CO($J=6$–5) Observations of the Quasar SDSS 1044−0125 at $z=5.8$

Ikuru Iwata and Kouji Ohta
Department of Astronomy, Faculty of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
iwata@kusastro.kyoto-u.ac.jp
Kouichiro Nakanishi and Kotaro Kohno
Nobeyama Radio Observatory, National Astronomical Observatory of Japan,
Minamimaki, Minamisaku, Nagano, 384-1305
and
Richard G. McMahon
Institute of Astronomy, Madingley Road, Cambridge, CB3 0HA, UK

(Received 2001 June 8; accepted 2001 July 9)

Abstract

We present a result of CO(J = 6–5) observations of a quasar SDSSp J104433.04−012502.2 at z = 5.8. Ten days of observations with the Nobeyama Millimeter Array yielded an rms noise level of $\sim$ 2.1 mJy beam^{-1} in a frequency range from 101.28 GHz to 101.99 GHz at a velocity resolution of 120 km s^{-1}. No significant clear emission line was detected in the observed field and frequency range. The three-sigma upper limit on the CO($J=6$–5) luminosity of the object is 2.8 $\times 10^{10}$ K km s^{-1} pc^2, corresponding to a molecular gas mass of $1.2\times10^{11}M_\odot$, if a conversion factor of 4.5 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ is adopted. The obtained upper limit on the CO luminosity is slightly smaller than those observed in quasars at $z=4$–5 toward which CO emissions are detected.

Key words: CO emission line — galaxies: formation — galaxies: individual (SDSSp 104433.04−012502.2) — quasars: formation — quasars: general

1. Introduction

A luminous quasar in a high-redshift universe has been supposed to inhabit a massive host galaxy in its forming phase. Haehnelt and Rees (1993) showed that this scenario can well-reproduce an observed evolution of the luminosity function of AGNs/QSOs. More recently, Kauffmann and Haehnelt (2000) showed that the star-formation history of the universe can also be accounted for by this scenario with some assumptions for the physical process of star formation and AGN formation. The scenario is also supported by a linear correlation between a black hole mass at the center of a galaxy and the mass of a spheroid component of its host galaxy in the local universe (e.g., Kormendy, Richstone 1995). Thus, a luminous quasar at high redshift may be a site where burst star formation under which the bulk of the stellar population of a present-day massive elliptical galaxy formed is on-going.

During these several years, huge amounts of molecular gas and dust have been found in quasars up to $z = 4.7$ (e.g., Ohta et al. 1996; Omont et al. 1996a; Isaak et al. 1994; Omont et al. 1996b; McMahon et al. 1999). Molecular gases have also been detected toward two radio galaxies at $z = 3.8$ (Papadopoulos et al. 2000). These detections strongly suggest the presence of intense starburst activity in the host galaxies, and that the inferred star-formation rates in these systems are on the order of 1000 $M_\odot$ yr^{-1}, judging from the estimated masses of the molecular gas and the dust ($10^{10-11} M_\odot$ and $10^9 M_\odot$, respectively). The physical conditions of the molecular clouds can also be examined by multi-transition CO observations (e.g., Ohta et al. 1998; Papadopoulos et al. 2001). Moreover, some of these objects show the presence of two molecular-gas components physically close to each other (Omont et al. 1996a; Papadopoulos et al. 2000); we may be witnessing a merging process and the star burst may be triggered by the interaction. Therefore, the detection of CO emission from a higher redshift quasar provides an opportunity to study the starting epoch of galaxy formation, the star-formation properties of a galaxy during a forming phase, and the dynamical assembling process of a galaxy. It may also be possible to obtain a clue to examine whether a quasar appeared before the formation of the bulk of stars in a galaxy by CO observations as well as submillimeter observations of quasars at the highest redshift.

SDSSp J104433.04−012502.2 (or SDSS 1044−0125 for short) is a quasar located at $z = 5.8$, which was the highest among quasars known at the time of the observation (Fan et al. 2000). This quasar is one of the most promising targets for a CO search, because (1) the continuum emission at 850 μm has recently been detected with a flux density of 6.2 ± 2.0 mJy by SCUBA on JCMT (McMahon, private communication). (2) The rest-frame B-band absolute magnitude is estimated to be ~ -28 mag, which is the brightest among high-z quasars and is comparable to those toward which CO emission was detected (Omont et al. 1996b). (3) The rest-frame UV spectrum shows a broad "weak"-type profile of Lyα; CO and dust tend to be detected in such quasars (Omont et al. 1996b). (4) A Lyman limit system at $z = 5.72$ is seen in the spectrum of the quasar; the presence of the Lyman limit system at such a close redshift is also a common feature seen in high-z quasars toward which CO emission is detected. Motivated by these data, we made CO($J = 6$–5) observations of the quasar, while aiming to push CO detection back to the earlier universe. Throughout this paper, we adopt a cosmological parameter set of $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0.5$, and $\Lambda = 0$.

