THE MOLECULAR GAS CONTENT OF $z > 6.5$ LYMAN-$\alpha$ EMITTERS

JEFF WAGG$^1$, NISSIM KANEKAR$^1$, AND CHRISTOPHER L. CARILLI

National Radio Astronomy Observatory, P.O. Box 0, Socorro, NM 87801, USA; jwagg@nrao.edu

Received 2008 December 29; accepted 2009 April 8; published 2009 April 29

ABSTRACT

We present results from a sensitive search for CO $J=1$–0 line emission in two $z > 6.5$ Lyman-$\alpha$ emitters (LAEs) with the Green Bank Telescope. CO $J=1$–0 emission was not detected from either object. For HCM 6A, at $z \sim 6.56$, the lensing magnification factor of $\sim 1.5$ implies that the CO nondetection yields stringent constraints on the CO $J=1$–0 line luminosity and molecular gas mass of the LAE, $L'_{\text{CO}} < 6.1 \times 10^{10} (\Delta V/300)^{1/2} \times (X_{\text{CO}}/0.8) M_\odot$. These are the strongest limits obtained so far for a $z \gtrsim 6$ galaxy. For IOK-1, the constraints are somewhat less sensitive, $L'_{\text{CO}} < 2.3 \times 10^{10} (\Delta V/300)^{1/2} K\text{ km s}^{-1}\text{ pc}^2$ and $M_{\text{HI}} < 1.9 \times 10^{10} (\Delta V/300)^{1/2} (X_{\text{CO}}/0.8) M_\odot$. The nondetection of CO $J=1$–0 emission in HCM 6A, whose high estimated star formation rate, dust extinction, and lensing magnification make it one of the best high-$z$ LAEs for such a search, implies that typical $z \gtrsim 6$ LAEs are likely to have significantly lower CO $J=1$–0 line luminosities than massive submillimeter galaxies and hyperluminous infrared quasars at similar redshifts, due to either a significantly lower molecular gas content or a higher CO-to-H$_2$ conversion factor.

Key words: cosmology: observations – early universe – galaxies: evolution – galaxies: formation – galaxies: high-redshift – galaxies: individual (HCM 6A)

1. INTRODUCTION

In recent years, multiwavelength selection techniques have been successful in identifying different populations of star-forming galaxies at high redshifts, $z \gtrsim 6$ (see Ellis 2008 for a recent review). An important class of such galaxies consists of the Lyman-$\alpha$ emitters (hereafter LAEs), objects identified through their excess emission in narrowband images centered on the redshifted Lyman-$\alpha$ wavelength (e.g., Hu et al. 1998; Rhoads et al. 2000; Taniguchi et al. 2005). Follow-up Lyman-$\alpha$ spectroscopy has yielded accurate redshifts for a significant fraction of the LAE population (e.g., Taniguchi et al. 2005; Kashikawa et al. 2006), unlike most other high-$z$ star-forming galaxies (e.g., Lyman-break systems, submillimeter galaxies), which typically only have photometric redshifts. In fact, an LAE at $z = 6.96$ (Iye et al. 2006) has the highest confirmed spectroscopic redshift of all presently known galaxies.

LAEs constitute a significant fraction of the star-forming galaxy population at $z \sim 6$, sufficient to reionize the universe at earlier epochs (e.g., Fan et al. 2006). The number density of LAEs and the typical shape of the Lyman-$\alpha$ emission line therefore provide important probes of physical conditions in the Universe around the epoch of reionization (e.g., Haiman & Spaans 1999; Haiman 2002; Kashikawa et al. 2006). Equally important, the steep drop in the space density of quasars at $z \gtrsim 6$ implies that they would be unable to produce the ultraviolet (UV) background radiation required to reionize the universe (e.g., Hu et al. 2002; Haiman 2002). We note that the tentative detection of the H$\alpha$ line in a single $z \sim 6.56$ LAE (Chary et al. 2005) yielded a significantly higher SFR estimate ($140 M_\odot \text{ yr}^{-1}$) than that obtained even from the rest-frame UV continuum ($\sim 9 M_\odot \text{ yr}^{-1}$); this emphasizes the possibility that the SFRs in other LAEs might have been underestimated due to dust extinction.

