SEARCH FOR MOLECULAR GAS IN THE QUASAR SDSS 1044–0125 AT $z = 5.73$

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ABSTRACT

We report upper limits on CO $J = 2–1$ and $J = 5–4$ emission from the quasar SDSSp J104433.04–012502.2, at $z = 5.73$, from observations made with the Berkeley-Illinois-Maryland Association array. Previously reported limits on CO $J = 6–5$ emission were obtained at $z = 5.80$, which is now thought to be off by 1%, and the observations likely missed the relevant redshifts for molecular gas. The new 3-sigma upper limits on the line luminosities are $L_{\text{CO}}(2–1) < 5.1 \times 10^{10}$ K km s$^{-1}$ pc$^2$ and $L_{\text{CO}}(5–4) < 3.0 \times 10^{10}$ K km s$^{-1}$ pc$^2$, assuming 200 km s$^{-1}$ line width. The CO $J = 5–4$ observations place an upper limit on warm, dense molecular gas mass comparable to amounts derived for some other high-redshift quasar systems from detections of this line. The limit on CO $J = 2–1$ emission suggests that excitation bias does not affect this conclusion. In addition, no companion galaxies rich in molecular gas are found in a ~1.4 Mpc field surrounding the quasar.

Key words: galaxies: ISM — quasars: individual (SDSSp J104433.04–012502.2) — radio emission lines

1. INTRODUCTION

The study of the star formation properties and gas content of galaxies at far cosmological distances is one important step toward understanding galaxy formation and evolution. The quasar SDSSp J104433.04–012502.2, at $z \approx 5.8$ (hereafter SDSS 1044–0125), discovered by Fan et al. (2000) using the Sloan Digital Sky Survey, is among the highest redshift objects known. Recent observations of this quasar with the Submillimetre Common-User Bolometer Array on the James Clerk Maxwell Telescope at 850 mm detect thermal continuum emission (reported by Iwata et al. 2001), which suggests a large reservoir of dust and also, therefore, molecular gas. The presence of a substantial gas mass gains support from the apparent X-ray weakness of the quasar, which likely results from heavy intrinsic absorption (Brandt et al. 2001; Mathur 2001). Molecular gas has been detected from at least a dozen objects through CO lines at millimeter wavelengths, and these observations provide important clues to the formation history of galaxies and their relationship to supermassive black holes.

A recent search for CO $J = 6–5$ emission from SDSS 1044–0125 by Iwata et al. (2001) reported an upper limit on the inferred molecular gas mass comparable to the detections for some high-redshift quasars. Unfortunately, the search was centered at $z = 5.80$, the initial redshift estimated by Fan et al. (2000). Recent spectroscopic studies of SDSS 1044–0125 give a more accurate value of $z = 5.73 \pm 0.01$ (Djorgovski et al. 2001; see also Goodrich et al. 2001), about 1% off from the initial estimate. Because of the narrow instantaneous bandwidth available to current millimeter interferometers, the revised redshift falls outside the window that was searched for CO $J = 6–5$ emission, and the observations likely missed the relevant redshifts for molecular gas in the quasar host. Since SDSS 1044–0125 has several properties in common with high-redshift quasars from which CO emission has been detected (enumerated by Iwata et al. 2001), the revision of the optical redshift determination gives impetus to a new search for molecular gas.

A potentially important limitation of searching for emission from CO lines with high rotational quantum numbers, such as the $J = 6–5$ transition, is that prevailing physical conditions may be insufficiently extreme to excite these lines. The surprising detection of extended emission in the low-excitation CO $J = 2–1$ line toward the quasar APM 08279+5255, at $z = 3.91$ (Papadopoulos et al. 2001), suggests that low-excitation CO lines can reveal molecular mass reservoirs that are 1 or 2 orders of magnitude larger than suggested by observations of high-excitation CO lines.

In this short paper, we present results of searches for CO $J = 2–1$ and $J = 5–4$ emission from SDSS 1044–0125 using the Berkeley-Illinois-Maryland Association (BIMA) array (Welch et al. 1996) that provide new limits on the amount of molecular gas associated with this luminous high-redshift quasar. The BIMA 1 cm band receiver system, which was developed primarily for observations of the Sunyaev-Zeldovich effect (Carlstrom, Joy, & Grego 1996; Grego et al. 2000), provides a unique facility to search for highly redshifted, low-lying CO lines. For SDSS 1044–0125, the CO $J = 2–1$ line is redshifted to 34 GHz, within the accessible tuning range. The standard digital correlator allows for several times’ larger velocity coverage than generally available at shorter wavelengths, sufficient to span the uncertainty in the quasar redshift determined from optical lines, as well as the typical kinematic offsets of molecular gas from the redshift derived optically. In addition, the small BIMA array antennas provide a large field of view, which enables imaging of the quasar environs over megaparsec scales at 34 GHz in a single pointing.

