CO (4–3) AND DUST EMISSION IN TWO POWERFUL HIGH-z RADIO GALAXIES, AND CO LINES AT HIGH REDSHIFTS

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ABSTRACT

We report the detection of submillimeter emission from dust at 850 μm and of the 12CO J = 4–3 line in the two distant powerful radio galaxies 4C 60.07 (z = 3.79) and 6C 1909 + 722 (z = 3.53). In 4C 60.07, the dust emission is also detected at 1.25 mm. The estimated molecular gas masses are large, of the order of ~ (0.5–1) x 10^11 M⊙. The large far-infrared (FIR) luminosities (L_{FIR} ~ 10^{13} L⊙) suggest that we are witnessing two major starburst phenomena, while the observed large velocity widths (ΔV_{FWHM} ~ 500 km s^{-1}) are characteristic of mergers. In the case of 4C 60.07, the CO emission extends over ~30 kpc and spans a velocity range of ~1000 km s^{-1}. It consists of two distinct features with FWHM ~ 550 km s^{-1} and ~150 km s^{-1}, and line centers separated by ~700 km s^{-1}. The least massive of these components is probably very gas rich, with potentially ~60% of its dynamical mass in the form of molecular gas. The extraordinary morphology of the CO emission in this object suggests that it is not just a scaled-up version of a local ultraluminous infrared galaxy, and it may be a formative stage of the elliptical host of the residing radio-loud active galactic nucleus (AGN). Finally, we briefly explore the effects of the wide range of gas-excitation conditions expected for starburst environments on the luminosity of high-J CO lines and conclude that in unlensed objects, CO (J + 1 → J), J + 1 > 3 lines can be significantly weak with respect to CO J = 1–0, and this can hinder their detection even in the presence of substantial molecular gas masses.

Subject headings: galaxies: active — galaxies: formation — galaxies: individual (4C 60.07, 6C 1909 + 722) — galaxies: ISM

1. INTRODUCTION

The successful detection of CO emission in many local (z ≤ 0.3) IRAS galaxies revealed large reservoirs of molecular gas mass that fuel nuclear starbursts and active nuclei (e.g., Tinney et al. 1988; Sanders, Scoville, & Soifer 1991; Solomon 1997). In the most IR-luminous galaxies (L_{FIR} ~ 10^{11} M⊙), gas-rich mergers and interactions are thought to play a crucial role in causing the rapid accumulation of molecular gas in the center and thus initiating the onset of spectacular starbursts. Subsequent high-resolution imaging of the CO emission in ultraluminous IR galaxies (hereafter ULIRGs; e.g., Scoville, Yun, & Bryant 1997; Downes & Solomon 1998) confirmed this picture by demonstrating the presence of molecular gas with high mass surface densities [Σ(H_2) ~ 5 x 10^4 M⊙ pc^{-2}] and large velocity widths (~500 km s^{-1}) confined within a few hundred pc in the nuclear regions.

In addition to being responsible for some of the most spectacular starbursts in the local universe, the merging process is thought to play an important role in galaxy formation at high redshift, especially for spheroidal systems. The favorite formation model for these systems is that they grow from the hierarchical clustering of gas-rich "fragments," in which the oldest stars (>10 Gyr) have already formed (e.g., Baron & White 1987; White 1996). The subsequent intense star formation rapidly consumes the gas mass and finally gives rise to a present-day giant elliptical galaxy with its red colors, evolved stellar population, and large mass, but devoid of substantial amounts of gas and dust. Powerful high-z radio galaxies (hereafter HzRGs) may be the progenitors of the massive present-day ellipticals hosting radio-loud active galactic nuclei (AGNs). Since such galaxies seem to have already settled into ellipticals (Best, Longair, & Röttgering 1997, 1998a, 1999) by z ~ 1, it is natural to assume that HzRGs at z > 2, with their frequently irregular morphologies (e.g., Pentericci et al. 1999), are where merger-induced large-scale starbursts may have occurred.

The first detection of CO in IRAS 10214 + 4724 at z = 2.286 (Brown & Vanden Bout 1991, 1992) and the subsequent detection of its millimeter/submillimeter continuum from dust (see Downes et al. 1992 and references therein) initiated ongoing efforts to detect CO and millimeter/submillimeter emission from the copious amounts of gas and dust expected in the high-z counterparts of ULIRGs and in galaxies undergoing their formative starbursts. The large negative K-corrections expected for the thermal dust spectrum and the high-J CO lines (e.g., Hughes 1996; van der Werf & Israel 1996) of high-z galaxies, as well as gravitational lensing, help to make such objects detectable to the current millimeter/submillimeter instruments. Lensing amplifies the expected emission but usually complicates the gas and dust mass estimates. The galaxy IRAS 10214 + 4724 and many high-z CO/submillimeter luminous objects, such as the QSO H1413 + 117 (Barvainis, Tacconi, & Antonucci 1994), the recent submillimeter-selected galaxies (Frayer et al. 1998, 1999a), and the BAL quasar APM 08279 + 5255 (Downes et al. 1999), are lensed.
Recently, there have been detections of large amounts of dust in HzRGs (e.g., Hughes 1996; Röttgering et al. 1998; Hughes & Dunlop 1999; Best et al. 1998b), and a systematic survey is now being conducted to detect submillimeter emission from dust for all $z > 3$ radio galaxies (H. J. A. Röttgering et al., in preparation) in order to understand the large range of far-infrared (FIR) luminosities of these objects. The most notable examples are the extremely FIR-luminous radio galaxies 8C 1435 + 635 (Ivison et al. 1998) and 4C 41.17 (Dunlop et al. 1994; Chini & Krügel 1994) whose properties do not appear to be influenced by gravitational lensing. In both cases, the inferred gas masses are large enough ($\sim 10^{11} M_\odot$) to suggest that the large FIR luminosities of these objects ($\sim 10^{13} L_\odot$) are due to the formative starbursts. However, despite systematic efforts (Evans et al. 1996; van Ojik et al. 1997), no CO emission has been detected from these two objects or any other powerful HzRGs. In this paper we present the detection of dust continuum and CO $J = 4 - 3$ line emission in two powerful high-$z$ radio galaxies and discuss the latter in the context of earlier unsuccessful attempts to detect CO in this class of objects. Throughout this work we assume $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$.

