GAS AND DUST IN THE EXTREMELY RED OBJECT ERO J164502+4626.4

THOMAS R. GREVE
Institute for Astronomy, University of Edinburgh, Blackford Hill, Edinburgh EH9 3HJ, UK; tgreve@roe.ac.uk

ROB J. IVISON
Astronomy Technology Centre, Royal Observatory, Blackford Hill, Edinburgh EH9 3HJ, UK; rji@roe.ac.uk

AND

PADELI P. PAPADOPoulos
Department of Physics and Astronomy, University College London, Gower Street, London WC1E 6BT, UK; and Sterrewacht Leiden, P.O. Box 9513, 2300 RA Leiden, Netherlands; pp@star.ucl.ac.uk

Received 2003 July 13; accepted 2003 September 3

ABSTRACT

We report the first detection of the lowest CO transition in a submillimeter bright galaxy and extremely red object (ERO) at $z = 1.44$ using the Very Large Array (VLA). The total $J = 1-0$ line luminosity of ERO J164502+4626.4 is $(7 \pm 1) \times 10^{10}$ K km s$^{-1}$ pc$^2$, which yields a total molecular gas mass of $\sim 6 \times 10^{10} M_\odot$. We also present a map of the $850 \mu$m continuum emission obtained using the Submillimeter Common-User Bolometric Array, from which we infer a far-IR luminosity and dust mass of $L_{\text{FIR}} \sim 9 \times 10^{12} L_\odot$ and $M_d \sim 9 \times 10^8 M_\odot$, respectively. We find tentative evidence that the CO and submillimeter dust emission is extended over several tens of kiloparsecs. If confirmed by high-resolution imaging, this implies that ERO J164502+4626.4 is not simply a high-redshift–counterpart of a typical ultra luminous infrared galaxy (ULIRG).

Subject headings: galaxies: high-redshift — galaxies: individual (HR 10) — galaxies: ISM — galaxies: starbursts — galaxies: structure — radio lines: galaxies

1. INTRODUCTION

Observations of CO provide one of the most powerful methods of probing the interstellar medium (ISM) in galaxies—i.e., determining the amount of molecular gas available to fuel star formation and accretion onto active galactic nuclei (AGNs), the two processes believed to generate the large far-infrared (far-IR) luminosities of star-forming galaxies (Sanders, Scoville, & Soifer 1991). The first detection of CO at high redshift (Brown & vanden Bout 1991) revealed its potential to trace metal-enriched molecular gas in the early universe. CO is thus key to our understanding of galaxy formation and evolution.

Extremely red objects (EROs, usually defined as galaxies with $R - K \gtrsim 5.3$; see, e.g., Moriondo, Cimatti, & Daddi 2000) constitute a bimodal population—a combination of dusty, starburst systems (Dey et al. 1999) and evolved ellipticals (Dunlop et al. 1996). While both types of objects appear similar in the optical/near-IR, the detection of submillimeter continuum emission and/or CO unambiguously pinpoints the dusty EROs. A significant fraction of the submillimeter-selected population of high-redshift, dust-enshrouded starburst galaxies is believed to be associated with EROs (Smail et al. 1999). Since the advent of large-format bolometer arrays such as the Submillimeter Common-User Bolometric Array (SCUBA; Holland et al. 1999) and the Max-Planck Millimeter Bolometer (MAMBO; Kreysa et al. 1998), over 100 sources have been detected in submillimeter surveys (Smail, Ivison, & Blain 1997; Hughes et al. 1998; Bertoldi et al. 2002). In cases in which optical/IR counterparts of submillimeter galaxies are available, it is found that the sources typically are distorted, multicomponent systems with one or more components being an ERO (Ivison et al. 2002). The submillimeter population has a median redshift of $z \sim 2.4$ (Chapman et al. 2003) and is widely believed to comprise the progenitors of present-day spheroids and massive ellipticals. At present, however, the molecular gas content of submillimeter-selected galaxies remains largely unknown, and a systematic inventory of the molecular gas and its properties in these sources is required in order to properly address the question of their typical mass and evolutionary status. Of particular importance is the ratio of gas and dynamical masses in such objects, since it can help determine whether submillimeter galaxies are merely high-redshift analogs of local ultraluminous infrared galaxies (ULIRGs) or massive, large-scale galaxy-formation events. The difficulties arise mainly because submillimeter-selected galaxies have proved extremely difficult to identify in the optical (e.g., Ivison et al. 1998, 2000). As a result only a handful of submillimeter-selected galaxies have been detected in CO to date (Frayer et al. 1998, 1999; Ivison et al. 2001; Downes & Solomon 2003; Genzel et al. 2003; Neri et al. 2004).

