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MOLECULAR GAS IN THE $z = 2.565$ SUBMILLIMETER GALAXY SMM J14011+0252

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ABSTRACT

We report the detection of CO $(3 \rightarrow 2)$ emission from the submillimeter-selected luminous galaxy SMM J14011+0252. The optical counterpart of the submillimeter source has been identified as a merger system with spectral characteristics consistent with a starburst at $z = 2.565$. The CO emission confirms the optical identification of the submillimeter source and implies a molecular gas mass of $5 \times 10^{10}\ h_{75}^{-2}\ M_{\odot}$, after correcting for a lensing amplification factor of 2.75. The large molecular gas mass and the radio emission are consistent with the starburst interpretation of the source. These results are similar to those found for SMM J02399−0136, which was the first submillimeter-selected CO source found at high redshift. The CO detections of these two high-redshift submillimeter galaxies suggest the presence of massive reservoirs of molecular gas, which is consistent with the inferred high rates of star formation ($10^3\ M_{\odot}\ \mathrm{yr}^{-1}$). These two systems appear to be associated with merger events which may evolve into present-day luminous elliptical galaxies.

Subject headings: early universe — galaxies: active — galaxies: evolution — galaxies: individual (SMM J14011+0252) — galaxies: starburst

1. INTRODUCTION

Deep surveys of the submillimeter sky using the Submillimeter Common-User Bolometer Array (SCUBA) on the James Clerk Maxwell Telescope have uncovered a population of distant dust-rich galaxies (Smail, Ivison, & Blain 1997; Blain et al. 1999; Barger et al. 1998; Hughes et al. 1998; Eales et al. 1999). Based on their optical colors, the majority of these systems are thought to lie at redshifts of $z \sim 1$–5 (Smail et al. 1998b). However, only a few of these systems currently have accurate redshifts. The first well-studied system, SMM J02399−0136 (hereafter SMM J02399) at $z = 2.8$, was shown to contain both an active galactic nucleus (AGN; Ivison et al. 1998) and a massive reservoir of molecular gas thought to be fueling a starburst (Frayer et al. 1998).

In order to test the generality of the properties of SMM J02399, we have initiated a search for CO emission in additional submillimeter sources. In this Letter, we report the results for the submillimeter source SMM J14011+0252 (hereafter SMM J14011). This submillimeter galaxy was discovered during a survey through rich, lensing clusters (Smail et al. 1998b). Follow-up optical spectroscopy places the submillimeter source at a redshift of approximately $z = 2.55$ (Barger et al. 1999; Ivison et al. 1999). SMM J14011 appears to be a merger/interacting system that has optical and radio properties consistent with an ultraluminous starburst (Ivison et al. 1999), albeit the presence of a heavily obscured AGN cannot be ruled out. The amplification factor for SMM J14011 is 2.75 ± 0.25, where the uncertainty comes from the allowed range of detailed mass models of the foreground cluster.

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2. OBSERVATIONS

SMM J14011 was observed using the Owens Valley Millimeter Array between 1998 October and December. A total of 41 hr of usable integration time on source was obtained in two configurations of six 10.4 m telescopes. The phase center for the CO observations was the position of the brightest optical component of the SMM J14011 system (J1): α (J2000) = $14^{\mathrm{h}}01^{\mathrm{m}}04\overset{\mathrm{s}}{.}97$, δ (J2000) + 02°52′24″.6 (Ivison et al. 1999). The CO $(3 \rightarrow 2)$ line was observed using a digital correlator configured with 112×4 MHz channels centered on 96.9975 GHz in the lower sideband, corresponding to CO $(3 \rightarrow 2)$ emission at the Hα redshift of $z = 2.565$ (Ivison et al. 1999). Typical single-sideband system temperatures were approximately 300–350 K, corrected for telescope losses and the atmosphere. In addition to the CO line data, we recorded the 3 mm continuum data with a 1 GHz bandwidth for both the upper (line-free, centered on 99.9975 GHz) and lower sidebands. The nearby quasar 1413+135 was observed every 25 minutes for gain and phase calibration. Absolute flux calibration was determined from observations of Uranus, Neptune, and 3C 273. The absolute calibration uncertainty for the data is approximately 15%.