2. OBSERVATIONS AND DATA REDUCTION

2.1. The SCUBA Observations

We used the Submillimeter Common User Bolometer Array (SCUBA) at the 15 m James Clerk Maxwell Telescope (JCMT) in the photometry mode to observe 4C 60.07 on 1998 April 15 and 6C 1909 + 722 on 1997 October 4 and 5 as part of an ongoing program to observe all HzRGs at $z > 3$ (H. J. A. Röttgering et al., in preparation). SCUBA is a dual camera system cooled to $\sim 0.1$ K, allowing sensitive observations with two arrays simultaneously. The short-wavelength array at 450 $\mu$m contains 91 pixels, and the long-wavelength array at 850 $\mu$m contains 37 pixels. The resolution is diffraction-limited, with HPBW $\sim 15''$ (850 $\mu$m), and $\sim 8''$ (450 $\mu$m), respectively. For a full description of the instrument see Holland et al. (1999).

We employed the recommended rapid beam switching at a frequency of 8 Hz and a beam throw of 60$''$ in azimuth. The pointing and focus of the telescope were monitored frequently using CRL 618 and QSO 0836 + 710, and the typical rms pointing error was $\sim 3''$. Frequent skydips were used to deduce the atmospheric extinction. Typical opacities at 850 $\mu$m were $\tau \sim 0.13$ for our 1998 run and $\tau \sim 0.20$ for our 1997 run. Beam maps of Mars, CRL 618, and Uranus were used to derive the gain $C_{850} \sim 280$ mJy beam$^{-1}$ mV$^{-1}$. The data were flat-fielded, corrected for extinction, and sky noise was removed before they were coadded following standard procedures outlined in the SCUBA Photometry Cookbook. The estimated rms of our measurements is consistent with what is expected from the total integration times and the NEFDs at the sky conditions of our runs. The systematic uncertainty in the flux density scale at 850 $\mu$m is of the order of $\sim 10\%$ (W. S. Holland 1998, private communication).

2.2. The IRAM Interferometric Observations

We used the IRAM Plateau de Bure Interferometer (PdBI) between 1998 April 20 and May 15 in the D configuration to observe CO $J = 4 - 3$ ($v_{\text{rest}} = 461.040$ GHz) in 6C 1909 + 722 at $z = 3.534$ in four tracks ranging from 4 to 14 hr each. The same configuration was also used on 1998 November 8 and 29 to obtain two 8 hr tracks for 4C 60.07 at $z = 3.788$ (Chambers et al. 1996). The correlator setup used for the 3 mm receivers involved $4 \times 160$ MHz modules covering a total bandwidth of 560 MHz tuned in single sideband (SSB). The band center was positioned at 96.290 GHz for 4C 60.07 and 101.770 GHz for 6C 1909 + 722. The 1 mm receivers were used in double-sideband (DSB) mode, with the two remaining correlator modules as back ends to simultaneously observe the continuum at 240 GHz. Typical SSB system temperatures were $\sim 120$ K (96.290 GHz) and $\sim 150$ K (101.770 GHz), and at 240 GHz they were 400–700 K (DSB). Bandpass calibration was obtained using 3C 454.3, and amplitude and phase calibrations were obtained using IAP 0444 + 634 and NRAO 150. For the 3 mm receivers, the residual phase noise was $\lesssim 20\%$, and for the amplitude $\lesssim 5\%$. For the 1 mm receivers, these figures are $\lesssim 30\%$ and $\lesssim 20\%$. The flux density scale is accurate to within $\sim 10\%$.

After calibration and editing, the data were processed with the standard NRAO AIPS software package. At 3 mm no continuum emission was detected in the line-free channels, and no continuum subtraction was performed. The maps were produced using the task MX, and in cases of low S/N, CLEAN was not applied. The rms noise of the maps is consistent with the thermal noise expected for the total observing time and average $T_{\text{sys}}$ in the runs.

3. RESULTS

Both radio galaxies are detected in 850 $\mu$m and CO $J = 4 - 3$ and are the brightest submillimeter objects found in the ongoing SCUBA survey of HzRGs at $z > 3$ so far, this being the main reason for selecting them for the follow-up sensitive CO observations. In 4C 60.07, the CO($4 - 3$) emission is clearly resolved (Fig. 1).

A remarkable characteristic of the CO emission in this galaxy is its large velocity range ($\gtrsim 1000$ km s$^{-1}$) and its two distinct components, with line centers separated by $\sim 700$ km s$^{-1}$. One component has $\Delta v_{\text{FWHM}} \gtrsim 550$ km s$^{-1}$ (extending beyond the observed band), while the other is narrower, with $\Delta v_{\text{FWHM}} \sim 150$ km s$^{-1}$. The feature with the narrow line width coincides with the position of the suspect- ed radio core, and thus the AGN, but a significant part of the broad line width component is clearly offset from it. This aspect of the CO $J = 4 - 3$ emission is reminiscent of the CO $J = 5 - 4$ emission detected in the radio-quiet quasar BR 1202 – 0725 at $z = 4.69$ (Omont et al. 1996), where a broad and a narrow line width component are also detected. In that object, the narrow line width component is centered on the AGN position, while the broad one is offset by $\sim 4''$.

The velocity-integrated map in Figure 2 shows extended CO emission with two peaks that are $\sim 7''$ apart ($\sim 30$ kpc at $z = 3.791$). Toward the same region, 1.25 mm emission
Fig. 1.—Naturally weighted channel maps of CO $J = 4-3$ for 4C 60.07 at a spatial resolution of $8''9 \times 5''5$ and frequency resolution of 35 MHz ($\sim 110$ km s$^{-1}$). The contours are $-3$, $-2$, $2$, $3$, $4$, $5$, and $6 \sigma$, with $\sigma = 0.55$ mJy beam$^{-1}$. The FWHM of the restoring beam is shown at the bottom left of the first channel. The cross marks the position of the radio core, R.A. (J2000): $05^h12^m55^s147$, decl. (J2000): $+60^\circ30'51''0$ (C. De Breuck 1999, private communication).
from dust is also detected, as shown in Figure 3. Both the CO and 1.25 mm continuum maps are overlaid on a map of the nonthermal radio emission at 6 cm (Carilli et al. 1997).