ERO J164502+4626.4 (Graham & Dey 1996) was among the first EROs discovered by Hu & Ridgway (1994). Deep near-IR and optical spectroscopy of J164502 put it at a redshift of $z = 1.44$ (Graham & Dey 1996; Dey et al. 1999), and the detection of the H$\alpha$ line and the [O II] $\lambda 3726, 3729$ doublet in its spectrum suggested that J164502 is an actively star-forming galaxy, possibly containing an AGN, and not

1 The VLA is operated by the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.
an evolved elliptical at \( z = 2-4 \), as initially suggested by Hu 
& Ridgway (1994). The presence of large amounts of dust 
was inferred from submillimeter observations by Cimatti 
et al. (1998) and Dey et al. (1999), the latter detecting 
\( J164502 \) in the continuum at 450, 850, and 1350 \( \mu m \). These 
observations, together with detections of CO \( J = 2-1 \) and 
\( J = 5-4 \) by Andreani et al. (2000), which revealed the pres-
ence of large quantities of molecular gas, unambiguously 
demonstrated that \( J164502 \) is a gas-rich, dust-enshrouded 
starburst galaxy.

Here we present observations of the CO \( J = 1-0 \) emis-
sion from \( J164502 \) using the Very Large Array (VLA), pro-
viding the first detection of the lowest, and thus least 
excitation biased, CO line in a galaxy typical of the sub-
millimeter population. We also present the 850 \( \mu m \) SCUBA 
map of this source. Throughout this paper we have assumed 
\( H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \) and \( \Omega_L = 0.7 \). In this 
cosmology the luminosity distance of \( J164502 \) is 11.2 Gpc, 
and 1\(^\circ\) corresponds to 9.1 kpc.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Very Large Array Observations

At \( z = 1.44 \) the CO \( J = 1-0 \) line from \( J164502 \) falls 
within the VLA’s \( Q \) band at 0.7 cm. The line widths of the 
CO \( J = 5-4 \) and \( J = 2-1 \) lines were \( \approx 400 \text{ km s}^{-1} \text{ FWHM} \) 
(Amendani et al. 2000), and a similar line width could be 
expected for the \( J = 1-0 \) line. In order to cover the entire 
CO line, two adjacent 50 MHz intermediate frequency (IF) 
pairs (left and right circular polarization) were centered at 
47.235 and 47.285 GHz, giving 635 \( \text{ km s}^{-1} \) of coverage. 
Measurements of \( J164502 \) in the radio have yielded 
\( \Delta S_{20 \text{ cm}} \leq 300 \mu Jy \) and \( S_{5.6 \text{ cm}} = (35 \pm 11) \mu Jy \) (Frayer 1996).

Fitting a power-law spectrum to these data points yields a 
spectral index of \( \alpha \geq -1.25 \). Adopting a more conservative 
spectrum with \( \alpha = -0.7 \), we find that the extrapolated syn-
chronous flux at 0.7 cm amounts to no more than 11 \( \mu Jy \). 
Furthermore, the dust contributes less than 10 \( \mu Jy \) at these 
 wavelengths (Dey et al. 1999). Hence, any contribution 
from continuum emission is negligible, and no continuum 
subtraction is necessary. Observations were obtained in D 
and C configurations (see Table 1). Due to bad weather, all 
The primary calibrator, 3C 286, was observed at the 
beginning and end of each observing run in order to fix the 
absolute flux density scale. Every 3–4 minutes the antennas 
were pointed toward a phase calibrator to ensure phase 
coherence throughout the run. This fast-switching

| Date          | Configuration | Frequency (GHz) | Integration Time (hr) |
|---------------|---------------|----------------|-----------------------|
| 2001 Oct 9    | D             | 47.235, 47.285  | 5.2                   |
| 2002 Oct 26   | C             | 47.235, 47.285  | 2.9                   |
| 2002 Nov 14   | C             | 47.235, 47.285  | 2.4                   |
| 2002 Dec 24   | C             | 47.235, 47.285  | 2.6                   |
| 2003 Feb 21   | D             | 47.235, 47.285  | 2.6                   |
| 2003 Mar 1    | D             | 47.235, 47.285  | 3.8                   |

2 The JCMT is operated by the Joint Astronomy Centre on behalf of the United Kingdom Particle Physics and Astronomy Research Council, the Netherlands Organization for Scientific Research, and the National Research Council of Canada.

3 UKIRT is operated by the Joint Astronomy Centre on behalf of the United Kingdom Particle Physics and Astronomy Research Council.
the entire $J = 1-0$ line with the two IFs, and that we have rectangular passbands, we estimate the velocity-integrated flux density using

$$\int_{\Delta v} S_{\nu,\text{obs}} \, dv = 2\Delta \nu_{\text{IF}} \frac{c}{\nu_{\text{obs}}} \overline{S}_{\text{CO}},$$

(1)

where $\Delta \nu_{\text{IF}}$ is the width of the IF, and $\overline{S}_{\text{CO}} = (S_1 + S_2)/2$ is the average of the flux density measured in the two IFs. Using the task $\text{imean}$ to get the flux density of the source in the two IF maps, we find $\overline{S}_{\text{CO}} = 1.0 \pm 0.2 \text{ mJy}$, which yields a velocity-integrated flux density of $0.6 \pm 0.1 \text{ Jy km s}^{-1}$, where we have used $\nu_{\text{obs}} = 47.26 \text{ GHz}$ and an IF bandwidth of $45 \text{ MHz}$ instead of $50 \text{ MHz}$, because of bandpass rollover.