The detectability of high-$z$ galaxies like the LAEs relies on their undergoing an elevated level of star formation activity, which naturally requires fuel in the form of molecular gas. Such gas is most effectively studied through observations of redshifted CO emission lines (e.g., Solomon & Vanden Bout 2005). The luminosity in the low-$J$ CO lines can be used to estimate the total molecular gas mass fueling the star formation activity, while the CO line widths provide a measure of the dynamical mass of the galaxy. Studies of molecular gas at high redshifts, $z > 4$, have so far focused on the most massive, far-infrared-luminous systems, the submillimeter galaxies or quasars (e.g., Schinnerer et al. 2008; Walter et al. 2003), and no information is available in the literature on the molecular gas content of “normal” star-forming galaxies, such as the LAEs.

In the present work, we address this outstanding problem by conducting a sensitive search for low-excitation CO line emission in two $z > 6.5$ LAEs with the Green Bank Telescope.

1 Max-Planck/NRAO Fellow.
(GBT), which allows us to place strong constraints on their total molecular gas masses. Throughout this Letter, we adopt a cosmological model with \((\Omega_m, \Omega_{\Lambda}, h) = (0.73, 0.27, 0.71)\) (Spergel et al. 2007).

2. THE TARGETS

Our two target LAEs were selected to have \(z > 6.5\), to ensure that their redshifted CO \(J = 1–0\) lines could be observed with the sensitive GBT Ku-band receiver. The first system, HCM 6A at \(z \sim 6.56\) (Hu et al. 2002), is perhaps the best candidate LAE for a search for molecular emission as it is strongly lensed by a foreground cluster (Abell 370, at \(z \sim 0.375\); Kneib et al. 1993), with a magnification factor of \(\sim 4.5\); this significantly improves the sensitivity to CO emission. It also has the highest estimated SFR of all known LAEs; Chary et al. (2005) found excess broadband emission in a Spitzer Infrared Array Camera (IRAC) 4.5 \(\mu m\) image, compared to the continuum at other wavelengths, and argue that this is due to strong \(Hz\) emission, with an implied SFR of \(140 M_{\odot} yr^{-1}\). The SFR inferred from the UV continuum (uncorrected for dust effects) is significantly lower than this, \(\sim 9 M_{\odot} yr^{-1}\) (Hu et al. 2002), similar to values obtained in other LAEs at \(z \sim 6.5\) (e.g., Taniguchi et al. 2005). If the SFR derived from the Spitzer image is correct, the discrepancy between the two SFR values implies a high dust extinction, \(A_{1400} \sim 2.6\) mag, consistent with the value independently derived from a fit to the broadband photometric data (Chary et al. 2005; see also Schaerer & Pelló 2005). Such a high SFR would be similar to that of nearby ultra-luminous infrared galaxies (ULIRGs), which have typical molecular gas masses of \(10^{10}–10^{11} M_{\odot}\) (e.g., Downes & Solomon 1998). Conversely, Boone et al. (2007) argue that the limits on the 850 \(\mu m\) and 1.2 mm continuum flux densities of HCM 6A imply upper limits to the SFR in the range 10–90 \(M_{\odot} yr^{-1}\), for assumed dust temperatures in the range 18–54 \(K\); these SFR estimates are somewhat lower than the values obtained by Chary et al. (2005) and Schaerer & Pelló (2005). Chary et al. (2005) argue that the properties of HCM 6A are similar to those of other \(z \gtrsim 6\) LAEs; the molecular gas properties derived for this object are thus likely to be representative of the entire population.