The radio galaxy 4C 60.07 is a powerful radio galaxy (\(P_{4\,\text{cm}} \sim 1.6 \times 10^{27}\) W Hz\(^{-1}\)) with a Fanaroff-Riley II (FR II) edge-brightened double-lobe morphology (Fanaroff & Riley 1974); hence, there is the possibility that the nonthermal emission makes a significant contribution to the observed 1.25 mm and 850 \(\mu\)m continuum. Extrapolating the nonthermal flux density of \(S_{6\,\text{cm}} = 19\) mJy of its brightest component with its associated spectral index\(^9\) of \(\alpha_{0\,\text{cm}} = -1.4\) (C. De Breuck 1999, private communication) yields a negligible contribution (\(<1\%\)) in both the 1.25 mm and 850 \(\mu\)m bands. Further confirmation of the thermal origin of the 1.25 mm continuum is offered by the high-resolution map in Figure 3, which shows that most of this emission is not associated with the observed nonthermal radio continuum, and the peak 1.25 mm brightness is \(~4''\) (17.6 kpc) offset from the radio core where the AGN probably resides (C. De Breuck 1999, private communication).

Deep \(K'\)-band images obtained with Keck (van Breugel et al. 1998) reveal faint emission toward the weak eastern radio component, but none from the regions with the brightest 1.25 mm continuum. Since at \(z \sim 3.8\) the \(K'\)-band is rest-frame \(B\)-band, this is consistent with the brightest 1.25 mm emission marking the place of a massive gas/dust reservoir with large amounts of extinction.

In order to obtain the highest S/N maps for the two distinct CO \(J = 4-3\) features, we averaged all the appropriate channels, and the two resulting maps are shown in Figure 4, overlaid with the 1.25 mm continuum. From these maps it becomes obvious that the component with the largest dynamical and molecular gas mass is closely associated with the peak of the dust emission, as expected.

In the case of the radio galaxy 6C 1909+722, a map of the averaged CO \(J = 4-3\) emission and its spectrum are shown in Figure 5. There it can be seen that its line width is also rather large. Extrapolation of the nonthermal flux, \(S_{6\,\text{cm}} = 59\) mJy, with the observed power law, \(\alpha_{0\,\text{cm}} = -1.3\) (C. De Breuck 1999, private communication) yields a nonthermal contribution of \(<2\%\) at 850 \(\mu\)m. All the observed parameters for the two HzRGs are given in Table 1.

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\(^9\) Spectral index is defined as \(S \propto v^\alpha\).
Fig. 3.—Naturally weighted map of the 1.25 mm continuum emission of 4C 60.07 (contours) overlaid on 6 cm continuum emission (gray scale) at a common resolution of 3.7 × 1.9. The contours are at −3, −2, 2, 3, and 5σ, with σ = 0.6 mJy beam⁻¹, and the gray-scale range is 0.6–12 mJy beam⁻¹. The FWHM of the restoring beam is shown at the bottom left. The cross marks the position of the radio core (see Fig. 1).

4. DISCUSSION

The two galaxies have extended radio emission and are unlikely candidates for gravitationally lensed objects. In the case of 4C 60.07, high-resolution radio images show a classical FR II source. Sensitive 6 cm (Carilli et al. 1997), K-band (Chambers et al. 1996), and deep K’-band images (van Breugel et al. 1998) do not reveal any obviously lensed features. For 6C 1909 + 722, Hubble Space Telescope (HST) images at 7000 Å do not reveal any lensed features either (L. Pentericci 1999, private communication). Henceforth, we assume that the two sources are unlensed, and we organize the discussion as follows:

1. We estimate the molecular gas mass implied by the CO $J = 4–3$ luminosity, assuming global gas excitation conditions similar to the ones found in local starburst galaxies.

2. We briefly explore the influence of various galactic environments on the molecular gas excitation conditions over large scales. Special emphasis is given to the effects of the various environments on the high-$J$ CO lines and their detectability at high redshift.

3. We use the millimeter/submillimeter data to find the dust masses and FIR luminosities and estimate the $M(\text{H}_2)/M_{\text{dust}}$ ratios, which we then compare to the values in the local universe.

4. We discuss the evolutionary status of these objects in terms of their gas mass relative to their dynamic mass, and their star formation rates and efficiencies. We focus particularly on 4C 60.07, where the two distinct molecular gas

| TABLE 1 | OBSERVATIONAL PARAMETERS |
|----------------|-------------------------|
| Parameter       | 4C 60.07  | 6C 1909 + 722 |
| R.A. (J2000)*   | 05h12m54s/0 | 19h08m23.0 |
| Decl. (J2000)*  | +60°30'51"/7 | +72°20'11.8 |
| $z_{\text{gal}}$ | 3.791      | 3.532       |
| $I_{\text{CO}}$ (Jy km s⁻¹) | 2.50 ± 0.43 | 1.62 ± 0.30 |
| $\Delta V_{\text{FWHM}}$ (km s⁻¹) | ≥1000         | 530 ± 70    |
| $S_{1.25\text{mm}}$ (mJy) | 4.5 ± 1.2  | ≤2 (2σ)     |
| $S_{3\text{mm}}$ (mJy) | ≤0.5 (2σ)   | ≤0.6 (2σ)   |
| $S_{350\text{um}}$ (mJy) | 11.0 ± 1.5 | 13.5 ± 2.8 |

* Coordinates of the image center.
components strongly suggest a large-scale starburst event, unlike the usually nuclear starbursts observed in local ULIRGs.

4.1. Molecular Gas Content

The estimation of molecular gas mass from the CO $J = 1-0$ luminosity involves the so-called standard conversion factor, $X_{\text{CO}}$ (e.g., Young & Scoville 1982, 1991; Bloemen 1985; Dickman, Snell, & Schoenber 1986), which is “calibrated” using molecular clouds in the Milky Way.

Fig. 4.—Naturally weighted CO $J = 4-3$ maps of the two kinematic components of 4C 60.07 (contours) overlaid on its 1.25 mm continuum (gray scale), at a common resolution of $8.9 \times 5.5$. The velocity offset is denoted at the upper right, and the FWHM of the line at the bottom right. The contours are at $-3, -2, 2, 3, 4, 5, 6$, and $7\sigma$, with $\sigma = 0.3$ mJy beam$^{-1}$ (top) and $\sigma = 0.4$ mJy beam$^{-1}$ (bottom), and the gray-scale range is $1.3$–$5.85$ mJy beam$^{-1}$. The FWHM of the CLEAN beam is shown at the bottom left. The cross marks the position of the radio core (see Fig. 1).