As first noted by Dey et al. (1999) using high-resolution $Hubble Space Telescope$ ($HST$) WFPC2 images, J164502 in the optical has a reflected S-shaped morphology with two bright knots at each end. A comparison with Keck $K$-band imaging revealed that the bulk of the near-IR emission comes from the region between the two bright knots located $\sim 0''4$ north of the brightest optical knot (Dey et al. 1999). As seen from Figure 1, the peak intensity in the CO $J = 1-0$ map coincides with the peak in the UKIRT $K$-band image, both of which are coincident with the region of low optical emission found by Dey et al. (1999). A similar offset between the $HST$ position and the CO $J = 2-1$ emission was reported by Andreani et al. (2000). While the near-IR emission traces the dust-enshrouded stars in J164502, the optical emission corresponds to regions of low extinction, and it is therefore not surprising to see such an offset between the two types of emission. Since gas should be a good tracer of dust, one would expect the CO to coincide with the $K$-band emission, as it appears to do within the limits of our astrometric errors.

A Gaussian fit to the CO data in the image plane yields a deconvolved source size of $4''5 \times 3''0$, suggesting that even in the D-configuration we have resolved the CO emission, albeit marginally. Different weighting schemes and tapering functions were tried in order to see the effects on the extended emission. Using a less restrictive tapering function ($\text{FWHM} = 200 \text{ k}\lambda$) and a robust parameter of 2 instead of 5 (natural weighting), thereby increasing the weight of the long baselines, the source still

Fig. 1.—Left: Naturally weighted CO $J = 1-0$ contour map of J164502 overlaid on the UFTI $K$-band image. The resolution of the CO map is $3''1 \times 2''8$ at PA = $157^\circ$ (see inset). The contours are $-2, 2, 3, 4, 5, 6,$ and $7 \sigma$, where $\sigma = 0.1 \text{ mJy beam}^{-1}$. Right: Real (top) and imaginary (bottom) part of the complex visibilities versus baseline. The visibilities have been binned. The solid line represents a point source with flux density of 1.0 mJy. The dashed curves represent a least-squares fit of a Gaussian source model to the visibilities.
appeared extended, although at a lower significance because of the larger noise on the longest baselines (see Fig. 1). In order to confirm or dismiss the reality of the extended emission, we shifted the peak of the CO emission to the phase center and then plotted the binned real and imaginary parts of the complex visibilities as a function of baseline distance (Fig. 1). The complex visibilities are the Fourier components of the source brightness distribution. Hence, for a Gaussian-source brightness distribution, the real part of the complex visibilities is a Gaussian, while the imaginary part is zero, since a Gaussian is an even function. The dashed curves in Figure 1 represent a least-squares fit of a circular Gaussian to the visibilities. The position of the Gaussian was fixed to the phase center during the fit, and only the amplitude and width were allowed to vary. We find that the real part of the visibilities is consistent with a Gaussian-source model with a FWHM = 3.9, in agreement with the Gaussian fit in the image plane. The imaginary part is consistent with zero at all baselines within the limits of our residual rms phase error of r x ~ 20°. The phase error would give rise to a dispersion around zero of

$$\sigma(\text{Im}(V)) = \sigma(S \sin \phi) \approx S\sigma(\phi)$$

$$= 1.0 \text{ mJy}$$

$$(20°/180°)\pi \approx 0.3 \text{ mJy},$$

which is close to the observed scatter.

The 850 μm SCUBA map of J164502 is shown in Figure 2 and is seen to contain at least two statistically significant sources. A 7σ emission feature showing up in the map is detected at a position that coincides with the near-IR and CO detections of J164502, and we take this to unambiguously be the 850 μm SCUBA detection of J164502. Another source, marked as J164502-SMM1 in Figure 2, detected at the 5σ level, is seen 50″ to the south, with faint emission at the 4σ level also seen just ~20″ south of J164502. We estimated the 850 μm flux density in four different ways. Two estimates were made by measuring the flux within apertures of 20″ and 16″ diameter. A third measurement was made by fitting a Gaussian to the emission, and a fourth by fitting a Gaussian with a fixed FWHM of 15″ to the emission. The

---

Fig. 2.—Left: SCUBA 850 μm jiggle maps of J164502. The resolution is FWHM = 14″, and the rms noise level is 1.6 mJy beam^{-1}. Contours start at 2σ. J164502-SMM1 denotes a statistically significant detection of 850 μm emission about 50″ south of J164502. Weak emission is also seen 20″ southeast of J164502. Right: Radial profiles of J164502 and J164502-SMM1 (filled circles) compared with the radial profile of the PSF (solid line).
values derived from each of these measurements are given in Table 2 for J164502 as well as J164502-SMM1. For J164502 we find $S_{850 \mu m} = 8 \pm 2$ mJy, where we have adopted the average of the four different measurements. While this is in good agreement with the 850 \mu m measurement by Cimatti et al. (1998), it is larger than the flux quoted by Dey et al. (1999). Both of these measurements were obtained using SCUBA in its photometry mode, but the latter value is based on a data set that is twice as large as the former, taken in excellent weather conditions, and is therefore the most reliable estimate. If this is the case, the large discrepancy between the flux density derived from our map and the value derived from the photometry measurements by Dey et al. (1999) could be due to extended emission from J164502, which would have been missed by the single-pixel measurement.

