 1996; Carilli et al. 2002; Clements et al. 2009; Trakhtenbrot et al. 2017); (3) gas-rich—gas-poor mergers (“wet–dry” mergers)—QSOs with gas-poor hosts merging with nearby dusty starbursts (e.g., SMM J04135+10277 at z = 2.84; Riechers 2013); or (4) a line-of-sight projected SMG–QSO pair (e.g., SDSS J171209+060144 at z = 2.821; Fu et al. 2016). The last two categories appear to be the least common, with only one example in each category so far.

The wide-area far-IR surveys of the Herschel Space Observatory (Plbratt et al. 2010) enabled investigations on the dust-obscured star formation in large samples of optically selected QSOs from spectroscopic surveys. The 3.5 m space telescope has a resolution of FWHM = 17″8 and 35″2 at 250 and 500 μm, respectively. Thus, the Herschel positions have large uncertainties: the positional offsets between Herschel sources and their Very Large Array (VLA) 6 GHz counterparts range between 2″7 and 7″9 (Fu et al. 2016). Previous studies have used a matching radius of 3″~5″ to identify the far-IR counterparts of the optically selected QSOs (e.g., Cao Orjales et al. 2012; Ma & Yan 2015; Dong & Wu 2016; Pitchford et al. 2016). The conservative matching radii may have resulted in reliable counterpart identification. However, like optically

7 Herschel is an ESA space observatory with science instruments provided by European-led Principal Investigator consortia and with important participation from NASA.
selected QSOs detected in single-dish (sub)millimeter observations, *Herschel* far-IR-detected QSOs are likely a mixed population, and only interferometer observations can reveal its constituents.

The advent of the Atacama Large Millimeter/submillimeter Array (ALMA) enables detailed studies of the host galaxies and close environment of high-redshift QSOs. Previous ALMA observations of QSO hosts include dust continuum and [C II] λ158 μm imaging of six millimeter-detected unobscured QSOs at z ~ 6 in band 6 (250 GHz; Wang et al. 2013; Willott et al. 2013), six QSOs at z ~ 4.8 in band 7 (350 GHz; Trakhtenbrot et al. 2017), and CO(3–2) imaging of four heavily reddened QSOs at z ~ 2.5 in band 3 (100 GHz; Banerji et al. 2017). These observations have revealed a population of luminous QSOs hosted by dusty starbursts with SFR ~ 1000 M☉ yr⁻¹, which represent an important coevolution phase when intense star formation and rapid black hole (BH) growth occur simultaneously.

As part of our program to probe the circumgalactic medium (CGM) of SMGs with QSO absorption line spectroscopy, we obtained ALMA band 7 observations for 29 bright *Herschel* sources near optically bright QSOs at z > 2.5 (i.e., purportedly projected SMG–QSO pairs). The positional offset between the optical QSO and the *Herschel* 250 μm detection (θ₁₂₅₀) is required to be between 5" and 30". We excluded pairs with θ₁₂₅₀ < 5" because the *Herschel* sources are most likely the QSOs. Here we present the ALMA observations; the QSO absorption line study of the ALMA sample will be presented in a future publication. The paper is organized as follows. In Section 2, we describe the sample selection, the ALMA observations, and the data reduction procedure. In Section 3, we analyze the ALMA images that provide a much sharper view of the sources that are responsible for the *Herschel* far-IR emission. In the process, we identified four QSOs hosted within SMGs (i.e., the SMG–QSO composite galaxies). In Section 4, we present the properties of the SMG–QSO composite galaxies and compare them with other *Herschel*-selected SMGs in the sample. We conclude with a summary of our main results in Section 5. The Appendix includes the ALMA images and the source catalog. Throughout we adopt a ΛCDM cosmology with Ω_m = 0.27, Ω_b = 0.73, and H_0 = 70 km s⁻¹ Mpc⁻¹.

### 2. Sample Selection and ALMA Observations

The *Herschel* sources are selected from three equatorial fields of the *Herschel* Astrophysical Terahertz Large Area Survey (H-ATLAS) survey (Eales et al. 2010). The *Herschel* maps cover a total of 161.6 deg² and overlap substantially with the Galaxy And Mass Assembly (GAMA; Driver et al. 2016) fields at R.A. = 9, 12, and 15 hr. The average 1σ noise of the maps, including both confusion and instrumental noise, is 7.4, 9.4, and 10.2 mJy at 250, 350, and 500 μm (Bourne et al. 2016; Valiante et al. 2016). We begin with a sample of *Herschel*-selected SMGs, which are a small subset of *Herschel* sources. They are sources with signal-to-noise ratio (S/N) > 3 in all three SPIRE (Spectral and Photometric Imaging Receiver; Griffin et al. 2010) bands (250, 350, and 500 μm), the SPIRE photometry peaking at 350 μm (i.e., “350 μm peakers”), and 500 μm flux density S₅₀₀ > 20 mJy. We then cross-match the SMGs with optically selected QSOs from a compilation of spectroscopic surveys and select the SMG–QSO pairs with apparent separations between 5" and 30". The apparent separation (θ₁₂₅₀) is defined as the angular offset between the QSO’s optical position and the 250 μm position of the nearest SPIRE source. These apparent separations are likely different from the true separations based on ALMA images because of the significant positional uncertainty of SPIRE sources (Section 3.3). Refer to Fu et al. (2016) for details about the parent sample. Finally, the ALMA targets in each of the three H-ATLAS/GAMA fields were selected to be located within a ~10'' diameter circle so that they can be observed in a single scheduling block (SB), optimizing the survey efficiency.

The ALMA Cycle 3 observations targeting 29 *Herschel* SMGs were carried out on 2016 March 14 and 30 (Project code: 2015.1.00031.S). A total of 38–44 12 m antennae were used, with a minimum baseline of 15.1 m and a maximum baseline of 460 m. This configuration provides a synthesized beam of ~0′′5 in FWHM and ensures that no flux on scales less than θ₉₀₆ = 7′′3 is resolved out by the interferometer (see Table 7.1 in the ALMA Cycle 4 Technical Handbook⁸). We used the band 7 (343 GHz/874 μm) receivers with four spectral windows of 2 GHz bandwidth. The spectral windows are centered at 337.5, 339.4, 347.5, and 349.5 GHz. We set the field centers at the *Herschel* 250 μm catalog positions. The ALMA 12 m antennae’s primary beam has a full width at half-power (FWHP) of 17″ at 874 μm (FWHP ≈ 1.13″/D; see Section 3.2 in the ALMA Cycle 4 Technical Handbook [see footnote 8]), comparable to the 17″8 FWHM of the *Herschel* PSF at 250 μm. This ensures a high detection rate given the uncertainty of the *Herschel* positions.

Each SB lasted between 47 and 51 minutes, giving a typical on-source integration time of 200 s per target. All science targets within an SB shared the track to optimize the uv coverage. For calibrations in the G09, G12, and G15 fields, we observed, respectively, (1) the QSOs J0854+2006, J1229+0203, and J1334–1257 for bandpass and pointing calibrations, (2) the QSOs J0909+0121, J1150–0023, and J1410+0203 for phase and amplitude gain calibration, and (3) the QSOs J0854+2006, J1229+0203, and Titan (Butler-JPL-Horizons 2012 models⁹) for absolute flux calibration. We assume a flux calibration uncertainty of 5% (see Section C.4.1 in the ALMA Cycle 4 Technical Handbook [see footnote 8]) and add it in quadrature to the error of the measured ALMA fluxes.