Fig. 5.—CO $J = 4-3$ spectrum of 6C 1909+722 (top) with $\Delta f_{\text{chan}} = 50$ MHz ($\sim 145$ km s$^{-1}$), and naturally weighted maps of the CO $J = 4-3$ emission centered at $f = 101.725$ GHz (middle) and $f = 101.975$ GHz (bottom). The averaged frequency interval in both maps is $\Delta f = 200$ MHz ($\sim 590$ km s$^{-1}$), and the contours are at $-3, -2, 2, 3, 4, 5, 6, 7, 8$, and $9\sigma$, with $\sigma = 0.3$ mJy beam$^{-1}$. The cross marks the map center (see Table 1), which is within $0.5$ of the position of the radio core (C. De Breuck 1999, private communication). The beam size is $7.65 \times 7.11$, and its FWHM is shown in the bottom map.
From the CO(4–3) luminosity, $M(H_2)$ is then given by

$$M(H_2) = \left( \frac{X_{\text{CO}}}{r_{43}} \right) \frac{c^2}{2kT_{\text{dust}}} \frac{D_L}{1+z} \int S_{\nu_{21}} dv,$$

where $D_L = 2cH_0^{-1}(1+z - (1+z)^{1/2})$ is the luminosity distance for $q_0 = 0.5$, $\nu_{43}$ is the rest-frame frequency of the CO $J = 4-3$ transition, $r_{43}$ is the $(4-3)/(1-0)$ line ratio of the area/velocity-integrated brightness temperatures, and $S_{\nu_{21}}$ is the observed flux density. Substituting astrophysical units yields

$$M(H_2) = 9.77 \times 10^9 \left( \frac{X_{\text{CO}}}{r_{43}} \right) \left( 1 + \frac{1 - \sqrt{1+z}}{z} \right) \frac{\int S_{\nu_{21}} dv}{1+z} (\text{km s}^{-1} \text{pc}^{-1}) \ M_\odot .$$

(2)

The dependence of $X_{\text{CO}}$ on the ambient conditions of the H$_2$ gas has been extensively explored (e.g., Bryant & Scoville 1996; Sakamoto 1996). An important recent result is that in the intense starburst environments of ULIRGs, the warm, diffuse gas phase dominating the $^{12}$CO emission does not consist of virialized clouds, hence leading to an overestimate of $M(H_2)$ when the standard $X_{\text{CO}} \sim 5 \ M_\odot$ (km s$^{-1}$ pc$^2$)$^{-1}$ is used (Solomon et al. 1997; Downes & Solomon 1998). A more appropriate value for such interstellar medium (ISM) environments and hence their high-z counterparts is $X_{\text{CO}} \sim 1 \ M_\odot$ (km s$^{-1}$ pc$^2$)$^{-1}$ (Downes & Solomon 1998).

A plausible value for $r_{43}$ can be found by assuming an ISM environment similar to that of a local “average” starburst. The average line ratios measured toward such objects are $r_{23} \approx 0.9$ (e.g., Braine & Combes 1992; Aalto et al. 1995) and $r_{32} \approx 0.64$ (Devereux et al. 1994), while the $^{12}$CO/$^{13}$CO $J = 1-0, 2-1$ ratios are $R_{10} \approx R_{21} \approx 13$ (Aalto et al. 1995). A large velocity gradient (LVG) code with the aforementioned ratios as inputs was employed to model the physical conditions of the gas (e.g., Richardson 1985). The conditions corresponding to the best fit are $T_{\text{kin}} = 50$ K, $n(H_2) \approx 10^3$ cm$^{-3}$, and $[\text{CO}/H_2](dv/dr) = 5 \times 10^{-5}$ (km s$^{-1}$ pc$^{-1}$)$^{-1}$ similar to the ones deduced for the high-z starburst IRAS 10214$+4724$ (Solomon, Downes, & Radford 1992). For these conditions, it is $r_{43} = 0.40$, which for $T_{\text{CMB}} = (1+z)(2.75)$ K $\approx 13$ K is slightly enhanced to $r_{43} = 0.45$. This ratio and $X_{\text{CO}} \sim 1 \ M_\odot$ (km s$^{-1}$ pc$^2$)$^{-1}$ yield $M(H_2) \approx 8 \times 10^{10}$ $M_\odot$ for 4C 60.07 and $M(H_2) \approx 4.5 \times 10^{10}$ $M_\odot$ for 6C 1909$+722$. These are most likely lower limits, since even in ULIRGs the ratio $r_{43}$ can be significantly smaller but not much larger. Indeed, the assumption of an “average” starburst excitation environment, while convenient, hides the fact that there is a wide range of physical conditions for the gas in IR-luminous galaxies, and in much of that range $\text{CO}(J + 1 \rightarrow J)$, $J + 1 > 3$ can be significantly weaker than $\text{CO}(1-0)$.

As we shall see, the potential faintness of the high-J CO transitions may partly explain why attempts to detect high-z CO have been less successful than attempts to detect millimeter/submillimeter continuum from dust. Especially for HzRGs, two large systematic searches (Evans et al. 1996; van Ojik et al. 1997) gave null results. On the other hand, observations of the submillimeter continuum come far better with such objects detected at 850 $\mu$m (see van der Werf 1999 and references therein). A similar situation also applies in other types of high-z objects. While the uncertainties of the gas-to-dust ratio and a rising $L_{\text{IR}}/L_{\text{CO}}$ ratio with FIR luminosity (van der Werf 1999) can still adequately account for this, the wide range of gas excitation observed in IR-luminous galaxies cannot but have an effect on the luminosity of CO lines, especially at high J-levels.

4.2. The High-J CO Transitions in ULIRGs at High z

In the attempts to detect CO in high-z objects, various transitions are observed, depending on the particular redshift and the receiver used. For $z \geq 2$, mostly CO($J + 1 \rightarrow J$) with $J + 1 \geq 3$ is observed, and in the systematic searches in HzRGs, transitions with $J + 1 = 4-9$ were routinely observed (Evans et al. 1996; van Ojik et al. 1997). It has been argued that observing higher J transitions can offset the dimming due to the distance in high-z objects in a manner similar to the negative K-corrections of the thermal spectrum from dust (van der Werf & Israel 1996). In this picture, the warm and dense gas in an “average” starburst environment thermalizes the CO transitions up to $J + 1 = 6$. However, the luminosity of the high-J CO transitions may be much smaller for two basic reasons, namely:

1. The presence of a warm ($T_{\text{kin}} = 50–100$ K) but diffuse [$n(H_2) \sim 10^2–10^3$ cm$^{-3}$] and subthermally excited (for $J + 1 > 2$) gas phase that dominates the $^{12}$CO emission (Aalto et al. 1995; Downes & Solomon 1998). The most conspicuous such galaxy is Arp 220, frequently used as the standard ULIRG for comparison with high-z FIR-luminous sources. In this source, a low $r_{21} = 0.53$ and high $R_{10} > 20$, $R_{21} = 18$ ratios are observed (Aalto et al. 1995; Papadopoulos & Seaquist 1998), in contrast to the “average” starburst ratios mentioned previously. Another important characteristic of this gas phase is the moderate optical depths ($\tau \sim 1–2$) of the $^{12}$CO (1–0) transition (Aalto et al. 1995).