From the 850 \mu m map in Figure 2, it is seen that the emission from J164502 does in fact appear to be extended, with emission to the northeast. The reality of this extended emission is strengthened by the high-resolution Keck K-band image obtained by Dey et al. (1999), which shows an emission feature extending in the same direction, albeit on a smaller scale of $\approx 1''$ (see Fig. 2 of Dey et al. 1999). However, the fact that the stars traced by the K-band emission are extended on scales of $\approx 9$ kpc means that cold dust is distributed on at least the same scales, and likely on much larger scales. Fitting a Gaussian to the SCUBA image yields a source size of $15''$ along the major axis, which is comparable to the $14''$ resolution of the map, although very tentatively suggestive of a slight extension. In Figure 2 we compare the azimuthally averaged radial profiles of J164502 and J164502-SMM1 with the point-spread function (PSF) of SCUBA at 850 \mu m derived from a beam map of a bright blazar obtained during the same observing run. The radial profile of J164502 agrees with the PSF out to $r \approx 20''$, beyond which it displays excess emission over that of a point source. This bump in the radial profile is due to the $4 \sigma$ emission feature $20''$ south ($\approx 180$ kpc) of J164502. The reality of this emission feature is questionable, but if real its close vicinity to J164502 could mean that it is an system in the process of merging with J164502. While there is thus tentative evidence that J164502 is extended, the large beam size of SCUBA does not allow for a firm conclusion on this issue.

For comparison we note that J164502-SMM1 is consistent with the PSF at all radii. The SCUBA 850 \mu m beam is too large to make a reliable identification of J164502-SMM1 with a near-IR/optical source. If J164502-SMM1 is a dusty system at the same redshift as J164502, one might expect that it too would shine in CO. No CO emission was detected at the position of J164502-SMM1, however, and we set an upper limit on the velocity-integrated line flux using the equation $S_CO \Delta v < 3\sigma (\Delta v)$, where $\sigma$ is the rms noise, $\Delta v$ the velocity resolution, and $dv$ the line width, which we assume to be equal to the $J = 2\rightarrow1$ line width, i.e., $\approx 400$ km s$^{-1}$ (Andrei et al. 2000). The measured rms noise in the image is $\sigma \approx 0.3$ mJy beam$^{-1}$, which yields $S_{CO} \Delta v < 0.2$ Jy km s$^{-1}$ for a velocity coverage of 635 km s$^{-1}$. The failure to detect CO emission from J164502-SMM1 does not rule out an association, since cluster velocity dispersions can go up to $\approx 1000$ km s$^{-1}$, and in some cases even closely associated CO-emitting regions can have velocity differences of $\approx 1000$ km s$^{-1}$, as was seen in the high-redshift radio galaxy 4C 60.07 (Papadopoulos et al. 2000). The probability of finding by chance a source with a flux density brighter than or equal to 6 mJy within $r = 50''$ from J164502 is given by $P = 1 - e^{-n N}$, where $N$ is the average surface density of sources with $S_{850 \mu m} \geq 6$ mJy (Downes et al. 1986). Adopting a surface density of $N \approx 400$ deg$^{-2}$ (Borys et al. 2003), one finds that $P = 0.22$. On that basis we conclude that J164502-SMM1 is most likely unrelated to J164502.

### Table 2: Observed Properties of J164502

| Parameter | J164502 | J164502-SMM1 |
|-----------|---------|-------------|
| $\alpha$ (J2000.0) | 16 45 02.26 | 16 45 01.20 |
| $\beta$ (J2000.0) | +46 26 26.50 | +46 25 39.0 |
| $z_{CO}$ | 1.439 | |
| $J_{45}$ | 0.6 | <0.2 |
| $S_{850 \mu m}$ (mJy) | 8 $\pm$ 2$^a$ | 6 $\pm$ 2$^a$ |
| $L_{CO}^{850}$ (K km s$^{-1}$ pc$^{-1}$) | $\left(7 \pm 1\right) \times 10^{10}$ | $<2 \times 10^{10}c$ |
| $L_{850}$ (K km s$^{-1}$) | 9 $\pm$ 1$^a$ | 7 $\pm$ 1$^a$ |

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

$^a$ The average of 7.5, 7.9, 7.3, and 9.8 mJy, which were the flux densities obtained using the four different methods described in § 3.

$^b$ The average of 6.7, 6.5, 6.0, and 6.5 mJy, which were the flux densities obtained using the four different methods described in § 3.

$^c$ This value assumes that J164502-SMM1 has a redshift of $z = 1.439$.

4. ANALYSIS AND DISCUSSION

Table 2 summarizes the CO and submillimeter observations of J164502 and J164502-SMM1, as well as the physical quantities derived from them.

