

IMAGING LOW-ORDER CO EMISSION FROM THE $z = 4.12$ QUASI-STELLAR OBJECT PSS J2322+1944

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ABSTRACT

We present observations of CO (1–0) and CO (2–1) emission from the $z = 4.12$ quasi-stellar object (QSO) PSS J2322+1944 using the Very Large Array.¹ The CO emission is extended on a spatial scale of $2''$. This extension could reflect the double nature of the QSO, as seen in the optical, or could be diffuse emission with a (redshift-corrected) mean brightness temperature of 2.8 K for the CO (2–1) line. We find that CO excitation conditions are lower than in two other IR-luminous $z > 4$ QSOs, suggesting the presence of a significant contribution from cooler, lower density molecular gas [$n(\text{H}_2) \sim 5 \times 10^3 \text{ cm}^{-3}$], although such a conclusion is complicated by the possibility of differential gravitational magnification.

Subject headings: galaxies: evolution — galaxies: starburst — infrared: galaxies — quasars: individual (PSS J2322+1944) — radio continuum: galaxies — radio lines: galaxies

1. INTRODUCTION

Two of the more important recent discoveries on nearby galaxies are (1) the large majority of spheroidal galaxies in the nearby universe contain massive black holes and (2) the black hole mass correlates with the mass of the spheroid of the parent galaxy (Richstone et al. 1998; Gebhardt et al. 2000; Ferrarese & Merritt 2000). These discoveries suggest a “causal connection between the formation and evolution of the black hole and the bulge” (Gebhardt et al. 2000) and have led to the hypothesis of coeval formation of massive black holes and galaxy spheroids, perhaps occurring in merging galaxies at high redshift (Franceschini et al. 1999; Blain et al. 1999; Kauffmann & Haenelt 2000; Page et al. 2002). We have undertaken an extensive observational program from radio through submillimeter wavelengths of high-redshift quasi-stellar objects (QSOs) in order to address the interesting possibility of coeval black hole and

spheroidal galaxy formation (Carilli et al. 2001a, 2001b, 2002; Omont et al. 2001; Carilli, Menten, & Yun 1999).

The $z = 4.12$ QSO PSS J2322+1944 has $M_B = -28.1$ and was discovered in the Digitized Palomar Sky Survey high-redshift QSO search (Djorgovski et al. 2002, in preparation²). Djorgovski et al. (2002) found that PSS J2322+1944 is a double source in the optical with two similar spectrum components separated by about $1''.5$. This morphology may indicate a QSO pair at $z = 4.12$ or gravitational lensing by an intervening galaxy.

PSS J2322+1944 is the brightest submillimeter source from the recent surveys of Omont et al. (2001) and Isaak et al. (2002), with a flux density of $9.6 \pm 0.5 \text{ mJy}$ at 250 GHz and $22.5 \pm 2.5 \text{ mJy}$ at 350 GHz. The rest-frame IR spectral energy distribution (SED) of PSS J2322+1944 is consistent with thermal emission from dust at a temperature of about 47 K (Cox et al. 2002). The apparent FIR luminosity is then $3 \times 10^{13} L_\odot$. Radio continuum emission from PSS

¹ The Very Large Array (VLA) is operated by the National Radio Observatory, which is a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

² Further information on Djorgovski et al. is available at <http://www.astro.caltech.edu/~george/z4.qsos>.

J2322+1944 was detected at 1.4 GHz with the Very Large Array (VLA), with a total flux density of $102 \pm 20 \mu\text{Jy}$ and an intrinsic size of about $2''$ (Carilli et al. 2001a).

Cox et al. (2002) show that the radio-to-IR SED for PSS J2322+1944 is similar to that of the dwarf nuclear starburst galaxy M82, supporting the idea of active star formation coeval with the active galactic nucleus (AGN) activity of the QSO. The implied star formation rate, up to $10^3 M_\odot \text{ yr}^{-1}$ if the source is not strongly gravitationally lensed, is adequate to form the majority of the stars in a normal spheroidal galaxy in a relatively short time ($\leq 10^8 \text{ yr}$). On the other hand, the global SED for PSS J2322+1944 from centimeter-to-optical wavelengths is not out of the range defined by lower redshift, lower luminosity QSOs (Carilli et al. 2001a; Sanders et al. 1989), and hence the case for dust heating by star formation based on the SED alone is by no means secure.