2. A large reservoir of cold and/or subthermally excited gas extending beyond the warm starbursting nuclear region of an ULIRG. Such excitation gradients are observed when large beams that sample the extended emission are used (Papadopoulos & Seaquist 1998). The associated cool dust in the ULIRG VV 114 was imaged recently with SCUBA (Frayer et al. 1999b), and extremely cold gas ($T_{\text{kin}} = 7–10$ K) is inferred over large scales for starbursts such as IC 5135 and NGC 7469 (Papadopoulos & Seaquist 1998). This gas phase, if present, can easily dominate the global CO excitation, especially in high-z systems, where a beam of $\geq 5''$ at $z \geq 2$ corresponds to $L \geq 30$ kpc.

Here we must stress that the effectiveness of a cold gas component in suppressing the observed global gas excitation is not altered by the higher cosmic microwave background (CMB) temperature at high $z$. Indeed, while the higher CMB temperature enhances the populations of the high J-levels of CO, it also corresponds to a higher background against which the respective lines must be detected. Moreover, the effective temperature of cold gas at high $z$ is not simply the sum of the temperature of this gas phase at $z = 0$ and $(1+z)(2.75)$ K, as one might naively assume. This can be demonstrated with some simple arguments. Obviously, the excitation temperature, $T_{\text{exc}}$, of any collisionally excited line at any redshift is bounded as

$$T_{\text{exc}} \leq \min\{T_{\text{kin}}, T_{\text{CMB}}\} \leq T_{\text{kin}},$$

where $T_{\text{CMB}} = 2.75$ K is the present-epoch CMB temperature, and $T_{\text{kin}}$ is the gas kinetic temperature. If we
further assume that on large scales in the ISM of a galaxy thermodynamic equilibrium exists between gas and dust, i.e., $T_{\text{dust}} = T_{\text{kin}}$, then for a dust emissivity of $\alpha = 2$, the energy balance within a typical giant molecular cloud is described by

$$U_{\text{ISRF}} + U_{\text{mech}} = \text{cooling rate} \propto \left[ T_{\text{dust}}(z)^6 - 2.75^6(1 + z)^6 \right], \quad (4)$$

where $U_{\text{ISRF}}$ is the energy density of the interstellar radiation field (O, B, and A stars) that heats the grains directly, and $U_{\text{mech}}$ is the “mechanical” heating energy density deposited in the molecular clouds (e.g., supernovae shocks, turbulent cascade, cloud-cloud collisions) that first heats the gas and then the dust. These are the two major heating mechanisms of an average molecular cloud, and since (1) more cooling processes are at play than just dust radiation (e.g., $C^+$, $C^-$, CO lines), (2) usually $T_{\text{kin}} \leq T_{\text{dust}}$ (except on the surfaces of UV-illuminated clouds; Hollenbach & Tielens 1997), it follows that the dust temperature yielded by the last equation will be an upper limit to the gas temperature.

The aforementioned physical processes responsible for heating the ISM do not depend on the particular value of the CMB temperature at a given $z$. Thus, the last equation, being redshift-invariant, allows us to find the high-$z$ equivalent temperature of any given ISM component from its temperature in the local universe (see also Combes, Maoli, & Omont 1999). It is easy to see that at high $z$, the low-temperature component of the local ISM has $T_{\text{dust}} \rightarrow (1 + z)T_{\text{CMB}}$ which also means (eq. [3]) that lines become thermalized at the expense of becoming invisible against the enhanced CMB radiation field.

Choosing a nominal redshift of $z = 3.5$ as representative of the redshifts of the two HzRGs, we find that for a warm ISM component of $T_{\text{dust}}(z = 0) = 50$ K, the $T_{\text{dust}}(z = 3.5)$ is essentially identical. However, for a cold component of $T_{\text{dust}} = 10$ K it is $T_{\text{dust}}(z = 3.5) = 12.892$ K, i.e., just $\sim 0.5$ K above the $(1 + z)(2.75 \text{ K}) = 12.375$ K temperature of the CMB at that redshift. In Table 2 we display the expected line ratios at $z = 3.5$ for three sets of conditions, namely, (1) an “average” starburst, (2) diffuse and warm gas of moderate $^{12}$CO $J = 1-0$ optical depth, and (3) cold gas, representative of the phase that may exist in ULIRGs beyond the central starburst region.

This table shows that a wide range is expected for CO$(J + 1 \rightarrow J)$, $J > 2$ line luminosities relative to CO $J = 1-0$. Several published $r_{12} = (3-2)/(1-0)$ line ratios (Lisenfeld et al. 1996) that sample the global CO emission in ULIRGs and a recent survey of this ratio in many nearby galaxies (Mauersberger et al. 1999) reveal a large range of values, namely $r_{12} \sim 0.1-1$; thus, a similar or larger range is to be expected for the higher $J$ transitions. Moreover, since the flux density ratio $S(J + 1 - J)/S(1-0) = (J + 1)^2 r_{J+1,J}$ determines whether a high-$J$ transition is easier to detect than $J = 1-0$ (assuming equal sensitivities), it can be seen (Table 2) that CO $J = 3-2$ is the highest transition for which this ratio is $\geq 1$ for all the expected conditions. Hence, many nondetections of CO$(J + 1 \rightarrow J)$, $J > 2$ in high-$z$ systems may be due to the globally subthermal excitation of these lines rather than a true molecular gas mass deficiency. At the same time, this makes the upper limits for $M(H_2)$ from such nondetections much less stringent. For example, if the CO $J = 5-4$ line was observed, and for $X_{\text{CO}} = 1 \ M_\odot$ (km s$^{-1}$ pc$^{-2}$)$^{-1}$, the upper limit in $M(H_2)$ can be $\sim 1(0.025)(1/5) = 8$ times larger than what is usually reported for this line (e.g., van Ojik 1997).