4.1. Molecular Gas and Dust in J164502

For an observed velocity-integrated line flux density of the $J + 1 \rightarrow J$ CO line, the intrinsic CO line luminosity is given by

$$L_{CO,j+1,j} = \frac{c^2}{2k} \frac{D_L^2}{1+z} \int_{V_{L0}} S_{V_{L0}} dV,$$

where $D_L$ is the luminosity distance, and $V_{L0,j+1,j}$ is the rest-frame frequency of the CO transition. Inserting astrophysical units, the equation reads

$$L_{CO,j+1,j} = 2.43 \times 10^2 (J+1)^{-2}(1+z)^{-1} \left(\frac{D_L}{Mpc}\right)^2 \left(\frac{f_{L0} S_{L0} dL}{Jy \text{ km s}^{-1}}\right),$$

where $L_{CO,j+1,j}$ is the so-called pseudoluminosity, which is measured in units of K km s$^{-1}$ pc$^2$. The observed CO $J = 1\rightarrow0$ line flux density for J164502 implies an intrinsic CO luminosity of $L_{CO}^{850} = (7 \pm 1) \times 10^{10}$ K km s$^{-1}$ pc$^2$. From the CO $J = 1\rightarrow0$ line, the molecular gas mass can be found using the scaling relation $M(H_2) = X_{CO} L_{CO}^{850}$, where $X_{CO} \approx 5$ $M_\odot$ (K km s$^{-1}$ pc$^2)^{-1}$ is the standard Galactic CO-H$_2$ conversion factor. The standard conversion factor $X_{CO}$ has been calibrated using giant molecular clouds (GMCs) in our Galaxy (e.g., Strong et al. 1988). However, the conditions of the ISM in active starbursting galaxies such as ULIRGs is markedly different from that in our Galaxy, and applying the Galactic conversion factor
would result in seriously underestimated gas masses. In particular, the concept of isolated and virialized GMCs breaks down, and instead the bulk of the CO emission is found to originate from a warm diffuse phase. In effect, this yields a lower conversion factor of

\[ X_{CO} = 0.8 \, M_\odot \, (K \, \text{cm}^{-2} \, \text{s}^{-1})^{-1}, \]

more appropriate for such extreme environments (Downes & Solomon 1998). It is reasonable to assume that in high-redshift starbursts, similar conditions prevail, and the aforementioned value of \( X_{CO} \) is also adopted for J164502. In doing so we estimate the molecular gas mass present in J164502 to be \( M(H_2) = (6 \pm 1) \times 10^{10} \, M_\odot \). This is in agreement with the \( J = 2 \rightarrow 1 \) detection by Andreani et al. (2000), which yields a molecular gas mass of \( \sim 4 \times 10^{10} \, M_\odot \) when converted to the cosmology adopted in this paper.

The CO \( J = 1 \rightarrow 0 \) line luminosity and the implied molecular gas mass of J164502 are somewhat lower than those found in the quasars APM 08279+5255 and PSS 2322+1944, and in the high-redshift radio galaxy 3C 60.07 \( [L_{CO}^{J=1-0}] \sim 10^{11} \, K \, \text{cm}^{-2} \, \text{pc}^{-2} \) and \( M(H_2) \sim 10^{11} \, M_\odot \); see Papadopoulos et al. 2001; Carilli et al. 2002; T. Greve et al. 2003, in preparation). This is not surprising, since these objects are among the most luminous systems in the universe and might therefore be expected to contain more gas. Solomon et al. (1997) observed CO \( J = 1 \rightarrow 0 \) in a sample of 37 local ULIRGs out to a redshift of \( z = 0.3 \) and found an average \( J = 1 \rightarrow 0 \) luminosity of \( L_{CO}^{J=1-0} \sim 8 \times 10^{10} \, K \, \text{cm}^{-2} \, \text{pc}^{-2} \), which is roughly the luminosity of Arp 220 and Mrk 231. The scatter on this result was only 30%. A more recent survey of CO \( J = 1 \rightarrow 0 \) observations of a complete sample of 60 ULIRGs selected from the SCUBA Local Universe Galaxy Survey (Dunne et al. 2000) yielded similar results (Yao et al. 2003). Hence, we find that J164502 has a CO \( J = 1 \rightarrow 0 \) luminosity and consequently a molecular gas mass that is about an order of magnitude larger than is found for local ULIRGs.

The dynamical mass of the system can be calculated from the observed size and line width of the source and assuming the gas is distributed in a disk with diameter \( L \) in Keplerian rotation, in which case it can be shown that the dynamical mass is given by

\[ M_{dyn} = \frac{\Delta V_{FWHM}^2 L}{2 \Omega_i G} \left( \frac{L}{\text{kpc}} \right) \left( \frac{1}{\sin^2 i} \right) M_\odot, \]