For imaging, we downloaded the reduced measurement sets from the North American ALMA Science Center (NAASC), which have been fully calibrated by the ALMA pipeline in the Common Astronomical Software Applications (CASA) package (v4.5.1; McMullin et al. 2007). We then ran the CASA task CLEAN to Fourier-transform the calibrated visibilities, to iteratively deconvolve the dirty beam, and to reconvolve with a CLEAN beam. We applied the Briggs weighting to the visibilities with a robustness parameter of 0.5 for an optimal balance between sensitivity and spatial resolution. We adopted a CLEAN loop gain of 0.1 and restricted the CLEANing regions with 1″-radius circular masks around all of the detected sources above the 3σ level. The CLEAN loop continues until the residuals inside the masks reach a threshold of 0.15 mJy beam⁻¹. Following common practice, we chose the CLEAN beam as the best-fit ellipsoidal Gaussian to the main lobe of the dirty beam. The CLEAN beams are on average 0″56 × 0″43.

⁸ https://almascience.nrao.edu/documents-and-tools/cycle4/almac-technical-handbook
⁹ https://science.nrao.edu/facilities/almac/aboutALMA/Technology/ALMA_Memo_Series/almac594/abs594
adequately sampled by the pixel size of $0^\prime\prime.08$. The CLEANed images have rms noises of 0.12 mJy beam$^{-1}$ in the G09 and G12 fields and 0.14 mJy beam$^{-1}$ in the G15 field. These are consistent with the expectation because only 38 antennae were used in the G15 field while 43/44 antennae were used in the G09/G12 fields. Finally, we construct primary-beam-corrected images with the CASA task IMPBCOR and the primary-beam pattern estimated by CLEAN.

### 3. Analysis of the ALMA Sources

In this section, we focus on the analysis of the ALMA data. We present the measurements of the ALMA counterparts of the Herschel sources (Section 3.1), examine the submillimeter emission from the QSOs and their host/companion galaxies (Section 3.2), and empirically calibrate the formula for Herschel positional uncertainty (Section 3.3).

#### 3.1. Properties of the ALMA Sources

For each field, we generate a $22^\prime\prime \times 22^\prime\prime$ CLEANed map along with a primary-beam pattern. We search for $>4\sigma$ peaks$^{10}$ in the S/N maps (Figure 9 in the Appendix) and fit elliptical Gaussians in the flux density maps (Figure 8 in the Appendix) to measure source properties. The ALMA primary beam has an FWHP of $\sim 17^\prime\prime$ at 870 $\mu$m, and the power response declines to almost zero at $\sim 18^\prime\prime$ off-axis. We thus primarily search for sources within $10^\prime\prime$ of the field center. Figure 1 shows the ALMA images of the six fields where the Herschel-QSO separations are less than $10^\prime\prime$, which will be discussed further in the next subsection. Using the CASA task IMFIT, we model all of the sources in a given map simultaneously with elliptical Gaussians to measure their centroid positions, flux densities, and beam-deconvolved sizes. The task also estimates the uncertainties of the fitted parameters following Condon (1997). Because IMFIT cannot handle the spatially variable background noise introduced by the primary-beam correction, we ran the task on the CLEANed maps without the primary-beam correction. The obtained flux densities and their uncertainties are then corrected for the primary beam’s power response function. Because of the small source sizes, running IMFIT on the primary-beam-corrected maps yields almost identical positions and sizes, although the errors are significantly underestimated for sources offset from the phase center.

A total of 39 sources with flux densities between $0.7$ mJy $\leq S_{870} \leq 14.4$ mJy are detected in 27 of the 29 ALMA fields. Table 2 in the Appendix presents the source catalog. All of the sources are detected above $5\sigma$ except one of the two sources in G09 0918−0039, whose peak S/N is 4.8. All of the sources are within $10^\prime\prime$ of the field center except the 9.6 mJy source in G12 1132+0023, which is 12$^\prime\prime$3 from the field center. Although we list the source in the catalog, we exclude it in our subsequent analysis, so our sample includes 38 ALMA sources. We consider only the fainter 1 mJy source as the counterpart of the Herschel source in G12 1132+0023. The two fields without ALMA detections are likely spurious Herschel detections, so they are excluded from our sample.

These observations confirm that 20 of the 29 (69%) Herschel sources in our sample are SMGs with $S_{870} > 2$ mJy. At our resolution, 9 of the 29 Herschel sources break up into multiple 870 $\mu$m sources. We find that source blending is important even for SMGs fainter than 10 mJy: 6 of the 16 (38%) SMGs with $2 < S_{870} < 10$ mJy and two of the four (50%) SMGs with $S_{870} > 10$ mJy break up into multiples at $0^\prime\prime.5$ resolution and a noise level of $\sim 0.1$ mJy beam$^{-1}$.

When the S/N is sufficiently high and the beam shape is accurately known, even sources with intrinsic sizes smaller than the beam size can be resolved. Consistent with previous work, here we define the intrinsic source size as the FWHM of the major axis of the beam-deconvolved Gaussian. Note that previous ALMA studies have shown that the sizes derived from IMFIT are consistent with those derived from directly fitting the $uv$ visibilities with circular Gaussian models (Simpson et al. 2015; Harrison et al. 2016). Previous interferometer observations with the Submillimeter Array (SMA) and ALMA have reported compact, subarcsecond sizes of SMGs in strongly lensed SMGs (e.g., Fu et al. 2012; Bussmann et al. 2013, 2015) and unlensed SMGs (e.g., Ikarashi et al. 2015; Simpson et al. 2015). Beam-deconvolved source sizes can be reliably measured in the 16 high-S/N ALMA sources, which also have the most reliable flux density measurements ($S_{870} / \delta S_{870} > 10$). In Figure 2, we show the ALMA-derived intrinsic angular size against the flux density for all of the ALMA sources, highlighting the 16 high-S/N sources. It is evident that size measurements on sources at lower S/Ns are biased to larger values. Thirteen of the 16 high-S/N sources appear resolved, with intrinsic source sizes between $\sim 0^\prime\prime.2$ and $0^\prime\prime.5$. The mean source size of those is $0^\prime\prime.29 \pm 0^\prime\prime.03$, where the uncertainty is from bootstrapping. The mean source size agrees well with that of the ALMA-detected SMGs in the Ultra Deep Survey field ($0^\prime\prime.30 \pm 0^\prime\prime.04$; Simpson et al. 2015).

On the other hand, the two brightest sources (>10 mJy) are almost 2 times larger than the median size ($\sim 0^\prime\prime.5$), suggesting that the source size may increase slowly with flux density. The trend is consistent with a luminosity-independent SFR surface density, which would imply a size–flux density relation of $R \propto \sqrt{S}$, given that $S_{870}$ is a good indicator of the IR luminosity (as a result of the negative K-correction) and the angular diameter distance decreases by only 8% between $1.5 < z < 3$.

