Molecular Gas in the Host Galaxy of a Quasar at Redshift z=6.42

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Observations of the molecular gas phase in quasar host galaxies provide fundamental constraints on galaxy evolution at the highest redshifts. Molecular gas is the material out of which stars form; it can be traced by spectral line emission of carbon–monoxide (CO). To date, CO emission was detected in more than a dozen quasar host galaxies with redshifts (z) larger 2, the record holder being at z=4.69[1–3]. At these distances the CO lines are shifted to longer wavelengths, enabling their observation with sensitive radio and millimetre interferometers[4]. Here we present the discovery of CO emission toward the quasar SDSS J114816.64+525150.3 (hereafter J1148+5251) at a redshift of z=6.42[5,6] (when the universe was only ∼1/16 of its present age). This is the first detection of molecular gas at the end of cosmic reionization. The presence of large amounts of molecular gas ($M(H_2)=2.2\times10^{10}\,M_\odot$) in an object at this time demonstrates that heavy element enriched molecular gas can be generated rapidly in the earliest galaxies.

The source J1148+5251 is a luminous quasar which is thought to be powered by mass accretion onto a supermassive black hole of mass 1–5$\times10^9$ $M_\odot$[7]. Optical spectra of J1148+5251 show a clear Gunn–Peterson trough[5,6] (i.e. Ly α absorption by the neutral intergalactic medium), indicating that this quasar is situated at the end of the epoch of reionization[8]. Thermal emission from warm dust was detected at millimetre wavelengths, implying a far infrared (FIR) luminosity of $1.3\times10^{13}\,L_\odot$[9], corresponding to about 10% of the bolometric luminosity of the system (we assume $H_0=71\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, Ω_Λ=0.73 and Ω_m=0.27 throughout). We searched for molecular gas in J1148+5251 using the National Radio Astronomy Observatory's (NRAO) Very Large Array (VLA) and the IRAM Plateau de Bure interferometer (PdBI) in February-April 2003. The VLA observations have higher spatial resolution, whereas the PdBI has better spectral resolution. We observed the CO(3-2), (6–5) and (7–6) lines which are shifted to 46.6, 93.2 and 108.7 GHz, respectively, at $z \sim 6.42$. For J1148+5251 the possible redshift range based on broad optical emission lines is $z = 6.35$[5] to 6.43[7]. We searched this entire range for CO(3–2) emission using the VLA at a resolution of 50 MHz (320 km s^{-1}, Δz=0.008) per channel. CO(3–2) emission is clearly detected at high Signal to Noise in the channel centred at 46.6149 GHz (see Figs. 1 and 2), corresponding to a redshift of z=6.418±0.004. The PdBI covered a redshift range from z=6.40–6.44 and the CO emission is also detected at high significance (Fig. 2)[10]. In this letter we concentrate on the VLA results; a more detailed analysis of the entire dataset will be presented elsewhere[10].

The velocity–integrated CO(3-2) flux is $S_{CO(3-2)}\Delta v = 0.18 \pm 0.04$ Jy km s^{-1}. On the Kelvin scale (1 Jy = 250 K for a 1.5″ beam) the source has a peak line flux of 0.14 K and a line integral of 44±10 K km s^{-1}. The CO luminosity is given by[11]:

$$L' = 3.25 \times 10^7 \times S_{CO}\Delta v\,[\mathrm{Jy\,km\,s^{-1}}] \times \nu_{obs}^{-2}\,[\mathrm{GHz}] \times D_L^2\,[\mathrm{Mpc}] \times (1+z)^{-3}\,\mathrm{K\,km\,s^{-1}\,pc^2},$$

where D_L is the luminosity distance. For J1148+5251 we obtain: $L'_{CO(3-2)} = 2.7 \times 10^{10}$ K km s^{-1} pc^2. The total molecular gas mass, $M(H_2)$, can be derived from the relation $M(H_2) = \alpha \times L'_{CO(1-0)}$. In Galactic molecular clouds the conversion factor is $\alpha \sim 2.0\ M_\odot\ (\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$ [12], but here we use the value $\alpha \sim 0.8\ M_\odot\ (\mathrm{K\,km\,s^{-1}\,pc^2})^{-1}$, appropriate for ultraluminous infrared galaxies[13] (ULIRGs, $L_{FIR} \geq 10^{12}\ L_\odot$) and nuclear starburst galaxies[14]. Assuming a constant brightness temperature from CO(3–2) to CO(1–0)[10], this leads to $M(H_2) = 2.2 \times 10^{10}\ M_\odot$ for J1148+5251.