where \( i \) is the inclination angle of the disk, and \( \Omega_i \) is a correction factor of an order of unity (Bryan & Scoville 1996). Adopting a line width of \( \Delta V_{FWHM} = 400 \, \text{km s}^{-1} \) (Andreani et al. 2000) and a source size of \( \theta \lesssim (4.5^\prime \times 3.0^\prime)_{1/2} = 3.7^\prime \), which corresponds to a maximum linear diameter of \( L \sim 34 \, \text{kpc} \) at a redshift of \( z = 1.44 \), we estimate the enclosed dynamical mass within the CO-emitting region to be \( M_{dyn} \lesssim 6.3 \times 10^{11} \, (\sin i)^{-2} \, M_\odot \). The inferred ratio of the molecular-to-dynamical mass for the system as a whole is then \( M(H_2)/M_{dyn} \gtrsim 0.1 \, \text{sin}^2 i \). Hence, geometrical factors aside, the amount of molecular gas accounts for at least 10% of the total dynamical mass within the CO-emitting region. The dynamical mass should be considered an upper limit on the total amount of molecular gas present in J164502, and the two mass estimates would only coincide if the CO emission were concentrated within the inner \( \sim 3 \, \text{kpc} \). Due to the higher spatial resolution and the fact that the \( J = 1 \rightarrow 0 \) line provides an unbiased estimate of \( M(H_2) \), our constraint on the molecular-to-dynamical mass ratio should be an improvement over that of Andreani et al. (2000). A gas mass fraction of \( \geq 10% \) is compatible with the range of gas mass fractions found for local ULIRGs (Downes & Solomon 1998), yet unlike the latter, it is distributed over significantly larger scales.

The extrapolated synchrotron radiation flux at 850 \( \mu \text{m} \) is less than 3 \( \mu \text{Jy} \), and it is therefore safe to assume that the observed 850 \( \mu \text{m} \) flux from J164502 is dominated by thermal dust emission, with the radio synchrotron emission contributing a negligible amount. The dust mass can therefore be estimated using

\[ M_d = \frac{S_{850} D_L^2}{(1+z) \kappa_d(\nu_{rest})} \times \left[ B(\nu_{rest}, T_d) - B(\nu_{rest}, T_{CMB}(z)) \right]^{-1}, \]

where \( \nu_{rest} = \nu_{obs}(1+z) \) is the rest-frame frequency, \( T_{CMB}(z) \) is the cosmic microwave background temperature at redshift \( z \), and \( \kappa_d \propto \nu^2 \) is the dust absorption coefficient. The emissivity index \( \beta \) depends on the dust temperature \( T_d \) (Dunne et al. 2000), both of which are poorly constrained for high-redshift objects—typical values are \( \beta = 1-2 \). Dey et al. (1999) found the spectral energy distribution of J164502 to be well described by an optically thin modified blackbody law with a dust temperature of \( T_d = 40 \, \text{K} \) and an emissivity law of \( \beta = 1.5 \), and we adopt those values here. In doing so we estimate the dust mass to be \( M_{dust} \gtrsim 9 \times 10^8 \, M_\odot \), where we have used a dust absorption coefficient of \( \kappa_d(\nu_{rest}) = 0.11 \, (\nu_{rest}/335 \, \text{GHz})^{4/3} \, \text{m}^2 \, \text{kg}^{-1} \) after Hildebrand (1983). The uncertainty in \( \kappa_d \) is large, so we present this estimate for comparison only. We can estimate the total far-IR luminosity by integrating the thermal spectrum

\[ L_{FIR} = 4\pi M_d \int_0^\infty \kappa_d(\nu) B(\nu, T_d) d\nu, \]

which yields a total far-IR luminosity of \( L_{FIR} \approx 9 \times 10^{12} \, L_\odot \). This almost puts J164502 in the class of hyper-luminous infrared galaxies (HyLIRGs), which have \( L_{FIR} \gtrsim 10^{13} \, L_\odot \). The dust masses and far-IR luminosities typically found in local ULIRGs are \( M_{dust} \approx 10^7-10^9 \, M_\odot \) and \( L_{FIR} \approx 10^{12} \, L_\odot \) (Sanders & Mirabel 1996; Dunne et al. 2000), i.e., nearly an order of magnitude smaller than what we find for J164502. It is comparable, however, to what is found in high-redshift QSOs and HzRGs (Omont et al. 2003; Archibald et al. 2001), and perhaps more importantly, similar to the dust masses and far-IR luminosities found in submillimeter—selected dust-enshrouded starbursts at high redshifts (Ivison et al. 1998, 2000). From the above we estimate the gas-to-dust mass ratio of J164502 to be \( M(H_2)/M_{dust} \approx 67 \), which is well within the range of 50–100 found for local ULIRGs. Note, however, that significant uncertainty is attached to the normalization of \( \kappa_d \), and values differing by as much as a factor of 2 have been reported (Draine & Lee 1984; Mathis & Whiffen 1989), which in turn could lead to a similar change in the dust mass but not in \( L_{FIR} \), which is independent of the normalization value of the dust absorption coefficient. Using \( \beta = 2.0 \) instead of 1.5 would decrease the dust mass by nearly a factor of 2 but increase \( L_{FIR} \) by a similar amount.
If the bulk of the far-IR emission can be ascribed to starburst activity, the corresponding star formation rate is given by

\[
\text{SFR} \simeq L_{\text{FIR}} 10^{-10} \delta_{\text{IMF}} \delta_{\text{SB}} M_\odot \text{ yr}^{-1},
\]