2. Observations and Data Reduction

The observations were executed during a total 10 nights (2000 November 25–29, and 2000 December 20–24) using Nobeyama Millimeter Array (NMA) of Nobeyama Radio Observatory (NRO).[1] The array configuration for both observations was D, which is the most compact configuration of NMA, giving an angular resolution (half-power beam size) of $7''$ at the observed frequency. The field of view was $\sim 70''$ centered on the quasar.

Fan et al. (2000) estimated the redshift of SDSS 1044−0125 to be 5.80 ± 0.02, using observed wavelengths of the O I + Si II λ1302 and Si IV + O IV] λ1400 emission lines. It is known that high-ionization rest-frame UV emission lines, such as Si IV, observed in quasars at $z > 1$ show blueshifts of several hundred km s^{-1} or larger with respect to systemic redshifts (McIntosh et al. 1999). We adopted 500 km s^{-1} for the amount of the blueshift, and obtained an estimated systemic redshift of 5.811. The difference between the observed frequencies of CO ($J = 6$–5) emission from objects at redshifts of 5.800 and 5.811 are $\sim$ 165 MHz, which is very small compared with a wide coverage of the spectrometer used (1024 MHz, $\sim$ 3000 km s^{-1}). The central frequency for the first observing run (November) was 101.52 GHz, the expected frequency of CO ($J = 6$–5) emission from the object located at $z = 5.811$. Among the data taken in the first observing run, some data showed a hint of the presence of an emission feature around 101.8 GHz; hence, we slightly shifted the observed frequency for the second observing run (December). The central frequency was set to be 101.76 GHz. The frequency range covered by both observing runs was $\sim$780 MHz (about 2300 km s^{-1} or a redshift ranging from 5.78 to 5.83).

In general, the weather conditions were fairly good, except for four nights, when the atmospheric phase stability was not always good. The system noise temperature (SSB) was $\sim$400 K during the observations. We used a quasar J1058+015 as a reference calibrator, which is located very close ($\sim 5^\circ$) to the quasar.

Data reduction and analysis were made using UVPROC2 developed by NRO, and AIPS developed by NRAO, USA. Data reduction was made independently by two of the authors (II and KN), by employing a different selection criterion for the quality of the data. K.N. severely judged the quality of the data and discarded any low-quality data, such as those taken under a relatively bad atmospheric condition or at low elevation. I.I. adopted a relatively loose criterion for data quality and included data of all 10 days; the resulting total effective on-source time was $\sim$ 36 hours. There is no distinct difference between the resulting two spectra at the quasar position, except for a rather poorer signal-to-noise ratio in the severe criterion case. We also examined the two dirty channel maps and found no significant difference at and around the quasar. We use the latter result below.

[1] NRO is a branch of the National Astronomical Observatory, an inter-university research institute operated by the Ministry of Education, Culture, Sports, Science and Technology.