3. RESULTS

Figure 1 shows the CO $(3 \rightarrow 2)$ spectrum for SMM J14011. The CO line is detected at the redshift of the narrow Hα line of SMM J14011 (Ivison et al. 1999). We achieved a 7 σ detection for the peak in the integrated CO $(3 \rightarrow 2)$ map (Fig. 2). The CO position (Table 1) is consistent with the optical position of SMM J14011 within the uncertainties of the data sets. The CO map shows marginal evidence for emission extended toward the south, but observations at higher resolution are required to test this possibility. The upper limit of the continuum emission is $S_{\nu}(3\ \mathrm{mm}) < 0.6$ mJy (1 σ). This is insufficient to detect the thermal dust emission discovered by SCUBA, assuming $S_{\nu} \propto \nu^{3.5}$.

Both the CO and Hα lines of SMM J14011 are redshifted from the UV lines by about 1100 ± 700 km s^{-1} (Ivison et al. 1999). Systematic blueward offsets of UV lines are not unusual

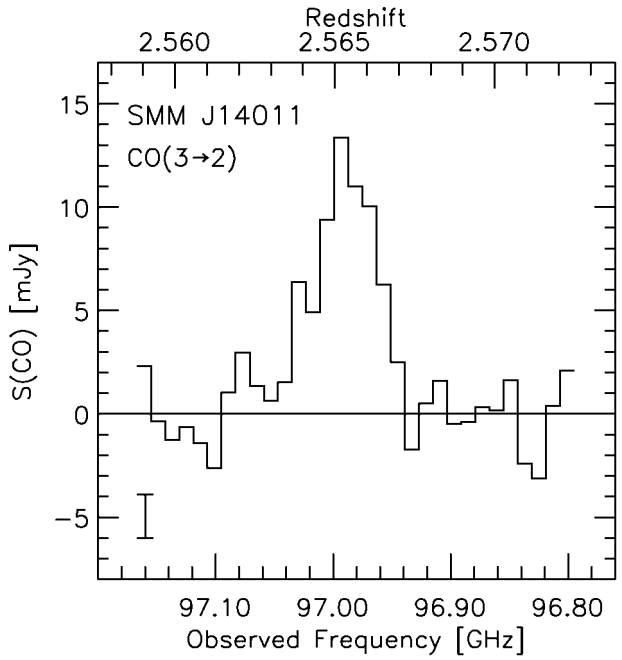

FIG. 1.—CO (3 → 2) spectrum for SMM J14011 observed with the Owens Valley Millimeter Array. The data have been smoothed to 24 MHz (74 km s^{-1}), and the channel separation is 12 MHz. The 1 σ rms error of each channel is shown in the lower left-hand corner.