Omont et al. (2001) point out that a prerequisite for star formation at the rate considered for PSS J2322+1944 is a massive reservoir of molecular gas ($\sim 10^{11} M_\odot$). Such reservoirs have been detected via their CO line emission in other IR-luminous QSOs at $z > 4$ (Omont et al. 1996; Ohta et al. 1996; Guilloteau et al. 1997, 1999; Carilli et al. 2002). Recently, Cox et al. (2002) have detected emission in the high-order CO transitions from PSS J2322+1944. They find that PSS J2322+1944 has the highest apparent CO (5–4) line luminosity of any $z > 4$ QSO.

In this paper we present observations of CO (1–0) and CO (2–1) emission from PSS J2322+1944 using the VLA. From these data we derive the spatial distribution and excitation conditions of the molecular gas. We assume $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.3$, and $\Omega_\Lambda = 0.7$.

2. OBSERVATIONS

PSS J2322+1944 was observed with the VLA in the fall of 2001 using the D configuration (1 km maximum baseline). Observations were made of the redshifted CO (1–0) line at 22.515 GHz and of the CO (2–1) line at 45.035 GHz. A total of 14 hr was spent on each transition.

The CO (1–0) observations at 22.5 GHz employed the spectral line correlator mode with two polarizations and seven spectral channels of 6.25 MHz width ($= 83 \text{ km s}^{-1}$). Because of limitations with the VLA bandwidth and correlator, the CO (2–1) observations at 45 GHz were done using the continuum correlator mode with two intermediate frequencies (IFs) of 50 MHz bandwidth and two polarizations each. One of the IFs was centered on the CO (2–1) emission line, while the second was centered 350 km s^{-1} off-line in order to determine the continuum level, if any. This mode maximizes sensitivity to the line but sacrifices a measurement of the line velocity profile. Our CO (2–1) analysis will necessarily assume the line profile as given by the CO (1–0) line.

Standard amplitude and phase calibration were applied, correcting for atmospheric opacity at high frequency, and the absolute flux density scale was set by observing 3C 286. In the analysis below, we include a 10% systematic error arising from calibration uncertainties at high frequency. Fast-switching phase calibration was employed (Carilli & Holdaway 1999) with a cycle time of 3 minutes, although subsequent inspection of the phase stability showed that a cycle time of 15 minutes, or even longer, would have been easily adequate to maintain phase coherence. The observations took place at night under excellent weather conditions,

with rms phase variations after calibration of typically less than 10° . The phase coherence was checked by imaging a calibrator with a similar calibration cycle time as that used for the target source. At all times the coherence was found to be better than 90%.

3. RESULTS AND ANALYSIS

Figure 1a shows the CO (1–0) emission spectrum from PSS J2322+1944. A Gaussian profile was fitted to the spectrum with a resulting full width at half-maximum (FWHM) of $200 \pm 70 \text{ km s}^{-1}$, a peak flux density of $0.89 \pm 0.22 \text{ mJy}$, and a velocity-integrated flux density of $0.19 \pm 0.08 \text{ Jy km s}^{-1}$. Zero velocity in Figure 1a is defined as the center of channel 4, corresponding to a heliocentric redshift of 4.11956 for CO (1–0). The Gaussian fit has a central velocity of $-22 \pm 24 \text{ km s}^{-1}$ relative to this redshift, corresponding to a redshift of 4.1192 ± 0.0004 . For comparison, the Gaussian fitted to the CO (5–4) line has a FWHM = $273 \pm 50 \text{ km s}^{-1}$ and a central redshift of 4.1199 ± 0.0008 (Cox et al. 2002).

The image of the CO (1–0) emission averaged over channels 3, 4, and 5 is shown in Figure 1b, and the average of the continuum channels (1 and 6) is shown in Figure 1c. The source is spatially unresolved, with an upper limit to the (deconvolved) source size of $3''$ (derived from Gaussian fitting) and a peak flux density of $0.65 \pm 0.07 \text{ mJy}$ (note that this peak corresponds to the average of channels 3, 4, and 5). The upper limit (2σ) to continuum emission at 22 GHz is 0.14 mJy.

