A DEEP SEARCH FOR CO J = 2−1 EMISSION FROM A Lyα BLOB AT z ∼ 6.595

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ABSTRACT

We have used the Green Bank Telescope to carry out a deep search for redshifted CO J = 2−1 line emission from an extended (>17 kpc) Lyα blob (LAB), “Himiko,” at z ∼ 6.595. Our non-detection of CO J = 2−1 emission places the strong 3σ upper limit of L_{CO} < 1.8 × 10^{10} × (ΔV/250)^{1/2} K km s^{-1} pc^{2} on the CO line luminosity. This is comparable to the best current limits on the CO line luminosity in LABs at z ∼ 3 and lower-luminosity Lyα emitters at z ∼ 6.5. High-z LABs appear to have lower CO line luminosities than the host galaxies of luminous quasars and submillimeter galaxies at similar redshifts, despite their high stellar mass. Although the CO-to-H\textsubscript{2} conversion factor is uncertain for galaxies in the early universe, we assume X_{CO} = 0.8 M\textsubscript{☉} (K km s^{-1} pc^{2})^{-1} to obtain the limit M(H\textsubscript{2}) < 1.4 × 10^{10} M\textsubscript{☉} on Himiko’s molecular gas mass; this is a factor of ∼2.5 lower than the stellar mass in the z ∼ 6.595 LAB.

Key words: galaxies: high-redshift – galaxies: ISM

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1. INTRODUCTION

Significant populations of star-forming galaxies have recently been discovered at high redshifts, z ∼ 6, toward the end of the reionization epoch (e.g., Ellis 2008). Many of these galaxies have been identified due to their excess emission in narrowband images centered on the redshifted Lyα wavelength (e.g., Rhoads et al. 2000; Taniguchi et al. 2005; Hu et al. 2010); such systems are referred to as Lyα emitters (hereafter LAEs). The star formation rates (SFRs) determined from measurements of the rest-frame UV continuum emission in LAEs at z ∼ 6.5 tend to be low, SFR ∼ 5−10 M\textsubscript{☉} yr^{-1} (e.g., Taniguchi et al. 2005), and the size of the emission region is typically small, ∼1 kpc (Cowie et al. 2011).

High-z LAEs thus appear to be relatively small galaxies, probably undergoing quiescent star formation. However, a recent Subaru narrowband imaging survey has discovered a highly extended LAE at z ∼ 6.6, with a spatial extent of >10 kpc, far larger than that of the bulk of the z ∼ 6.5 LAE population (Ouchi et al. 2009). The object, “Himiko,” also has a far higher Lyα line luminosity, >10^{43} erg s^{-1}, than any other LAE at z > 6. Both the large size and the high Lyα luminosity make Himiko similar to the “Lyα blobs” (LABs) that have so far been detected at z ∼ 2.5−4 (e.g., Steidel et al. 2000; Matsuda et al. 2004, 2011; Dey et al. 2005; Nilsson et al. 2006). The LABs discovered at z ∼ 3 are extremely large (≥50 kpc in size) Lyα-emitting nebulae that show a striking correlation with overdense regions in the universe. These have Lyα luminosities >10^{43} erg s^{-1}, similar to the luminosities seen in massive high-z radio galaxies (e.g., Reuland et al. 2003), but do not show radio emission. Follow-up multi-wavelength studies have shown that LABs tend to be associated with bright submillimeter or infrared-luminous galaxies (e.g., Geach et al. 2005) or obscured active galactic nuclei (AGNs; e.g., Basu-Zych & Scharf 2004; Geach et al. 2009), often with high SFRs (∼1000 M\textsubscript{☉} per year). Recent Spitzer studies have found that the infrared (IR) images of 60% of z ∼ 3 LABs are consistent with an origin due to star formation, with the remaining 40% of the sample likely to arise either due to AGN activity or an extreme starburst (Colbert et al. 2011). A few LABs have also been detected without a known associated bright galaxy (e.g., Nilsson et al. 2006).