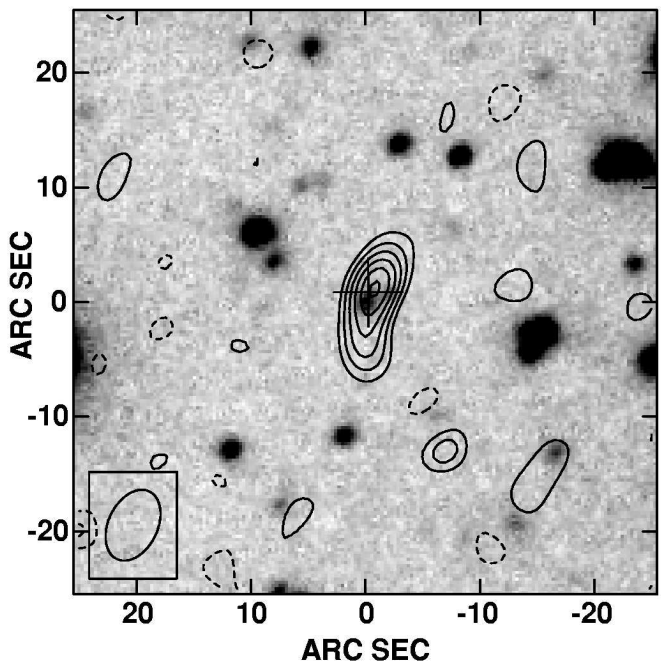

FIG. 2.—Integrated CO (3 → 2) map averaged over 104 MHz (322 km s^{-1}) overlaid on an optical *I*-band image taken at the Palomar 5 m (Smail et al. 1998a). The positional offsets are relative to the optical position, and the cross marks the position of the SCUBA source (Ivison et al. 1999). The 1 σ rms error is 0.32 Jy km s^{-1} beam^{-1}, and the contour levels are 1 σ × (−3, −2, 2, 3, 4, 5, 6, 7). The synthesized beam size for the observations is shown in the lower left-hand corner (6.″5 × 4.″3, PA = −26°).

for starbursts and have been attributed to outflows with dust obscuration at systemic and redshifted velocities (Mirabel & Sanders 1988; González Delgado et al. 1998; Heckman et al. 1998). In an extreme example, the $z = 3.9$ quasar APM 08279+5255 shows a 2500 km s^{-1} blueward offset of the UV lines from the systemic CO redshift (Downes et al. 1999).

The observed CO (3 → 2) line flux is $S(\mathrm{CO}) = 2.4 \pm 0.3$ Jy km s^{-1}. No adjustment has been made to account for the continuum level since it is negligible. The observed CO (3 → 2) line flux implies an intrinsic CO line luminosity[8] of $L'(\mathrm{CO}) = 1.2 \times 10^{10}\ h_{75}^{-2}$ K km s^{-1} pc^2 (see formulae in Solomon, Downes, & Radford 1992). The CO luminosity is related to the mass of molecular gas (including He) by $M(\mathrm{H_2})/L'(\mathrm{CO}) = \alpha$. The value for α is expected to be between $\alpha \simeq 1\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$ (Solomon et al. 1997) and the Galactic value of $\alpha \simeq 5\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$ (e.g., Sanders, Scoville, & Soifer 1991). We adopt a value of $\alpha = 4\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$, which is consistent with that estimated for Arp 220 (Scoville, Yun, & Bryant 1997a) after correcting for the line brightness ratio of $T_b\,[\mathrm{CO}(3 \rightarrow 2)]\,/T_b\,[\mathrm{CO}(1 \rightarrow 0)] \simeq 0.6$ typically observed in starbursts (Devereux et al. 1994). The inferred molecular gas mass of SMM J14011 is $5 \times 10^{10}\ h_{75}^{-2}\ M_\odot$, which is consistent with that of the most massive low-redshift ultraluminous infrared galaxies (ULIGs; Sanders & Mirabel 1996).

The implied gas-to-dust ratio for SMM J14011 is $M(\mathrm{H_2})/M$ (dust) = 200–900, assuming a reasonable range of possible dust temperatures (30–70 K). These gas-to-dust ratios are similar to those seen in spiral galaxies (Devereux & Young 1990), local ULIGs (Sanders et al. 1991), and other high-redshift CO sources. The similarities of the derived gas-to-dust ratios at high redshift reflect the small scatter (only a factor of 2–3) in their $L'(\mathrm{CO})/L_\nu(\mathrm{submm})$ luminosity ratios. These results are somewhat remarkable considering that some of the sources are more likely to be dominated by AGNs than others and considering the possibility of different dust temperatures.

