LARGE-SCALE STRUCTURE TRACED BY MOLECULAR GAS AT HIGH REDSHIFT

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ABSTRACT

We present observations of redshifted CO(1–0) and CO(2–1) in a field containing an overdensity of Lyman break galaxies (LBGs) at \( z = 5.12 \). Our Australia Telescope Compact Array observations were centered between two spectroscopically confirmed \( z = 5.12 \) galaxies. We place upper limits on the molecular gas masses in these two galaxies of \( M(H_2) < 1.7 \times 10^{10} \) and \( < 2.9 \times 10^9 M_{\odot} \) (2 \( \sigma \)), comparable to their stellar masses. We detect an optically faint line emitter situated between the two LBGs which we identify as warm molecular gas at \( z = 5.1245 \pm 0.0001 \). This source, detected in the CO(2–1) transition but undetected in CO(1–0), has an integrated line flux of 0.106 ± 0.012 Jy km s\(^{-1}\), yielding an inferred gas mass \( M(H_2) = (1.9 \pm 0.2) \times 10^9 M_{\odot} \).

Molecular line emitters without detectable counterparts at optical and infrared wavelengths may be crucial tracers of structure and mass at high redshift.

Subject headings: galaxies: evolution — galaxies: high-redshift

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1. INTRODUCTION

Lyman break galaxies have given us our first detailed look at star formation at high redshifts (\( z > 4 \)). However, our picture of the distant universe is limited because these objects are selected for strong rest-frame ultraviolet emission arising from substantial unobscured starbursts in the galaxies. Individually, they tell us little about darker baryons at the same redshift, whether the systems containing the baryons are intrinsically less UV-luminous or are obscured by dust.

The Lyman break galaxy (LBG) population has now been verified by \( z = 2 \) (Steidel et al. 2004) up to \( z = 6 \) (Stanway et al. 2007), with tentative detections reported at redshifts as high as \( z = 10 \) (Bouwens et al. 2005). The photometric and spectroscopic properties of LBGs evolve with increasing redshift. Typical LBGs at \( z \approx 5 \) have stellar masses of a few \( \times 10^9 M_{\odot} \), are predominantly young (\( < 50 \) Myr), and are subsonic but not primordial in their metallicity (\( Z \approx Z_{\odot} \)), where these properties are deduced from their rest-frame optical and near-infrared spectral energy distribution (Verma et al. 2007).

However, something is missing in our picture of the universe at \( z > 5 \). The youth of Lyman break objects when compared to the look-back times probed in a given survey suggests that only a small fraction of the overall universe is undergoing stages of strong ongoing star formation, and hence is detectable in the rest UV, at a given time. Fossil stellar populations in the most massive galaxies at the present time suggest that the bulk of their stars were formed at \( z > 3 \) (Heavens et al. 2004), but the mass assembly history of the universe as traced by LBGs implies that only 1% of the baryonic material that will eventually form today’s galaxies is in collapsed systems at \( z = 5 \). Where is the other 99%? The bulk of the baryonic material at these high redshifts must be in either low-mass systems or the gas phase.

Damped Ly\( \alpha \) systems in the spectra of distant quasars have shown that dense neutral gas is ubiquitous at high redshift, holding a third of the H \( \text{I} \) atoms at \( z = 5 \) and appearing in 10% of sight lines per unit cosmological distance (Prochaska et al. 2005). These sources represent reservoirs of neutral gas for star formation, yet are known to be deficient in H \( \text{II} \) relative to local galaxies. Molecular gas is instead more tightly concentrated in high-density, relatively dusty regions (Zwaan & Prochaska 2006).

Securely identifying this material is challenging. At \( z \approx 5 \), the far-infrared lines emitted by cool and obscured material are redshifted to millimeter wavelengths, but not necessarily into an atmospheric window. At these extreme luminosity distances lines are faint, requiring long integration times to secure even a tentative detection. The fields of view of existing millimeter interferometers are small, and their correlators have, until recently, been limited to bandwidths of a few hundred MHz (equivalent to \( \Delta z / z < 0.01 \)). The resulting small volumes made survey work at high redshift unfeasible. As a result, the few detections of line emission from molecular and atomic gas at high redshift have been toward active galactic nuclei—quasars to \( z = 6.4 \) (Bertoldi et al. 2003), radio galaxies to \( z = 5.2 \) (Klamer et al. 2005)—and hence probed highly atypical environments.