Figure 2a shows the integrated CO (2–1) emission from PSS J2322+1944, while Figure 2b shows the continuum channel. No continuum emission is detected to a 2σ limit of 0.15 mJy. The CO emission is resolved spatially. A Gaussian fit results in a deconvolved source size of FWHM = $2''.1 \times 1''.6$ with a major-axis position angle of 152° and a total flux density of $2.7 \pm 0.24 \text{ mJy}$. The implied (redshift-corrected) mean brightness temperature is 2.8 K. The velocity-integrated flux density is $0.92 \pm 0.30 \text{ Jy km s}^{-1}$, assuming a line width as given by the CO (1–0) transition. The CO (2–1) image also shows emission extending about $2''$ southwest of the peak position. This structure repeats (to within the noise) on the 3 different observing days. The average (redshift-corrected) brightness temperature of this emission is $0.5 \pm 0.1 \text{ K}$. We note that the observed morphology of the CO (2–1) emission agrees within the errors with that observed for the radio continuum emission at 1.4 GHz (Carilli et al. 2001a).

The data for the velocity-integrated flux densities for various CO transitions for PSS J2322+1944 are plotted in Figure 3. The higher order transition data is taken from Cox et al. (2002). Also plotted are the corresponding numbers for two other IR-luminous QSOs at $z > 4$, BRI 1202–0725 at $z = 4.7$ and BRI 1335–0417 at $z = 4.4$, for which multiple CO transitions have been observed (see Carilli et al. 2002; Cox et al. 2002). The data have been normalized to the velocity-integrated line flux density for CO (5–4). For comparison, we have included the CO ladder observed for the best-studied nuclear starburst galaxy, M82 (Güsten et al. 1993; Mao et al. 2000), and that for the integrated emission from the Milky Way disk inside the solar radius (excluding the Galactic center) as seen by COBE (Fixsen, Bennett, & Mather 1999).