If the FIR luminosity of J1148+5251 is powered by star formation, the implied star formation rate (SFR) is 3000 $M_\odot\ yr^{-1}$ [9]. Comparing this to the molecular gas mass implies a short gas depletion timescale of order 10^7 years. However, given the high luminosity of the quasar it is possible that some fraction of the dust is heated by the quasar, in which case the star formation rate quoted above becomes an upper limit (resulting in a longer gas depletion timescale). The FIR continuum–to–CO line ratio for J1148+5251 is large, 440 $L_\odot$ (K km s^{-1} $pc^2)^{-1}$, which is an order of magnitude larger than for normal star forming galaxies (5-50)[15], but is comparable to that seen in ULIRGs and other high redshift quasars[9]. Some authors have suggested that high continuum–to–line ratios indicate high star formation efficiencies[15]. Alternatively, dust heating by the AGN could lead to large continuum–to–line ratios.

A dynamical mass for the system can be derived from the CO observations, assuming that the CO is rotationally supported. The upper limit to the CO source diameter derived from Gaussian fitting is 1.5″ (1″=5.46 kpc). A lower limit to the source diameter can be derived from the measured brightness temperature (T_{obs}) by assuming an intrinsic brightness temperature T_b: Ω_S/Ω_B=(T_{obs}/T_b)(1+z), where Ω_S and Ω_B are the source and beam solid angles. The most extreme case is a single optically thick emission region, in which case T_b equals T_{ex}–T_{CMB}, the excitation brightness temperture minus the continuum temperature of the cosmic background at z=6.4 ($\sim$ 20 K). This gives a minimum source diameter of $0.2''(T_b/50\,K)^{-1/2}$. Assuming a rotational velocity of $v_{rot} = 130\sin^{-1}(i)\,km\,s^{-1}$ (Fig. 2), where i is the inclination angle with respect to the sky plane, yields a range for the dynamical mass of $M_{dyn} = 2$ to $16 \times 10^9 \times \sin^{-2}(i)$ $M_\odot$. This is comparable to the molecular gas mass in J1148+5251, implying that either molecular gas dominates the dynamics of the system, or that the plane of rotation is close to the sky plane. The optical spectrum of the quasar shows no significant reddening[5], despite the large dust mass of the host galaxy[9]. This suggests that the disk of molecular gas (and dust) is oriented close to the sky plane such that the line–of–sight to the nucleus is relatively unobscured. We note that the mass of the central black hole[4] likely constitutes a significant fraction ($\sim 1 - 10\%$) of the total dynamical mass in the inner few kpc of J1148+5251, in contrast to what is generally found for nearby galaxies[16,17].

The CO redshift of z=6.419 (Fig. 2) corresponds to the systemic redshift of the host galaxy of J1148+5251, since it traces the extended molecular gas distribution in the quasar and is not associated with emission supposedly emerging from energetic processes, e.g. lines of shocked outflow gas or gas related to AGN accretion. The latter has been found to be shifted significantly in frequency with respect to the systemic redshift[18]. Indeed, studies of high ionization UV lines (in particular SiIV)[5] in J1148+5251 yield a redshift of z=6.37 corresponding to a velocity offset of $\sim$2000 km s^{-1}. The CO redshift is however in good agreement with the redshift derived from the low ionization MgII line[7].

Measuring an accurate redshift is particularly important to determine the state of the IGM around the quasar (the 'proximity effect'). In the optical spectrum[5,7] there is essentially zero emission present in the wavelength range corresponding to Lyα at z=5.7–6.33 (due to the Gunn–Peterson effect); emission for $z > 6.33$ can be attributed to the ionized medium around the quasar. Using the source redshift of 6.419 results in a Strömgren sphere around J1148+5251 with a comoving radius of R_S=4.8 Mpc. An estimate for the age for this sphere (and hence for the quasar itself) can be derived from R_S using[19,6]

$$\dot{N}_{ph}/(10^{58}\,\mathrm{s}^{-1}) \times t_q/(10^7\,\mathrm{yr}) = 0.34 \times [R_S/(4.8\,\mathrm{Mpc}) \times (1+z_q)/7.419)]^3$$

and assuming $\dot{N}_{\rm ph} = 0.2 - 1.3 \times 10^{58}\,\mathrm{s}^{-1}$ [20,21,6]. This calculation results in an age of order 10^7 yr for the quasar activity in J1148+5251. Interestingly, this timescale is comparable to the formation timescale for the central black hole, which has an e-folding timescale for accretion of order 4×10^7 yr (assuming a radiative efficiency of 0.1 and that the black hole is accreting at the Eddington limit)[7], suggesting that the AGN ionizes a significant volume around the quasar.