Finally, for strongly gravitationally lensed objects with underlying steep gas excitation gradients, differential amplification can render line ratios useless in deducing the average gas excitation unless an accurate description of the lensing potential is available. Such gradients are expected in nuclear starbursts, where gas warm and dense enough to excite high-$J$ CO lines is more centrally confined in the immediate area of the starburst. Recent mapping of CO $J = 4-3$ in M51 and NGC 6946 (Nieten et al. 1999) show that even in more quiescent galaxies, the highly excited gas is strongly concentrated in the center. Under such circumstances, differential amplification can enlarge the effective size of the high-$J$ CO-emitting region with respect to the low-$J$ one and thus alter the observed $g_{\text{lobal}}$ line ratios toward the ones expected for warm and dense gas. The frustrating aspect of this effect is that it can become progressively severe for lines that are widely separated in $J$, i.e., exactly the ones whose ratios are most sensitive to the gas excitation conditions under normal circumstances.

Clearly, more observations of high-$J$ CO lines in local ULIRGs are needed in order to reveal the range of their $g_{\text{lobal}}$ luminosities and relative brightness distributions and thus engender a better understanding of similar systems at high $z$.

4.3. Dust Mass, Gas-to-Dust Ratio, and $L_{FIR}$

There are many uncertainties associated with the estimate of the dust mass from millimeter/submillimeter measurements (e.g., Gordon 1995), of which the uncertainty of the dust temperature is one of the most important (Hughes 1996). In the case of 4C 60.07, the detection of the dust continuum at both 1.25 mm and 850 $\mu$m allows us to place some broad constraints on the dust temperature, as long as the emissivity law is $\alpha > 1$. Indeed, for an optically thin isothermal reservoir of dust mass, it is

$$R(\alpha, T_d) = \frac{S_{850 \mu m}}{S_{1.25 \mu m}} = 1.47^2 \left( \frac{\epsilon^{0.75}}{\epsilon^{1}} \right)^{-1} \left( \frac{e^{657/14} - 1}{e^{657/14} - 1} \right) - 0.0162 , \quad (5)$$

where $T_d$ is the dust temperature, and $\alpha = 1-2$ is the exponent of the emissivity law.
For 4C 60.07, we find \( R(a, T_d) = 2.44 \pm 0.73 \). We adopt an emissivity law of \( a = 2 \), which was deduced in other high-z objects, e.g., IRAS 10214+4724 (Downes et al. 1992) and 8C 1435+635 (Ivison et al. 1998), over a similar rest-frame spectral range. For this emissivity law the \( \pm 1 \sigma \) range of the observed \( R(a, T_d) \) yields a range of \( T_d \sim 20–50 \) K. Given the starburst nature of these two objects and their luminous CO (4–3) line (the \( J = 4 \) level is \( \sim 55 \) K above the ground state), we assume a dust temperature of \( T_d \sim 50 \) K. Then the dust mass can be estimated from

\[
M_{\text{dust}} = \frac{D_L^2 S_{\text{obs}}}{(1+z)k_{\nu}(\nu_{\text{em}})} [B(\nu_{\text{em}}, T_d) - B(\nu_{\text{em}}, T_{\text{cmb}}(z))]^{-1},
\]

(6)

where \( \nu_{\text{em}} = (1+z)\nu_{\text{obs}} \) is the emitted frequency, \( B(\nu, T) \) is the Planck function, \( T_{\text{cmb}}(z) \) is the CMB temperature at redshift \( z \), and \( k_{\nu}(\nu_{\text{em}}) = 0.04(\nu_{\text{em}}/250 \text{ GHz})^2 \text{ m}^2 \text{ kg}^{-1} \) is the adopted dust emissivity (e.g., Krügel, Stecke, & Chini 1990). For the assumed \( T_d \), the CMB term can be omitted with \( \lesssim 3\% \) error. Here it is worth noting that for cold dust this term can be significant. For example, \( T_{\text{cmb}}(z = 4) = 13.75 \) K; hence, a dust component with \( T_d = 15 \) K at that redshift is a very cold component, just \( \sim 1 \) K above \( T_{\text{cmb}}(z = 4) \). An observed wavelength of 1.25 mm corresponds to \( h\nu_{\text{em}}/k \sim 57.4 \) K at \( z = 4 \), and for this wavelength the CMB term is \( \sim 70\% \) of the dust term.

Assuming similar parameters for the dust emission in 6C 1909+722, the 850 \( \mu \)m flux density yields \( M_{\text{dust}} \sim 1.5 \times 10^8 M_\odot \) for both objects. This gives warm gas-to-dust ratios of \( M(H_2)/M_{\text{dust}} \approx 530 \) (4C 60.07) and \( M(H_2)/M_{\text{dust}} \approx 300 \) (6C 1909+722), i.e., within the range of the values found for local IRAS galaxies (e.g., Young et al. 1986, 1989; Stark et al. 1986) and ULIRGs (Sanders et al. 1991). This suggests that in a universe at \( \sim 10\% \) of its current age, these two HzRGs already have heavy-element abundance comparable to the galaxies in the contemporary universe. It is also worth noting that while many uncertain factors enter into the estimate of the gas-to-dust ratio, the values chosen for them here are the ones considered plausible from the study of the ISM in local ULIRGs.

