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 Plateau de Bure, millimeter interferometry of three $z \sim 2.4$ to 3.4, SCUBA 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 ($10^{10}$ to $10^{11}$ $M_\odot$). 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 submm-population consists of gas rich (gas to dynamical mass ratio $\sim 0.5$) and massive, composite starburst/AGN systems, which are undergoing a major burst of star formation and are evolving into m$^\star$-galaxies.

Subject headings: cosmology: observations - galaxies: formation - galaxies: high-redshift - galaxies: evolution

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1. Introduction

The strength of the extragalactic mid- and far-IR/submillimeter background indicates that about half of the cosmic energy density comes from distant, dusty starbursts and AGN (Puget et al. 1996; Pei, Fall, & Hauser 1999). Mid-IR and submillimeter surveys suggest that this background is dominated by luminous and ultra-luminous infrared galaxies (LIRGs/ULIRGs: $L_{\text{IR}} \sim 10^{11.5}$ to $10^{13.5} L_\odot$) at $z \gtrsim 1$ (e.g. Smail, Ivison & Blain 1997; Aussel et al. 2000; Genzel & Cesarsky 2000; Bertoldi et al. 2002; Elbaz et al. 2002; Scott et al. 2002; Cowie, Barger & Kneib 2002). Since 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), redshifts and spectroscopic parameters have thus far been confirmed with CO interferometry for only two (SMMJ02399$-$0136 – Frayer et al. 1998, and SMMJ14011+0252 – Frayer et al. 1999) of the $\sim 100$ detected systems (Blain et al. 2002).

Recently a subgroup of the authors have initiated a new program of obtaining spectroscopic redshifts with the Keck telescope for a number of sources detected with the SCUBA camera at 850\,$\mu$m, to a large extent aided by more precise positions derived from deep 1.4 GHz VLA observations of the same fields (Ivison et al. 2002; Chapman et al. 2003a, 2003b). Here we report the first results on the millimeter follow-up of three of these submm sources, undertaken with the IRAM Plateau de Bure interferometer. Our main goals were the confirmation by a direct millimeter spectroscopic measurement of the redshifts of the sources, as well as a determination of their gas and dynamical masses.

2. Observations

The observations were carried out between late summer 2002 and winter 2003 with the IRAM Plateau de Bure interferometer, consisting of six 15m-diameter telescopes. We used the compact D configuration, and for follow-up observations of two of the sources the more extended C and B configurations. The correlator was configured for line and continuum observations to simultaneously cover 580 MHz in each of the 3 mm and 1.3 mm bands. The frequency settings had to be adjusted for all three sources by 70 to 240 MHz for optimizing the line centering in the bandpass. SMMJ04431+0210 ($z = 2.51$) was observed between Sep ’02 and Feb ’03 in D and BC configurations for a total integration time of 22 hrs.

by the Centre Nationale de la Recherche Scientifique (France), the Max-Planck Gesellschaft (Germany), and the Instituto Geografico Nacional (Spain).
SMMJ09431+4700 \((z = 3.35)\) was observed in D configuration only, in Nov ’02, for a total integration time of 13 hours. SMMJ16358+4057 \((z = 2.39)\) was observed between Sep ’02 and Feb ’03 for a total on-source integration time of 24 hrs. All three sources were observed in good to excellent observing conditions. We calibrated the data using the CLIC program in the IRAM GILDAS package (Guilloteau & Lucas 2000). Passband calibration used one or more bright quasars. Phase and amplitude variations within each track were calibrated out by interleaving reference observations of closeby quasars every 20 minutes. The overall flux scale for each epoch was set on MWC 349. After flagging bad and high phase noise data (less than 2% at 3 mm), we created data cubes in natural weighting with the GILDAS package.