The fact that we detect CO emission implies that the process of enrichment of the ISM in J1148+5251 with heavy elements is relatively advanced, i.e., that significant star formation has occurred in the quasar host galaxy prior to $z = 6.4$. This conclusion is supported by the fact that both strong metal emission lines[5], and thermal emission from warm dust[9], were detected from J1148+5251. A recent optical study of a z=6.28 quasar even suggests supersolar metallicities in these early objects[22]. Assuming a Galactic abundance for J1148+5251 we derive an order of magnitude estimate for the total mass in CO of M(CO)$\sim 3 \times 10^{7}\,M_{\odot}$ [10]. This amount of C and O could be produced relatively quickly by $\sim 10^{7}$ hundred solar mass Population III stars[23] with lifetimes $< 10^{7}$ yr. Likewise, if enrichment was achieved by conventional supernovae[24] and assuming a star formation rate of order $3000\,M_{\odot}\,yr^{-1}$ [9], we estimate a time for enrichment of order 10^{7} yr. We consider this time a lower limit for enrichment of the ISM since redistribution and cooling of the gas will occur on timescales of order 10^{8} yr. This implies that the ISM enrichment process in J1148+5251 presumably started at redshifts $z > 8$. This is in agreement with the recent results from the Wilkinson Microwave Anisotropy Probe (WMAP) which indicate that the first onset of star formation most likely occured at redshifts z$\sim 15 - 17$ (~ 250 Myr after the Big Bang)[25,26,27].

The presence of Lyα emitting galaxies and luminous quasars at the end of cosmic reionization ($z > 6.3$), at a time when the IGM was at least 1% neutral, was clearly demonstrated[5,28]. This epoch of reionization represents a key bench–mark in cosmic structure formation, indicating the formation of the first luminous structures. Detecting a large reservoir of molecular gas in this epoch demonstrates the existence of the requisite fuel for active star formation in primeval galaxies. The existence of such reservoirs of molecular gas at early times implies that studies of the youngest galaxies will be possible at millimetre and centimetre wavelengths, unhindered by obscuration by the neutral IGM.