Our second target, IOK-1, was discovered in a Subaru survey for \(z \sim 7\) LAEs (Iye et al. 2006) and has the highest spectroscopically confirmed redshift of all known galaxies. Iye et al. (2006) obtain a SFR of \((10 \pm 2) M_{\odot} yr^{-1}\) from the Lyman-\(\alpha\) line luminosity. Taniguchi et al. (2005) find that the SFR estimated from the UV continua of \(z \sim 6.5\) LAEs is typically \(\sim 5\) times larger than that inferred from the Lyman-\(\alpha\) line, implying that the SFR of IOK-1 is likely to be \(\gtrsim 50 M_{\odot} yr^{-1}\), among the highest of the \(z > 6\) LAE population. This system has not so far been observed at submillimeter or infrared wavelengths and no information is thus available on its dust properties.

3. OBSERVATIONS AND DATA ANALYSIS

The search for CO \(J = 1–0\) emission (\(v_{\text{rest}} = 115.2712\) GHz) from the two LAEs was carried out with the GBT 12.0–15.4 GHz Ku-band receiver between 2008 August and September, during excellent summer observing conditions. The Auto-Correlation Spectrometer was used as the backend, with two circular polarizations and a bandwidth of 200 MHz, subdivided into 8192 channels and centered on the redshifted CO \(J = 1–0\) line frequencies (14.48 GHz and 15.25 GHz). This yielded a total velocity coverage of \(\sim 4000 \text{ km s}^{-1}\) and an initial velocity resolution of \(\sim 1 \text{ km s}^{-1}\), after Hanning-smoothing and resampling. Dual-beam nodding was used to calibrate the system bandpass, with a nodding timescale of 2 minutes. The telescope pointing was corrected every 2 hr by observations of nearby bright calibrators. System temperatures were measured online by firing a noise diode, and were typically found to lie in the range 22–30 \(K\). The standard flux calibrators, 3C48, 3C147, and/or 3C286 were used to verify the absolute flux scales at the observing frequencies; we estimate that the uncertainty in the flux calibration is less than 10%. The total observing times were \(\sim 25\) hr for HCM 6A and \(\sim 23\) hr for IOK-1, including overheads associated with dual-beam nodding, pointing, and flux calibration. Note that the full width at half-maximum of the GBT Ku-band beam is \(\sim 50''\) (corresponding to a spatial scale of \(\sim 280 \text{ kpc}\) at \(z = 6.56\)), implying that all CO \(J = 1–0\) emission from the LAEs (and any nearby galaxies at similar redshifts) would lie within the telescope beam.

The data were analyzed using the GBTIDL2 data analysis package, following standard procedures. A second-order baseline was fit to each scan during the initial calibration, after which the data were examined on a scan-by-scan basis for residual baseline structure; this was done independently for both polarizations. Conservatively, all scans showing baseline structure on scales of a few tens of MHz (that might mimic a putative spectral line) were edited out and not included in the final analysis; this resulted in the exclusion of \(\sim 25\%\) of data for each target. The final on-source integration times were \(\sim 12\) hr for HCM 6A and \(\sim 11\) hr for IOK-1. For each source, data from the two polarizations were combined together with appropriate weights, based on their root-mean-square (rms) noise values to produce the final spectra. The spectra were then smoothed to coarser resolutions (50, 150, and 300 \(\text{ km s}^{-1}\)) to search for CO \(J = 1–0\) line emission.

4. RESULTS

The final spectra obtained toward HCM 6A and IOK-1 are shown in the four panels of Figure 1, at velocity resolutions of \(\sim 50 \text{ km s}^{-1}\) and \(\sim 150 \text{ km s}^{-1}\). The final rms noise values per \(50 \text{ km s}^{-1}\) channel are 52 \(\text{ mJy}\) (GBT 6A) and 51 \(\text{ mJy}\) (IKO-1), and per \(150 \text{ km s}^{-1}\) channel are 31 \(\text{ mJy}\) (HCM 6A) and 30 \(\text{ mJy}\) (IKO-1). No evidence for CO \(J = 1–0\) line emission was seen in the spectra at these (or other) velocity resolutions.