#### 3.2. Submillimeter Emission from the QSOs and Their Host/Companion Galaxies

Our ALMA sample can be divided into two parts based on the apparent separation ($\theta_{250}$) between the QSO’s optical position and the 250 $\mu$m position of the nearest Herschel-selected SMG. The six pairs with $5^\prime\prime < \theta_{250} < 10^\prime\prime$ are the Herschel-detected QSOs because the separation is comparable with the FWHM of the Herschel beam (FWHM = 17$^\prime\prime.8$, 24$^\prime\prime.0$, and 35$^\prime\prime.2$ at 250, 350, and 500 $\mu$m, respectively; Valiante et al. 2016). More importantly, the QSOs are covered within the sensitive field of view of ALMA, given that the FWHP of the ALMA primary beam is $\sim 17^\prime\prime$ at 874 $\mu$m.

For the remaining 23 fields where $10^\prime\prime < \theta_{250} < 30^\prime\prime$, the QSOs are undetected in the ALMA images because (1) they are unlikely far-IR luminous given that the nearest Herschel source is more than 10$^\prime$ away from the QSO position and (2) the ALMA sensitivity drops severely at off-axis distances beyond 10$^\prime$. To provide an upper limit on the intrinsic submillimeter flux density of these QSOs, we stack the ALMA images at the QSO positions for the 10 QSOs that are undetected but are within 18$^\prime$ of the field center. Although the rms noise of the stacked image reaches $\sim 0.04$ mJy beam$^{-1}$ (before primary-beam corrections),

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$^{10}$ Here $\sigma$ means the rms of the CLEANed map in units of Jy beam$^{-1}$. 
In the remaining two fields, the QSOs themselves are undetected by ALMA, yet there is a bright ALMA source within 12″ of the QSO position. At the redshifts of the two QSOs (z ~ 2.9), 10″ translates to a transverse proper distance of 80 kpc. Are they interacting pairs or line-of-sight projected pairs? If the former, these cases would represent a rare population of “wet—dry” mergers similar to SMM J04135 +10277 at z = 2.846 (Riechers 2013). They would likely be “wet—dry” mergers because the ALMA nondetection of the QSOs implies little interstellar gas in the QSO host galaxies. If the latter, the background QSO sightlines could probe the CGM of SMGs at unprecedentedly small impact parameters (i.e., transverse proper distances). Without spectroscopic redshifts of the submillimeter sources, we attempt to answer this question statistically.

We can estimate the number of projected pairs in our sample using the surface density of the Herschel-selected SMGs (Σ_SMG) and the number of QSOs (N_QSO) in the GAMA fields. That is because for a Poisson distribution of random positions on the sky, the probability density of finding a nearest neighbor at a distance between θ and θ+dθ is described by the nearest-neighbor distribution function (Hertz 1909):

$$H(\theta) = \frac{dp}{d\theta} = 2\pi \Sigma_{\text{SMG}} \theta \exp(-\pi \Sigma_{\text{SMG}} \theta^2),$$  

(1)
Knowing the positional uncertainties is important for identifying the multiwavelength counterparts of *Herschel* sources. With accurate ALMA positions, we can empirically calibrate the expected positional uncertainties. In Figure 4(a), we show the spatial offsets between the ALMA positions and the *Herschel* 250 μm positions. For the nine fields that contain multiple ALMA detections, we use the flux-weighted mean positions. We find that 18 of the 27 fields (67%) show ALMA positions within 4″22±0″14 of the *Herschel* position. This empirical positional uncertainty of σ2D ≃ 4″2 is appropriate for samples whose median S/N is comparable to that of our sample (≈6.4).

The theoretical positional uncertainty is a function of the FWHM of the beam and the flux-deboosted S/N (Condon 1997; Ivison et al. 2007):

\[ \sigma_{\text{R.A.}} = \sigma_{\text{decl.}} = 0.6 \times \text{FWHM}/S/N. \]  

In Figure 4(b), we show the positional offset between the ALMA and *Herschel* positions as a function of *Herschel* 250 μm S/N, where we have deboosted the 250 μm flux density following Valiante et al. (2016). To directly compare with predictions from the theoretical formula, we have converted the observed angular offsets in two dimensions to offsets in one dimension:

\[ \Delta_{\text{ND}} = \Delta_{2D}/1.517 = \sqrt{\Delta_{\text{R.A.}}^2 + \Delta_{\text{decl.}}^2}/1.517. \]

Note that the radius of the 1σ confidence region of a joint two-dimensional normal distribution is 1.517 × larger than that of the corresponding one-dimensional normal distribution. The ratio is not √2 as frequently assumed in the literature. Given FWHM = 17″8, Equation (3) encloses only 14 out of the 27 data points (i.e., 52% instead of the expected 68%). This result indicates that the formulae have underestimated the true uncertainty for a given S/N, consistent with previous results based on ALMA counterparts of LABOCA sources (e.g., Hodge et al. 2013).

To make the curve enclose 18 out of the 27 fields (i.e., 67% or 1σ) in our sample, one can either multiply a factor of 1.4 or add a constant offset of 0″7 to Equation (3). We prefer the latter because the positional uncertainty of *Herschel* should not decrease to a fraction of an arcsecond even at the highest S/N, as a result of the imperfect *Herschel* pointing model and complications introduced in the mapmaking process (e.g., Smith et al. 2011). Therefore, below is our empirically calibrated formula for the positional uncertainty of *Herschel* at 250 μm:

\[ \sigma_{\text{R.A.}} = \sigma_{\text{decl.}} = 0.6 \times \text{FWHM}/S/N + 0″7, \]

where FWHM = 17″8 and the S/N is the flux-deboosted S/N. We recommend using Equation (5) to define the search radii of *Herschel* counterparts at other wavelengths.

### 4. SMG–QSO Composite Galaxies

In this section, we focus on the physical properties of the four SMG–QSO composite galaxies identified in Section 3.2. We compare these SMGs that host luminous QSOs with other SMGs in the sample in terms of physical sizes and surface densities of dust mass and SFR in Section 4.1, estimate the BH virial masses and their accretion rates for the QSOs within
Table 1
Properties of the SMG–QSO Composite Galaxies