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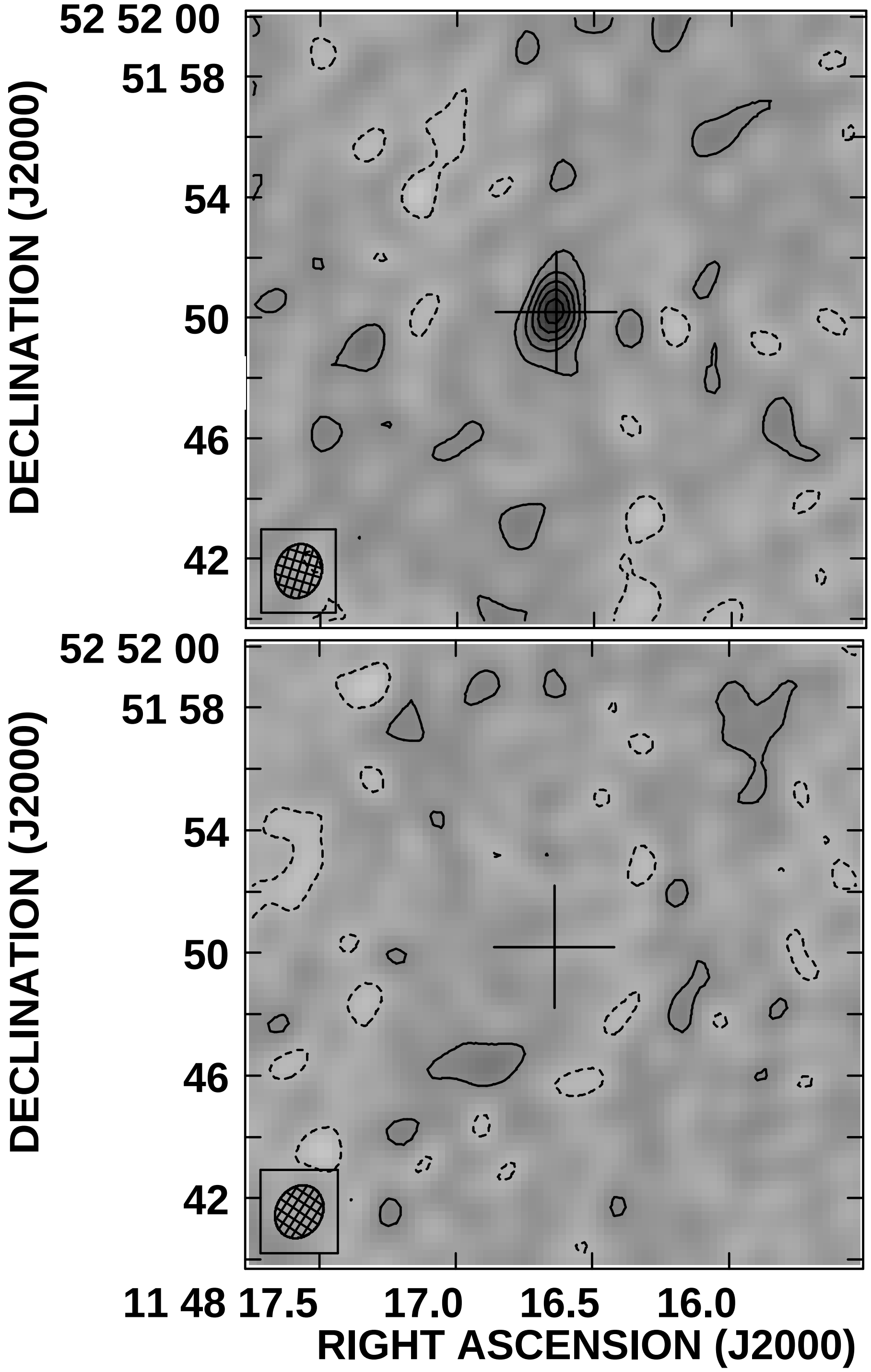
Fig. 1: CO detection in J1148+5251. Top: VLA CO(3–2) emission detected at 46.6149 GHz (z=6.418, bandwith: 50 MHz, Δz=0.008). *Bottom:* Co–added VLA emission in the neighboring line–free channels. The ($1\,\sigma$) noise in both images is 0.057 mJy beam^{-1} and contours are plotted at -0.1, 0.1, 0.2, 0.3, 0.4 and 0.5 mJy beam^{-1}. The peak flux in the top panel is 0.570 mJy beam^{-1}; i.e. J1148+5251 is detected at 10σ. Based on the line free channels we derive a 2σ upper limit to the continuum emission at 46.6 GHz (restframe wavelength=870μm) of 0.10 mJy. The cross indicates the optical position of J1148+5251. The optical and radio positions are coincident within the uncertainties ($\sim 0.1'' = 0.6$ kpc). The observations were taken with the VLA in the most compact configuration (D array, maximum baseline: $\sim$1 km, leading to a resolution of $1.8'' \times 1.5''$; the beam is plotted in the lower left of each panel). Only two 50 MHz channels can be observed at once with the VLA, i.e., the source has been observed repeatedly with different frequency settings; observations were made using two polarizations and 2 IFs of 50 MHz each, scanning in frequency from 47.065 GHz to 46.515 GHz, corresponding to a CO(3–2) redshift range of 6.347 to 6.434. The observing time for the channels shown are $\sim$20 hours, respectively. Observations were obtained in fast switching mode, and the phase stability was excellent at all times. We used the nearby quasar 11534+49311 (flux density = 1.6 Jy at 46.6 GHz) for phase and amplitude calibration. The absolute flux calibration was derived by observing 3C286. No evidence for strong gravitational lensing is seen in optical images[5], rendering strong magnification unlikely. However, the presence of an intervening galaxy at z=4.9 has been suggested based on optical spectroscopy[6], and counts of radio and optical sources in the vicinity of J1148+5251 argue for a foreground cluster, such that weak magnification ($\sim$ factor two) is possible[9,5].