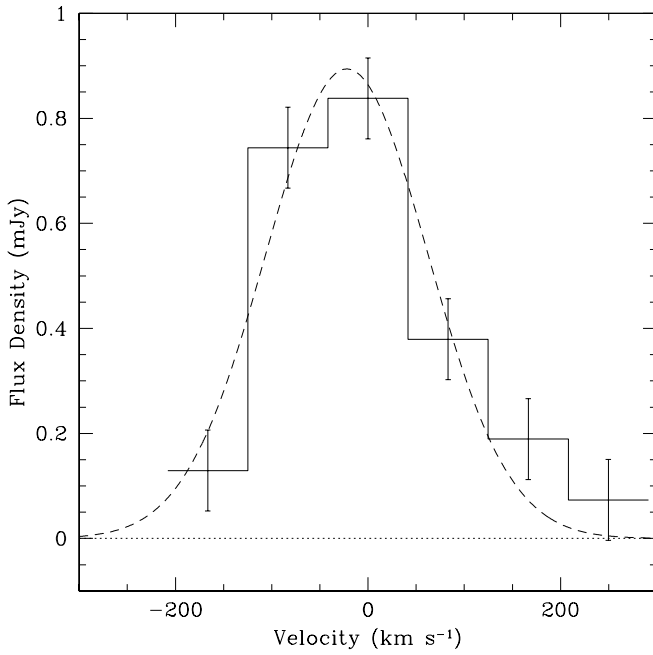


FIG. 1a

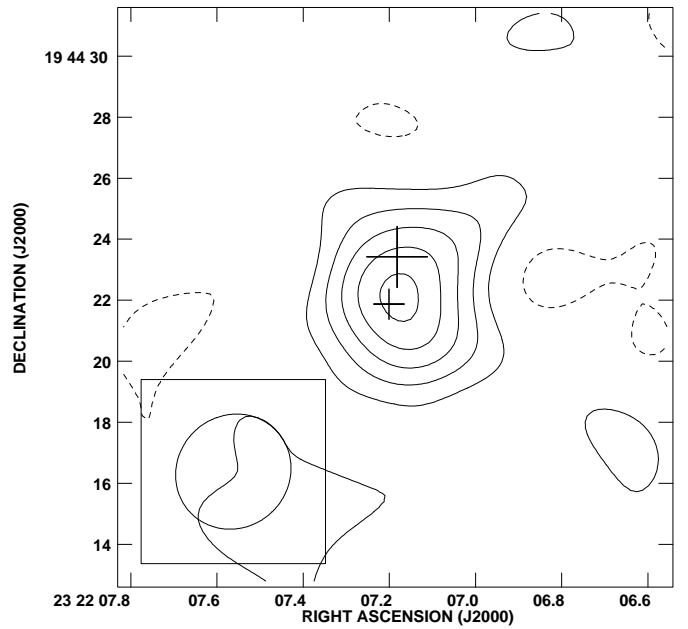


FIG. 1b

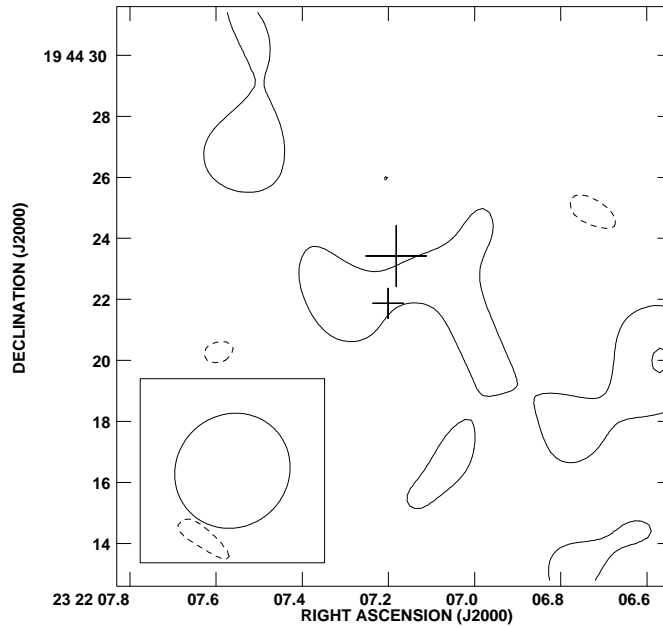


FIG. 1c

FIG. 1.—(a) CO (1–0) spectrum of PSS J2322+1944 as measured at 22.515 GHz at a spatial resolution of $3''.8$. Zero velocity is defined as the center of channel 4, corresponding to a heliocentric redshift of 4.11956 for CO (1–0). Each channel is 83 km s^{-1} wide, and the rms noise in each channel is $0.12 \text{ mJy beam}^{-1}$. The dashed line is a Gaussian fit to the velocity profile (see § 3). (b) Contour image of the average of channels 3, 4, and 5 from the spectrum shown in Fig. 1a with channel 1 being defined at $+250 \text{ km s}^{-1}$. The contour levels are $-0.24, -0.12, 0.12, 0.24, 0.36, 0.48$, and $0.60 \text{ mJy beam}^{-1}$. The Gaussian restoring CLEAN beam has $\text{FWHM} = 3''.9 \times 3''.7$ with a major-axis position angle of -46° , as shown in the inset. The rms noise on this image is $74 \mu\text{Jy beam}^{-1}$. The crosses in this and subsequent images show the position of the two optical QSOs found by Djorgovski et al. (2002). (c) Contour image of the off-line channels (1 and 6) from the spectrum is shown in Fig. 1a. The contour levels and beam are the same as Fig. 1b.