| Object           | $z_{\text{QSO}}$ | $S_{870}$ (mJy) | Offset (arcsec) | FWHM (kpc) | $L_{\text{IR}}^{\text{QSO}}$ (log($L_{\odot}$)) | $L_{\text{IR}}^{\text{SF}}$ (log($L_{\odot}$)) | $L_{\text{bol}}$ (log($L_{\odot}$)) | $M_{\text{gas}}$ (log($M_{\odot}$)) | SFR ($M_{\odot}$ yr$^{-1}$) | $M_{\text{BH}}$ (log($M_{\odot}$)) | $M_{\text{BH}}$ ($M_{\odot}$ yr$^{-1}$) | $\eta_{\text{Edd}}$ |
|------------------|------------------|-----------------|----------------|------------|-------------------------------------------|-------------------------------------------|--------------------------------|--------------------------------|-----------------|-------------------------------|-------------------------------|----------------|
| G09 0902+0101    | 3.1204           | 14.4 ± 0.8      | 0.03           | 3.5 ± 0.2  | 12.2 ± 0.1                                 | 13.2 ± 0.2                                 | 13.0 ± 0.2                                 | 11.95 ± 0.12         | 1700             | 9.1 ± 0.4                   | 5.5 ± 0.4                     | 0.22            |
| G15 1419+0052    | 2.6711           | 6.4 ± 0.6       | 0.05           | 2.2 ± 0.8  | 11.8 ± 0.1                                 | 13.0 ± 0.2                                 | 12.6 ± 0.2                                 | 11.58 ± 0.12         | 1000             | 9.0 ± 0.4                   | 2.3 ± 0.4                     | 0.12            |
| G15 1444–0044    | 3.3750           | 6.0 ± 0.6       | 0.01           | <2.1       | 12.2 ± 0.1                                 | 13.3 ± 0.2                                 | 13.0 ± 0.2                                 | 11.56 ± 0.12         | 1900             | 9.3 ± 0.4                   | 6.2 ± 0.4                     | 0.18            |
| G15 1450+0026    | 2.8220           | 3.0 ± 0.8       | 0.15           | 3.5 ± 1.4  | 12.7 ± 0.1                                 | 12.9 ± 0.2                                 | 13.1 ± 0.2                                 | 11.04 ± 0.16         | 800              | 9.1 ± 0.4                   | 7.1 ± 0.4                     | 0.30            |

Note. Columns: (1) Designation. (2) Spectroscopic redshift of the QSO. (3) ALMA 870 μm flux density. (4) Offset between the ALMA position and the optical QSO position. (5) Beam-deconvolved FWHM along the major axis from elliptical Gaussian fits to the ALMA 870 μm image. (6–7) Rest-frame 8–1000 μm luminosity powered by BH accretion and star formation, respectively. (8) QSO bolometric luminosity extrapolated from the rest-frame 1350 Å luminosity. (9) Total gas mass derived from the AGN-corrected ALMA 870 μm photometry. (10) SFR from $L_{\text{IR}}^{\text{SF}}$. (11) Virial BH mass based on C IV. (12) BH accretion rate from the bolometric luminosity of the QSO and a radiative efficiency of $\epsilon = 0.1$. (13) Eddington ratio of the QSO.
Figure 3. Distribution of the angular separation between QSOs and the 250 µm positions of Herschel-selected SMGs in all three H-ATLAS GAMA fields. The top panel shows a histogram of the observed distribution. The red filled circle highlights the 5°–10° bin that includes the six Herschel-detected QSOs in Figure 1. The red dashed curve is the predicted distribution of pairs due to random superpositions, which follows the nearest-neighbor distribution function (Equation (2)). The yellow stripes delineate the 1σ uncertainty of the predicted distribution due to Poisson noise. The bottom panel shows the difference between the observed distribution and the predicted distribution in units of the 1σ Poisson noise of the prediction. There is a clear excess over random superpositions at a separation of less than 20″.

SMGs in Section 4.2, and discuss the implications on the galaxy–BH coevolution at z ~ 3 in Section 4.3. The derived properties of the SMG–QSO composite galaxies are given in Table 1.

4.1. Properties of the QSO Host Galaxies

We compile and model the spectral energy distributions (SEDs) of the ALMA sources to derive their SFRs and other physical properties. For the SMGs, which may or may not host QSOs, we used photometry from Herschel/ SPIRE and our ALMA 870 µm data. None of our sources are detected by Herschel/PACS at 100 and 160 µm, which reach depths of σ = 40 and 60 mJy, respectively. For the Herschel sources that are resolved into multiples by ALMA, we use the total 870 µm flux densities from all sources so that they are comparable with the Herschel photometry. For the SMG–QSO composite galaxies, we extend the SEDs with the SDSS photometry between 3500 and 9000 Å (Ahn et al. 2012) and the SDSS-position “forced” Wide-Field Infrared Survey Explorer (WISE; Wright et al. 2010) photometry between 3.4 and 22 µm (Lang et al. 2014).

To fix the redshifts of the models, we adopt the QSO spectroscopic redshifts for the four SMG–QSO composite galaxies and assume a redshift of 2.5 for the remaining ALMA sources since they are selected to be “350 µm peakers” (see Section 2). Optical photometric redshifts are unavailable for the ALMA sources because the depths of the optical and near-IR coverages of the GAMA fields (Driver et al. 2016) are too shallow to detect the counterparts of the ALMA sources. Note that, due to our sample selection, the SMG–QSO composites are at higher redshifts (zQSO = 3.0) than the other SMGs (zSMG = 2.5).

4.1.1. QSO Contribution to the IR Emission

For the SMG–QSO composite galaxies, the far-IR emission could be powered by both star formation and BH accretion. We thus need to correct the observed far-IR and submillimeter photometry for the QSO contribution. Figure 5 shows the observed SEDs of the SMG–QSO composite galaxies. By assuming negligible contribution from dust-obscured star formation at λrest < 10 µm, we can fit the SDSS and WISE photometry with a QSO SED template and then estimate the QSO correction in the far-IR by extrapolating the best-fit QSO template. We adopt the intrinsic QSO SED from Symeonidis et al. (2016) and extend it below 0.4 µm with the composite median QSO spectrum from the SDSS (Vanden Berk et al. 2001). The template is derived from a sample of unobscured luminous PG QSOs at z < 0.18. We choose this SED template because it contains a dust component at a cooler temperature than that of Richards et al. (2006). Whether this cooler dust component is due to AGN heating or star formation remains under debate (Lani et al. 2017; Lyu & Rieke 2017). We thus note that the Symeonidis et al. (2016) AGN SED provides a conservative upper bound on the QSO’s IR luminosity.

As shown in Figure 5, the QSO template fits the SDSS and WISE photometry well. An exception might be G15 1450 +0026, which shows extra amount of emission above rest frame ~3 µm. It is also the only object that is detected by WISE at 12 µm and 22 µm. So for this object, we include a separate “torus” component to improve the fit (Polletta et al. 2006). The torus model represents a dust-obscured QSO component, and it is constructed by reddening the QSO template by A_V = 4 mag with the Calzetti et al. (2000) extinction law.

In all four cases, the best-fit QSO(=torus) models severely underpredict the far-IR emission, indicating that most of the far-IR emission is powered by star formation instead of BH accretion. Puzzlingly, none of the QSOs show evidence of significant dust reddening in the rest-frame UV (λrest < 0.3 µm), even though the compact host galaxies appear extremely dusty. Based on the best-fit QSO(=torus) model, we estimate the QSO contribution to the observed 870 µm flux density and the total integrated IR luminosity. The uncertainty of these estimates is at least 0.13 dex, which is the dispersion of individual QSO SEDs around the mean SED.

4.1.2. Mass and Surface Density of the Interstellar Medium

Following the method of Scoville et al. (2016) to estimate the dust mass from the optically thin Rayleigh–Jeans dust emission, we extrapolate the observed 870 µm luminosity to rest-frame 850 µm luminosity using a modified blackbody with T = 25 K, β = 1.8, and λ0 = 50 µm. This procedure is equivalent to using their K-correction formula. Note that, for the SMG–QSO composite galaxies, we use the QSO-corrected 870 µm flux densities from Section 4.1.1. We adopt the mean ratio of luminosity to gas mass of L_{850}/M_{gas} = (6.7 ± 1.7) × 10^{19} erg s^{-1} Hz^{-1} M_{⊙}^{-1} and the Milky Way gas-to-dust ratio of M_{gas}/M_{dust} = 140 (Draine et al. 2007) to obtain the dust mass.