3. Results

Figure 1 shows the CO 3-2/4-3 spectra and Figure 2 the CO line integrated maps superposed on rest-frame UV \((I\)-band) and optical \((K\)-band) images of the three sources. The observed properties (redshifts, positions, line integrated fluxes and continuum flux densities and line widths) derived from our observations are listed in Table 1. Table 2 gives the basic cosmological parameters, assumed lensing magnifications and the resulting inferred intrinsic CO luminosities, gas masses and IR luminosities. We adopt a flat, \(\Omega_M = 0.3 \Lambda\)-cosmology with a Hubble constant of 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 canonical conversion factor \(\alpha = 0.8 \ M_\odot/(K\ km\ s^{-1}\ pc^2) = 0.2\alpha\) 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. As an estimate of the dynamical mass we adopt

\[
M_{\text{dyn}} \left(\sin i\right)^2 = 4.0 \times 10^4 \Delta v_{\text{FWHM}}^2 R \ (M_\odot) .
\]  

(1)

This relationship assumes that the molecular emission comes from a rotating disk of outer radius \(R\) (in kpc) 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, \(\Delta v_{\text{FWHM}}\) (in km/s), and the product of rotation velocity and \(\sin i\). This factor is estimated from appropriate model disks in which we take into account local line broadening, as well as beam and spectral smearing. We also deduce integrated infrared luminosities from the 850\(\mu\)m/1.3mm continuum flux densities \(S\) by adopting a modified greybody model \((T = 40\) K\) with frequency dependent emissivity \((\propto \nu^{1.5})\), such that in the redshift range from 2 to 3.5
\[ L_{\text{IR}} \left( L_{\odot} \right) = 1.9 \times 10^{12} S_{850}, \]  

with \( S_{850} \) in mJy, and \( S_{850}/S_{1.3} = 3.2 \) (Blain et al. 2002). Dust temperature and emissivity law may vary from source to source and there may be a range of dust temperatures (Blain, Barnard & Chapman 2003). The resulting luminosities are, therefore, uncertain by a factor of 2 to 3. In the following, we discuss in detail the properties of the three SCUBA sources. All linear sizes, masses and luminosities are corrected for foreground lensing.

### 3.1. SMMJ04431+0210 (\( z = 2.51 \))

SMMJ04431+0210 is one of the fifteen original submm sources found in the SCUBA Lens Survey (\( S_{850} = 7.2 \) mJy – Smail, Ivison & Blain 1997; Smail et al. 2002). It is located behind the \( z = 0.18 \) cluster MS0440+02. Smail et al. (1999) identified the submm source with the \( K = 19.4 \) extremely red object (ERO) N4 about 3″ north-west 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 H\( \alpha \)/[N\( \text{II} \)]/[O\( \text{III} \)] line emission observed with NIRSPEC on the Keck telescope. The rest frame optical line ratios also suggest that N4 is a composite starburst/narrow line AGN. We adopt the foreground lens magnification of 4.4 deduced by Smail et al. (1999) from a lens model of MS0440+02 and including the impact of N1. Our BCD configuration data show a strong CO 3-2 line centered at \( z = 2.5094 \pm 0.0002, \pm 17 (\pm 17) \) km s\(^{-1} \) red of the nominal redshift of the H\( \alpha \) line. The line width is FWHM 350 ± 60 km s\(^{-1} \) (FWZP 600 km s\(^{-1} \)), somewhat smaller than that of H\( \alpha \) reported by Frayer et al. (2003 – FWHM 520 km s\(^{-1} \)). The molecular line profile is asymmetric, with a triangular shape, and peaking close to the blue-shifted edge. The integrated CO line flux corresponds to a total gas mass of \( 8 \times 10^9 \) M\( _{\odot} \). Our integrated line map indicates that most of the CO line emission comes from within 1″ but weaker emission is extended over ~3″ along p.a. 110°. The CO emission centroid is 1.1″ south-west of the near-IR position of N4, as determined by a new astrometric solution of the near-IR/radio astrometry we obtained by comparing USNO stars with radio sources in the field (N4: 04h43m07.25s 02°10′24.4″ (J2000) – the uncertainty is ±0.5″). This new position of N4 is 2.2″ east and 0.6″ south of the position reported by Smail et al. (1999) based on the APM coordinate system. The 1.3mm continuum data show a marginally significant detection (1.1 mJy, 3.7\( \sigma \)) near the position of N4. The unusually high 850 to 1.3mm flux density ratio (6.5±2.5) may be ascribed to a combination of the flux density uncertainties, extended 1.3mm dust emission and high dust temperature. We do not detect CO 7-6 emission and set a limit of \( \leq 0.8 \) Jy km s\(^{-1} \) (2\( \sigma \)). For comparison, the H\( \alpha \) emission of Frayer et al. (2003) exhibits a velocity gradient of \( \geq 400 \) km s\(^{-1} \) over about 1″ and along the slit at p.a. –20°, 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″) at redshift z ~ 2.5 but with some differences in the spatial structure in the two wavelength ranges. SMMJ04431+0210 has by far the lowest intrinsic infrared luminosity (3 × 10^{12} L_⊙) and gas/dynamical mass of the SCUBA sample we are discussing in this paper. From equation (1) we deduce a dynamical mass of 4.5 × 10^9 \sin^{-2}(i) M_⊙ for a source diameter of 1″. In terms of luminosity, gas and dynamical mass, SMMJ04431+0210 thus resembles local ULIRGs.