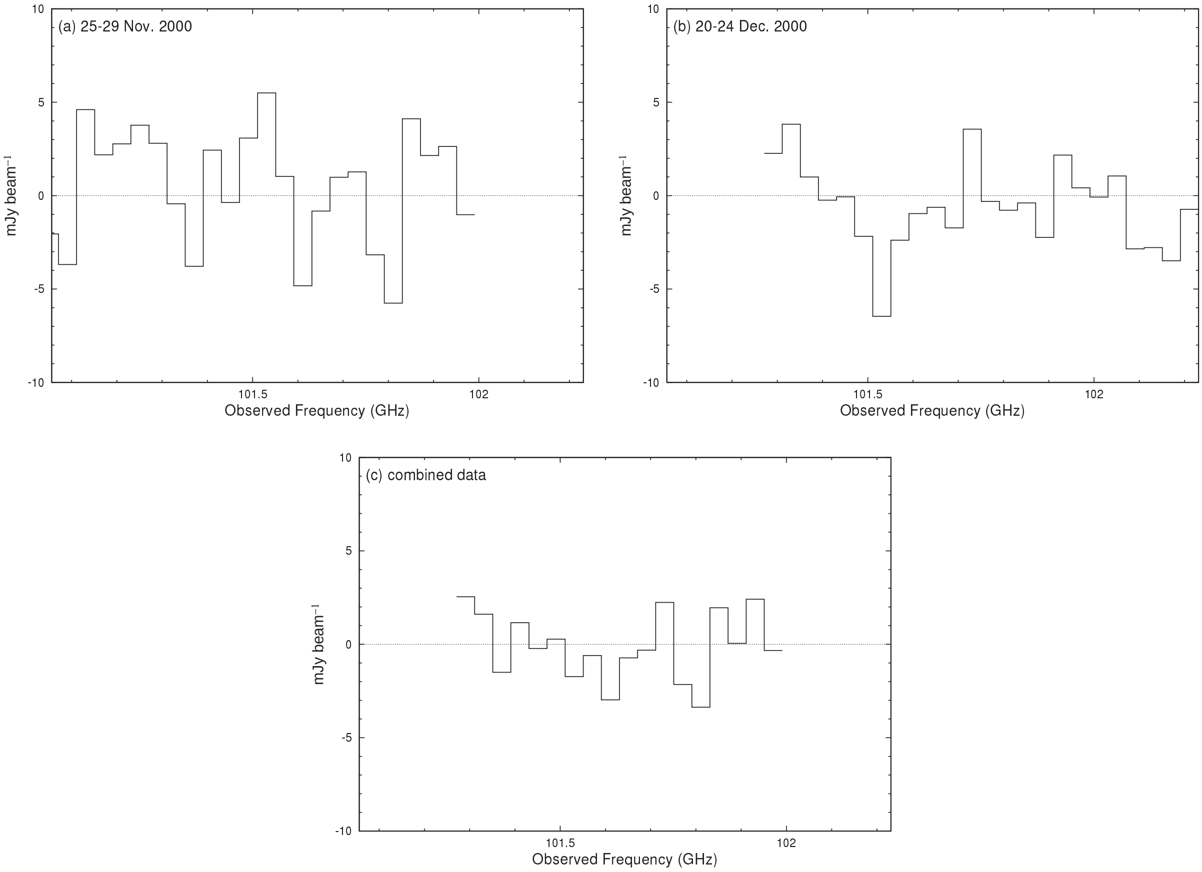

Fig. 1. Spectra at the optical position of the quasar SDSS 1044−0125. (a) and (b) show spectra obtained during the first and the second observing run, respectively. (c) A spectrum made by combining 10 days of data. Only the frequency range common to both observing runs is plotted.

3. Results and Discussion

In figure 1 we present spectra at the optical position of the quasar with a resolution of 40 MHz ($\sim$ 120 km s^{-1}). Figures 1a and b show the spectra obtained in the first and second observing runs, respectively. Note that the observed frequency range for the two runs is slightly different from each other. For each spectrum, data of five-days are combined. The resulting rms noise at a 40 MHz bin is 3.2 mJy beam^{-1} and 2.7 mJy beam^{-1}, respectively. There is no significant emission feature appearing in both spectra. Figure 1c shows a spectrum made by combining 10 days of data. Only the frequency range common to both observations was plotted, and a typical rms noise is 2.1 mJy beam^{-1}. Within the reduced rms noise level, figure 1c indicates no significant emission feature. Although we also checked spectra with different frequency resolutions, we could not find any significant sign of emission lines.

We carefully examined the channel maps of each observing run and combined data with different channel binings. There are some "spikes" in the field around the quasar, each of which was not common to all of observing days but appeared in data taken in particular one or two days. Some of them remain in combined data. We consider that they are spurious noise, since no such features appeared throughout the other observing days.

The 3σ upper limit on the CO luminosity ($L'_{\rm CO}$) of the quasar was calculated by modifying the equation by Solomon, Downes, and Radford (1992) as follows:

$$L'_{\rm CO} = \frac{c^2}{2k} \frac{d_L^2 \; 3\sigma_\nu \; \sqrt{\delta v \Delta v}}{\nu_{\rm rest}^2 \; (1+z)} \; , \tag{1}$$

where c is the speed of light, k the Boltzmann constant, d_L the luminosity distance to the object, σ_ν the rms noise flux density (2.1 mJy beam^{-1} for a frequency range 101.28 GHz to 101.99 GHz), δv the velocity resolution (120 km s^{-1}), Δv the assumed velocity width of the emission line (250 km s^{-1}), $\nu_{\rm rest}$ the rest-frame central frequency observed, and z the redshift of the object. The 3σ upper limit of the CO(J = 6–5) luminosity of SDSS1044$-$0125 was thus derived to be 2.8 $\times 10^{10}$ K km s^{-1} pc^2. If we adopt a CO-to-H_2 conversion factor of 4.5 $M_\odot$ (K km s^{-1} pc^2)$^{-1}$ (e.g., Solomon et al. 1992), the upper limit on the molecular gas mass is estimated to be 1.2×10^{11} $M_\odot$. The CO luminosity upper limits for the frequency ranges covered by just one observing run are 4.2 $\times 10^{10}$ K km s^{-1} pc^2 in 101.04 GHz to 101.28 GHz, and 3.5 $\times 10^{10}$ K km s^{-1} pc^2 in 101.992 GHz to 102.272 GHz.