To estimate the dust mass surface densities, we plot the beam-deconvolved physical sizes against the dust mass in Figure 6(a). Note that the size estimates are biased high at S/N < 10, so these data points should be considered as upper

![Image](https://example.com/image.png)
limits. All of the sources detected at sufficiently high S/N (>10) show similar dust mass surface densities; the average dust mass surface density is \( \sim 8 \times 10^{8} M_{\odot} \text{ kpc}^{-2} \), and almost all data points are bracketed between \( 10^{8} \) and \( 10^{10} M_{\odot} \text{ kpc}^{-2} \). There is apparently no difference between the SMGs hosting luminous QSOs and the other SMGs in the sample, in terms of both the surface density and the total gas/dust mass.

Note that the Rayleigh–Jeans method assumes the Galactic CO-to-H\(_{2}\) conversion factor, \( X_{\text{CO}} \equiv N_{\text{H}}/W_{\text{CO}} = 3 \times 10^{20} \text{ cm}^{-2} \text{ (K km s}^{-1})^{-1} \), where \( W_{\text{CO}} \) is the CO line intensity or equivalently \( \alpha_{\text{CO}} \equiv L_{\text{CO}}/M_{\text{gas}} = 6.5 M_{\odot} \text{ pc}^{-2} \text{ (K km s}^{-1})^{-1} \) after correcting for helium and heavier elements (\( M_{\text{gas}}/M_{\text{HI}} = 1.36 \)). We thus could have overestimated the dust masses by \( 4.6 \times \) if a lower conversion factor is more suitable for SMGs (e.g., \( \alpha_{\text{CO}} \approx 1.4 \); Magdis et al. 2011; Hodge et al. 2012; Magnelli et al. 2012), increasing the ratio of luminosity to gas mass (\( L_{\nu}/M_{\text{gas}} \)). Adopting \( \alpha_{\text{CO}} = 1.4 \), the mean dust mass surface density of our sample becomes \( \sim 2 \times 10^{8} M_{\odot} \text{ kpc}^{-2} \).

### 4.1.3. IR Luminosity and SFR Surface Density

We estimate the IR luminosity integrated between 8 \( \mu \text{m} < \lambda_{\text{rest}} < 1000 \mu\text{m} \) (\( L_{\text{IR}} \)) by fitting a modified blackbody curve to the Herschel/SPIRE and ALMA photometry. We adopt the general solution of the radiative transfer equation assuming local thermal equilibrium at a constant temperature \( T \):

\[
S_{\nu} \propto (1 - e^{-\tau_{\nu}}) B_{\nu}(T) = (1 - e^{-\lambda/(\lambda_{0})^{\beta}}) B_{\nu}(T),
\]

where \( B_{\nu}(T) \) is the Planck function, \( \tau_{\nu} \) is the frequency-dependent optical depth, and \( \lambda_{0} \) is the wavelength at which \( \tau_{\nu} = 1 \). We have assumed that the dust opacity follows a power law with a slope of \( \beta \) at wavelengths greater than the dust size (i.e., \( \lambda > 10 \mu\text{m} \)), i.e., \( \tau_{\nu} = (\nu/\nu_{0})^{\beta} = (\lambda/\lambda_{0})^{-\beta} \) and \( \beta > 0 \). Given the dust mass-absorption coefficient of \( \kappa = 0.07 \text{ m}^{2} \text{ kg}^{-1} \) at 850 \( \mu\text{m} \) for Galactic dust (Dunne et al. 2000; James et al. 2002), it can be shown that \( \lambda_{0} \) depends on the dust surface density:

\[
\lambda_{0} = 850 \mu\text{m} \left( \Sigma_{\text{dust}}/6.8 \times 10^{8} M_{\odot} \text{ kpc}^{-2} \right)^{1/3},
\]

where \( \Sigma_{\text{dust}} \) is the dust surface density. We fixed \( \lambda_{0} \) at 150 \( \mu\text{m} \) for a typical power-law slope of \( \beta = 2 \) and a typical dust mass surface density of \( \sim 2 \times 10^{8} M_{\odot} \text{ kpc}^{-2} \). The best-fit dust temperatures range between 35 and 65 K. We note that \( L_{\text{IR}} \) is insensitive to our choice of \( \lambda_{0} \) and the analytical form of the modified blackbody, because the peak of the dust emission is relatively well constrained by the Herschel data and the redshift is fixed. Even optically thin models, i.e., \( S_{\nu} \propto \nu^{\beta} B_{\nu}(T) \), give similar \( L_{\text{IR}} \) despite significantly lower best-fit dust temperatures (20–45 K).

The 27 Herschel sources with ALMA detections have IR luminosities between 12.6 < \( \log(L_{\text{IR}}) < 13.3 \) \( L_{\odot} \) with a mean at 12.9 \( L_{\odot} \). For the SMG–QSO composite galaxies, we subtract the QSO IR luminosity based on the best-fit QSO (+Torus) SED from Section 4.1.1. The QSO-corrected IR luminosity, \( L_{\text{IR}}^{\text{QSO}} = L_{\text{IR}} - L_{\text{QSO}} \), has an uncertainty of \( \sim 0.2 \) dex. The uncertainty has three components. First, we find that the statistical error of \( L_{\text{IR}} \) is \( \sim 0.1 \) dex for sources with spectroscopic redshifts, through Monte Carlo simulations of synthetic Herschel and ALMA photometry. The systematic uncertainty due to the choice of SED model introduces an additional 0.1 dex uncertainty. For example, in Figure 5 we also show the best-fit model for the far-IR photometry using the SED of the local ultraluminous IR galaxy (ULIRG) Arp 220.
and the blackbody emission \( L_{\text{IR}} \) of the QSO has a minimum uncertainty of 0.13 dex. The resulting \( L_{\text{IR}} \) can be higher than the blackbody fits by \( \sim 0.1 \) dex because the Arp 220 SED contains hotter dust that gives a shallower Wien’s tail. Finally, the extrapolated IR luminosity of the QSO has a minimum uncertainty of 0.13 dex. Combining the three uncertainties in quadrature, we estimate an uncertainty of 0.2 dex for \( L_{\text{IR}}^{\text{SF}} \).