No LABs have so far been detected at low redshifts, z < 1 (Keel et al. 2009); the blobs thus appear to be a high-redshift phenomenon. The fact that LABs are typically located in overdense regions suggests that they are linked to the formation of the massive galaxies (e.g., Steidel et al. 2000; Erb et al. 2011). Although a number of mechanisms have been suggested for the sources that power the Lyα emission (e.g., cooling inflows of gas, outflows of gas from starburst galaxies or AGNs, or even AGN photoionization; Taniguchi & Shioya 2000; Haiman & Rees 2001; Matsuda et al. 2004; Dey et al. 2005; Dijkstra & Loeb 2009; Geach et al. 2009), it appears unclear whether any single mechanism is capable of explaining the entire LAB population. However, while cooling radiation from gas streams may contribute some fraction of the LAB power (Haiman et al. 2000; Goerdt et al. 2010), radiative transfer calculations have shown that such streams of halo gas cannot account for all the Lyα luminosity (Faucher-Giguère et al. 2010). Galaxy formation must hence be responsible for a significant fraction of the Lyα emission from LABs. Studies of the star formation activity of galaxies in the vicinity of LABs are thus essential to understanding their nature. Observations of molecular and atomic gas tracers in the LABs would provide crucial insight into the fuel for star formation. The most effective means of studying the cold molecular gas reservoir in high-z galaxies is through observations of redshifted CO line emission (e.g., Solomon & Vanden Bout 2005), which provide a means of studying gas kinematics and estimating the total molecular gas mass available for star formation.

At present, only two LABs have been searched for CO line emission, both at z ∼ 3, but with no detections of molecular gas (Yang et al. 2012). We present here a search for CO J = 2−1 line emission in the z ∼ 6.595 LAB, Himiko, in order to measure its cold molecular gas mass and constrain the kinematics of
the interstellar gas in a massive galaxy during the epoch of reionization.\textsuperscript{4}

2. HIMIKO: A Ly\textalpha\ BLOB AT z = 6.595

The target of our CO line observations, Himiko, is a giant (\gtrsim 17 kpc) LAE at z = 6.595, discovered in the Subaru/XMM-Newton Deep Survey (Ouchi et al. 2009). Himiko has an extremely high Ly\textalpha\ line luminosity, \(L_{\text{Ly}\alpha} = (3.9 \pm 0.2) \times 10^{43} \text{ erg s}^{-1}\), well into the LAB category. The Ly\textalpha\ emission yields an SFR of \(\sim 36 M_\odot \text{ yr}^{-1}\) (Ouchi et al. 2009); however, this is likely to be an underestimate by a factor of at least a few, given that the Ly\textalpha\ line is both resonantly scattered by dust, and, for these redshifts, attenuated due to absorption by the damping wing of neutral hydrogen in the intergalactic medium. The SFR of Himiko is thus likely to be significantly larger than the estimate of 36 \(M_\odot \text{ yr}^{-1}\) (Ouchi et al. 2009) used fits of stellar synthesis models to the spectral energy distribution over the optical to near-infrared (near-IR) wavelength range to obtain an extremely high stellar mass, \((0.9-5) \times 10^{10} M_\odot\), indicating that Himiko is a massive galaxy. The large transverse size of the Ly\textalpha-emitting region is also consistent with Himiko being an extremely massive object, in the context of hierarchical models of structure formation. It is thus an excellent candidate for a search for the molecular gas that fuels its high rate of star formation.

3. OBSERVATIONS AND DATA ANALYSIS

Observations of the CO J = 2–1 line emission in Himiko were made with the 110 m Green Bank Telescope (GBT) in project AGBT10B-010, using the Ka-band receiver which covers the frequency range 26–40 GHz. At the redshift of Himiko, the CO J = 2–1 line \(\nu_{\text{rest}} = 230.538 \text{ GHz}\) is redshifted to 30.354 GHz. The GBT beam at this frequency has a full width at half-maximum (FWHM) of \(30.354 \text{ GHz}\). When required, this paper uses a \(\Lambda\)CDM cosmology, with \(H_0 = 71 \text{ km s}^{-1} \text{ Mpc}^{-1}\), \(\Omega_\Lambda = 0.73\), \(\Omega_m = 0.27\) (Spergel et al. 2007).

