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High-excitation CO in a quasar host galaxy at $z = 6.42$[⋆]

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Abstract. We report the detection of high excitation CO emission from the most distant quasar currently known, SDSS J114816.64+525150.3 (hereafter J1148+5251), at a redshift $z = 6.419$. The CO ($J = 6 \rightarrow 5$) and ($J = 7 \rightarrow 6$) lines were detected using the IRAM Plateau de Bure interferometer, showing a width of ≈ 280 km s^{-1}. An upper flux limit for the CO ($J = 1 \rightarrow 0$) line was obtained from observations with the Effelsberg 100-meter telescope. Assuming no gravitational magnification, we estimate a molecular gas mass of $\approx 2 \times 10^{10}\,M_\odot$. Using the CO ($3 \rightarrow 2$) observations by Walter et al. (2003), a comparison of the line flux ratios with predictions from a large velocity gradient model suggests that the gas is likely of high excitation, at densities $\sim 10^{4.5}$ cm^{-3} and a temperature $\sim$100 K. Since in this case the CO lines appear to have moderate optical depths, the gas must be extended over a few kpc. The gas mass detected in J1148+5251 can fuel star formation at the rate implied by the far-infrared luminosity for less than 10 million years, a time comparable to the dynamical time scale of the region. The gas must therefore be replenished quickly, and metal and dust enrichment must occur fast. The strong dust emission and the massive, dense gas reservoir at $z \sim 6.4$ provide further evidence that vigorous star formation is co-eval with the rapid growth of massive black holes at these early epochs of the Universe.

Key words. galaxies: formation – galaxies: starburst – galaxies: high-redshift – quasars: emission lines – quasars: individual: SDSS J1148+5251 – cosmology: observations

1. Introduction

The luminous quasars at redshifts $z > 6$ found in the Sloan Digital Sky Survey by Fan et al. (2001, 2003) provide a unique opportunity to study the formation of massive objects during the epoch at which the intergalactic medium was being reionized by the first luminous sources (Becker et al. 2001; Kogut et al. 2003; Cen 2003). Studying signatures of star formation in these exceptional objects is also of great interest to test whether the correlation between the central black hole mass and the stellar bulge mass observed in local spheroids (Magorrian et al. 1998; Gebhardt et al. 2000) can be traced to the early formation stages of quasars and their host galaxies.

J1148+5251, at a redshift of $z = 6.42$ (Fan et al. 2003), is the most distant quasar known, observed only $\approx$850 million years after the Big Bang (we adopt $H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_\Lambda = 0.73$ and $\Omega_m = 0.27$ – Spergel et al. 2003). Optical, radio and millimeter observations indicate that J1148+5251 could be weakly amplified by an intervening lens (Fan et al. 2003; White et al. 2003; Bertoldi et al. 2003), but in what follows, we will assume no lens amplification. J1148+5251 is a very luminous quasar ($M_{1450} = -27.8$, $L_{\rm bol} \sim 10^{14}\,L_\odot$) powered by a supermassive ($\approx 3 \times 10^9\,M_\odot$) black hole radiating close to its Eddington luminosity (Willott et al. 2003). If the mass of the dark matter halo associated with J1148+5251 is proportional to the black hole mass in a way similar to what is found in local spheroids (Shields et al. 2003), its mass would be $\approx 2 \times 10^{12}\,M_\odot$, and J1148+5251 would be among the most massive collapsed structures to have formed in the early Universe (e.g., Haiman & Loeb 2001).

The recent detection of thermal dust emission in J1148+5251 (Bertoldi et al. 2003) implies a far-infrared luminosity of $\approx 10^{13}\,L_\odot$ and a dust mass of $\approx 7 \times 10^8\,M_\odot$. If the dominant heating mechanism is radiation from young stars, then the star formation rate implied from the FIR luminosity is $\sim 3000\,M_\odot$ yr^{-1} which requires vast amounts of molecular gas to be maintained.

Molecular gas in excess of $10^{10}\,M_\odot$ was detected through their CO emission in fifteen $z > 2$ far-infrared ultraluminous ($L_{\rm FIR} > 10^{12}\,L_\odot$) radio galaxies and quasars (e.g.,

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[⋆] Based on observations obtained with the IRAM Plateau de Bure Interferometer, and with the Effelsberg 100 m telescope.