3.2. SMMJ09431+4700 (z = 3.35)

SMMJ09431+4700 was first identified by Cowie, Barger & Kneib (2002) in a deep SCUBA map of the z = 0.41 cluster Abell 851 (S_850=10.5 mJy). From GMOS spectroscopy with Gemini-North, Ledlow et al. (2002) proposed that the counterpart of the SCUBA source is the 1.4 GHz radio source H6 (72μJy), for which they identified a redshift of z = 3.349 from Lyα. H6 appears to be a UV bright, narrow line Seyfert 1 galaxy. Cowie et al. (2002) estimated the foreground lens magnification to be 1.2. The middle panels in Figures 1 and 2 show the line profile and the integrated CO 4-3 line D configuration map superposed on a Keck I-band image on which we identify the positions of H6 and H7. The profile is flat-topped with a FWHM 420 ± 50 km s^{-1} centered at z = 3.3460 ± 0.0001, −207 (±7) km s^{-1} red relative to the nominal Lyα redshift. The 1.3mm continuum was also detected with 2.3 ± 0.4 mJy and is centered at the same position. The CO line and continuum emission is centered 3.8″ west and 1″ south of the position of H6, positionally coincident with the second, weaker 1.4 GHz source H7 (55 μJy) at 09h43m03.7s 47°00′15.1″ (J2000). H7 is also faintly visible on the Subaru R-band image of Kodama et al. (2001: m_R =25.5). Again, the CO observations confirm the optical redshift of the source. However, the submm/mm source is not coincident with the UV bright (Lyα) radio source, but with the UV-fainter source H7, at the same redshift and 24 kpc separation in the source plane. H6 and H7 are very probably physically related. The gas mass deduced from the CO 4-3 flux is 2.1×10^{10} M_⊙, and the IR luminosity is 1.5×10^{13} L_⊙. For an assumed source size of 1″ of H7 we deduce a dynamical mass of 2.5×10^{10} \sin^{-2}(i) M_⊙. A lower limit to the combined virial mass of the H6/7 system is 6×10^{10} M_⊙.