The data were analyzed using the GBTIDL\textsuperscript{5} data analysis package, following standard procedures. The data were first visually inspected and any data affected by correlator failures or boxcar smoothing and re-sampling to resolutions of 50, 100, 150, and 250 \(\text{ km s}^{-1}\).

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\textsuperscript{5} http://gbitidl.nrao.edu

any residual baseline structure that might introduce spurious signals into the final spectrum. Around 10\% of the data were found to be affected by such artifacts and were edited out. The individual spectral records were then averaged together, weighting by the system temperature, to produce the final CO spectrum. This was then Hanning-smoothed and re-sampled, before further boxcar smoothing and re-sampling to resolutions of 50, 100, 150, and 250 \(\text{ km s}^{-1}\).

4. RESULTS AND DISCUSSION

The two panels of Figure 1 show the final CO J = 2–1 spectra of Himiko at velocity resolutions of 100 \(\text{ km s}^{-1}\) (left panel) and 250 \(\text{ km s}^{-1}\) (right panel). The root-mean-square (rms) noise is 99 \(\mu\text{Jy}\) per 100 \(\text{ km s}^{-1}\) channel and 68 \(\mu\text{Jy}\) per 250 \(\text{ km s}^{-1}\) channel. No statistically significant spectral features are visible in either spectrum.

Our non-detection of CO J = 2–1 line emission in Himiko places strong constraints on the CO line luminosity. The CO line luminosity, \(L_{\text{CO}}\), can be written as

\[L_{\text{CO}} = 3.25 \times 10^5 S_{\text{CO}} \Delta V \nu_{\text{obs}}^{-2} D_L^2 (1+z)^{-3},\]

where \(\nu_{\text{obs}}\) is the observing frequency (in GHz), \(D_L\) is the luminosity distance (in Mpc), and \(L_{\text{CO}}\) is in K km s\(^{-1}\) pc\(^2\) (Solomon et al. 1997). In the case of a non-detection, \(S_{\text{CO}} \times \Delta V \equiv 3 \sigma_{\text{AV}} \times \Delta V\) (in 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 assume a line width of \(\Delta V = 250 \text{ km s}^{-1}\) from the observed Ly\textalpha\ line width and similar to the median observed line width in quasar host galaxies at intermediate redshifts (e.g., Carilli & Wang 2006). This results in a 3\(\sigma\) limit of \(L_{\text{CO}} < 1.8 \times 10^{10} \times (AV/250)^{1/2}\) K km s\(^{-1}\) pc\(^2\) on the CO J = 2–1 line luminosity.