where \( \delta_{\text{IMF}} \sim 1-6 \) is a function of the initial mass function, and \( \delta_{\text{SB}} \) is the fraction of the FIR emission that is heated by the starburst (Omont et al. 2001). Assuming a conservative value of \( \delta_{\text{IMF}} = 1 \), we estimate the star formation rate in J164502 to be \( \text{SFR} \simeq 900 \delta_{\text{SB}} M_\odot \text{ yr}^{-1} \). It is possible that J164502 harbors an AGN in its center, so a significant fraction of the far-IR luminosity could be due to dust being heated by the AGN and not by the starburst. The derived value for the SFR could therefore be overestimated. However, the narrow line widths seen in optical and NIR spectra of J164502 (Dey et al. 1999) favor young hot stars over an AGN as the main source of energy. Furthermore, as pointed out by Dey et al. (1999), J164502 deviates from the 60 \( \mu \)m–6 cm relation obeyed by local star-forming galaxies by having almost an order of magnitude less radio emission at 6 cm, which is unlikely if an AGN dominates the energetics of the system (Dey & van Breugel 1994). In addition, it is found that the bulk of the far-IR emission from local ULIRGs is powered by starburst activity even though an AGN is present (Downes & Solomon 1998). Finally, if the submillimeter emission is extended, it would strongly suggest that the main power source for the far-IR emission is a massive starburst, since it is difficult to imagine the AGN heating the dust on scales of tens of kiloparsecs. The large quantity of molecular gas revealed by the CO detections in this system could provide the necessary fuel for such a massive starburst for a period of \( \sim 10^7 \) yr.

The efficiency of star formation should be measured relative to the amount of molecular gas available to form stars. Such a measure of the star-formation efficiency is the rate of star formation per solar mass of molecular hydrogen, i.e., \( L_{\text{FIR}}/M(H_2) \). For J164502 we find \( L_{\text{FIR}}/M(H_2) \simeq 150 L_\odot M_\odot^{-1} \). Probably a better gauge of the star-formation efficiency is the continuum-to-line ratio \( L_{\text{FIR}}/L_{\text{CO}}(1-0) \), since it is independent of \( X_{\text{CO}} \). GMCs in our Galaxy typically have values of \( \sim 15 \), and similar ratios are found in nearby spirals (Mooney & Solomon 1988). Starburst galaxies and ULIRGs have \( L_{\text{FIR}}/L_{\text{CO}}(1-0) \) ratios that are 10 times higher than this, ranging in values from 80 to 250, with a median of 160 \( L_\odot \) (K km s\(^{-1}\) pc\(^2\)) \(^{-1} \) (Solomon et al. 1997). For J164502 we find \( L_{\text{FIR}}/L_{\text{CO}}(1-0) \simeq 129 L_\odot \) (K km s\(^{-1}\) pc\(^2\)) \(^{-1} \), i.e., in line with what is found for local ULIRGs. Recent studies of large samples of ULIRGs at low and intermediate redshifts have shown that the \( L_{\text{FIR}}/L_{\text{CO}}(1-0) \) ratio increases with increasing \( L_{\text{FIR}} \) (Young et al. 1986; Tutui et al. 2000; Yao et al. 2003). Such behavior can be explained if the more far-IR luminous galaxies, in addition to having more dust and gas, which would just continue the linear relation between \( L_{\text{FIR}} \) and \( L_{\text{CO}}(1-0) \), have higher dust temperatures due to extra heating by an AGN, or a higher star-formation efficiency. Assuming that there is no contribution to \( L_{\text{FIR}} \) from an AGN, the derived \( L_{\text{FIR}}/L_{\text{CO}}(1-0) \) ratio should probably be taken as a lower limit on the star-formation efficiency, since in the extreme starburst regions dominating the emission from ULIRGs, the bulk of the CO luminosity comes from a diffuse intercloud medium, rather than from the dense gas gravitationally bound in clouds where the stars are formed (Downes et al. 1993; Solomon et al. 1997). The dense gas is better traced by HCN, and as shown by Gao, Solomon, & Philip (1999); the \( L_{\text{FIR}}/L_{\text{HCN}} \) ratio is the same for GMCs to ULIRGs, indicating that anywhere in the universe only dense gas is relevant to star formation. In ULIRGs the dense/diffuse gas mass ratio (roughly quantified by \( L_{\text{HCN}}/L_{\text{CO}} \)) is particularly high, which is not a surprise given their merger status and the way the gas responds to a merger.

### 4.2. Excitation Conditions of the Molecular Gas in J164502

The velocity/area-averaged brightness temperature ratio between CO \( J = 1 \rightarrow 0 \) and CO \( 1 \rightarrow 0 \) is

\[
r_{J+1,J} = \frac{T_b(J+1 \rightarrow J)}{T_b(1 \rightarrow 0)} = \frac{L(J+1 \rightarrow J)}{L(1 \rightarrow 0)}. \tag{9}
\]

Andreani et al. (2000) estimated the CO \( J = 2 \rightarrow 1 \) and \( J = 3 \rightarrow 2 \) to be \( 4 \times 10^{10} \) and \( 7 \times 10^{10} \) K km s\(^{-1}\) pc\(^2\), respectively, where we have converted the luminosities to the cosmology adopted here. The line ratios estimated from equation (8) are \( r_{21} = 0.6 \pm 0.2 \) and \( r_{32} = 0.10 \pm 0.05 \). The majority of high-redshift systems detected in CO to date are strongly gravitationally lensed. This makes estimating the excitation conditions in such systems complicated, since differential magnification of the high-J lines, compared to lower transitions, may bias the line ratios significantly. There is nothing to suggest that J164502 is gravitationally lensed, and the above derived line ratios ought to represent the intrinsic excitation conditions of the gas, albeit still averaged over the entire galaxy.