The nondetections of CO \(J = 1–0\) line emission place strong constraints on the CO line luminosities, which can, in turn, be used to derive limits on the total mass of cold molecular gas in the two LAEs. Following Solomon & Vanden Bout (2005), the CO \(J = 1–0\) line luminosity \(L_{\text{CO}}\) can be written as

\[
L'_{\text{CO}} = 3.25 \times 10^7 S_{\text{CO}} \Delta V v_{\text{obs}}^2 D_L^2(1+z)^{-3} \text{ (Jy km s}^{-1}\text{pc}^2\text{),}
\]

where \(v_{\text{obs}}\) is the observing frequency (in GHz), \(D_L\) is the luminosity distance (in Mpc), and \(L'_{\text{CO}}\) is in \(\text{ K km s}^{-1}\text{pc}^2\). For our nondetections, \(S_{\text{CO}} \Delta V \equiv \sigma_{\text{AV}} \Delta V\) (in \(\text{ Jy km s}^{-1}\)) gives the \(3\sigma\) upper limit on the integrated flux density in the CO \(J = 1–0\) line, where \(\sigma_{\text{AV}}\) is the rms noise at the velocity resolution \(\Delta V\). We will assume a line width of \(\Delta V = 300 \text{ km s}^{-1}\), similar to the median observed width in high-z quasars (e.g., Carilli & Wang 2006). We then obtain \(3\sigma\) CO \(J = 1–0\) line luminosity limits of \(L'_{\text{CO}} < 6.1 \times 10^7 (\Delta V/300)^{1/2} \text{ K km s}^{-1}\text{ pc}^2\) (GBT 6A) and \(L'_{\text{CO}} < 2.3 \times 10^{10} (\Delta V/300)^{1/2} \text{ K km s}^{-1}\text{ pc}^2\) (IKO-1),

\(^2\) http://gbtidl.sourceforge.net
after correcting the HCM 6A luminosity for the lensing magnification factor of 4.5 (Kneib et al. 1993).

To convert the CO \(J = 1–0\) line luminosity to an estimate of the total molecular gas mass, we use the CO-to-H\(_2\) conversion factor \(X_{\text{CO}}\) (e.g., Solomon & Vanden Bout 2005). For virialized molecular clouds in a quiescent galaxy like the Milky Way, the conversion factor is typically \(X_{\text{CO}} \approx 4.6\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\) (e.g., Solomon & Barrett 1991); conversely, luminous infrared galaxies have far lower CO-to-H\(_2\) conversion factors (\(X_{\text{CO}} \approx 0.8\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\); e.g., Downes & Solomon 1998). For the nearby dwarf starburst galaxy, M82, Weiß et al. (2001) find that the lowest values of the conversion factor are measured toward the central star-forming regions where the UV radiation field is most intense. Given that the two LAEs observed here appear to be undergoing elevated levels of star formation, we adopt the conversion factor \(X_{\text{CO}} = 0.8\) \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\).

Note that this conversion factor is also used for CO line studies of high-z submillimeter galaxies (e.g., Greve et al. 2005), allowing a direct comparison between the inferred molecular masses of submillimeter galaxies and LAEs. Using this conversion factor then yields \(M_\text{H}_2 < 4.9 \times 10^9 \times (\Delta V/300)^{1/2} \times (X_{\text{CO}}/0.8) M_\odot\) for HCM 6A, and \(M_\text{H}_2 < 1.9 \times 10^9 \times (\Delta V/300)^{1/2} \times (X_{\text{CO}}/0.8) M_\odot\) for IOK-1. We emphasize that the upper limits to the molecular gas mass would be higher than the above values if the Milky Way conversion factor were applicable to these LAEs. The results of our observations are summarized in Table 1.