In this Letter we present the results of a pilot program to explore the cool gas associated with a large-scale structure at \( z > 5 \) marked out by Lyman break galaxies rather than by an active galaxy. Our 40 arcmin\(^2\) target field contains seven UV-luminous sources with spectroscopically confirmed redshifts in a narrow range (\( \Delta z < 0.1 \)), a 6 \( \sigma \) excess over the typical density of such sources in our survey, but shows no clear spatial clustering.\(^1\) Given the redshift dispersion and spatial distribution of these galaxies, it is clear that their star formation cannot be a response to a common triggering event, and yet the probability of such a configuration arising by chance is small. The simplest explanation is that there is a large mass of hidden baryons in this field at this redshift. At any one time this structure is traced by the small fraction of that material undergoing comparatively

\(^1\) The detailed properties of this field, and of others probed in our ESO Remote Galaxy Survey (ERGS), will be discussed in a forthcoming paper by L. Douglas et al.
short-term UV-luminous star formation events and appearing as LBGs. While the stars within the LBGs are likely to end up in the most massive current-day galaxies after subsequent mergers, the total stellar mass in even this overdensity of LBGs is an order of magnitude too small to account for the stars in the most massive spheroids. Consequently, there should be far more baryons in the vicinity of the LBGs than revealed in the UV. Our pilot program was designed to probe the cool gas mass in a small section of the structure, centered on a pair of LBGs with Lyα emission redshifts separated by $\Delta z = 0.004$. The observations target not only the two LBGs, but any darker/fainter systems in the underlying large-scale structure. The results for lower redshift LBGs (e.g., Baker et al. 2004), suggested that we were unlikely to detect the two known galaxies directly.

All magnitudes in this Letter are quoted in the AB system (Oke & Gunn 1983). We adopt a $\Lambda$CDM cosmology with $(\Omega_m, \Omega_{\Lambda}, h) = (0.7, 0.3, 0.7)$.

2. OBSERVATIONS AT THE ATCA

The observations were carried out at the Australia Telescope Compact Array in 2008 March–April. The array was in the relatively compact H168 configuration, with both north-south and east-west baselines. We used the correlator in the 128 MHz/22–24 (although data taken on the 23rd were discarded due to poor weather). A single pointing was observed for the entire observing period, and a nearby bright source (1045–188) observed every 15 minutes to determine phase stability. Pointing accuracy was checked every hour. Absolute flux calibration was through observations of 1921–293 (the standard flux calibrator at the ATCA) each night. The half-power beamwidth (HPBW) of the ATCA at this frequency is 2.5$''$ and the naturally weighted restoring beam in this configuration is 15.9$''$ × 10.9$''$.

The CO(2–1) line was observed in four 11 hr observations on the nights of 2008 April 4–7 using the recently commissioned 7 mm receiver system. The IF bands were tuned to 37.762 and 37.792 GHz (giving redshift coverage $z = 5.09–5.13$). A single pointing centered on the 18.8 GHz field center was observed, and 1045–188 was used as a pointing and phase calibrator. Uranus, the primary flux calibrator for the ATCA at millimeter wavelengths, was not visible at any point in our observing period. Instead we bootstrap our primary flux calibration from two compact H I regions, observed each night, which were also observed using our configuration by ATCA staff on the afternoon of 2008 April 4 together with Uranus and a bandpass calibrator. At this frequency, the HPBW is 74$''$ and the restoring beam is 7.3$''$ × 4.8$''$.

The total useful observing time was 16 hr at 18.9 GHz and 44 hr at 37.7 GHz. The rms noise in the final images is 0.11 and 0.10 mJy beam$^{-1}$ in each 4 MHz channel at 18.9 and 37.7 GHz respectively.

The positions of the two Lyman break galaxies at $z = 5.120$ and $z = 5.116$ respectively are shown as small circles. The half-power point of the synthesized beam at 37.7 GHz is indicated by a large circle. The HPBW at 18.9 GHz is twice as large and encompasses the whole image. Contours mark formal 2.5, 5 and 7.5 $\sigma$ surface brightness levels. Negative contours are shown with dashed lines. Although the right-hand LBG is situated within a few arcseconds of a $5$ and $7.5$ $\sigma$ area, this is part of an extended low-level artifact. [See the electronic edition of the Journal for a color version of this figure.]