We used the observed line ratios of \( r_{21} = 0.6 \pm 0.2 \) and \( r_{32} = 0.10 \pm 0.05 \) as constraints to a large velocity gradient (LVG) code in order to gain some insight on the bulk properties of the molecular gas in J164502. A lower limit on gas temperature \( T_{\text{kin}} = 40 \) K is assumed, since this value is deduced for the bulk of the dust (Dey et al. 1999), and \( T_{\text{kin}} \geq T_{\text{dust}} \) is expected for FUV-heated gas/dust (e.g., Hollenbach & Tielens 1999). A wide range of temperatures (\( T_{\text{kin}} = 60-90 \) K) offers an acceptable fit to the aforementioned line ratios, with \( T_{\text{kin}} = 70 \) K being the optimal value. This wide range is due to the poor constraints offered by only two line ratios, while the high gas temperatures may reflect the UV-intense environment of the molecular gas in J164502 and/or turbulent motions heating only the gas, a situation that has already been noted for molecular gas in the Galactic center (Rodriguez-Fernandez et al. 2001).

A common feature of all the LVG solutions is the low gas densities \( n(H_2) \sim 300 \) cm\(^{-3}\). This has already been noted when only the CO (5–4)/(2–1) line ratio was available (Papadopoulos & Ivison 2002) and is a property often found for the bulk of the gas in extreme starbursts (e.g., Aalto et al. 1995; Downes & Solomon 1998). Interestingly, for such low gas densities, all CO \( J + 1 \rightarrow J \) transitions with \( J + 1 \geq 5 \) have flux-density ratios with respect to the lowest \( 1-0 \) transition of

\[
S(J + 1 - J)/S(1-0) = (J + 1)^2 r_{J+1,J}, \quad J \leq 0.25
\]

for any plausible gas temperature (\( T_{\text{kin}} \sim 40-100 \) K), thus no longer offering the advantage of a higher flux density with respect to the latter.

As a consequence, any estimate of the \( H_2 \) mass based on the assumption of optically thick, thermalized high-J CO lines could be severely underestimated. Using the 5–4 line in
J164502 only, and assuming it is optically thick and thermalized ($r_{\text{f2}} \sim 1$), one would find a molecular gas mass that is an order of magnitude lower than that inferred from the $J = 1-0$ line. There is no significant flux advantage between the 2–1 and 1–0 lines, since

$$S_{\text{CO}}(2-1)/S_{\text{CO}}(1-0) = 4 T_b(2-1)/T_b(1-0) > 1$$

even for a very subthermal ratio of $r_{\text{f2}} = 0.3$, for instance. This is consistent with the fact that we find the molecular masses derived from the two lines to be similar (§ 4.1). The above demonstrates the importance of using low-J CO lines in order to infer the amount of molecular gas in a galaxy. This is particularly true at redshifts beyond 3, since at those redshifts the current millimeter interferometers can only hope to detect CO $J = 1 \rightarrow J, J > 2$, and the excitation bias of the high-$J$ lines could become very severe.

4.3. Comparison with High-Redshift Submillimeter Galaxies

Although J164502 was originally selected as an ERO and not a submillimeter galaxy, subsequent observations at optical/IR and submillimeter wavelengths have shown that it can, in fact, be considered a typical submillimeter galaxy (Dey et al. 1999a; see also Smail et al. 1999). Our detection of CO $J = 1-0$ in J164502 is therefore the first detection of this transition in a galaxy that is thought to be similar to the SCUBA population of dust-enshrouded galaxies at high redshifts. J164502 has a far-IR and CO luminosity about 10 times that of the average values found in ULIRGs, and the amount of molecular gas present in J164502 is comparable to the median gas mass ($\sim 2 \times 10^{10} M_\odot$) of the five SCUBA galaxies detected in CO to date (Neri et al. 2004), although a thorough characterization of the gas content of this population has to await CO observations of a large, unbiased sample of submillimeter-selected galaxies. Hence, the observations presented here further support the assertion that J164502 is more similar in its properties to submillimeter galaxies than to a high-redshift analog of Arp 220.

Recently, a subject of some debate has been whether the CO emission detected from high-redshift submillimeter galaxies originates from a massive reservoir of molecular gas $\sim 10$ kpc in size, or from a much more compact circumnuclear disk, typically of radius $r \sim 100$ pc, as seen in local ULIRGs such as Arp 220 (Ivison et al. 2001; Genzel et al. 2003; Downes & Solomon 2003). If, as the observations seem to suggest, the starburst in J164502 is extended over several tens of kiloparsecs, that would set it apart from the local ULIRG population and point toward the former scenario.