1 The BIMA array is operated by the Berkeley-Illinois-Maryland Association under funding from the National Science Foundation.


2. OBSERVATIONS

2.1. CO J = 2–1 Line

Observations of the CO J = 2–1 line [redshifted frequency 230.5380/(1 + 5.73) = 34.255 GHz] were conducted in two parts, in 2000 September and 2001 September. Both sets of observations used the nine antennas of the BIMA array equipped with 1 cm band receivers. The pointing center was \(\alpha = 10^h44^m33^s.04\), \(\delta = -1^\circ25^\prime02^\prime.2\) (J2000.0). The 2000 observations, made with the correlator centered at the nominal redshift 5.80 estimated by Fan et al. (2001), were obtained on 14 days, generally in short tracks of less than a few hours near source transit. The array antennas were in C configuration, giving \(\sim 25''\) resolution. The 2001 observations, made with the correlator centered at the revised redshift 5.73 determined by Djorgovski et al. (2001), were obtained on 2 days in longer tracks. The array antennas were in B configuration, giving \(\sim 8''\) resolution. For both sets of observations, the hybrid correlator was configured with eight individual windows, each with 32 channels spanning 100 MHz, in some cases overlapped to avoid gaps at the window edges. The system temperatures ranged from about 50 to 100 K (single sideband). Short observations of the nearby calibrator J1058+015 were made every half-hour to track the interferometer phase and also for bandpass calibration. The flux density scale was derived from observations of Mars and should be accurate to 20%. The frequency coverage and parameters of the resulting images are 85.22 to 85.92 GHz, beam 26''\(\times\)20'' p.a. 20°, rms 3.0 mJy, for 200 km s\(^{-1}\) resolution.

2.2. CO J = 5–4 Line

Observations of the CO J = 5–4 line [redshifted frequency 576.2679220/(1 + 5.73) = 85.627 GHz] were conducted on 2 days in 2001 October. These observations used 10 antennas in D configuration, giving \(\sim 20''\) resolution. As for the 2001 September observations with the 1 cm receiver system, the correlator was configured to span nearly 800 MHz centered near the revised redshift of \(z = 5.73\). The system temperatures ranged from 150 to 600 K (single sideband). Frequent observations of the nearby calibrator J1058+015 were used to track amplitude and phase, and bandpass calibration was checked with short observations of the strong source 3C 273. The flux density scale was derived from observations of Mars and should be accurate to 20%. The frequency coverage and parameters of the resulting images are 85.22 to 85.92 GHz, beam 26''\(\times\)20'' p.a. 20°, rms 3.0 mJy, for 200 km s\(^{-1}\) resolution.

3. RESULTS AND DISCUSSION

Figure 1 shows the CO J = 2–1 and CO J = 5–4 spectra obtained at the quasar position. The velocity binnings for the two lines are 200 and 162 km s\(^{-1}\), respectively. The noise in the CO J = 2–1 spectrum is not uniform, and empirical \(\pm 1\) \(\sigma\) error bars derived from the rms noise measured from the images are shown for each velocity bin. There are some tantalizing hints of signal in adjacent channels close to the expected velocities, but features with similar (low) significance are present elsewhere in the data, and we do not consider any of these features to be reliable line detections. Figure 2 shows a series of maps with 200 km s\(^{-1}\) width that span the full half-power field of view (6:6) for the J = 2–1 line. Various attempts at smoothing in both space and frequency did not uncover any significant CO emission in either of the observed transitions.

Two mechanisms have been suggested for heating large masses of dust and gas in high-redshift quasar systems: (1)
high-energy photons emitted from gases accreted onto a massive black hole and (2) bursts of star formation. If the dust is heated by the activity of a massive black hole, then bright emission may be expected from high-excitation CO lines in a compact region close to the exciting source, from large amounts of warm, dense gas involved in fueling and accretion. The CO $J = 5–4$ line, whose upper energy level lies 88 K above the ground state, requires warm gas ($>30$ K) at high densities ($>10^3$ cm$^{-3}$) to be populated significantly by H$_2$ collisions. Consequently, the upper limits on CO emission from the $J = 5–4$ line primarily constrain the amount of molecular gas with these conditions close to the massive black hole or other powerful heating sources. On the other hand, such extreme physical conditions are not necessarily appropriate for starbursts, which are likely to be distributed over larger spatial scales and involve cooler, more diffuse molecular gas. If the dust is heated primarily by star formation, then emission in CO $J = 2–1$ may be a more appropriate tracer of molecular gas content, given that the upper energy level lies just 16 K above ground and the excitation requirements are significantly less stringent.