We have fitted a standard one-component large velocity gradient (LVG) model simulating a spherical cloud to interpret the observed line ratios (for details, see Carilli et al. 2002). Because of the lack of constraints, there is a degeneracy in LVG modeling between various parameters such as the density and kinetic temperature (Güsten et al. 1993). Our modeling is not meant as an exhaustive analysis but is merely representative of the types of conditions that can

give rise to the observed line ratios. Given the paucity of information, we adopt a kinetic temperature of 47 K, corresponding to the temperature derived from the far-IR spectrum of thermal emission by warm dust (Cox et al. 2002). We also use the cosmic microwave background radiation temperature at $z = 4.12$ of 14 K. The CO data can be reasonably fitted by a model with $N(\text{CO}) = 2 \times 10^{19} \text{ cm}^{-2}$, $n(\text{H}_2) = 5 \times 10^3 \text{ cm}^{-3}$, and $\nabla V = 1 \text{ km s}^{-1} \text{ pc}^{-1}$. Given the

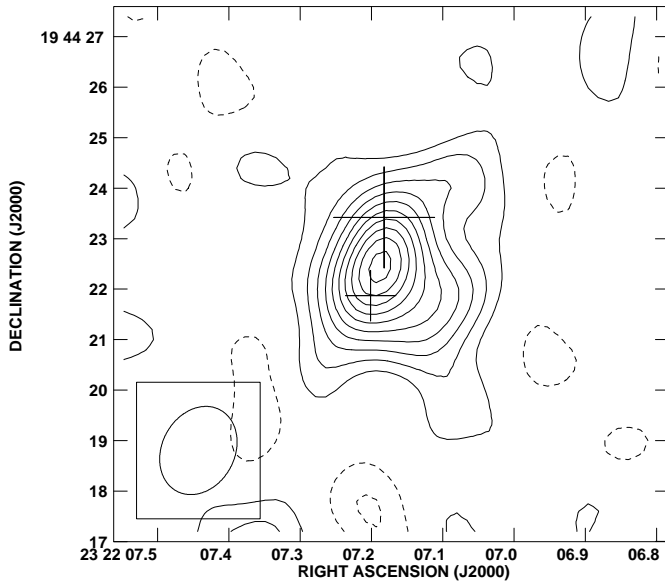


FIG. 2a

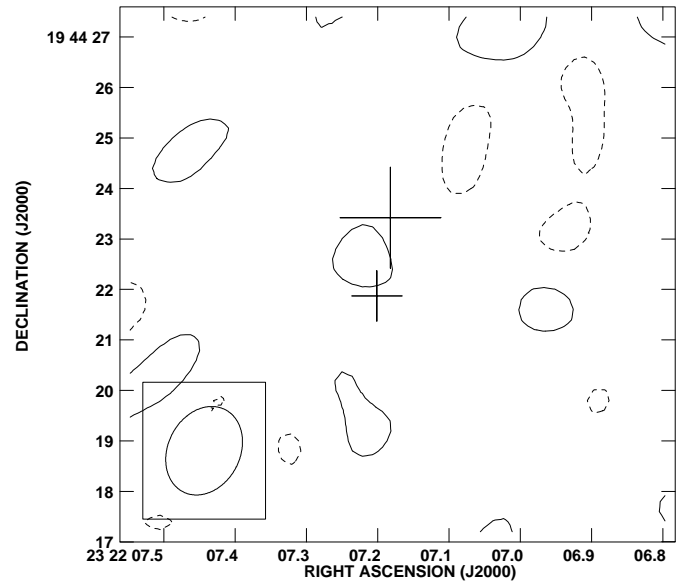


FIG. 2b

FIG. 2.—(a) Contour image of the average of the on-line IF for the CO (2–1) observations of PSS J2322+1944. The IF bandwidth is 50 MHz (= 350 km s⁻¹) and is centered at 45.035 GHz, corresponding to a heliocentric redshift of 4.1191 GHz for CO (2–1). The contour levels are -0.24, -0.12, 0.12, 0.24, 0.36, 0.48, and 0.60 mJy beam⁻¹. The Gaussian restoring CLEAN beam has FWHM = 1''.8 × 1''.4 with a major-axis position angle of -28°, as shown in the inset. The rms noise on this image is 77 μJy beam⁻¹. (b) Contour image of the off-line IF for the 44.985 GHz VLA observations of PSS J2322+1944. The contour levels and beam are the same as in Fig. 2a.

