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INTERFEROMETRIC OBSERVATIONS OF POWERFUL CO EMISSION FROM THREE SUBMILLIMETER GALAXIES AT $z = 2.39$, 2.51, AND 3.35

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ABSTRACT

We report IRAM millimeter interferometry of three $z \sim 2.4$–3.4 Submillimeter Common-User Bolometric Array deep field galaxies. Our CO line observations confirm the rest-frame UV/optical redshifts, thus more than doubling the number of confirmed published redshifts of the faint submillimeter population and proving their high-z nature. In all three sources our measurements of the intrinsic gas and dynamical mass are large (10^{10}–10^{11} $M_\odot$). In at least two cases the data show that the submillimeter sources are part of an interacting system. Together with recent information gathered in the X-ray, optical, and radio bands, our observations support the interpretation that the submillimeter population, at least the radio-detected ones, consists of gas-rich (gas–to–dynamical mass ratio ∼0.5) and massive interacting starburst/active galactic nucleus systems.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: formation

The extragalactic far-IR/submillimeter background is probably dominated by luminous and ultraluminous infrared galaxies (LIRGs/ULIRGs: $L_{\rm IR} \sim 10^{11.5}$–$10^{13}$ $L_\odot$) at $z \gtrsim 1$ (e.g., Smail, Ivison, & Blain 1997; Bertoldi et al. 2002; Scott et al. 2002; Cowie, Barger, & Kneib 2002). However, far-IR/submillimeter sources in most cases have relatively poorly known positions and frequently have only weak counterparts in the rest-frame UV and optical (Smail et al. 2000, 2002; Dannerbauer et al. 2002). As a result, redshifts have thus far been confirmed with CO interferometry for only two of the ∼100 detected systems (Blain et al. 2002). Recently a subgroup of the authors have obtained optical spectroscopic redshifts for a number of sources detected with the Submillimeter Common-User Bolometric Array (SCUBA) camera at 850 μm, to a large extent aided by more precise positions derived from deep 1.4 GHz Very Large Array observations of the same fields. Here we report the first results on the millimeter CO line follow-up of these submillimeter sources. We believe that these observations mark a sensitive breakthrough in the notoriously difficult study of the faint far-IR/submillimeter galaxy population.

The observations were carried out between late summer 2002 and winter 2003 with the IRAM Plateau de Bure interferometer, consisting of six 15 m diameter telescopes. We used the compact D configuration and for follow-up observations of two of the sources the more extended BC configurations. The correlator was configured for CO line and continuum observations to simultaneously cover 580 MHz in the 3 and 1.3 mm bands. The frequency settings were adjusted for all three sources to optimize the CO line centering in the bandpass. SMMJ 04431+0210 was observed between 2002 September and 2003 February in D and BC configurations for a total integration time of 22 hr. SMMJ 09431+4700 was observed in D configuration only, in 2002 November, for 13 hr. SMMJ 16368+4057 was observed between 2002 September and 2003 February for 24 hr. All sources were observed in very good observing conditions. Passband calibration used one or more bright quasars. Phase and amplitude variations within each track were calibrated out by interleaving reference observations of nearby quasars every 20 minutes. The overall flux scale for each epoch was set on MWC 349.

Figures 1 and 2 show the CO spectra and maps. The derived properties are listed in Tables 1 and 2. We adopt a flat, $\Omega_M = 0.3$ Λ-cosmology with $H_0 = 70$ km s^{-1} Mpc^{-1}. To convert CO luminosities to gas masses, including a 37% correction for helium, we adopt, under the assumption of constant brightness temperature for the lowest rotational transitions from (1–0) to (4–3), a factor of $\alpha = 0.8$ $M_\odot$/(K km s^{-1} pc^2) $= 0.2\alpha$ (Galactic), as derived from observations of $z \sim 0.1$ ULIRGs (Downes & Solomon 1998). The gas masses are probably uncertain by a factor of at least 2. We estimate dynamical masses from $M_{\rm dyn} \sin^2 i\ (M_\odot) = 4 \times 10^4 \Delta v_{\rm FWHM}^2 R$.