Finally, the CO \(J = 1–0\) line luminosity and the far-infrared (FIR) luminosity are correlated in nearby starburst and spiral galaxies (Gao & Solomon 2004), with

\[
\log L_{\text{FIR}} = (1.26 \pm 0.08) \times \log L_{\text{CO}} - 0.81
\]

(Riechers et al. 2006). Our limits on the CO \(J = 1–0\) line luminosity can be combined with this relation to infer the FIR luminosity of the two LAEs and, hence, their SFRs. We obtain \(L_{\text{FIR}} < 3.3 \times 10^{11} L_\odot\) (HCM 6A) and \(L_{\text{FIR}} < 1.8 \times 10^{12} L_\odot\) (IOK-1), and SFRs of \(< 66\) \(M_\odot\) yr\(^{-1}\) (HCM 6A) and \(< 360\) \(M_\odot\) yr\(^{-1}\) (IOK-1), using the relation

\[
\frac{L_{\text{FIR}}}{L_{\text{CO}}} = (2 \times 10^{-10}) (L_{\text{FIR}}/L_\odot) (M_\odot\text{yr}^{-1})^{-1}
\]

(Kennicutt 1998). The limit to the SFR in HCM 6A is similar to that obtained from the 1.2 mm and 850 \(\mu\)m continuum imaging (SFR \(< 10–90\) \(M_\odot\) yr\(^{-1}\); Boone et al. 2007). While our SFR limit in HCM 6A is significantly lower than the estimate of 140 \(M_\odot\) yr\(^{-1}\) from the tentative detection of \(\alpha\) emission (Chary et al. 2005), it should be pointed out that our result depends on the assumption that the local correlation between CO \(J = 1–0\) line luminosity and FIR luminosity is applicable in \(z > 6\) LAEs. Note, however, that some classes of high-redshift galaxies (e.g., the “BzK” galaxies, selected as outliers in plots of (B – \( z\)) versus (\( z\) – K) colors; Daddi et al. 2004) have larger CO line luminosities than predicted by the FIR–CO relation, with large molecular gas masses but low star formation efficiencies (Daddi et al. 2008). If the high-redshift LAEs are similar to the BzK galaxies, our limits to the CO \(J = 1–0\) line luminosities would imply even lower FIR luminosities, and SFRs, than those listed above.

5. DISCUSSION

These are the first constraints on the CO \(J = 1–0\) line luminosity and the molecular gas mass of \(z \gtrsim 6\) LAEs, providing a new window into physical conditions in star-forming galaxies at the highest redshifts. The high inferred SFR and dust
extinction in HCM 6A, as well as its large magnification factor, imply that it is one of the best candidates for a detection of CO emission in a high-z LAE. The limit on its CO \( J = 1-0 \) line luminosity obtained here is the deepest ever obtained for a \( z \gtrsim 6 \) galaxy. For the assumed CO-to-H\(_2\) conversion factor, the molecular gas mass limit is within a factor of \( \sim 2 \) of the molecular gas mass of the Milky Way (e.g., Combes 1991). While the limit on the CO \( J = 1-0 \) line luminosity of IOK-1 is not as strong, it is lower than the median luminosity in high-z submillimeter galaxies \( L_{\text{CO}} = 3.8 \times 10^{10} \) K m s\(^{-1}\) pc\(^2\); Greve et al. 2005) and similar to the luminosities of lower redshift BzK galaxies (which have similar SFRs; e.g., Daddi et al. 2008). Our results for both LAEs rule out the presence of extreme CO \( J = 1-0 \) line luminosities, such as those seen in submillimeter galaxies or hyperluminous IR quasars (e.g., Greve et al. 2005; Walter et al. 2003; Carilli et al. 2007). LAEs thus appear to either contain significantly lower quantities of cold molecular gas or have significantly higher CO-to-H\(_2\) conversion factors than submillimeter galaxies or FIR-bright quasar hosts. The latter possibility cannot be ruled out as the CO-to-H\(_2\) conversion factor is likely to depend on metallicity (e.g., Maloney & Black 1988), and quasar host galaxies and submillimeter galaxies appear to be dusty, metal-rich systems.