To estimate the SFR surface densities, we plot the beam-deconvolved FWHMs against the IR luminosity in Figure 6(b). SFRs are estimated with the Kennicutt (1998) calibration for the Chabrier (2003) IMF:

\[
\text{SFR}/M_\odot \text{ yr}^{-1} = L_{\text{IR}}^{\text{SF}}/10^{10} L_\odot.
\]  

In Figure 6(b), we compare our measurements against curves at fixed SFR surface densities. The mean SFR surface density of the SMG–QSO composites is \( \sim 260 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \), G15 1444–0044 shows the highest surface density; its unresolved size places a 3σ lower limit at \( > 520 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \), approaching the Eddington limit of \( 10^3 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \) for maximum starbursts (Thompson et al. 2005). The results for the rest of the sample are less reliable because of their unknown redshifts, but their mean surface density of \( \sim 240 M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \) is almost the same as that of the SMG–QSO composites, and most of the data points are constrained within a narrow surface density range between 100 and 300 \( M_\odot \text{ yr}^{-1} \text{ kpc}^{-2} \). Note that the higher average redshift of the SMG–QSO composite galaxies compared to the other SMGs probably has caused the apparent horizontal offset between the two subsamples. These SFR surface densities are similar to previous ALMA-observed SMGs (e.g., Ikarashi et al. 2015; Simpson et al. 2015; Harrison et al. 2016), although only photometric redshifts were used in these previous studies.

4.2. Properties of the Supermassive Black Holes

We estimate the BH virial masses with the calibration of Vestergaard & Peterson (2006) that involves the \( \text{C IV} \lambda 1500 \) line width (FWHM\textsubscript{CIV}) and the continuum luminosity at \( \lambda_{\text{rest}} = 1350 \, \text{Å} \) (\( L_{1350} \)):

\[
\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = 6.66 + 0.53 \log \left( \frac{L_{1350}}{10^{44} \text{ erg s}^{-1}} \right) + 2 \log \left( \frac{\text{FWHM}_{\text{CIV}}}{10^3 \text{ km s}^{-1}} \right)
\]  

The 1σ uncertainty of the zero-point is 0.36 dex. We measure the \( \text{C IV} \lambda 1500 \) line width from the optical spectrum. G15 1450+0026 does not have an SDSS/BOSS spectrum, so we measure the \( \text{C IV} \) FWHM using the spectrum from the 2dF QSO Redshift Survey (2QZ; Croom et al. 2004). The other five QSOs all have BOSS spectra, so we adopt the line widths in the SDSS Data Release 12 Quasar catalog (DR12Q; Pâris et al. 2017), which are based on principle component fits. We
estimate the QSO continuum luminosity at rest frame 1350 Å by interpolating the SDSS broadband photometry. The BH masses are similar among the four QSOs: \( \log(M_{\text{BH}}/M_\odot) \approx 9.1 \).

The broad C IV lines often show evidence of nonvirial kinematics (e.g., outflows); thus, the C IV-based virial masses are biased high when compared with virial masses from hydrogen Balmer lines (e.g., Coatman et al. 2017). However, we do not correct our BH masses, because the systematic bias is low at \( \sim 10^3 M_\odot \) and the precise systematic redshifts of the QSO host galaxies are currently undefined.

To estimate the BH accretion rates and the Eddington ratios, we apply a bolometric correction to the quasar continuum luminosity at rest frame 1350 Å

\[
\log(L_{\text{bol}}/\text{erg s}^{-1}) = 1.40 + 0.93 \log(L_{\text{1350}}/\text{erg s}^{-1}).
\]

The bolometric correction has an uncertainty of \( \pm 0.2 \) dex given the level of dispersion among individual QSO SEDs. We find that the bolometric luminosities of the QSOs are comparable to the integrated IR luminosities from star formation \( (L_{\text{IR}}) \). BH accretion contributes a large fraction (30%–60%) of the total bolometric luminosity \( (L_{\text{bol}} + L_{\text{IR}}) \) in the SMG–QSO composite galaxies, similar to previously studied far-IR-bright QSOs at \( z \sim 4.8 \) (Netzer et al. 2014; Trakhtenbrot et al. 2017).

Given that \( L_{\text{bol}} = \epsilon M_{\text{BH}} c^2/(1 - \epsilon) \), we then assume a radiative efficiency of \( \epsilon = 0.1 \) to convert the bolometric luminosity to an accretion rate:

\[
M_{\text{BH}}/M_\odot \, \text{yr}^{-1} = L_{\text{bol}}/6.3 \times 10^{45} \, \text{erg s}^{-1}.
\]

The estimated BH accretion rates range between 2 and 7 \( M_\odot \, \text{yr}^{-1} \), with Eddington ratios between 10% and 30% when compared to the C IV BH masses (Table 1). In the next subsection, we discuss the implications of these measurements in the context of coevolution.

4.3. Star Formation–AGN Coevolution at \( z \sim 3 \)

Star formation and supermassive BH accretion seem to be strongly connected, at least when averaged over the \( \sim 100 \) Myr star formation timescales (Hickox et al. 2014). The star formation–AGN coevolution scenario is supported by two major pieces of observational evidence. First, the comoving luminosity densities of AGNs and star-forming galaxies have shown that the cosmic BH accretion history closely follows the star formation history over a wide redshift range (e.g., Boyle & Terlevich 1998; Hopkins et al. 2007; Zheng et al. 2009). Second, the average BH accretion rate of star-forming galaxies scales almost linearly with the SFR (e.g., Rafferty et al. 2011; Chen et al. 2013).

However, there are some quantitative disagreements between the two. The present-day ratio of the integrated BH mass density \( (\rho_{\text{BH}}/M_\odot \, \text{Mpc}^{-3}) \approx 5.66 \pm 0.15; \) Marconi et al. 2004 and stellar mass density \( (\rho_{\text{star}}/M_\odot \, \text{Mpc}^{-3}) = 8.4 \pm 0.1; \) Bell et al. 2003 is \( (\rho_{\text{BH}}/\rho_{\text{BH}}) = 2.74 \pm 0.18 \). This implies a growth rate of \( \text{SFR}/M_{\text{BH}} = 2 \times \rho_{\text{star}}/\rho_{\text{BH}} = 1100 \, 3\times 10^{-4} \), provided that 50% of the formed stellar mass is recycled into the interstellar medium. This is consistent with the ratio of the integrated BH accretion rate \( (M_{\text{BH}}) \) and SFR, \( M_{\text{BH}}(z)/\text{SFR}(z) \approx (5–8) \times 10^{-4} \), based on observed luminosity functions (Hopkins et al. 2007; Zheng et al. 2009). On the other hand, the average X-ray AGN luminosity for star-forming galaxies implies a growth rate of \( \text{SFR}/M_{\text{BH}} \approx 3000 \). This is \( \sim 3 \times \) higher than the growth ratios based on the luminosity functions and the present-day mass ratio.
Figure 7. AGN bolometric luminosity vs. host galaxy IR luminosity. The corresponding BH accretion rate and the SFR are indicated on the right and top axes, respectively. The SMG-QSO composite galaxies are shown as red diamonds, and the QSO contribution has been removed from the IR luminosity. The mean luminosities traced by these data points (big red diamond) should be treated as an upper limit because the sample does not include SMGs without AGN activity. For example, if ~30% of the SMGs with $L_{\mu m} \sim 10^{12} L_\odot$ host luminous QSOs, the mean data point would shift downward by the length of the downward-pointing arrow (0.5 dex). For comparison, we show the average AGN bolometric luminosities vs. the average IR luminosities for samples of star-forming galaxies. Note the different AGN tracers that were used to estimate the bolometric luminosity: for our SMG–QSO composites we used the luminosity at 1350 Å, Rafferty et al. (2011) and Chen et al. (2013) used 2–10 keV X-ray luminosity, and Fu et al. (2010) used 15 μm continuum luminosity. For the literature values, the error bars of the X-axis show the range of IR luminosities covered by each subsample, while the error bars of the Y-axis show the bootstrap 1σ uncertainty of the mean AGN luminosities. The black dot-dashed line and the black dashed line show the growth rates required by the present-day ratio of integrated BH mass density and stellar mass density and the local $M_{\text{BH}}-M_{\text{bulge}}$ correlation (Kormendy & Ho 2013). The gray shaded regions around the lines show the 1σ uncertainties of the local relations. See Section 4.3 for the assumptions used in converting these mass ratios to luminosity ratios.