3. LIMITS ON THE CO IN LYMAN BREAK GALAXIES

As illustrated in Figure 1, our pointing included two Lyα-emitting, Lyman break galaxies within the HPBW at 18.9 GHz (Table 1). At 37.7 GHz one of these (at $z = 5.116$) lies well outside the beam half-power point, while the second (at $z = 5.120$) remains close to the pointing center. Neither galaxy shows evidence for line or continuum emission in either of the two transitions surveyed. This is not, in itself, surprising given the youth and low masses (typically a few × 10$^9$ $M_\odot$; Verma et al. 2007) of Lyman break galaxies. However, these observations provide the strongest constraint yet on the molecular gas content of $z > 5$ star-forming galaxies.

We use our limiting flux at the frequency of the redshifted CO(1–0) line to constrain the molecular gas content of these galaxies, while source C is the millimeter line emitter discussed in § 4. $S_{\nu,\Delta v}$ is in units of Jy km s$^{-1}$ and $M(H_2)$ in units of 10$^{10}$ $M_\odot$ as discussed in the text. 2 $\sigma$ limits are given where appropriate.

### Table 1: High-z Sources in Our Target Field

| Source | R.A. (J2000.0) | Decl. (J2000.0) | $z$ | $I_{\text{tot}}$ | $S_{\nu,\Delta v}$ | $M(H_2)$ |
|--------|---------------|----------------|-----|----------------|------------------|----------|
| A ...... | 10 40 46.66 | −11 58 33.8 | 5.120 | 27.00 ± 0.57 | ... | < 1.7 |
| B ...... | 10 40 41.51 | −11 58 21.6 | 5.116 | 25.71 ± 0.21 | 0.29 | 0.2 |
| C ...... | 10 40 43.50 | −11 57 56.8 | 5.125 | 26.63 ± 0.16 | 0.106 ± 0.012 | 1.9 ± 0.2 |

Notes.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds. Sources A and B are spectroscopically confirmed Lyman break galaxies, while source C is the millimeter line emitter discussed in § 4. $S_{\nu,\Delta v}$ is in units of Jy km s$^{-1}$ and $M(H_2)$ in units of 10$^{10}$ $M_\odot$ as discussed in the text. 2 $\sigma$ limits are given where appropriate.
galaxies. We employ the widely used conversion factor of \( M_{\odot}/L_{\text{CO}} = 0.8 M_{\odot} (\text{K km s}^{-1} \text{pc}^{-2})^{-1} \) based on local infrared-luminous galaxies (Solomon & Vanden Bout 2005). Our image rms noise of 0.11 mJy beam\(^{-1}\) at the CO(1–0) line corresponds to a formal \( 2 \sigma \) limit \( L_{\text{CO}} < 2.2 \times 10^{10} \text{ K km s}^{-1} \text{ pc}^{-2} \) for the luminosity of an unresolved 200 km s\(^{-1}\) emission line at \( z = 5.12 \). Thus we constrain the molecular gas mass of the known Lyman break galaxies in this field to be \( M(H_2) < 1.7 \times 10^{10} M_{\odot} \) (2 \( \sigma \)).

One of our LBGs (source B in Table 1) is also close to the center of the beam in our 37 GHz observations. For thermalized, optically thick CO emission, the line luminosity is independent of transition. Making this assumption, nondetection of the 2–1 line places a tighter constraint on the mass of \( M(H_2) < 2.9 \times 10^9 M_{\odot} \) (2 \( \sigma \)), comparable to the inferred stellar mass in such sources.

4. AN OPTICALLY FAINT MOLECULAR LINE EMITTER

Inspection of the ATCA data cubes revealed no evidence for continuum sources. Only one emission feature was found to extend over more than two adjacent frequency channels. This feature, a spatially unresolved emission line centered at 37.642 GHz with a FWHM of 110 km s\(^{-1}\) (equivalent to four independent frequency channels), lies on the beam half-power point. It has a peak flux of 0.94 \pm 0.15 mJy beam\(^{-1}\), and a velocity integrated flux of 0.106 \pm 0.012 Jy km s\(^{-1}\) (Fig. 2). A combined frame of channels not containing line emission (a total bandwidth of 180 MHz) shows no significant continuum emission with a formal limit on the continuum of <0.49 mJy beam\(^{-1}\) at 37.73 GHz. The line emission is centered 1′ (370 kpc, comoving) northwest and 40′ (250 kpc) northeast of our spectroscopically confirmed Lyman break galaxies at \( z = 5.120 \) and \( z = 5.116 \) respectively, toward more LBGs in the field.