Finally, it is clear that molecular gas must be present in LAEs to fuel the observed star formation activity and dust reddening. In cases where the CO line emission is optically thick and thermalized, the flux density in the CO lines scales \( \propto v^2 \propto J_U^2 \), where \( J_U \) is the rotational quantum number of the upper level. This suggests that, despite the sensitive limits obtained here, the \( J_U \gtrsim 5 \) CO lines may provide a more effective avenue to probe the molecular gas content of high-z LAEs, with planned facilities like the Expanded Very Large Array (EVLA) and the Atacama Large Millimetre Array (ALMA). For example, for optically thick, thermalized emission, ALMA would be able to detect the CO \( J = 6-5 \) line from a \( z = 6.5 \) star-forming galaxy with \( M_{\text{H}_2} = 3 \times 10^9 M_\odot \) in 3 h of on-source integration time. Unfortunately, the high kinetic temperatures and densities required to raise the CO molecules to the high-\( J \) excitation states are unlikely to be present in “normal” star-forming galaxies like the LAEs. For example, Figure 9 of Ao et al. (2008) shows that the CO line intensities are subthermal at \( J_U \gtrsim 5 \) in almost all galaxies (including ULIRGs and submillimeter galaxies) with observations of these lines. The sole exception is the lensed quasar APM08279+5255, where a combination of active galactic nucleus (AGN) heating and very high gas densities appears to yield the high CO excitation (Weiß et al. 2007). This implies that it is likely to be difficult to detect the high-\( J \) CO lines from \( z \gtrsim 6 \) LAEs even with ALMA. The 158 \( \mu m \) fine-structure transition of ionized carbon may hence prove the best candidate for mapping the large-scale structure of high-z star-forming galaxies and determining their dynamical masses (Walter & Carilli 2008). A search for this transition in HCM 6A is currently in progress (N. Kanekar et al. 2009, in preparation).

6. SUMMARY

We have carried out a deep GBT Ku-band search for CO \( J = 1-0 \) line emission from two high-redshift Lyman-\( \alpha \) emitters, HCM 6A at \( z \sim 5.66 \) and IOK-1 at \( z \sim 6.96 \). Our nondetection of CO emission from the lensed LAE, HCM 6A, implies strong constraints on its CO \( J = 1-0 \) line luminosity and molecular gas mass, \( L_{\text{CO}} \lesssim 6.1 \times 10^8 \) \((AV/300)^{1/2} \) K km s\(^{-1}\) pc\(^2\) and \( M_{\text{H}_2} < 4.9 \times 10^9 \) \((AV/300)^{1/2} \times (X_{\text{CO}}/0.8) \) \( M_\odot \), the strongest obtained to date for a \( z \gtrsim 6 \) galaxy. In the case of IOK-1, the absence of a lensing magnification factor implies that the limits on the line luminosity and molecular gas mass are somewhat less sensitive than for HCM 6A; we obtain \( L_{\text{CO}} < 2.3 \times 10^9 \) \((AV/300)^{1/2} \) K km s\(^{-1}\) pc\(^2\) and \( M_{\text{H}_2} < 1.9 \times 10^{10} \) \((AV/300)^{1/2} \times (X_{\text{CO}}/0.8) \) \( M_\odot \). If HCM 6A is a typical LAE at these redshifts, our results imply that LAEs are unlikely to show high CO \( J = 1-0 \) line luminosities (such as those found in quasar host galaxies at similar redshifts), due to either a lower molecular gas content or a higher value of the CO-to-H\(_2\) conversion factor. It hence appears that observations of redshifted CO line emission are unlikely to be an effective means of studying gas dynamics in the less-luminous galaxies responsible for reionizing the universe, even with upcoming arrays such as ALMA and the EVLA.

J.W., N.K., and C.C. are grateful for support from the Max-Planck Society and the Alexander von Humboldt Foundation. We thank the Green Bank staff for the development and implementation of a new dynamic scheduling system which enabled us to obtain excellent high-frequency observing conditions for this project (GBT08B-043). We thank the anonymous referee for helpful suggestions on the original manuscript, and Frederic Boone for comments. The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under cooperative agreement with the National Science Foundation.