The observed line width for SMM J14011 (FWHM = 200 km s^{-1}) is much narrower than that observed for SMM J02399 (700 km s^{-1}), but is within the range of values typically observed for ULIGs (200–400 km s^{-1}; Solomon et al. 1997). The narrow line width may indicate that we are viewing the system somewhat face-on. By using the observed line width and the upper limit on the CO source size of $\theta < 7''$, we can constrain the total dynamical mass contained within the CO emission regions. The angular size limit corresponds to a maximum linear diameter of $D < 36\ h_{75}^{-1}$ kpc at $z = 2.565$, or $D < 13\ h_{75}^{-1}$ kpc after correcting for lensing. The dynamical mass is $M_{\mathrm{dyn}} \simeq R(\Delta V/[2 \sin(i)])^2/G$, where ΔV is the observed FWHM line width and i is the inclination. We find $M_{\mathrm{dyn}} <$

TABLE 1
CO OBSERVATIONAL RESULTS

Parameter	Value
α(J2000)	$14^{\mathrm{h}}01^{\mathrm{m}}04\overset{\mathrm{s}}{.}92 \pm 0\overset{\mathrm{s}}{.}03$
δ(J2000)	$+02°52'25\overset{''}{.}6 \pm 0\overset{''}{.}6$
z(CO)	2.5653 ± 0.0003
Line width (FWHM)	200 ± 40 km s^{-1}
$S(\mathrm{CO})$[a]	2.4 ± 0.3 Jy km s^{-1}
$L(\mathrm{CO})$[b]	$1.6 \times 10^7\ h_{75}^{-2}\ L_\odot$
$L'(\mathrm{CO})$[b]	$1.2 \times 10^{10}\ h_{75}^{-2}$ K km s^{-1} pc^2
$M(\mathrm{H_2})$[b,c]	$5 \times 10^{10}\ h_{75}^{-2}\ M_\odot$

[a] Observed CO (3 → 2) line flux.
[b] Intrinsic value assuming a lensing amplification factor of 2.75, $q_0 = 0.5$, and $H_0 = 75\ h_{75}$ km s^{-1} Mpc^{-1}.
[c] Estimated using $\alpha = 4\ M_\odot$ (K km s^{-1} pc^2)$^{-1}$.

[8] We adopt $q_0 = 0.5$, $H_0 = 75\ h_{75}$ km s^{-1} Mpc^{-1}, and a lensing amplification factor of 2.75 throughout this Letter.

$1.5 \times 10^{10} \sin^{-2}(i)\ h_{75}^{-1}\ M_\odot$, which is consistent with the derived gas mass, provided $i \lesssim 35°$.

4. DISCUSSION

The intrinsic far-infrared luminosity of SMM J14011 is approximately $3 \times 10^{12}\ h_{75}^{-2}\ L_\odot$. If its luminosity is powered by star formation, as suggested by the optical data (Ivison et al. 1999), the implied star formation rate of massive stars ($M > 5\ M_\odot$) is $300\ M_\odot\ \mathrm{yr}^{-1}$ (Condon 1992). Including the presence of low-mass stars, the total star formation rate would be of order $10^3\ M_\odot\ \mathrm{yr}^{-1}$. The CO data is consistent with this view by showing the presence of enough gaseous material to support a high level of star formation. The large molecular gas mass and the high star formation rate suggest a starburst timescale of order 5×10^7 yr. In addition, the far-infrared–to–radio flux ratio for SMM J14011 is the same as that found for nearby starburst galaxies (Condon, Frayer, & Broderick 1991). Alternatively, if SMM J14011 is powered by an AGN, the AGN could not be a powerful radio source (less than $3 \times 10^{30}\ h_{75}^{-2}$ $\mathrm{ergs}^{-1}\ \mathrm{Hz}^{-1}$).