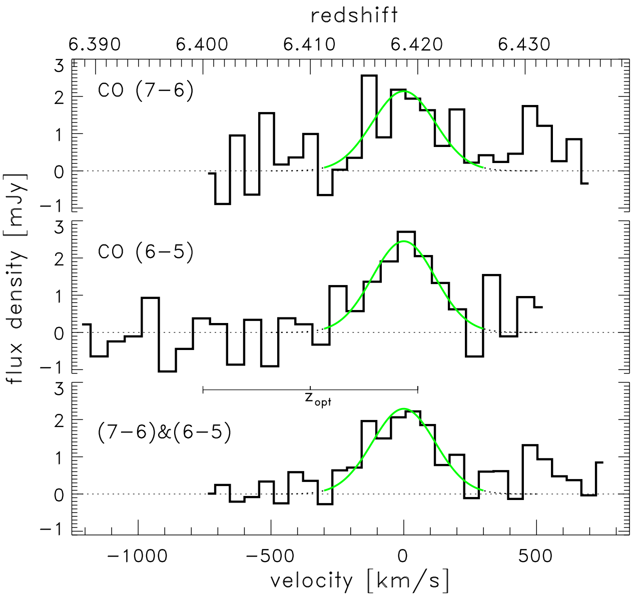

Fig. 1. J1148+5251 spectra of CO (6 → 5), (7 → 6), and their average, binned to 64, 55, and 55 km s^{-1}, respectively, four times the original spectral resolution. Zero velocity corresponds to the centroid of the (6 → 5) line at 93.204 GHz. Gaussian fits with $FWHM = 279$ km s^{-1} are shown as light lines.

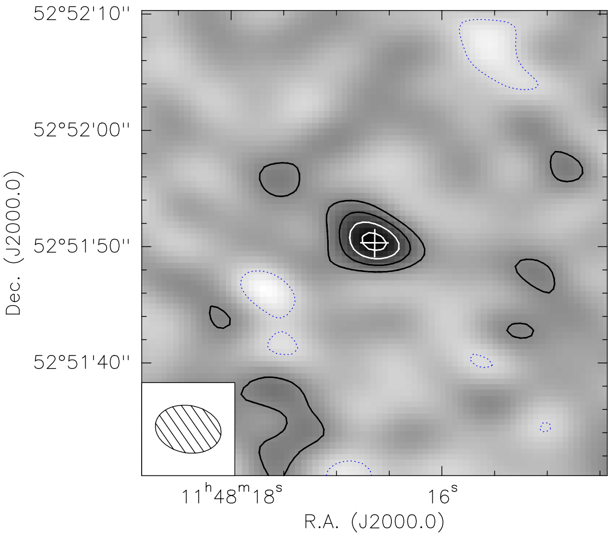

Fig. 2. Velocity-integrated (from −227 to +213 km s^{-1}) map of the averaged CO (6 → 5) and (7 → 6) emission. Contour steps are 0.34 mJy/beam = 2σ. The cross indicates the optical position.

Cox et al. 2002). At $z > 4$, CO emission was detected towards four quasars (Omont et al. 1996; Ohta et al. 1996; Guilloteau et al. 1997, 1999; Cox et al. 2002). The CO emission was resolved in BR 1202−0725 (Carilli et al. 2002) at $z = 4.69$, the highest redshift CO detected so far, and PSS 2322+1944 at $z = 4.12$ (Carilli et al. 2003). The extended nature of the CO provides the most direct evidence for active star formation in the host galaxies of distant quasars, and indicates that black hole accretion and star-formation are closely related.

To explore the growth of massive black holes and their associated stellar populations at the end of the "dark ages", we have searched for CO emission toward J1148+5251. We here report the detection of CO (6 → 5) and (7 → 6) line emission. In a separate study, Walter et al. (2003) report the discovery of CO (3 → 2) emission using the Very Large Array (VLA).

2. Observations

Observations of the CO (7 → 6) and (6 → 5) emission lines were made with the IRAM Plateau de Bure interferometer between March and May 2003. We used the 6 antenna D configuration which results in a beam of 5.7″ × 4.1″ at 3.2 mm. The 3 mm receivers were tuned in single sideband and the typical SSB system temperatures were ≈150 K. The total integration time was 14 hours for CO (6 → 5), and 22 hours for CO (7 → 6). The spectra are displayed in Fig. 1, and the image of the averaged data is shown in Fig. 2. Within the astrometric uncertainties of ±0.″3, the CO emission coincides with the optical position given by Fan et al. (2003). At the 5″ resolution of our Plateau de Bure observations, the CO emission is unresolved, consistent with the VLA CO (3 → 2) detection, which is unresolved at 1.″5 (Walter et al. 2003).