REFERENCES

Ao, Y., Weiß, A., Downes, D., Walter, F., Henkel, C., & Menten, K. M. 2008, A&A, 491, 747
Boone, F., Schrerrer, D., Pelló, R., Combes, F., & Egami, E. 2007, A&A, 475, 513
Carilli, C. L., & Wang, R. 2006, AJ, 131, 2763
Carilli, C. L., et al. 2007, ApJ, 666, L9
Chary, R.-R., Stern, D., & Eisenhardt, P. 2005, ApJ, 635, L5
Combes, F. 1991, ARA&A, 29, 195
Daddi, E., Cimatti, A., Renzini, A., Fontana, A., Mignoli, M., Pozzetti, L., Tozzi, P., & Zamorani, G. 2004, ApJ, 617, 746
Daddi, E., Dannerbauer, H., Elbaz, D., Dickinson, M., Morrison, G., Stern, D., & Ravindranath, S. 2008, ApJ, 673, L21
Downes, D., & Solomon, P. M. 1998, ApJ, 507, 615
Ellis, R. S. 2008, in Saas-Fee Advanced Course 36, Cold Aqueous Planetary Geochemistry with FREZCHEM, 259
Fan, X., Carilli, C. L., & Keating, B. 2006, ARA&A, 44, 415
Fan, X., et al. 2001, AJ, 122, 2833
Finkelstein, S. L., Rhoads, J. E., Malhotra, S., & Grogin, N. 2009, ApJ, 691, 465
Gao, Y., & Solomon, P. M. 2004, ApJ, 606, 271
Greve, T. R., et al. 2005, MNRAS, 359, 1165
Haiman, Z. 2002, ApJ, 576, L1
Haiman, Z., & Spaans, M. 1999, ApJ, 518, 138
Hu, E. M., Cowie, L. L., & McMahon, R. G. 1998, ApJ, 502, L99
Hu, E. M., Cowie, L. L., McMahon, R. G., Capak, P., Iwamuro, F., Kneib, J.-P., Mairaha, T., & Motohara, K. 2002, ApJ, 568, L75
Iye, M., et al. 2006, Nature, 443, 186
Kashikawa, N., et al. 2006, ApJ, 648, 7
Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189
Kneib, J.-P., Mellier, Y., Fort, B., & Matzez, G. 1993, A&A, 273, 367
Lai, K., Huang, J.-S., Fazio, G., Cowie, L. L., Hu, E. M., & Kakazu, Y. 2007, ApJ, 655, 704
Maloney, P., & Black, J. H. 1988, ApJ, 325, 389
Rhoads, J. E., Malhotra, S., Dey, A., Stern, D., Spinrad, H., & Jannuzi, B. T. 2000, ApJ, 545, L85
Riechers, D. A., et al. 2006, ApJ, 650, 604
Schaerer, D., & Pelló, R. 2005, MNRAS, 362, 1054
Schinnerer, E., et al. 2008, ApJ, 689, L5
Solomon, P. M., & Barrett, J. W. 1991, in IAU Symp. 146, Dynamics of Galaxies and Their Molecular Cloud Distributions, ed. F. Combes & F. Casoli (Dordrecht: Kluwer), 235
Solomon, P. M., & Vanden Bout, P. A. 2005, ARA&A, 43, 677
Spergel, D. N., et al. 2007, ApJS, 170, 377
Stanway, E. R., Bunker, A. J., McMahon, R. G., Ellis, R. S., Treu, T., & McCarthy, P. J. 2004, ApJ, 607, 704
Taniguchi, Y., et al. 2005, PASJ, 57, 165
Walter, F., & Carilli, C. 2008, in ASP Conf. Ser. 395, Frontiers of Astrophysics: A Celebration of NRAO's 50th Anniversary, ed. A. H. Bridle, J. J. Condon, & G. C. Hunt (San Francisco, CA: ASP), 49
Walter, F., et al. 2003, Nature, 424, 406
Weiß, A., Downes, D., Neri, R., Walter, F., Henkel, C., Wilner, D. J., Wagg, J., & Wiklind, T. 2007, A&A, 467, 955
Weiß, A., Neininger, N., Hüttemeister, S., & Klein, U. 2001, A&A, 365, 571
Yan, H., & Windhorst, R. A. 2004, ApJ, 600, L1