Here we assume that the gas emission comes from a rotating disk of outer radius R (in units of kiloparsecs) observed at inclination angle i. In a merger model the dynamical masses would be a factor of 2 larger (Genzel et al. 2003). The numerical constant incorporates a factor of 2.4 between observed FWHM velocity width of the line emission, $\Delta v_{\rm FWHM}$ (in units of km s^{-1}), and the product of rotation velocity and $\sin i$. This factor is estimated from model disks taking into account local line broadening, beam, and spectral smearing. We deduce IR luminosities from the 850 μm continuum flux densities S by adopting a modified gray-body model ($T = 40$ K) with proportional $\nu^{1.5}$ dependent emissivity, such that in the range from $z = 2$ to 3.5 $L_{\rm IR}$ ($L_\odot$) $= 1.9 \times 10^{12}$ S_{850}, with S_{850} in units of mJy (Blain et al. 2002). These luminosities are uncertain by a factor of 2–3 since dust temperature and emissivity law may

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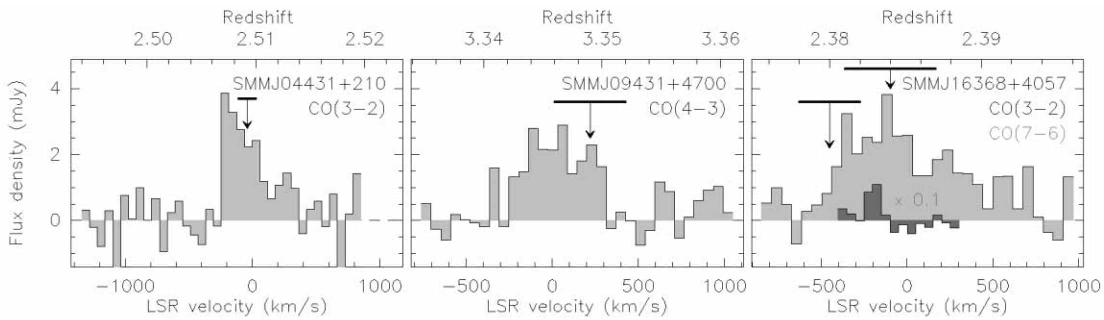

FIG. 1.—CO spectra of the three SCUBA sources. The LSR velocity scale is with respect to the CO redshift listed in Table 1. Optical redshifts (arrows, horizontal bars are uncertainties) are from Frayer et al. 2003 (Hα+[N II], *left panel*), Ledlow et al. 2002 (Lyα, *center*), and Smail et al. 2003 (UV photospheric+Seyfert 2), respectively. The rms noise per 20 MHz channel is 0.7, 0.9, and 0.6 mJy for the three sources, respectively (*left to right*), in the spectral region where the frequency settings were overlapping, and increases to about 20% toward the edges of the bandpass. Overplotted on the CO (3–2) spectrum of SMMJ 16368+4057 is the CO (7–6) spectrum scaled down to 1/10 of its flux density. The rms noise per 40 MHz channel is here 2.2 mJy.

vary from source to source (Blain, Barnard, & Chapman 2003). In the following, all linear sizes, masses, and luminosities are corrected for the foreground lensing factors in Table 2.