The FIR luminosities of the two HzRGs were estimated by assuming the underlying spectrum of an optically thin, isothermal reservoir of dust mass; hence,

\[
L_{\text{FIR}} = \int_0^\infty L_{\nu_{\text{em}}} d\nu_{\text{em}} = 4\pi M_{\text{dust}} \int_0^\infty k_{\nu}(\nu_{\text{em}})B(\nu_{\text{em}}, T_d)d\nu_{\text{em}};
\]

(7)

after using equation (6) to substitute for \( M_{\text{dust}} \), this finally yields

\[
L_{\text{FIR}} = 4\pi \lambda(\nu)D_L^2 x^{-(\alpha+4)}(e^x - 1)S_{\text{obs}}v_{\text{obs}},
\]

(8)

where \( x = h\nu_{\text{em}}/kT_d \), and \( \lambda(\nu) \) is a numerical constant that depends on the emissivity law. In astrophysical units this becomes

\[
L_{\text{FIR}} = 2 \times 10^7(1 + z - \sqrt{1 + z})^2 \lambda(\nu)x^{-(\alpha+4)} \times (e^x - 1)S_{\text{obs}}(v_{\text{obs}}/\text{GHz})L_\odot.
\]

(9)

For the assumed \( T_{\text{dust}} \sim 50 \) K, the last expression will yield a lower limit to the true \( L_{\text{FIR}} \), since in some ULIRGs the optical depth may become significant even at FIR frequencies (e.g., Solomon et al. 1997), and in a starburst environment dust can be warmer still. We find \( L_{\text{FIR}} \sim 1.5 \times 10^{12} L_\odot \) for both HzRGs, a luminosity comparable to 8C 1435+635 and 4C 41.17 (Ivison et al. 1998 and references therein), the other two high-z radio galaxies detected in the submillimeter (rest-frame FIR) spectral range whose properties do not appear to be influenced by gravitational lensing.

4.4. The Evolutionary Status of 4C 60.07 and 6C 1909+722

The usual conclusion drawn when such large FIR luminosities are deduced for a galaxy is that we are witnessing it during a starburst phase. However, many of the IR-luminous galaxies in the local universe, and certainly the two particular HzRGs, also harbor an AGN; thus, part of the FIR luminosity may be due to AGN-heated dust. Nevertheless, recent studies of ULIRGs (Genzel et al. 1998; Downes & Solomon 1998) reveal that most of them are powered by recently formed massive stars. In addition, even when an AGN does make a significant contribution to \( L_{\text{FIR}} \), it is usually \( \lesssim 30\% \) (Genzel et al. 1998; Downes & Solomon 1998). Therefore, the qualitative arguments behind converting FIR luminosities to star formation rates are not likely to change even if an AGN is present. For 4C 60.07, the case for the starburst origin of its FIR luminosity is made stronger by the fact that most of its 1.25 mm dust emission is not emanating in the vicinity of the AGN.

The FIR luminosity provides a measure of the current star formation rate (SFR) according to

\[
\text{SFR} = 10^{-10}\Psi L_{\text{FIR}} M_\odot \text{ yr}^{-1},
\]

(10)

where \( \Psi \sim 1–6 \), depending on the assumed IMF (Telesco 1988 and references therein).

Adopting the most conservative value, \( \Psi \sim 1 \), the FIR luminosity of the two HzRGs implies a SFR \( \sim 1500 M_\odot \) yr\(^{-1}\). Such a high rate of star formation can, if sustained, produce \( 10^3–10^5 M_\odot \) of stars in \( \sim 0.06–0.6 \) Gyr, and it is comparable to the SFRs found for 8C 1435+635 and 4C 41.17 (Ivison et al. 1998). The efficiency with which such a burst converts molecular gas into stars is given by \( \text{SFR}/M(H_2) \), or, equivalently, by \( L_{\text{FIR}}/M(H_2) \) (assuming the same \( \Psi \) for all the galaxies). On many occasions, the quantity \( L_{\text{FIR}}/L_{\text{CO}} \) is used instead, but since the \( X_{\text{CO}} \) conversion factor is \( \sim 4–5 \) times smaller in ULIRG systems, the latter ratio can be misleading when a single value for \( X_{\text{CO}} \) is used for galaxies spanning a FIR range from moderately IR-luminous galaxies (\( L_{\text{FIR}} \sim 10^{10} L_\odot \)) to ULIRGs (\( L_{\text{FIR}} \gtrsim 10^{12} L_\odot \)).

The star formation efficiencies estimated are \( \sim 190 L_\odot M_\odot^{-1} \) (4C 60.07) and \( \sim 330 L_\odot M_\odot^{-1} \) (6C 1909+722), comparable to the ones found for ULIRGs (Solomon et al. 1997) once \( M(H_2) \) has been estimated using the same \( X_{\text{CO}} \) factor. The implied star formation rates and efficiencies of these galaxies point toward spectacular starbursts occurring at high redshift. In addition, the large line widths observed, which in the case of 4C 60.07 exceed \( \sim 1000 \text{ km s}^{-1} \), are routinely observed toward ULIRGs (e.g., Solomon et al. 1997) and are a kinematic signature of the ongoing mergers/interactions that trigger their enormous starbursts (Sanders et al. 1991).

The tantalizing question raised when high-z starbursts are found is to what extent the observed star formation
episode is forming the bulk of their eventual stellar mass. The main difficulty in answering this important question stems from the uncertainties involved in deducing the total gas mass from CO measurements. If we assume an atomic-molecular gas ratio of $M(H)/M(\text{H}_2) \sim 2$ found for IRAS galaxies (Andreani, Casoli, & Gerin 1995) and a large sample of spirals (Casoli et al. 1998), we obtain a total gas content of $M_{\text{gas}} = 1.0 \times 10^{11}(X_{\text{CO}/r_{A3}}) (4C\ 60.07)$ and $M_{\text{gas}} = 6.0 \times 10^{10}(X_{\text{CO}/r_{A3}}) (6C\ 1909+722)$. For the “average” starburst value of $r_{A3} = 0.45$, this gives gas masses of the order of $(1.3-2.2) \times 10^{11} M_\odot$. These are an order of magnitude higher than typical gas masses in local ULIRGs (e.g., Downes & Solomon 1998) and constitute $\sim 15\% - 20\%$ of the total stellar mass of a typical elliptical associated with the 3CR radio galaxies at $z \sim 1$ (Best et al. 1998). Thus, it is clear that these enormous starbursts still have a vast reservoir of gas eventually to be turned into stars.

The best evidence yet that at least in the case of 4C 60.07 we are witnessing an extraordinary starburst and not a scaled-up version of an ULIRG comes from the fact that in this galaxy the CO $J = 4-3$ emission from gas is distributed over scales of $\sim 30$ kpc. This is in contrast to the local ULIRGs, where most of the molecular gas and starburst activity is confined within the central $\leq 1-5$ kpc. Since starburst activity is usually coextensive with the molecular gas reservoir, and this will be particularly true for the high-excitation CO $J = 4-3$ line, it seems that the starburst in 4C 60.07 occurs on galaxy-wide scales.