The CO (6 → 5) and (7 → 6) lines are detected at centroid frequencies of 93.206 GHz and 108.724 GHz, corresponding to a redshift 6.419 (Table 1). Within the uncertainties this agrees with the $z = 6.41 \pm 0.01$ of the MgII λ2799 line (Willott et al. 2003) (Fig. 1). The CO redshift, which is likely to correspond to the systemic redshift of the quasar, differs significantly from the range $z = 6.36$–6.39 derived from high ionization UV lines (White et al. 2003), which trace high velocity (≥1000 km s^{-1}), blue-shifted gas related to the quasar activity.

No continuum emission was detected in our coadded 3 mm data, which includes observations at other frequencies, but excludes the continuum redward of the CO lines; here we noticed the possible presence of weak line emission that we plan to investigate further through observations later this year. At the position of J1148+5251 we obtain a continuum flux of 0.09 ± 0.13 mJy. At 43 GHz the continuum remains undetected with -31 ± 57 μJy. These upper limits are consistent with the measured 250 GHz flux density of 5.0 ± 0.6 mJy (Bertoldi et al. 2003), if we adopt a grey body spectrum with temperature >50 K and dust emissivity $\propto\nu^2$.

We fit Gaussians to the line spectra within ±300 km s^{-1} of the centroid, with no baseline subtraction. The best fit line widths of the three spectra shown in Fig. 1 range between 280 and 320 km s^{-1}, similar to the widths found in other high redshift quasars (e.g., Cox et al. 2002). The width and centroid of the best Gaussian fit to the (6 → 5) line were adopted for the Gaussian fit to the lower quality (7 → 6) line to determine its flux. The CO (6 → 5) and (7 → 6) line fluxes are determined at strong confidence levels of 10σ and 7σ, respectively.

We searched for CO (1 → 0) emission using the Effelsberg 100-meter telescope in March and April 2003 with a 1.9 cm HEMT receiver ($T_{\rm sys} \sim 40$ K on a $T_{\rm A}^*$ scale, aperture efficiency ~40%, beam width 60″, position switching mode). The integration time was ~50 hours, yielding a rms of $T_{\rm A}^* \sim 0.4$ mK

Table 1. Properties of the CO lines observed toward SDSS J1148+5251.

Line	$\nu_{\rm rest}$	$\nu_{\rm obs}$	$z_{\rm CO}$	Peak int.	Δv_{FWHM}	$I_{\rm CO}$	$L'_{\rm CO}$	$L_{\rm CO}$
	[GHz]			[mJy]	[km s^{-1}]	[Jy km s^{-1}]	[10^{10} K km s^{-1} pc^2]	[10^8 $L_\odot$]
CO (7→6)	806.652	108.725	6.4192 ± 0.0009	2.14	279†	0.64 ± 0.088	1.73 ± 0.24	2.92 ± 0.40
CO (6→5)	691.473	93.204	6.4189 ± 0.0006	2.45	279	0.73 ± 0.076	2.69 ± 0.24	2.86 ± 0.25
CO (3→2)	345.796	46.610	6.419 ± 0.004	0.6	320‡	0.18 ± 0.02	2.68 ± 0.27	0.35 ± 0.04
CO (1→0)	115.271	15.537	–	<0.36	–	<0.11†	<14.2	<0.070

NOTE.
– For J1148+5251, the apparent CO line luminosity is given by $L'_{\rm CO} = 3.2 \times 10^4\, I_{\rm CO} \nu_{\rm obs}^{-2}$, the intrinsic line luminosity $L_{\rm CO} = 4.2 \times 10^6\, I_{\rm CO} \nu_{\rm obs}$, in the units given above (see Solomon et al. 1997). Upper limits are 3σ.
† Adopting the line width of CO (6→5).
‡ Line width corresponds to the 50 MHz channel width of the VLA 46.6 GHz observations.