SMMJ 04431+0210 ($z = 2.51$) was originally found in the SCUBA Lens Survey ($S_{850} = 7.2$ mJy; Smail et al. 1997, 2002). It is located behind the $z = 0.18$ cluster MS 0440+02. Smail et al. (1999) identified the submillimeter source with the $K = 19.4$ extremely red object (ERO) N4 about 3″ northwest of an edge-on cluster spiral galaxy N1 (N4: $R-K = 6.3$; Frayer et al. 2003). Frayer et al. deduced a redshift of $z = 2.5092 \pm 0.0008$ from Hα/[N II]/[O III] line emission. The rest-frame optical line ratios suggest that N4 is a composite starburst/narrow-line active galactic nucleus (AGN). We adopt the foreground lens magnification of 4.4 deduced by Smail et al. (1999). Our BCD configuration data show a strong CO (3–2) line centered at $z = 2.5094 \pm 0.0002$, $+17$ (± 17) km s^{-1} redward of the nominal redshift of the Hα line. The line width is FWHM $= 350 \pm 60$ km s^{-1}, somewhat smaller than that of Hα (520 km s^{-1}). The integrated CO line flux corresponds to a total gas mass of $8 \times 10^9\ M_\odot$. Most of the CO line emission comes from within 1″. The CO emission centroid is 1″.1 southwest of the near-IR position of N4, as determined by a new astrometric solution of the near-IR/radio astrometry that we obtained by comparing USNO stars with radio sources in the field [N4: R.A. = 04^{h}43^{m}07^s.25, decl. = 02°10′24″.4 (J2000.0); the uncertainty is $\pm$0″.5]. This new position of N4 is 2″.2 east and 0″.6 south of the position reported by Smail et al. (1999). The 1.3 mm continuum data show a marginally significant detection (1.1 mJy, 3.7 σ) near the position of N4. We set a limit to the CO (7–6) emission of $\leq$0.8 Jy km s^{-1} (2 σ). For comparison, the Hα emission exhibits a velocity gradient of $\geq$400 km s^{-1} over about 1″ and along the slit at a position angle (P.A.) of $-14°$, that is, at about 50° relative to the direction of the extended CO emission. The centroid of the Hα emission is on N4. It thus appears that the rest-frame submillimeter and optical observations sample a similar region (size ~1″) but with some differences in the spatial structure in the two wavelength ranges. SMMJ 04431+0210 has by far the lowest intrinsic IR luminosity ($3 \times 10^{12}\ L_\odot$) and gas/dynamic mass of our three galaxies. We deduce an upper limit to the dynamical mass of $4.5 \times 10^9 \sin^{-2} i\ (M_\odot)$ for a source diameter of $\leq$1″. In terms of luminosity, gas, and dynamical mass, SMMJ 04431+0210 thus resembles local ULIRGs.

SMMJ 09431+4700 ($z = 3.35$) was first identified by Cowie

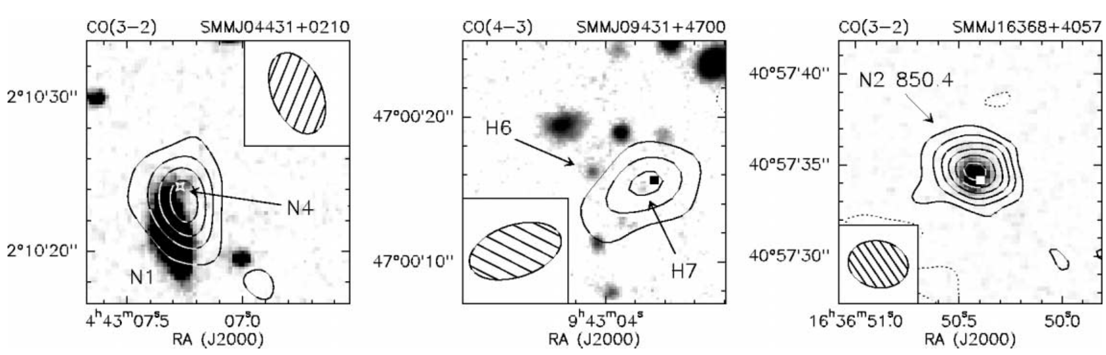

FIG. 2.—Velocity-integrated natural-weighted CO maps of the three SCUBA sources, superposed on gray-scale images of the optical emission. The contours are in units of 2 σ of the noise level and are 0.26, 0.31, and 0.20 Jy km s^{-1} in the three panels (*left to right*), respectively. The synthesized beams are (*left to right*, shown as hatched ellipses) 5″.6 × 3″.3 at position angle 23° (east of north), 6″.6 × 3″.6 at 108°, and 3″.3 × 2″.6 at 79°. The three underlying images are in the *K* band (*left panel*: Frayer et al. 2003; *right panel*: Smail et al. 2003) and in the *I* band (*center panel*: Ledlow et al. 2002). The asterisk (*left image*) is the position of the ERO N4 (uncertainty $\pm$0″.5; see text); the filled squares (*black and light*) are the millimeter continuum positions (*center and right*). The edge-on spiral galaxy 2″ southeast of the CO source is the source N1 in the foreground cluster at redshift $z = 0.18$. In the center panel, the positions of the two radio sources H6 and H7 are denoted by arrows. The stronger optical and radio source H6 is a narrow-line Seyfert 1 galaxy at redshift $z = 3.349$ (Lyα). The CO (4–3) emission from N2 850.4 remains largely unresolved.