The discrepancy can be explained if two-thirds of BH accretion occurs in AGNs that are intrinsically X-ray under-luminous (and thus require larger bolometric corrections). If so, one would expect a higher $M_{\text{BH}}/\text{SFR}$ ratio when mid-IR-selected AGNs are included. This is indeed the case. Using Spitzer mid-IR spectra of a complete sample of 24 μm selected galaxies at $z \sim 0.7$ in the COSMOS field, we have determined an average AGN bolometric luminosity of $L_{\text{bol}} = 10^{46}$ erg s$^{-1}$ for star-forming galaxies with an average IR luminosity of $L_{\text{IR}} = 10^{12} L_\odot$ (Fu et al. 2010). We estimate a ~0.13 dex bootstrap uncertainty for the mean AGN luminosity, although the uncertainty in the bolometric correction dominates the error budget (~0.2 dex). The luminosity ratio indicates a growth ratio of SFR/$M_{\text{BH}} = 570 \pm 230$.

Figure 7 compares the requirements on growth rates from the present-day BH–stellar mass ratios and the direct measurements at higher redshifts. It plots the AGN bolometric luminosity against the IR luminosities. These luminosities directly trace the BH accretion rates (Equation 11) and the SFRs (Equation 8), as shown on the right and top axes of the figure. In a strong coevolution scenario, the BH accretion rate should scale with the SFR following the present-day BH–galaxy mass ratio at all redshifts. The dot-dashed line and the associated striped region show the relation required by the present-day mass ratio, i.e., SFR/$M_{\text{BH}} = 1100$~360. For comparison, the dashed line and the associated gray shaded region show the local $M_{\text{BH}}-M_{\text{bulge}}$ correlation and its 1σ scatter of 0.28 dex (Kormendy & Ho 2013). Because it is a nonlinear relation, we make the following assumption to convert the mass ratio to the growth rate ratio: (1) a 50% gas fraction ($M_{\text{gas}} = 0.5 M_{\text{bulge}}$), (2) a gas exhaustion timescale of $\tau = 2 M_{\text{gas}}/\text{SFR} = 200$ Myr, and (3) a 50% recycling rate of the stellar mass. Note that the location of the curve is not sensitive to these parameters. Because the bulge mass is a fraction of the total stellar mass, the relation requires lower SFRs at any given BH accretion rate. The dashed line is thus systematically shifted to the left side of the dot-dashed line.

Then, we show the average AGN luminosities for star-forming galaxies at various IR luminosities from Fu et al. (2010), Rafferty et al. (2011), and Chen et al. (2013). Note that Fu et al. (2010) performed spectral decomposition on the mid-IR spectra and used the 15 μm luminosity from the AGN to extrapolate the bolometric luminosities, while Rafferty et al. (2011) and Chen et al. (2013) extrapolated 2–10 keV X-ray luminosity to obtain the AGN luminosities. For these literature values, the error bars of the X-axis show the range of IR luminosities covered by each subsample, while the error bars of the Y-axis show the bootstrap 1σ uncertainty of the mean QSO luminosities. As described above, many of the X-ray-derived AGN luminosities from Rafferty et al. (2011) and Chen et al. (2013) are systematically lower (by up to ~0.5 dex) than that required to explain the present-day mass ratio, while the mid-IR-derived average AGN luminosity from Fu et al. (2010) is consistent with that required by the present-day BH–stellar density ratio within the uncertainties.

Finally, we plot the SMG–QSO composite galaxies from this study. We have subtracted the QSO contribution to the IR luminosities so that they trace star formation only. These composite galaxies offer us a glimpse into the coevolution phase of massive galaxies at $z \sim 3$ in an extremely luminous regime that has not been probed in previous studies. As QSOs selected to be IR luminous, this sample does not include SMGs without AGN activity. Hence, the average QSO luminosity of our sample provides an upper limit on the average QSO luminosity of IR-selected galaxies with $L_{15} \sim 10^{13} L_\odot$. A rough estimate of the AGN fraction in SMGs can be made using the offset between the observed QSO luminosity and the relation based on the present-day density ratio. If we were to shift the average QSO luminosity downward by 0.5 dex so that it reaches the level required by the present-day density ratio, then it implies a QSO duty cycle of ~30% among SMGs with $L_{15} \sim 10^{13} L_\odot$ at $z \sim 3$. This estimate of the QSO duty cycle should be considered as an upper limit because we had assumed no BH accretion in SMGs without detectable QSOs. As the BH accretion rate “flickers” (e.g., Hickox et al. 2014), an SMG may rise above and descend below the local relation multiple times throughout its lifetime of ~200 Myr (e.g., Fu et al. 2013).

With average IR and AGN luminosities of $\log(L_{15}) \sim 13.1 L_\odot = 46.7$ erg s$^{-1}$ and $\log(L_{\text{AGN}}) \sim 46.6$ erg s$^{-1}$, the mean IR luminosity of the SMG–QSO composite galaxies is 3–5× greater than that of the general AGN population at $z \sim 2$–3 and the same bolometric luminosities (e.g., Rosario et al. 2012;
confirming that the IR emission is dominated by unusually high star formation activity (consistent with the observation in Figure 5).

5. Summary and Conclusions

We have observed 29 bright Herschel 350 μm peakers within 30″ of a QSO sightline with ALMA at 870 μm. The ALMA continuum images reach a resolution of ~0″5 and an rms of ~0.14 mJy beam⁻¹, allowing us to measure the intrinsic sizes of the sources and to obtain precise astrometry for spectroscopic follow-up. Six of the Herschel sources are less than 10″ from the QSO, so that the QSOs are within the Herschel beam as well as the ALMA primary beam. The Herschel data indicate that these QSOs are likely associated with strong far-IR emission. The ALMA data allow us to check whether these are physical associations or line-of-sight projections. Our main findings are as follows:

1. We detect a total of 38 ALMA sources with flux densities between 0.7 mJy ≤ Sₖ₇₀ ≤ 14.4 mJy within 10″ of the Herschel positions in 27 of the 29 ALMA fields. At 0″5 resolution, 9 of the 27 Herschel sources are resolved into multiple sources, and the remaining 18 Herschel sources are single sources. No detection was made in 2 of the 29 fields, so these Herschel sources may be spurious.

2. We confirm that 20 of the 29 Herschel sources are SMGs with Sₖ₇₀ ≥ 2 mJy, and we identify 16 new SMG–QSO pairs that can be used to probe the CGM of SMGs.