Following Solomon, Downes, & Radford (1992), we calculate upper limits to CO line luminosities with the expression

$$L_{CO}' = 3.25 \times 10^7 S_{CO}\Delta v_{obs}^2 D_L^2 (1+z)^{-\frac{1}{2}} \text{ K km s}^{-1} \text{ pc}^2,$$

where $S_{CO}\Delta v$ is the limit on the velocity-integrated line flux in Jy km s$^{-1}$, $\nu_{obs}$ is the observing frequency in GHz, and $D_L$ is the luminosity distance in Mpc. The choice of cosmological parameters enters in $D_L$, and we adopt $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $\Omega = 1$, and $\Omega_\Lambda = 0$ for consistency with most work in this field. (An alternative cosmology with $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$, $\Omega = 1$, and $\Omega_\Lambda = 0.7$ results in $D_L$ larger by a factor of 1.54 for this redshift.) The effective line width is not known, but it likely falls in the range 150 to 550 km s$^{-1}$ found for a large sample of ultraluminous galaxies in the local universe (Solomon et al. 1997). For the 3 $\sigma$ flux limit obtained in the more sensitive part of the CO $J = 2–1$ spectrum, assuming a line width of 200 km s$^{-1}$, $L_{CO}'(2–1) < 5.1 \times 10^{10}$ K km s$^{-1}$ pc$^2$. For the 3 $\sigma$ flux limit obtained for CO $J = 5–4$, again assuming a line width of 200 km s$^{-1}$, $L_{CO}'(5–4) < 3.0 \times 10^{10}$ K km s$^{-1}$ pc$^2$. If the assumed line width were 2 times larger, then these luminosity limits would be $\sqrt{2}$ times higher.

Fig. 2.—Channel maps for the CO $J = 2–1$ line observations over the full 6/6 primary-beam half-power field of view (dashed circle). The plus sign in each panel marks the quasar position. The frequency for each panel is noted in its upper right corner. The contour levels are $\pm (3, 5) \times 0.86$ mJy. Negative contours are dotted. The top left panel shows the synthesized beam of 24" $\times$ 15" in its lower left corner.
Conversion of these CO luminosity limits to molecular gas mass limits is fraught with uncertainties. But a simple conversion factor from CO luminosity to H$_2$ mass is commonly taken to be $4.5 \times 10^{10} M_\odot$ (K km s$^{-1}$ pc$^2$)$^{-1}$, the value determined for Milky Way molecular clouds (Sanders, Scoville, & Soifer 1991). There is evidence from comparisons of luminosity-based mass estimates with dynamical mass estimates that the conversion factor may be perhaps 5 times lower in ultraluminous objects (Downes & Solomon 1998). Additional corrections of order unity are also needed to account properly for excitation from the elevated cosmic background radiation at high redshift. Adopting the Galactic conversion factor for CO $J = 2$–1 line luminosity gives a limit on the cold or diffuse molecular gas mass of $\sim 2.3 \times 10^{10} M_\odot$ in the SDSS 1044–0125 system. Using the same conversion factor for the CO $J = 5$–4 line luminosity gives a limit on the warm and dense molecular gas mass of $\sim 1.3 \times 10^{11} M_\odot$ in the SDSS 1044–0125 system.

These mass limits are comparable to the mass indicated from the detection of CO $J = 5$–4 emission from some $z > 4$ quasars, including at least two thought not to be amplified by gravitational lensing. In particular, observations of CO $J = 5$–4 emission from BR 1202–0725, at $z = 4.7$ (Omont al. 1996; Ohta et al. 1996), and BRI 1335–0417, at $z = 4.4$ (Guilloteau et al. 1997), indicate molecular gas masses in excess of $10^{11} M_\odot$ (adjusted for the cosmology and CO-to-H$_2$ conversion factor adopted here). There is no clear physical argument to explain why some quasar environments show CO emission at this sensitivity level while others do not (Guilloteau et al. 1999). In any case, the CO $J = 2$–1 and $J = 5$–4 luminosity limits suggest that the environment of SDSS 1044–0125 does not possess an enormous mass reservoir of either low-excitation or high-excitation molecular gas.

The CO $J = 2$–1 limit is comparable to the amount of molecular gas detected toward the lensed quasar APM 08279+5255, where Papadopoulos et al. (2001) found several CO $J = 2$–1 emission features with total luminosity $(6.6 \pm 3.1) \times 10^{11}$ K km s$^{-1}$ pc$^2$ attributed to (unlensed) molecular gas–rich companion galaxies to the quasar host. For the SDSS 1044–0125 observations, such features would have been contained within 1 synthesized beam (together with any nuclear emission). The luminosity limit suggests that no comparable population of nearby massive companions is present. Moreover, no significant CO $J = 2$–1 emission features are found within the entire field of view, which spans $\sim 1.4$ Mpc, suggesting that such massive cold molecular gas concentrations are rare. Observations of SDSS 1044–0125 with better sensitivity are needed to explore whether smaller but still significant concentrations of low-excitation molecular gas are present in the environment of this high-redshift quasar.

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