Equally intriguing is the fact that the CO emission consists of two distinct components widely separated in velocity (Figs. 1 and 4). Their velocity-integrated CO flux densities of $1.65 \pm 0.35$ Jy km s$^{-1}$ (wide line width component) and $0.85 \pm 0.20$ Jy km s$^{-1}$ (narrow line width component) yield masses of $M(\text{H}_2) \geq 5 \times 10^{10} M_\odot$ and $M(\text{H}_2) \approx 2.6 \times 10^{11} M_\odot$, respectively (eq. [2], $r_{A3} = 0.45$). We derived size estimates for these two components by fitting both the image and the visibility plane of the CO emission shown in Figure 4 with an underlying Gaussian brightness distribution. The narrow line width component appears unresolved, with an upper limit of $\sim 4'$, while the wide line width component is marginally resolved, with the largest size being $\sim 5'$. In the absence of adequate spatial/kinematic information to make a distinction between the possible geometrical arrangements of the CO-emitting gas, we assume that the largest estimated size, $L$, corresponds to the diameter of a disk, and hence its mass is given by

$$M_{\text{dyn}} \approx \frac{\Delta V_{\text{FWHM}}^2 L}{2dG \sin^2 i} = 1.16 \times 10^9 \left(\frac{\Delta V_{\text{FWHM}}}{100 \text{ km s}^{-1}}\right)^2 \times \left(\frac{L}{\text{kpc}}\right)(\sin^2 i)^{-1} M_\odot,$$

where $i$ is the inclination of the disk, and $d \sim 1$ (Bryant & Scoville 1996).

For the wide line width component, the largest estimated size corresponds to $L \sim 22$ kpc, which gives $M_{\text{dyn}} \approx 7.7 \times 10^{11}(\sin^2 i)^{-1} M_\odot$, comparable to the mass of a present-day giant elliptical. The ratio of the inferred molecular-to-dynamic gas mass then is $M(\text{H}_2)/M_{\text{dyn}} \sim 0.06\sin^2 i$. For the narrow velocity component, the upper limit corresponds to $L \sim 17.5$ kpc, yielding a dynamic mass of $M_{\text{dyn}} \lesssim 4.6 \times 10^{10}(\sin^2 i)^{-1} M_\odot$. This is $\lesssim 5\%$ of the mass of a typical giant elliptical, and a comparison with its molecular gas mass gives $M(\text{H}_2)/M_{\text{dyn}} \approx 0.60\sin^2 i$. Thus, geometrical factors aside, this component is significantly richer in molecular gas than the more massive one, and it may be the component in which star formation has yet to form the bulk of its eventual stellar mass.

It is easy to contrive a combination of different excitation properties, $X_{\text{CO}}$ values, and inclinations so that $M(\text{H}_2)/M_{\text{dyn}}$ in one or both molecular gas components is altered significantly. Still, the fact remains unaltered that in 4C 60.07, unlike a typical ULIRG, the intense star formation occurs over large scales in two spatially and kinematically distinct molecular gas reservoirs. This brings to mind the scenario for the formation of a giant elliptical at high redshift, in which several star-forming clumps merge to eventually form the galaxy. In this picture, a gas-rich low-mass clump like the one seen in 4C 60.07 is still in the process of merging and vigorous star formation, while the higher mass object has already formed most of its stars. Of course, the possibility that the wide line width component itself consists of several virialized gas-rich clumps that do not necessarily constitute a bound system cannot be discarded in light of the present data.

For 6C 1909+722, the CO emission is unresolved with a size of $\lesssim 4'$ ($L \lesssim 18$ kpc), which for the observed line width (Table 1) corresponds to $M_{\text{dyn}} \lesssim 5.85 \times 10^{11}(\sin^2 i)^{-1} M_\odot$ and $M(\text{H}_2)/M_{\text{dyn}} \gtrsim 0.08\sin^2 i$. Thus, while there is little doubt that this galaxy is a starburst, it could still be a high-$z$ counterpart of a ULIRG, in which most of its eventual stellar population has already formed and the intense star formation is confined in its central region.

Finally, the case of 4C 60.07 makes it clear that when searching for high-$z$ CO lines a large velocity coverage is necessary, not only because of their often uncertain redshift, but in order to be able to detect various components that may be far apart in velocity. Higher resolution observations are necessary in order to reveal more structure in the molecular gas reservoir of this galaxy and to allow better constraints on its dynamical mass. However, the faintness of the CO emission observed here may hinder such efforts, and a systematic study of such objects may have to await the advent of the next generation of millimeter interferometers with significantly larger collecting areas.

5. CONCLUSIONS

In this paper the detection of millimeter/submillimeter emission from dust and the first detection of CO $J = 4-3$ in two powerful high-$z$ radio galaxies has been presented. The analysis of the data leads us to the following conclusions:

1. Using the most conservative CO/H$_2$ conversion factor (5 of the Galactic value), the CO $J = 4-3$ emission implies molecular gas masses of the order of $M(\text{H}_2) \sim (0.5-1) \times 10^{11} M_\odot$ in the two high-$z$ powerful radio galaxies. Their submillimeter continuum corresponds to large FIR luminosities $(\sim 10^{13} L_\odot)$, which imply that we are witnessing intense starburst phenomena at $z \sim 3.5-3.8$, converting the aforementioned gas mass into stars.

2. The wide range of molecular gas excitation expected in ultraluminous IR galaxies over large scales is briefly explored, and we conclude that observing objects with
similar ISM conditions at high $z$ using high-J CO transitions may in some cases hinder their detection. This can partly explain why, despite systematic efforts, CO detections of unlensed objects are fewer than detections of their millimeter/submillimeter continuum from dust. Therefore, it is still too early to draw any general conclusions about the abundance of molecular gas in high-$z$ systems from the data currently available in the literature.

3. The estimated molecular gas-to-dust ratios found in these two objects are in the range found for the local IRAS galaxies, revealing that in both, most of the heavy elements have already been produced at present-day abundances.

4. In 4C 60.07, the CO emission and presumably the starburst activity implied by its large FIR luminosity are distributed over scales of ~30 kpc and consists of two distinct components spanning a total velocity range of $\geq 1000$ km s$^{-1}$. Thus, this galaxy does not seem to be just a scaled-up high-$z$ version of a local ultraluminous IR galaxy in which most of the starburst activity and the accompanying bright CO/dust emission are confined to a more compact region in the center. A plausible scenario is that we are witnessing the ongoing formation event of a giant elliptical galaxy, the future host of the residing radio-loud AGN.

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