TABLE 1
Observed Properties for the Three SMM Sources

Source	Transition	Redshift	R.A. (J2000.0)	Decl. (J2000.0)	I_{CO} (Jy km s^{-1})	Flux (mJy)	Line Width (km s^{-1})
SMM J04431+0210	CO (3–2)	2.5094 ± 0.0002	04 43 07.25	02 10 23.3	1.4 ± 0.2[a,b]	...	350 ± 60
	CO (7–6)	...	...	...	≤0.8	...	...
	3.0 mm	...	...	...	...	≤0.3	...
	1.3 mm	...	...	...		1.1 ± 0.3	...
SMM J09431+4700	CO (4–3)	3.3460 ± 0.0001	09 43 03.74	47 00 15.3	1.1 ± 0.1[a,c]	...	420 ± 50
	CO (9–8)	...	...	...	≤1	...	...
	2.8 mm	...	...	...	...	≤0.4	...
	1.3 mm	...	09 43 03.69	47 00 15.5	...	2.3 ± 0.4	...
SMM J16368+4057	CO (3–2)	2.3853 ± 0.0014	16 36 50.43	40 57 34.7	2.3 ± 0.2[a,c]	...	840 ± 110
	CO (7–6)	~2.383	16 36 50.41	40 57 34.3	1.1 ± 0.2	...	...
	2.9 mm	...	...	...	...	≤1	...
	1.3 mm	...	16 36 50.40	40 57 34.2	...	2.5 ± 0.4	...

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. The astrometric accuracy is ≤0''.3 (= σ); limits on I_{CO} and flux are 2 σ, and uncertainties include statistical errors as well as absolute flux errors. Line width is FWHM; line velocity and 1 σ error are rounded to 10 km s^{-1}.

[a] No continuum subtracted.

[b] Frayer et al. 2003 report an upper limit of 2.5 Jy km s^{-1} using the Owens Valley Radio Observatory interferometer.

[c] Gaussian fit.

et al. (2002) in a deep SCUBA map of the $z = 0.41$ cluster A851 ($S_{850} = 10.5$ mJy). They estimated a foreground lens magnification of 1.2. Ledlow et al. (2002) proposed that the counterpart of the SCUBA source is the 1.4 GHz radio source H6 (72 μJy), for which they identified a redshift of $z = 3.349$ from Lyα. H6 appears to be a UV-bright narrow-line Seyfert 1 galaxy. We find strong CO (4–3) emission with a flat-topped profile and FWHM = 420 km s^{-1} centered at $z = 3.3460 \pm 0.0001$, -207 (± 7) km s^{-1} blueward of the nominal Lyα redshift. The 1.3 mm continuum was also detected with 2.3 ± 0.4 mJy and is centered at the same position. CO line and continuum emission are centered 3''.8 west and 1'' south of the position of H6 (24 kpc in the source plane), positionally coincident with the second, weaker 1.4 GHz source H7 (55 μJy) at R.A. = $09^h43^m03^s.7$, decl. = 47°00'15''.1 (J2000.0; Fig. 2). H6 and H7 are very probably physically related. The gas mass deduced from the CO (4–3) flux is $2.1 \times 10^{10}\ M_\odot$, and the IR luminosity based on S_{850} is $1.7 \times 10^{13}\ L_\odot$. For an assumed source size of 1'' of H7, we infer a dynamical mass of $2.5 \times 10^{10} \sin^{-2} i$ ($M_\odot$). A lower limit to the virial mass of the H6/7 system is $6 \times 10^{10}\ M_\odot$.