The success of the first two searches for CO from the high-redshift submillimeter-selected galaxies is encouraging. Unlike SMM J02399, whose UV/optical spectral properties show significant AGN activity, there is currently no evidence for an AGN in SMM J14011. However, the presence of a dust-enshrouded AGN cannot be completely ruled out. Even though the UV/optical characteristics of SMM J14011 and SMM J02399 appear different, their radio, submillimeter, and CO properties are fairly similar and suggest that star formation is important in the far-infrared emission of both sources. SMM J14011 and SMM J02399 share many of the same properties of the local population of ULIGs, such as (1) high infrared luminosities, (2) association with mergers, (3) large reservoirs of molecular gas, and (4) comparable CO line widths. The most important distinction is that the high-redshift submillimeter galaxies are about a factor of 10^2–10^3 times more numerous per unit comoving volume than the low-redshift ULIGs (Kim & Sanders 1998). The submillimeter galaxies may also have slightly larger amounts of molecular gas (by factors of 2–3) than typical ULIGs.

Figure 3 shows the CO luminosities plotted as a function of redshift. When lensing corrections are taken into account, the high-redshift sources have CO luminosities similar to those of the most luminous low-redshift ULIGs. These consistencies could suggest roughly similar gas masses in the progenitor systems or may indicate the importance of self-regulating mechanisms such as galactic winds (Heckman, Armus, & Miley 1990). For comparison, theoretical evolutionary curves are also presented in Figure 3. We show three models based on numerical calculations of chemical evolution (Frayer & Brown 1997). The models are designed to represent a spiral galaxy, an elliptical galaxy, and a merger event. All three models start as purely gaseous systems with zero metallicity. The spiral galaxy model uses an infall model (run 11 of Frayer & Brown 1997) which starts at $z = 5$ and reaches a final mass similar to that of the current Milky Way disk ($6 \times 10^{10}\ M_\odot$). The CO luminosity of a disk with the mass of the Milky Way is never expected to reach the high CO luminosities ($\gtrsim 10^{10}$ K km s^{-1} pc^2) observed in the high-redshift systems. For the elliptical galaxy model, we assume a closed-box model (run 8 of Frayer & Brown 1997) with a mass of $2 \times 10^{11}\ M_\odot$ which begins its evolution at $z = 5$. Although galactic systems are not expected to evolve in such a simple manner, the closed-box model is

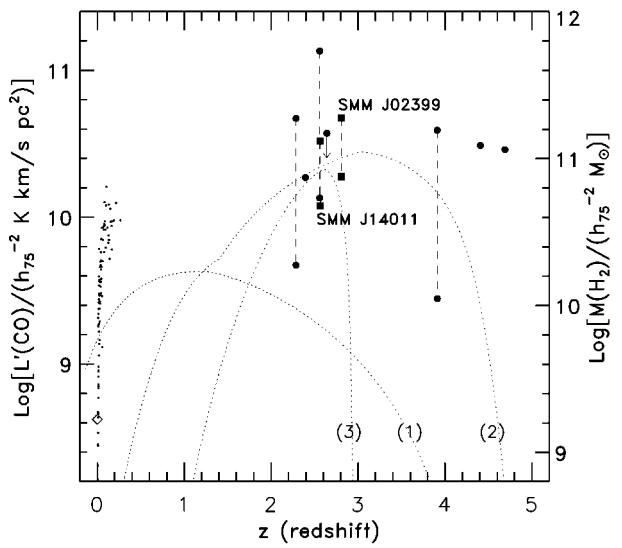

FIG. 3.—The L'(CO) luminosity as a function of redshift. The molecular mass scale (at right) assumes $\alpha = 4\ M_\odot$ (K km s^{-1} $\mathrm{pc}^2)^{-1}$. Besides SMM J14011 and SMM J02399 (*boxes*), the other high-redshift CO sources (*large dots*) are IRAS F10214+4724 at $z = 2.3$ (Brown & Vanden Bout 1991; Solomon et al. 1992), 53W002 at $z = 2.4$ (Scoville et al. 1997b), the $z = 2.6$ Cloverleaf quasar H1413+117 (Barvainis et al. 1994), MG 0414+0534 at $z = 2.6$, which has an unknown lensing magnification factor signified by the downward arrow (Barvainis et al. 1998), APM 08279+5255 at $z = 3.9$ (Downes et al. 1999), BRI 1335−0417 at $z = 4.4$ (Guilloteau et al. 1997), and BR 1202−0725 at $z = 4.7$ (Ohta et al. 1996; Omont et al. 1996). For known lensed sources, the observed and intrinsic values are connected by a dashed line. In addition, we plot (*small dots*) the low-redshift luminous *IRAS* sources from Sanders et al. (1991) and additional ultraluminous *IRAS* sources from Solomon et al. (1997). The Milky Way is shown as a diamond (Solomon & Rivolo 1989). Theoretical evolutionary curves are shown as dotted lines (see text): (1) galactic disk model, (2) closed-box elliptical galaxy model, and (3) starburst merger model.