3.3. SMMJ16358+4057 (z = 2.39)

SMMJ16358+4057 (Elais N2 850.4) was identified by Ivison et al. (2002 – S_850=8.2 mJy) from the 8mJy SCUBA blank field survey of the Elais N2 field (Scott et al. 2002) with
a 220µJy bright 1.4 GHz radio source. Optical spectroscopic follow-up of this source by Chapman et al. (2003a) 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 \( z = 2.380 \pm 0.002 \), plus a Seyfert 2 galaxy at \( z = 2.384 \pm 0.003 \), located about 0.3–0.5” NE of the UV bright galaxy. There is no evidence for gravitational lensing of that source. The right panels of Figures 1 and 2 show the line profile and the integrated BCD array CO 3-2 map of N2 850.4 superposed on a Keck K-band image. We also detected the 1.3 mm continuum emission \( (2.5 \pm 0.4 \text{ mJy}) \) and CO 7-6 emission. The CO 3-2 emission is very broad \((840 \text{ km s}^{-1} \text{ FWHM})\) and is centered \( z = 2.3853 \pm 0.0004 \), \(+115 \text{ km s}^{-1} \pm 36 \text{ km s}^{-1}\) of the nominal redshift of the Seyfert 2 nucleus. CO 7-6 emission is tentatively detected in an apparently narrow component centered \(-200 \text{ km s}^{-1}\) of the CO 3-2 line centroid. At the peak of the detected CO 7-6 line the observed 7-6/3-2 brightness temperature ratio is 0.5 ± 0.2. Although uncertain because of the low signal to noise ratio of the 7-6 line and possibly because of bandwidth limitations, large velocity gradient modeling of this ratio indicates that the higher excitation CO 7-6 emission may come from a specific warm \((T \geq 50 \text{ K})\) and dense \(n(H_2) \geq 10^4 \text{ cm}^{-3}\) region in the galaxy. The absolute astrometry of the rest-frame optical/UV, submm and radio positions (each ±0.3") is not yet sufficient to establish with certainty the relative locations of the emission sources at different wavebands. Relative positions are more precise and indicate, for instance, that the UV bright source is about 0.5” W or SW of the optical source, and both have a size of about 0.7", or 5.7 kpc. Likewise, we find that the different submm components are spread over \( \sim 0.7\" \), with the CO 7-6 and submm continuum about 0.3” to the SW, while the CO 3-2 emission is centered to the NE. Keeping in mind that these differences are marginally significant it is nevertheless interesting that the spatial offsets appear to be on approximately along p.a. 45°, which is also the direction of the separation between the UV and optical line emission sources of Smail et al. (2003). The 1.3 mm continuum source \((1.6 \times 10^{13} \text{ L}_\odot)\) is unresolved, with an upper limit of about 1”. Unless there is as yet unrecognized, foreground lensing, SMMJ16358+4057 must be a very massive system, similar to SMMJ02399–0136 (Genzel et al. 2003; Chapman et al. 2003b). The gas mass estimated from the CO emission is about \( 5.4 \times 10^{10} \text{ M}_\odot \), and the dynamical mass is \( 4.5 \times 10^{10} \sin^{-2}(i) \text{ M}_\odot \) for a source diameter of 0.7”.

4. Discussion

Our PdBI observations of three SCUBA selected galaxies confirm the redshifts identified from rest-frame UV/optical spectroscopy, although for SMMJ09431+4700 the optical redshift is inferred from a source that is physically distinct from the submillimeter source. This
is the more remarkable since the input redshifts are from rest-frame UV spectroscopy and since our success rate was 100%. The three SCUBA galaxies we report on were the only ones observed (more were observed since, also with a high success rate: T. Greve et al. in preparation). Our data thus more than double the number of published, mm-confirmed SCUBA redshifts. In addition to the three galaxies discussed here, these are SMMJ14011+0252 \((z = 2.56 - \text{Frayer et al. 1999; Ivison et al. 2001; Downes & Solomon 2003})\) and SMMJ02399−0136 \((z = 2.81 - \text{Frayer et al. 1998; Ivison et al. 1998; Genzel et al. 2003})\). Our observations support the conclusion of Chapman et al. (2003a) that bright \((\sim 10 \text{mJy})\) SCUBA galaxies have a median redshift near \(z = 2.5\), similar to that of the high-z QSO population (Boyle et al. 2000) and of the UV bright Lyman-break galaxies (Steidel et al. 1999).

All five SCUBA galaxies are rich in molecular gas. For the CO luminosity to gas mass conversion factor appropriate for \(z \sim 0.1\) ULIRGs the median gas mass of the five SCUBA sources is \(2.1 \times 10^{10} \text{M}_\odot\) (with a dispersion of \(1.7 \times 10^{10} \text{M}_\odot\)), 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 et al. 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 \(\sim 0.5\), again 3 times greater than in \(z \sim 0.1\) ULIRGs (Downes & Solomon 1998), and similar to the \(z = 2.72\) Lyman break galaxy cB58 (Baker et al. 2003). Four of the five systems are composite AGN/starburst galaxies in a complex environment, such as a merger/interacting system. This is not unexpected. Most local ULIRGs with luminosities approaching those of the SCUBA galaxies are composite AGN/starburst systems as well (Genzel et al. 1998). High-z radio-galaxies (HzRGs) also often exhibit irregular morphologies and strong CO and dust emission (Pentericci et al. 1999; de Breuck et al. 2003; Papadopoulos et al. 2000). Essentially all local ULIRGs are advanced mergers of disk galaxies (e.g. Sanders & Mirabel 1996). 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.