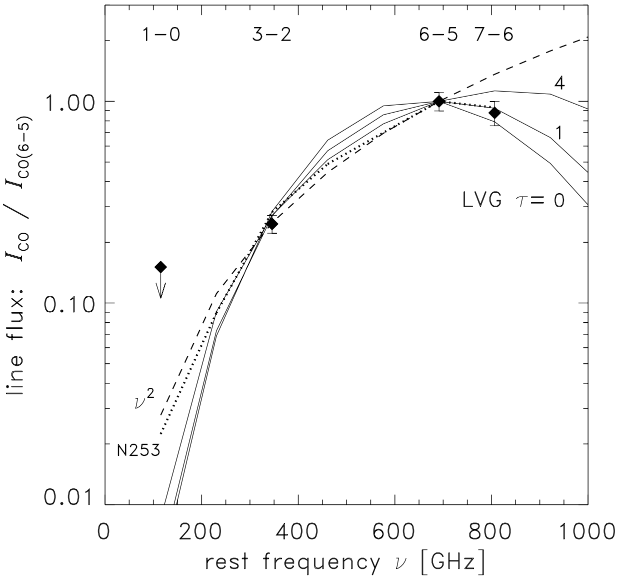

Fig. 3. Integrated line flux, $I_{\rm CO}$, normalized to CO (6→5). Diamonds show the values for J1148+5251. The dashed line shows line flux increasing as ν^2, which is expected for optically thick conditions. The solid lines show LVG models with $T_{\rm kin} = 120$ K and $n({\rm H_2}) = 4.5 \times 10^4$ cm^{-3}, with different maximum optical depth in the CO lines. The dotted line shows the line flux distribution observed for the starburst nucleus of NGC 253 (Bradford et al. 2003).

(~0.4 mJy per 24 km s^{-1}). No CO (1 → 0) emission was detected at the redshift found for the higher CO transitions (Table 1).

3. Discussion

To constrain the physical conditions of the molecular gas in J1148+5251 we compared the observed CO line flux ratios with those predicted by a one-component large velocity gradient (LVG) model (Mao et al. 2000). The line flux ratios are determined by the gas density, temperature, and the optical depth in the CO lines, i.e., the column density of CO per velocity interval. The large flux ratio between the (6 → 5) and (3 → 2) lines implies that the gas has a high excitation. The lower excitation of the $J = 7$ level suggests a moderate optical depth (Fig. 3).

High gas densities are typical of the molecular gas present in the nuclear regions of nearby starburst galaxies (Solomon & Downes 1998). The most extreme conditions so far were found in the starburst nucleus of NGC 253 (Fig. 3), where the CO excitation is similar to that in J1148+5251. Detailed LVG modeling by Bradford et al. (2003) indicate that the CO, ^{13}CO, and H_2 data of NGC 253 are consistent with $n({\rm H_2}) = 4.5{\times}10^4$ cm^{-3} and $T = 120$ K, and CO line optical depths $\tau < 4$ (Fig. 3). With only three line fluxes and one upper limit, we cannot constrain the physical conditions of the gas in J1148+5251 as tightly: the data can be fit both with low-opacity models, in which temperature and density are degenerate, $Tn^{1/2} \approx 2.5{\times}10^4$ K cm$^{-1.5}$, and with high-opacity lower-excitation models. With the high excitation temperatures for the gas in NGC 253 and J1148+5251 the cosmic background temperature (3 K and 20 K, respectively) does not affect the gas excitation notably.

To infer the total molecular mass from the CO emission in the absence of constraints on the CO abundance, one typically adopts an empirical conversion factor, α, between the apparent CO (1 → 0) line luminosity $L'_{\rm CO}$, and the total molecular mass, $M_{\rm H_2}$. However, this conversion may depend on the CO excitation. In nearby starbursts with moderate gas excitation, Downes & Solomon (1998) derive $\alpha = 0.8\, M_\odot$ (K km s^{-1} pc^2)$^{-1}$. The high excitation and moderate line opacities of our one-component LVG model for J1148+5251 predict a CO (1→0) line flux much lower than that of an optically thick distribution (Fig. 3). As observed for NGC 253, it is likely that an optically thick, low-excitation molecular component adds to the lower J level populations. Given this uncertainty, and since a value of α for very high excitation conditions is unknown, we do not estimate the mass on the one component LVG predictions, but extrapolate to $L'_{\rm CO(1\to0)} = 2.7 \times 10^{10}$ K km s^{-1} pc^2, with the assumption of a constant line brightness temperature (the optically thick case) from $J = 1$ to 6. With the quoted conversion factor, we find $M_{\rm H_2} \approx 2 \times 10^{10}\, M_\odot$. We then estimate the gas to dust mass ratio $M_{\rm H_2}/M_{\rm dust} \approx 30$, which is similar to the values found for local ULIRGs and other high redshift quasars (e.g., Guilloteau et al. 1999; Cox et al. 2002).