SMMJ 16368+4057 ($z = 2.39$, Elais N2 850.4) was identified by Ivison et al. (2002; $S_{850} = 8.2$ mJy) in the 8 mJy SCUBA blank field survey of the Elais N2 field (Scott et al. 2002) with a 220 μJy bright 1.4 GHz radio source. Optical spectroscopy by Chapman et al. (2003) and Smail et al. (2003) showed bright Lyα, N v, C iv, [O ii], and [O iii] emission with a complex spatial and velocity structure. Smail et al. (2003) proposed that N2 850.4 consists of a UV-bright starburst galaxy at $z = 2.380$ (± 0.002), plus a Seyfert 2 galaxy at $z = 2.384$ (± 0.003). There is no evidence for gravitational lensing. We also detected the 1.3 mm continuum emission (2.5 ± 0.4 mJy) and CO (7–6) emission. The CO (3–2) emission is very broad (840 km s^{-1} FWHM) and is centered at $z = 2.3853$ (± 0.0004), $+115$ km s^{-1} (± 36 km s^{-1}) redward of the nominal redshift of the Seyfert 2 nucleus. CO (7–6) emission is tentatively detected in a narrow component centered at -200 km s^{-1} of the CO (3–2) line centroid. At the (7–6) peak, the observed (7–6)/(3–2) brightness temperature ratio is 0.5 ± 0.2. Large velocity gradient modeling of this ratio indicates that the higher excitation CO (7–6) emission may come from a specific warm ($T \geq 50$ K) and dense [$n(H_2) \geq 10^4$ cm^{-3}] region. The absolute astrometry of the rest-frame optical/UV, submillimeter, and radio positions (each $\pm$0''.3) is not yet sufficient to establish with certainty the relative locations of the emission sources at different wave bands. Relative positions are more precise and indicate that the UV-bright source is about 0''.5 west or southwest of the optical source, and both have a size of about 0''.7 or 5.7 kpc. Likewise, we find that the different submillimeter components are spread over ~0''.7, with the CO (7–6) and submillimeter continuum about 0''.3 to the southwest, while the CO (3–2) emission is centered to the northeast. Keeping in mind that these differences are marginally significant, we note that the spatial offsets appear to be along P.A. = 45°, the direction of the separation between the UV and optical line

TABLE 2
Derived Properties for the Three SMM Sources

Source	D_A (Gpc)	$A = \mu_L$[a]	$D = 1''$[b] (kpc)	L'_{CO}[b] (10^{10} K km s^{-1} pc^{-1})	M_{gas}[b,c] ($10^{10}\ M_\odot$)	L_{FIR}[b,d] ($10^{13}\ L_\odot$)
SMM J04431+0210	1.66	4.4[e]	1.8	1.0 ± 0.2	0.8	0.3
SMM J09431+4700	1.53	1.2[f]	6.2	2.7 ± 0.3	2.2	1.7
SMM J16368+4057	1.68	...	8.1	6.9 ± 0.6	5.5	1.6

Note.—Adopting a flat cosmology of $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H = 70$ km s^{-1} Mpc^{-1}.

[a] Assuming equal flux amplification and linear magnification.

[b] Corrected for the lensing magnification μ_L, if applicable.

[c] Adopting a conversion factor $\alpha = M_{gas}/L'_{CO} = 0.8\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$. L'_{CO} is the apparent CO line luminosity corrected for the lensing magnification (Solomon et al. 1997).

[d] Obtained from 850 μm flux densities (Blain et al. 2002).

[e] From Smail et al. 1999.

[f] From Cowie et al. 2002.

emission sources (Smail et al. 2003). The 1.3 mm continuum ($1.6 \times 10^{13}\ L_{\odot}$) is unresolved, with an upper limit of about 1″. The gas mass estimated from the CO emission is about $5.4 \times 10^{10}\ M_{\odot}$, and the dynamical mass is $4.5 \times 10^{10} \sin^{-2} i$ ($M_{\odot}$) for an adopted source diameter of 0″.7.