Fig. 2: The CO spectrum of J1148+5251. The spectrum of the CO(3–2) line of J1148+5251 at 320 km s^{-1} resolution as observed with the VLA (top panel). The plotted errors are $\pm 1\sigma$. The averaged CO(6–5) and CO(7–6) observations from the PdBI are shown in the bottom panel[10] (channel width: 5 MHz = 13.8 km s^{-1}, noise per channel: 0.8 mJy, beam size: $\sim 5''$) to demonstrate the consistency of the results obtained by the two instruments. A Gauss fit to the PdBI data gives a velocity width of 250 km s^{-1} and a redshift of z=6.419 (corresponding to '0' velocity).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51 58
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DECLINATION (J2000)
52 52 00
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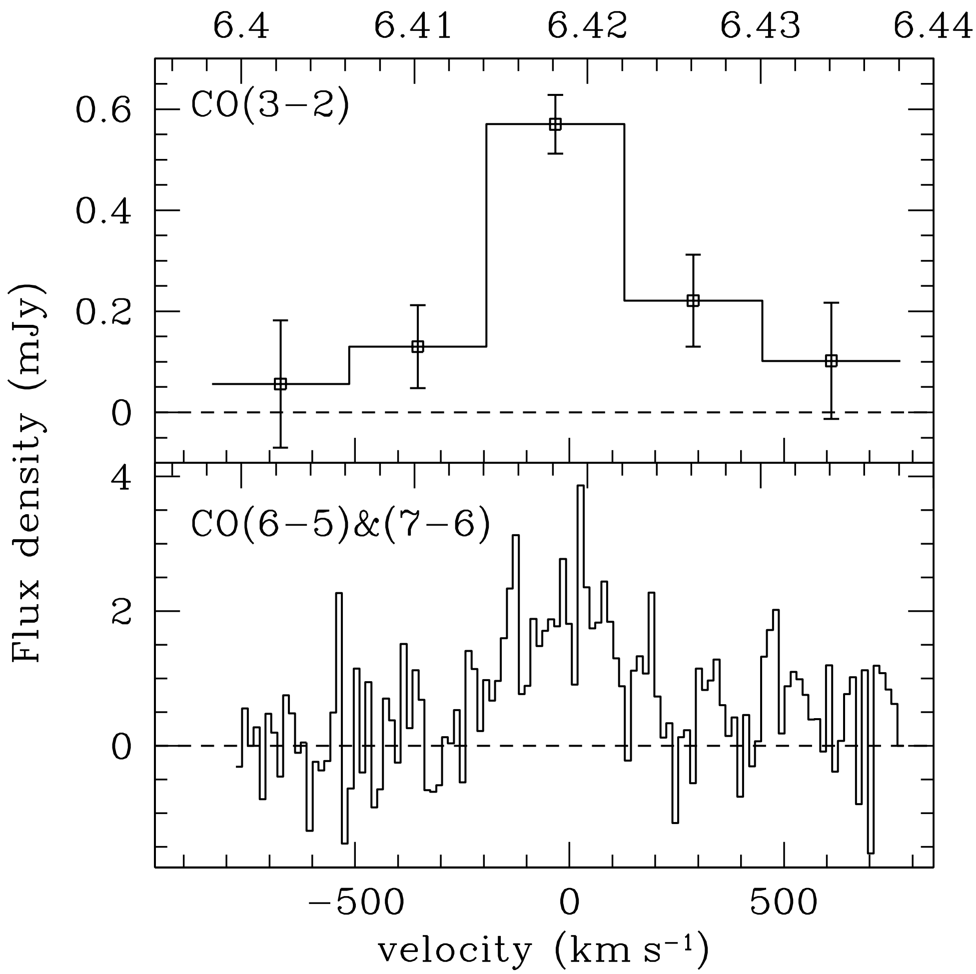
DECLINATION (J2000)
11 48 17.5
17.0
16.5
16.0
RIGHT ASCENSION (J2000)



6.4
6.41
6.42
6.43
6.44
CO(3−2)
0.6
0.4
0.2
0
Flux density (mJy)
4
CO(6−5)&(7−6)
2
0
−500
0
500
velocity (km s⁻¹)