Assuming that the CO J = 2–1 line emission is thermalized, we can use the CO line luminosity limit to obtain an upper limit to the cold molecular gas mass in Himiko, assuming an appropriate conversion factor, \(X_{\text{CO}}\), from line luminosity to molecular gas mass (Solomon & Vanden Bout 2005). This factor can vary between 0.8 and 4.6 \(M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\), depending on whether the galaxy is an ultraluminous infrared galaxy (ULIRG) undergoing starburst activity (\(X_{\text{CO}} \sim 0.8 M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\); Downes & Solomon 1998) or a more quiescent object like the Milky Way (\(X_{\text{CO}} \sim 4.6 M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\); e.g., Solomon & Barrett 1991). This factor may be even higher in regions of low-metallicity gas (e.g., Hughes et al. 2010; Leroy et al. 2011), such as those expected to be found within the stellar- and quasar-molecular gas mass of Himiko (Ouchi et al. 2009) obtain a stellar mass of \(\sim 3.5 \times 10^{10} M_\odot\) from a fit to the spectral energy distribution; the molecular gas mass is thus less than the stellar mass by a factor of \(\gtrsim 2.5\). Conversely, a Milky Way conversion factor, \(X_{\text{CO}} = 4.6 M_\odot\) (K km s\(^{-1}\) pc\(^2\))\(^{-1}\), yields the limit \(M(H_2) < 8.3 \times 10^{10} M_\odot\) (3\(\sigma\) on the gas mass.)
Our limit on the CO line luminosity in Himiko can be converted to a limit on the total far-infrared (FIR) luminosity due to star formation. The best-fit parametrization of the relationship between $L_{\text{FIR}}$ and $L_{\text{CO}}$, valid for nearby spiral galaxies and starbursts, is $L_{\text{FIR}} = (1.26 \pm 0.05) \times \log L_{\text{CO}} - 0.81$ (Gao & Solomon 2004). Assuming that this relationship also holds for the interstellar medium of high-$z$ LABs, our upper limit to the CO line luminosity yields the upper limit $L_{\text{FIR}} < 1.3 \times 10^{12} L_\odot$ on the total FIR luminosity. Using the relation of Kennicutt (1998) to convert this limit on the FIR luminosity to a limit on the obscured SFR, we obtain SFR $< 225 M_\odot$ yr$^{-1}$. This is consistent with the lower limit of SFR $> 36 M_\odot$ yr$^{-1}$ obtained from the Ly$\alpha$ line luminosity, even if obscuration/absorption effects cause the SFR derived from the Ly$\alpha$ line to be underestimated by a factor of a few.

Searches for CO emission have been carried out in only two LABs, LABd05 at $z \sim 6.595$ and SSA22-LAB01 at $z \sim 3.09$, prior to this work (Yang et al. 2012). These authors used the IRAM 30 m telescope to observe the CO 5–4 and CO 3–2 transitions in LABd05 and the Plateau de Bure interferometer to observe the CO 4–3 and CO 3–2 lines in SSA22-LAB01. The non-detections yielded limits of $L'_\text{CO(5–4)} < 1.4 \times 10^{10} (\Delta V/400)^{1/2} K$ km s$^{-1}$ pc$^2$ (LABd05) and $L'_\text{CO(3–2)} < 1.5 \times 10^{10} (\Delta V/400)^{1/2} K$ km s$^{-1}$ pc$^2$ (SSA22-LAB01), similar to our limit on the CO $J = 2–1$ line luminosity in the $z \sim 6.595$ LAB. We note, in passing, that similar limits on the CO line luminosity have been obtained from GBT CO $J = 1–0$ studies of two LAEs at $z \sim 6.56$ and $z \sim 6.96$ (Wagg et al. 2009). Thus, at present, there is no evidence for significant amounts of molecular gas in high-$z$ LABs, despite their large stellar masses (e.g., Ouchi et al. 2009; Colbert et al. 2011). The CO luminosity in LABs appears to be significantly lower than that in the luminous quasar host galaxy population at $z > 6$ (e.g., Walter et al. 2003; Wang et al. 2010, 2011), in submillimeter starburst and quasar host galaxies at $z \sim 2$, as well as in quiescent BzK-selected disk galaxies at $z \sim 1.5$ (e.g., Solomon & Vanden Bout 2005; Daddi et al. 2008; Aravena et al. 2010).