In the local ULIRGs star formation appears to dominate the overall energetics for 75% of the systems with luminosities \(\leq 3 \times 10^{12} \text{L}_\odot\), while AGNs dominate about half of the galaxies at higher luminosities (Lutz et al. 1998; Kim, Veilleux & Sanders 1998). In this respect, submm-galaxies rarely harbor QSO-luminosity AGN (Fabian et al. 2000; Almaini et al. 2003), but frequently have apparently low-luminosity AGN as shown by their spectroscopic and deep X-ray imaging (Chapman et al. 2003a; Alexander et al. 2003). 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 \(380 \pm 170 \text{L}_\odot/\text{M}_\odot\), lower than high-z QSOs \((750 \pm 350)\), somewhat larger than HzRGs \((260 \pm 70 - \text{Papadopoulos et al. 2000})\) and local ULIRGs \((260 \pm 160 - \text{Solomon et al. 1997})\), and 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 between 1 and 100 M\(\odot\) has L/M≈10\(^3\) L\(\odot\)/M\(\odot\). If most of the IR luminosity of our submm sources is due to star formation, their star formation efficiency must be high, or the initial mass function must be biased toward high mass stars. We note, despite the similarity, that the SCUBA population appears to have a space density about one order of magnitude higher than gas-rich high-z QSOs (Smail et al. 1999), possibly because QSOs have a smaller life-time and because obscured type 2 QSOs are missing in the optical surveys (Genzel et al. 2003). Perhaps the multiple nature of the SCUBA sources, along with the action of winds and outflows may explain how Chapman et al. (2003a) were able to see strong UV line emission (including Ly\(\alpha\)) in sources as rich in gas and dust as the submillimeter population.

Finally 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 kpc that are comparable to massive, local early type galaxies (\(M_{\text{gas}}+M_{\text{stars}} \sim m^* \sim 7 \times 10^{10} h_{0.7}^{-2} M_{\odot} – \text{Cole et al. 2001}\)). For \(\sin^{-2} i = \pi^2/4\) we obtain a median dynamical mass of \(5.5\times10^{10} M_{\odot} \sim 0.8 m^*\). Most of this dynamical mass must be baryonic (Genzel et al. 2003). Current semianalytic models of star formation in hierarchical CDM cosmogonies have difficulties accounting for the observed space density of such massive baryonic systems at \(z \sim 3\). These models (e.g. Baugh et al. 2003; Kaufmann et al. 1999) 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).

We are grateful to Prof. M. Grewing for granting us the discretionary time that made this project possible on a short time scale. We also thank Linda Tacconi for help with the data reduction, Stella Seitz for discussions on the lensing model for SMMJ04431+0210, and Ian Smail, Andrew Baker and Dieter Lutz for thoughtful comments. We also thank Omar Almaini and Chris Willott for permission to use their optical images of N2 850.4. AWB acknowledges partial funding support by NSF grant AST0205937, and TRG from the Danish Research Council and from the European Union RTN network, POE.
REFERENCES


Table 1. Observed Properties for the Three SMM Sources.