3. ALMA robustly resolved 13 of the 38 sources. The sources are extremely compact: the mean beam-deconvolved 870 μm size is 0″29 ± 0″03 or 2.3 kpc at z = 3.

4. The theoretical formula for positional uncertainty based on S/N and beam FWHM underestimates the true uncertainty—almost half of our sample has Herschel–ALMA offsets greater than the predicted values. Our empirical calibration suggests adding a baseline term of ~0″7 to the formula to agree with the data (Equation (5)).

5. Four out of the six Herschel-detected QSOs are QSOs hosted by SMGs, or SMG–QSO composite galaxies. SED modeling indicates that the QSOs contribute a large fraction (30%–60%) of the total bolometric luminosity, although dust-obscured star formation dominates the far-IR emission. The BH accretion rates exceed the amount required to maintain the present-day BH–stellar mass ratio for their concurrent SFRs, and the exceeding amount suggests a luminous AGN fraction of ≥30% in SMGs with Lₜ ≤ 10¹³ L☉.

6. Two out of the six Herschel-detected QSOs are close SMG–QSO pairs with separations at 8″9 and 11″9. They are either line-of-sight projection or clustered sources. Based on the surface densities of Herschel 350 μm peakers and the number of high-redshift QSOs in the overlapping area, there should be 1.4 ± 1.0 projected pairs in a sample of six that have Herschel–QSO separations between 5″ and 10″. Thus, at least one of the two is a projected pair with impact parameters less than 100 kpc. Probing the CGM of SMGs at such small impact parameters would be unprecedented. On the other hand, if the QSO and the SMG are in a merger, it would represent a rare case of a “wet–dry” merger similar to SMM J04135+10277 (Riechers 2013). Spectroscopic redshifts are needed to separate between the two scenarios.

The ALMA observations have provided subarcsecond positions of 35 submillimeter sources near QSOs, enabling absorption-line studies of the CGM of dusty starbursts at angular distances between 9″ and 30″, or impact parameters between 71 and 240 kpc at z ∼ 3. The four physical associations between luminous unobscured QSOs and bright Herschel sources highlight an intense episode of the star formation–AGN coevolution over the cosmic history. However, their infallion in samples of projected pairs poses a major challenge to our study of the CGM of dusty starburst galaxies. The limited spatial resolution of Herschel is clearly the culprit. Even at an apparent Herschel–QSO separation of 5″–10″, two-thirds of our “pairs” are QSOs hosted within SMGs. The fraction is likely to increase to essentially 100% at Herschel–QSO separations below 5″, making it difficult to probe the CGM of SMGs within ~40 kpc. Resolving this issue relies on future far-IR and submillimeter observatories that enable wide-field extragalactic surveys at arcsecond resolutions.

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Facilities: ALMA, Herschel, Sloan, WISE.

Appendix

ALMA Images and Source Catalog

Figures 8 and 9 show, respectively, the ALMA flux density maps and the S/N maps for all of our 29 fields. Table 2 lists the source properties from Herschel and ALMA. Out of the 29 Herschel sources, 9 have multiple 870 μm counterparts, 18 have single 870 μm counterparts, and 2 are undetected. Note that the 9.6 mJy source in GI2 1132+0023 is not considered as the Herschel source’s counterpart because it is too far (12″3) from the Herschel 250 μm position.
Figure 8. ALMA 870 μm flux density maps of the entire sample. The contours are drawn at (4, 12, 36) × σ. Detected sources are indicated by blue squares, and their 870 μm flux densities are labeled in units of mJy. The position of the QSO is marked by a red diamond whenever it is within the field of view.
Figure 9. Same as Figure 8, but showing the 870 μm S/N maps. The peak S/N is labeled above each ALMA detection and is listed in Table 2.
Table 2
ALMA Photometry and Intrinsic Source Sizes

| Field       | R.A. 250 (deg) | Decl.250 (deg) | $S_{250}$ (mJy) | $S_{350}$ (mJy) | $S_{500}$ (mJy) | R.A. 870 (deg) | Decl.870 (deg) | offset (arcsec) | Peak S/N | $S_{870}$ (mJy) | Maj (arcsec) |
|-------------|----------------|----------------|-----------------|-----------------|-----------------|----------------|----------------|-----------------|----------|-----------------|--------------|
| G09 0847+0045 | 131.79600      | +0.76550       | 34.2 ± 6.4      | 47.5 ± 7.8      | 38.8 ± 8.4      | 131.79533      | +0.76469        | 3.8             | 41.5     | 6.1 ± 0.4        | <0.10        |
| G09 0850+0108 | 132.72487      | +1.13350       | 33.9 ± 7.1      | 43.0 ± 8.5      | 30.0 ± 9.1      | 132.72529      | +1.13352        | 1.5             | 48.8     | 7.5 ± 0.5        | 0.25 ± 0.07   |
| G09 0850–0019 | 132.72521      | –0.32056       | 17.6 ± 7.0      | 44.9 ± 8.5      | 35.1 ± 9.2      | 132.72636      | –0.32094        | 4.4             | 13.8     | 2.5 ± 0.3        | 0.39 ± 0.12   |
| G09 0854–0012 | 133.55339      | –0.20131       | 79.3 ± 8.2      | 81.5 ± 9.3      | 55.5 ± 9.4      | 133.55308      | –0.20167        | 1.7             | 30.9     | 4.0 ± 0.3        | <0.17        |
| G09 0902+0101 | 135.68767      | +1.02593       | 53.7 ± 7.5      | 56.7 ± 8.6      | 45.9 ± 9.3      | 135.68556      | +1.02665        | 5.1             | 63.2     | 14.4 ± 0.8       | 0.45 ± 0.02   |
| G09 0913–0106 | 138.41382      | –1.11628       | 52.5 ± 7.4      | 69.4 ± 8.8      | 48.2 ± 9.2      | 138.41478      | –1.11568        | 4.1             | 35.8     | 7.4 ± 0.5        | 0.46 ± 0.04   |
| G09 0918–0039 | 139.61586      | –0.66437       | 36.9 ± 7.2      | 48.1 ± 8.5      | 29.4 ± 9.2      | 139.61669      | –0.66351        | 4.3             | 6.7      | 2.1 ± 0.5        | 0.63 ± 0.22   |

Note. Columns: (1) Field designation. Note that in many cases ALMA resolved the *Herschel* source into multiples. (2–3) *Herschel* coordinates from the 250 μm detection. (4–6) *Herschel* photometry at 250, 350, and 500 μm in mJy. The flux densities have been deboosted using the flux bias table of Valiante et al. (2016). The uncertainties include the 5.5% systematic uncertainty for SPIRE absolute flux calibration. (7–8) Coordinates of all ALMA detections within 12.5′ of the pointing position (i.e., the *Herschel* 250 μm position). (9) Angular offset from the *Herschel* position in arcsec. (10) 870 μm peak signal-to-noise ratio. (11) Integrated flux density at 870 μm in mJy based on Gaussian fits. The uncertainty includes the 5% systematic uncertainty in the ALMA flux density scale. (12) Beam-deconvolved FWHMs along the major axis. The ALMA source coordinates, the integrated flux densities, the beam-deconvolved FWHMs, and their associated uncertainties are all derived from elliptical Gaussian fits with the CASA MTT task.