Finally, it should be emphasized that the conversion factor from CO line luminosity to molecular gas mass is highly uncertain in high-$z$ galaxies. A low conversion factor [X$_{\text{CO}} = 0.8 M_\odot (K \text{ km s}^{-1} \text{ pc}^2)^{-1}$], applicable to the local ULIRG population, is usually assumed for FIR-luminous objects like high-$z$ submillimeter galaxies and quasars (e.g., Tacconi et al. 2006). Conversely, values closer to ones found in the Milky Way have been obtained in star-forming BzK-selected galaxies at $z \sim 1.5$ [X$_{\text{CO}} = 3.6 \pm 0.8 M_\odot (K \text{ km s}^{-1} \text{ pc}^2)^{-1}$; Daddi et al. 2010]. While studies of the high-$z$ LAB and LAE population have typically assumed the ULIRG conversion factor (e.g., Wagg et al. 2009; Yang et al. 2012), it is quite possible that a high conversion factor is applicable to LAEs and LABs at $z > 6.5$. This may be especially critical for the $z > 6$ LAE population, which appears to consist of relatively small galaxies with low SFRs, $\lesssim 10 M_\odot$ yr$^{-1}$, and low stellar masses, $\lesssim 10^9 M_\odot$ (e.g., Finkelstein et al. 2009; Pentericci et al. 2009; Ono et al. 2010). A low CO-to-H$_2$ conversion factor value would imply that detections of low-$J$ CO line emission would be extremely challenging in these systems, even with new facilities like the Expanded Very Large Array (EVLA) or the Atacama Large Millimeter Array (ALMA). For example, the CO $J = 3–2$ line from a $z = 6.5$ LAE with SFR $= 10 M_\odot$ yr$^{-1}$ would be redshifted to a frequency of $\sim 46$ GHz with a peak flux density of $S_{\text{CO}} \sim 27 \mu$Jy, assuming a line FWHM of $\Delta V = 300$ km s$^{-1}$), if we assume $X_{\text{CO}} = 4.6 M_\odot (K \text{ km s}^{-1} \text{ pc}^2)^{-1}$. Detecting such a line would require hundreds of hours with either the EVLA Q-band receivers or the ALMA Band-1 receivers. This issue would be exacerbated for the $z > 6$ LAEs if, as is likely (e.g., Finkelstein et al. 2011), they are low-metallicity systems. For such systems, with metallicities similar to the Small Magellanic Cloud, the CO-to-H$_2$ conversion factor could be as high as $30 M_\odot (K \text{ km s}^{-1} \text{ pc}^2)^{-1}$ (Hughes et al. 2010; Leroy et al. 2011), making it even harder to detect redshifted CO emission. Similarly, the models of Vallini et al. (2012) also suggest that the detection of high-$J$ CO line emission in

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**Figure 1.** Final GBT Ka-band spectra from the $z \sim 6.595$ LAB, Himiko, covering the expected redshifted frequency of the CO $J = 2–1$ line emission; the velocity scale is relative to $z = 6.595$. The spectra in the left and right panels have been smoothed to, and re-sampled at, velocity resolutions of 100 km s$^{-1}$ and 250 km s$^{-1}$, respectively. The rms noise on the spectra are 99 $\mu$Jy per 100 km s$^{-1}$ channel and 68 $\mu$Jy per 250 km s$^{-1}$ channel, respectively. (A color version of this figure is available in the online journal.)
z \sim 6.6\text{ LAEs will not be possible in reasonable ALMA integration times.}

5. SUMMARY

We present results from a deep GBT search for redshifted CO \( J = 2−1\) line emission in Himiko, a Ly\( \alpha \) blob, at \( z \sim 6.595\). We do not detect CO \( J = 2−1\) line emission, with an upper limit of \( L_{\text{CO}}^{90} < 1.8 \times 10^{10} \times (\Delta V / 250)^{1/2} \text{ K km s}^{-1} \text{ pc}^2\). This limit is similar to the limits on the CO line luminosity obtained in two LABs at \( z \sim 3\) by Yang et al. (2012) and in two Ly\( \alpha \) emitters at \( z \gtrsim 6.5\) by Wagg et al. (2009). Despite their high stellar masses, high-\( z\) LABs appear to have significantly lower CO line luminosities than luminous quasars or submillimeter galaxies at similar redshifts. Our constraint on the CO line luminosity implies an upper limit of \( M(H_2) < 1.4 \times 10^{10} M_\odot\) on the molecular gas mass, assuming a ULIRG conversion factor, \( X_{\text{CO}} = 0.8 M_\odot (\text{K km s}^{-1} \text{ pc}^2)^{-1}\). However, it should be noted that this conversion factor is unknown for LABs. A high value of \( X_{\text{CO}}\), similar to values in the Milky Way or \( \sim 1.5\) BzK galaxies, would make it extremely difficult to detect CO line emission from LABs and LAEs at \( z > 6\), even for upcoming telescopes like ALMA and the EVLA.

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