<table>
<thead>
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<th>Source</th>
<th>Transition</th>
<th>Redshift</th>
<th>R.A.$^a$ (J2000.0)</th>
<th>Decl.$^a$ (J2000.0)</th>
<th>$I_{CO}^b$ (Jy km s$^{-1}$)</th>
<th>Flux (mJy)</th>
</tr>
</thead>
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<td>SMM J04431+0210</td>
<td>CO(3–2)</td>
<td>2.5094 ± .0002</td>
<td>04 43 07.25</td>
<td>02 10 23.3</td>
<td>1.4 ± 0.2$^{(e,g)}$</td>
<td>1.1 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>CO(7–6)</td>
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<td>...</td>
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<td>≤ 0.8</td>
<td>≤ 1.3</td>
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<td>3.3460 ± .0001</td>
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<td>47 00 15.3</td>
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<td>09 43 03.69</td>
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<td>SMM J16358+4057</td>
<td>CO(3–2)</td>
<td>2.3853 ± .0014</td>
<td>16 36 50.43</td>
<td>40 57 34.7</td>
<td>2.3 ± 0.2$^{(e,f)}$</td>
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<tr>
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<td>CO(7–6)</td>
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<td>16 36 50.41</td>
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<td></td>
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<td>16 36 50.40</td>
<td>40 57 34.2</td>
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</tr>
</tbody>
</table>

$^a$The astrometric accuracy is ≤ 0.3″ (= σ).

$^b$Limits are 2σ, and uncertainties include statistical errors, as well as absolute flux errors.

$^c$Full width at half maximum (FWHM).

$^d$Velocity and 1σ error rounded to 10 km s$^{-1}$.

$^e$No continuum subtracted.

$^f$Gaussian fit.

$^g$Frayer et al. (2003) report an upper limit of 2.5 Jy km s$^{-1}$ using the OVRO interferometer.
<table>
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<th>Source</th>
<th>$D_A$ (Gpc)</th>
<th>$A = \mu_L$</th>
<th>$D = 1^{\mu_L}$ (Kpc)</th>
<th>$L'_{\text{CO}}$</th>
<th>$M_{\text{gas}}$</th>
<th>$L_{\text{FIR}}$</th>
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<tbody>
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<td>1.66</td>
<td>4.4$^b$</td>
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<td>1.0 ± 0.2</td>
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<td>1.2$^c$</td>
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<td>2.7 ± 0.3</td>
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<td>1.7</td>
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<tr>
<td>SMM J16358+4057 . .</td>
<td>1.68</td>
<td>1.0$^b$</td>
<td>8.1</td>
<td>6.9 ± 0.6</td>
<td>5.5</td>
<td>1.6</td>
</tr>
</tbody>
</table>

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

$^a$Corrected for the lensing magnification $\mu_L$.

$^b$From Smail et al. 1999.

$^c$From Cowie et al. 2002.

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

$^e$Assuming equal flux amplification and linear magnification.

$^f$Obtained from 850$\mu$m flux densities with a modified greybody model (T=40 K) and a frequency dependent emissivity (equ. 2, Blain et al. 2002)
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) are from Frayer et al. 2003 ($\text{H}$α+[$\text{N II}$], left panel), Ledlow et al. 2002 (Ly$\alpha$, 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 (from left to right), in the spectral region where the frequency settings were overlapping, and increases to about 20 percent toward the edges of the bandpass. Overplotted on the CO 3-2 spectrum of SMMJ16368+4057 is the CO 7-6 spectrum scaled down to one-tenth of its flux density. The rms noise per 40 MHz channel is here 2.2 mJy.
Fig. 2.—Velocity integrated, natural weighted CO maps of the three SCUBA sources, superposed on greyscale images of the optical emission. The contour scale of the mm-line emission is in units of 2σ of the noise level, and is 0.26, 0.31 and 0.20 Jy km s$^{-1}$ in the three panels (from left to right), respectively. The FWHM interferometer beams in the natural weighted data are (left to right, shown as hatched ellipses) $5.6 \times 3.3''$ at position angle 23° (east of north), $6.6 \times 3.6''$ at position angle 108°, and $3.3 \times 2.6''$ at position angle 79°. The three underlying images are in the $K$-band (left and right panel) and in the $I$-band (center panel). The asterisk in the 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'' SE of the CO source is the source N1 in the foreground cluster at redshift $z = 0.18$. In the middle panel, denoted by arrows, the positions of the two radio sources H6 and H7. The stronger optical and radio source H6 is a narrow line Seyfert galaxy at redshift $z = 3.349$ (Lyα). CO 4-3 emission from N2 850.4 remains largely unresolved.