able to match the high CO luminosities detected at high redshift and the low CO luminosities ($\lesssim 10^7$ K km s^{-1} pc^2) observed for local elliptical galaxies (Wiklind, Combes, & Henkel 1995). The third model in Figure 3 is a more realistic model for SMM J14011 and SMM J02399. It assumes a starburst resulting from the merger of two $2 \times 10^{11}\ M_\odot$ gaseous systems at $z = 3$. This starburst model uses the parameters of run 8 in Frayer & Brown (1997), except for a factor of 10 increase in the star formation efficiency, and assumes a formation timescale of $\tau_f = 3 \times 10^8$ yr for the merger (Mihos & Hernquist 1996). These theoretical calculations only show the approximate evolution expected for different types of galactic systems and depend strongly on the parameters governing star formation, the initial mass function, infall, and cosmology.

An important unanswered question is what SMM J14011 will evolve into at the present epoch. By using the observed near-infrared K-band flux density (Ivison et al. 1999) and assuming the burst model from Bruzual & Charlot (1993), SMM J14011 has already formed of order $10^{10}\ M_\odot$ of stars. There is enough molecular gas present to form an additional L^* galaxy (adopting $5 \times 10^{10}\ M_\odot$ per L^*), suggesting that SMM J14011 will evolve into a ~ 1–$2\ h_{75}^{-2}\ L^*$ galaxy. Given that the low-redshift ULIGs may eventually evolve into elliptical galaxies (Kormendy & Sanders 1992; Mihos & Hernquist 1996), the high-redshift submillimeter population could represent luminous elliptical galaxies in their formative phases (Smail et al. 1997; Eales et al. 1999). The consistency of this hypothesis can be checked by comparing the number density of the submillimeter

population represented by SMM J14011 and SMM J02399 with that of luminous elliptical galaxies at low redshift. Within an effective source plane area of 25 arcmin^2, Smail et al. (1998b) have detected nine distant, noncluster, submillimeter sources above the 4 σ noise level. SMM J14011 and SMM J02399 represent about 20% of this sample. The corresponding number density of such sources per unit comoving volume within the redshift range of $z = 1$–5 is approximately $10^{-4}\ h_{75}^3$ Mpc^{-3}. The number density of luminous elliptical galaxies found at low redshift is roughly similar (Loveday et al. 1992). Although no definitive conclusions can be made due to the small sample size, the current data are at least consistent with the submillimeter population evolving into the luminous elliptical galaxies at the present epoch.

5. CONCLUSIONS

We report the detection of CO in a second ultraluminous galaxy, SMM J14011, selected from a submillimeter survey of the distant universe (Smail et al. 1998b). The CO emission is coincident in position and redshift with the optical counterpart of SMM J14011 and indicates the presence of approximately $5 \times 10^{10}\ h_{75}^{-2}\ M_\odot$ of molecular gas. Both SMM J14011 and the first high-redshift submillimeter galaxy, SMM J02399, show CO emission and are thought to be associated with a major burst of star formation. The massive molecular gas reservoirs of SMM J14011 and SMM J02399 and their comoving number densities are consistent with these sources evolving into present-day luminous elliptical galaxies. Further observations are needed to constrain the redshift distribution and the molecular gas masses of submillimeter population in order to test the generality of these early results.

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