We can now compare the values with those detected in high-redshift ($z > 4$) quasars. Since the CO(J = 7–6) and CO(J = 5–4) flux densities of BR 1202$-$0725 at $z = 4.7$ are very similar to each other (Omont et al. 1996a), it would be reasonable to regard that the CO(J=6–5) flux density of the object is close to that of CO(J = 5–4) emission (9.3 mJy). Then, the CO(J = 6–5) luminosity of BR 1202$-$0725 is estimated to be 5.1 $\times 10^{10}$ K km s^{-1} pc^2. (We also suppose that the line width of 220 $\pm$ 74 km s^{-1} does not change with the transitions.) The upper limit of CO(J = 6–5) luminosity of SDSS 1044$-$0125 is slightly smaller than that of BR 1202$-$0725. CO(J = 5–4) emission from BRI 1335$-$0417 at $z = 4.4$ (Guilloteau et al. 1997) and from BRI 0952$-$0115 at $z = 4.4$ (Guilloteau et al. 1999) are detected. As is the case for BR 1202$-$0725, if we suppose that their CO(J = 6–5) flux densities are close to the CO(J = 5–4) flux densities (peak flux of 6mJy, velocity width of 420 $\pm$ 60 km s^{-1} for BRI 1335$-$0417, 4mJy, 230 $\pm$ 30 km s^{-1} for BRI 0952$-$0115), the CO(J = 6–5) luminosities for BRI 1335$-$0417 and BRI 0952$-$0115 are 4.3×10^{10} and 1.6×10^{10} K km s^{-1} pc^2, respectively. SDSS 1044$-$0125 is less luminous than BRI 1335$-$0417, though our 3σ upper limit is slightly larger than the CO luminosity of BRI 0952$-$0115. Note, however, that there is a possibility of amplification by gravitional lensing for these quasars, especially for BRI 0952$-$0115. Much deeper CO observations would be required to discuss the amount of molecular gas in this object.

References

Fan, X., White, R. L., Davis, M., Becker, R. H., Strauss, M. A., Haiman, Z., Schneider, D. P., Gregg, M. D., et al. 2000, AJ, 120, 1167

Guilloteau, S., Omont, A., Cox, P., McMahon, R. G., & Petitjean, P. 1999, A&A, 349, 363

Guilloteau, S., Omont, A., McMahon, R. G., Cox, P., & Petitjean, P. 1997, A&A, 328, L1

Haehnelt, M. G., & Rees, M. J. 1993, MNRAS, 263, 168

Isaak, K. G., McMahon, R. G., Hills, R. E., & Withington, S. 1994, MNRAS, 269, L28

Kauffmann, G., & Haehnelt, M. 2000, MNRAS, 311, 576

Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581

McIntosh, D. H., Rix, H.-W., Rieke, M. J., & Foltz, C. B. 1999, ApJ, 517, L73

McMahon, R. G., Priddey, R. S., Omont, A., Snellen, I., & Withington, S. 1999, MNRAS, 309, L1

Ohta, K., Nakanishi, K., Akiyama, M., Yamada, T., Kohno, K., Kawabe, R., Kuno, N., & Nakai, N. 1998, PASJ, 50, 303

Ohta, K., Yamada, T., Nakanishi, K., Kohno, K., Akiyama, M., & Kawabe, R. 1996, Nature, 382, 426

Omont, A., McMahon, R. G., Cox, P., Kreysa, E., Bergeron, J., Pajot, F., & Storrie-Lombardi, L. J. 1996b, A&A, 315, 1

Omont, A., Petitjean, P., Guilloteau, S., McMahon, R. G., Solomon, P. M., & Pécontal, E. 1996a, Nature, 382, 428

Papadopoulos, P., Ivison, R., Carilli, C., & Lewis, G. 2001, Nature, 409, 58

Papadopoulos, P. P., Röttgering, H. J. A., van der Werf, P. P., Guilloteau, S., Omont, A., van Breugel, W. J. M., & Tilanus, R. P. J. 2000, ApJ, 528, 626

Solomon, P. M., Downes, D., Radford, S. J. E. 1992, ApJ, 398, L29