Our observations of three SCUBA selected galaxies confirm the redshifts identified from rest-frame UV/optical spectroscopy, although for SMMJ 09431+4700 the optical redshift is inferred from a source that is physically distinct from the submillimeter source. Our data more than double the number of published millimeter-confirmed SCUBA redshifts. In addition to the three galaxies discussed here, these are SMMJ 14011+0252 ($z = 2.56$; Frayer et al. 1999; Ivison et al. 2001; Downes & Solomon 2003) and SMMJ 02399−0136 ($z = 2.81$; Frayer et al. 1998; Ivison et al. 1998; Genzel et al. 2003). Our observations confirm that at least some SCUBA galaxies are luminous and gas-rich systems seen at a similar epoch to the UV-bright quasi-stellar object (QSO) and Lyman break galaxies' populations (Boyle et al. 2000; Steidel et al. 1999).

All five SCUBA galaxies are rich in molecular gas. For the CO luminosity to gas mass conversion factor appropriate for local ULIRGs, the median gas mass of the five SCUBA sources is $2.1(\pm 1.7) \times 10^{10}\ M_{\odot}$, similar to the median molecular gas masses found in high-z QSOs (e.g., Alloin et al. 1997; Downes et al. 1999; Guilloteau et al. 1999; Barvainis, Alloin, & Bremer 2002; Cox et al. 2002) but about three times greater than those of local ULIRGs (Solomon et al. 1997). Assuming the most probable value for $\sin i = 2/\pi$, the median ratio of gas mass to dynamical mass in the five galaxies is ~0.5, again 3 times greater than in ULIRGs (Downes & Solomon 1998) and similar to the $z = 2.72$ Lyman break galaxy cB58 (A. J. Baker et al. 2003, in preparation). Four of the five systems are composite AGN/starburst galaxies in a complex environment, such as a merger/interacting system. The fact that the submillimeter galaxies are complex systems is the more noteworthy, as their redshift range is close to the peak of the merging assembly history of galaxy evolution. Perhaps the multiple nature of the SCUBA sources, along with the action of winds and outflows, may explain how Chapman et al. (2003) were able to see strong UV line emission in sources as rich in gas and dust as the submillimeter population.

Relative to their gas reservoir, submillimeter galaxies are very efficient emitters of radiation. The ratio of IR luminosity to gas mass in our five sources has a median of $380 \pm 170\ L_{\odot}/M_{\odot}$, similar to high-$z$ QSOs (750 ± 350), high-redshift radio galaxies (260 ± 70; Papadopoulos et al. 2000), and local ULIRGs (260 ± 160; Solomon et al. 1997) but significantly larger than local LIRGs and more moderate luminosity starbursts (45 ± 30; Solomon et al. 1997). A young starburst with a Salpeter initial mass function (IMF) between 1 and 100 $M_{\odot}$ has $\sim 10^3\ L_{\odot}/M_{\odot}$. If most of the IR luminosity of our submillimeter sources is due to star formation, their star formation efficiency must be high, or the IMF must be biased toward high-mass stars.

Our observations strengthen the conclusion (e.g., Genzel et al. 2003) that the brightest submillimeter galaxies ($S_{850} \sim$ 2–10 mJy, corrected for lensing) have dynamical masses within the central few kiloparsecs that are comparable to massive, local early-type galaxies ($M_{\rm gas} + M_{\rm stars} \sim m^* \sim 7 \times 10^{10}\ M_{\odot}$; Cole et al. 2001). Keeping in mind that our observations strictly give only upper limits or rough estimates of source sizes, we obtain a median dynamical mass of $5.5 \times 10^{10}\ M_{\odot} \sim 0.8m^*$, for $\sin^{-2} i = \pi^2/4$. Current semianalytic models of star formation in hierarchical cold dark matter cosmogonies have difficulties accounting for the observed space density of such massive baryonic systems at $z \sim 3$. These models predict too few m^* galaxies at that redshift, by about an order of magnitude, perhaps as a result of too slow baryonic cooling and low star formation efficiencies in the models (Genzel et al. 2003).

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