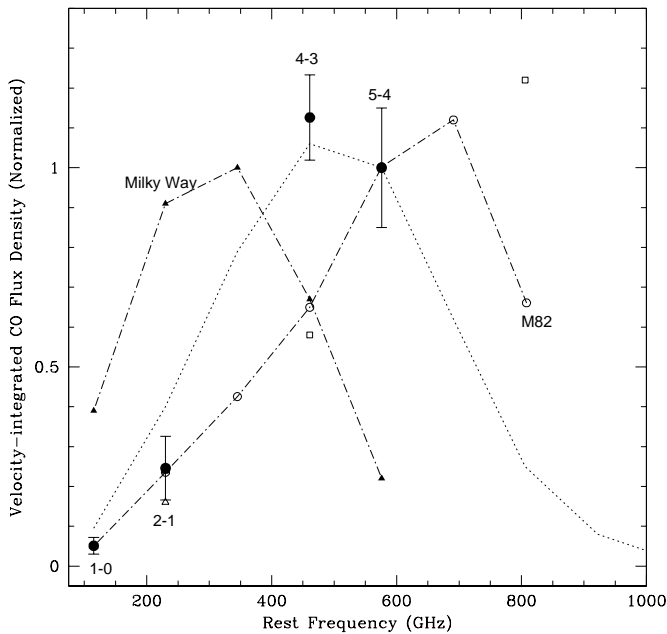


FIG. 3.—Velocity-integrated flux densities for CO emission from PSS J2322+1944, as derived from data from this paper and from Cox et al. (2002), are shown as large filled circles with error bars. Also plotted are the corresponding values for the QSOs BRI 1202–0725 at $z = 4.7$ (open squares) and BRI 1335–0417 at $z = 4.4$ (open triangles) from Carilli et al. 2002. The solid triangles are the data for the CO ladder for the integrated emission from the Milky Way disk inside the solar radius (excluding the Galactic center) as seen by *COBE* (Fixsen, Bennett, & Mather 1999). The open circles are the results for the starburst nucleus of M82 (Güsten et al. 1993; Mao et al. 2000). The ordinate is the velocity-integrated line flux density. The CO (5–4) line has been detected in all the sources, and the velocity-integrated line flux densities for the other transitions in each source have all been normalized by the corresponding CO (5–4) values, except for the Milky Way, for which the values are normalized at CO (3–2). The short-dashed line shows an LVG model with $T_{\text{kin}} = 47$ K and $n(\text{H}_2) = 5 \times 10^3$ cm⁻³.

inhomogeneity of the interstellar medium in the Milky Way and nearby galaxies, our assumption of uniform physical conditions is crude but appropriate for a source with four detected lines from the main CO species and no information on rare isotopomers.

4. DISCUSSION

The optical QSO positions are shown as crosses on Figure 2a. The deconvolved size and position angle of the CO (2–1) emission from PSS J2322+1944 are consistent with the separation and position angle of the double optical QSO components found by Djorgovski et al. (2002), as is the observed radio continuum morphology at 1.4 GHz (Carilli et al. 2001a). However, the resolution of the current VLA image is insufficient to determine whether the CO emission is from two small components associated with the optical QSOs or from more diffuse emission with a mean (redshift-corrected) brightness temperature of 2.8 K. The more extended emission to the southwest appears to be robust, although, given the relatively low surface brightness, we feel this extension needs to be confirmed with further observations.

As discussed in Carilli et al. (2002), the CO excitation conditions for two other IR-luminous QSOs at $z > 4$, BRI 1202–0725 and BRI 1335–0417, are similar to those seen in the dwarf nuclear starburst galaxy M82 and are consistent with a fairly high kinetic temperature of 70 K and a high (mean) molecular gas density of 2×10^4 cm⁻³. For PSS J2322+1944 we find excitation conditions between those seen in M82 and those seen for the disk of the Milky Way. The data are consistent with a kinetic temperature equal to the temperature derived from the far-IR SED of the thermal emission by warm dust (47 K) and a density for the molecular gas of $n(\text{H}_2) = 5 \times 10^3$ cm⁻³, i.e., a factor of 4 lower than

that found for BRI 1202–0725 and BRI 1335–0417. These results may indicate that the CO emission from PSS J2322+1944 is dominated by gas that is more diffuse and cooler than that seen in the other two QSOs. However, if the CO emission from PSS J2322+1944 is strongly lensed, then differential magnification resulting from (possibly) different source plane spatial distributions for the low- and high-excitation molecular gas makes a detailed excitation analysis problematic until higher resolution observations, and a proper lens model, are available.