The minimum area of the molecular region can be estimated from the ratio of the observed line brightness temperature (11 mK for CO (6→5)) and the intrinsic line brightness, which is 23 and 56 K in the LVG models with $\tau = 4$ and 1, respectively (Fig. 3). With a 5″ beam the corresponding source radius (assuming uniform coverage) is 0.1–0.15″, or 560–840 pc. Placing $2 \times 10^{10}\ M_\odot$ in a volume of radius 560 pc gives an average CO column density $1.2 \times 10^{20}\ (X_{\rm CO}/10^{-4})\ {\rm cm}^{-2}$, where $X_{\rm CO}$ is the CO abundance relative to H_2. If the observed CO lines have moderate optical depth, $\tau < 4$, the CO column is $<2 \times 10^{19}\ {\rm cm}^{-2}$, which would either require a low CO abundance, $X_{\rm CO} < 2 \times 10^{-5}$, or a larger volume. Considering the low gas-to-dust ratio estimated above and the high metalicities implied by the optical lines (Fan et al. 2003), a CO abundance much lower than the Galactic $\sim 10^{-4}$ seems unlikely. Rather, a larger radius of ∼1400 pc for the gas distribution could account for the moderate CO line opacities.

If the molecular gas forms an inclined disk (angle i relative to the sky plane) in Keplerian rotation about a spherical mass, the line width and a minimum source radius between 560 and 1400 pc yield a minimum gravitating (dynamical) mass enclosed by the disk of $(2{-}6) \times 10^9\ \sin^{-2} i\ M_\odot$. For large inclination angles this mass would not be much larger than that of the black hole, and a factor 4–10 smaller than the gas mass implied by the line intensities. The latter may have been overestimated given the approximate nature of our estimate; alternatively, the CO disk inclination is close to the sky plane, $i \sim 20{-}30$ deg, which is more likely considering the large dust mass, and the fact that the AGN is optically unobscured.

The detection of large amounts of dense molecular gas in J1148+5251 supports the conjecture that the strong far-infrared luminosity seen from many quasars arises from extended star forming regions, and is not due to heating from the AGN (Omont et al. 2001, 2003; Carilli et al. 2001). Although for J1148+5251 the emission remains spatially unresolved, the large masses of warm CO are unlikely to be heated by the AGN at a kpc distance. With the estimated mass of molecular gas of $\sim 2 \times 10^{10}\ M_\odot$ star formation in J1148+5251 could be sustained at the rate $\sim 3000\ M_\odot\ {\rm yr}^{-1}$ implied by the far-infrared luminosity for a short time only, <10 million years. This is comparable to the estimated duty cycle time of quasars (e.g. Wyithe & Loeb 2003), and to the dynamical time of the star forming region, which implies a rapid gas depletion unless the system continues to accrete gas at a high rate. If the replenishing gas is of low-metalicity, the short depletion time suggests that the enrichment with heavy elements and dust is rapid, which leaves only supernovae and winds from the most massive stars as possible sources.

Our low estimate for the dynamical to luminous mass ratio excludes the presence of a large stellar mass within the volume of the CO emission. The duration of star formation at the present rate could therefore not have been much longer than 10^7 yr, unless the starburst does not form many long-lived, low-mass stars, in which case the star formation rate would have been overestimated and the depletion time could be longer.

The dynamical mass is an order of magnitude smaller than the bulge mass deduced from the correlation between the black hole mass and the bulge mass (or velocity dispersion) in local spheroids (Magorrian et al. 1998). This could be due to a biased selection of a non-representative, bright quasar, or it confirms a tendency for the stellar to black hole mass ratio to decrease at higher redshifts (Rix et al. 2001), possibly due to self-regulating star formation mechanisms (Wyithe & Loeb 2003).

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