The apparent CO (1–0) luminosity, L' , for PSS J2322+1944 is $1.5 \times 10^{11} \text{ K km s}^{-1} \text{ pc}^2$. The H_2 gas mass can be calculated from the CO luminosity assuming a value of X = the H_2 mass-to-CO (1–0) luminosity conversion factor in $M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$ (Solomon et al. 1997). We adopt a value of $X \simeq 0.8$, as found for ultraluminous IR galaxies (ULIRGs; $L_{\text{FIR}} \sim 10^{12} L_\odot$) by Downes & Solomon (1998), leading to a molecular gas mass of $1.2 \times 10^{11} M_\odot$. Of course, X depends on a number of factors, including the excitation conditions, and, in the case of PSS J2322+1944, the possibility of gravitational lensing complicates the situation.

Lastly, we consider the continuum-to-line ratio $[L_{\text{FIR}}]/[L'_{\text{CO}(1-0)}]$ in units of $L_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. Solomon et al. (1997) show that this ratio increases with increasing L_{FIR} , with values between 5 and 50 for galactic giant molecular clouds and nearby galaxies with $L_{\text{FIR}} \leq 10^{10} L_\odot$, and values between 80 and 250 for ULIRGs. Evans et al. (2001) have extended this relationship to include IR-excess, optically selected QSOs at $z \leq 0.17$. These QSOs have L_{FIR} values ranging from a few times $10^{11} L_\odot$ to $10^{12} L_\odot$. They find that the low- z QSOs typically show continuum-to-line ratios (as defined above) between 100 and 260, with the majority of sources toward the low end of this range. (Note that we have converted from their L_{IR} to L_{FIR} using a ratio of 0.52, as found by Dale et al. 2001 for a large sample of IR-selected galaxies.) Evans et al. (2001) also find that the QSOs with high continuum-to-line ratios reside in optically disturbed galaxies, i.e., ongoing mergers of gas-rich spiral galaxies, while the sources with low values reside in more normal-looking galaxies.

For PSS J2322+1944 we find $[L_{\text{FIR}}]/[L'_{\text{CO}(1-0)}] = 200 L_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}$. For comparison, in BRI 1335–0417 and

BRI 1202–0725, values of about 340 were found by Carilli et al. (2002), who argued that the large continuum-to-line ratio in these latter two QSOs, both of which have $L_{\text{FIR}} \geq 10^{13} L_\odot$, continues the trend of increasing continuum-to-line ratios with increasing IR luminosity. The fact that PSS J2322+1944 has a continuum-to-line ratio more consistent with ULIRGs, and with low-redshift, lower IR luminosity QSOs, could be used to argue for strong (factor of ~ 10) gravitational magnification of the emission regions, thereby lowering its IR luminosity to $\sim 10^{12} L_\odot$. However, given the scatter in the relationship between IR luminosity and the continuum-to-line ratio, this is at best a weak argument in favor of gravitational lensing.

Detecting the massive reservoir of molecular gas in PSS J2322+1944 is one of the required (although not sufficient) elements for demonstrating the existence of active star formation coeval with the AGN activity in this high- z QSO. However, the possibility of gravitational lensing in PSS J2322+1944 complicates the physical analysis. An argument in favor of lensing is the relatively low velocity dispersion for the CO emission. The observed value of 200 km s^{-1} is typical for a galaxy potential but is low for a group potential, as might be expected if the observed CO line was the sum of emission from the host galaxies of a QSO pair at $z = 4.12$. If the system is strongly gravitationally lensed, then judicious use of a lens model could elucidate structure in the source plane on finer physical scales ($\leq 100 \text{ pc}$) than can be obtained normally (Yun et al. 1997; Lewis et al. 2002). Sensitive, high-resolution observations of the CO (2–1) emission from PSS J2322+1944 are planned to confirm, and better resolve, the molecular line-emitting regions, while observations of higher order transitions at high spatial resolution are planned to better constrain the CO excitation conditions.

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