This line emitter is undetected at 18.9 GHz and not spatially coincident with a known source at any observed wavelength (from 0.5 \( \mu \text{m} \) to 21 cm). Our optical and IR data require that the host galaxy must have a flux density <0.2 \( \mu \text{Jy} \) at an observed frame wavelength of 4.5 \( \mu \text{m} \) (0.7 \( \mu \text{m} \) rest if at \( z = 5.125 \)) and <0.08 \( \mu \text{Jy} \) at a 0.8 \( \mu \text{m} \) (1300 Å rest). No submillimeter data exist at this location. We note that the lensing properties of this field are well understood, and we use the lensing maps of Clowe et al. (2006) to estimate a maximum 10% enhancement in the flux of a source at this location.

In order to verify the reality of the 37.6 GHz line, we investigated its properties thoroughly. The velocity-integrated line is a formal \( 8 \sigma \) detection in a multifrequency synthesis image of six channels centered on the line emission. It is detected in the \( u-v \) data set on multiple baselines, and in two independent subsets of the data. Its strength in the flux-calibrated image is independent of image deconvolution algorithm and the location of the imaging center. We conclude that this is unlikely to be a spurious detection.

We evaluate the probability that this is a line emitter at a redshift unrelated to our high-redshift system [i.e., not a CO(2–1) emission line], by considering the population models of Blain et al. (2000). These authors calculated the expected number density of line emitters as a function of frequency and line flux, given models for galaxy and dark matter distributions at \( z < 10 \). As a cautious assumption, we consider the source counts predicted at 50 GHz at our integrated flux density (while noting that source counts at 37.6 GHz are likely to be lower). In our 256 MHz total bandwidth, and allowing for source detections within 1.5 HPBW, we would expect 0.003 line emitters in our survey, with these dominated by redshifted CO(1–0) lines at \( z = 2.1 \). Coupled with the known existence of structure at \( z = 5.12 \) in this field, we interpret the line detection as CO(2–1) emission at \( z = 5.1245 \pm 0.0001 \) at high confidence.

At the measured line flux in the CO(2–1) transition, and assuming constant luminosity, the expected counterpart in the 1–0 transition would be below the \( 2 \sigma \) level at 18.8 GHz, consistent with our nondetection. Using the same CO-to-H\(_2\) conversion factor discussed in § 3 applied to the luminosity of the CO(2–1) transition, we infer a molecular gas mass of \( M(H_2) = (1.9 \pm 0.2) \times 10^{10} M_{\odot} \) in this source.

The beam width at 37.7 GHz implies an upper limit on the physical size of our unresolved source of 45 × 30 kpc\(^2\). A simple virial calculation assuming a uniform mass distribution suggests that our derived gas mass could represent up to 50% of the dynamical mass in the system, while remaining both bound and smaller than our beam size.

5. LARGE-SCALE STRUCTURE AT \( z = 5.12 \)

This pilot survey at 37.7 GHz probed only 3% of the projected spatial distribution and 35% of the redshift range occupied by clustered UV-luminous galaxies in our target field. Despite this, the gas mass inferred from our single detection is comparable to the total stellar mass in UV-luminous sources in the structure. If this detection is typical of the space density of molecular line emitters in this field, then galaxies with obscured star formation represent at best a few percent of the baryons present (consistent with Verma et al. 2007).

In the nomenclature of Solomon & Vanden Bout (2005) our detected source is an early universe molecular emission line galaxy (EMG), a broad category including radio galaxies, submillimeter galaxies, and QSOs at \( z > 2 \). It represents 10\(^5\) \( M_{\odot} \) of CO, formed within 1.1 Gyr of the big bang. This yield is plausible from 3 × 10\(^5\) Gyr Population III stars, each of 100 \( M_{\odot} \), in as little as the stellar lifetime (10 Myr; Heger & Woosley 2002). By contrast, the yield of more conventional supernovae...
and the typical star formation rates of UV-luminous sources in this field ($\sim 30 M_\odot \text{yr}^{-1}$), $10^7$ years would be required (see Walter et al. 2003), implying either early and continuous star formation, or an early, intense starburst. A source with unobscured star formation of $10 M_\odot \text{yr}^{-1}$ at $z = 5.12$ would have been detected in our deep optical imaging, but observations of dust emission in the rest-frame far-infrared will be necessary to distinguish between a mature stellar population at the time of observation and ongoing, but dust-obscured, star formation.

It is interesting to compare our detection with a similar observation at $z = 5.2$, also using the ATCA. Klammer et al. (2005) studied a high-mass system at this redshift, marked out by the presence of at least six Ly$\alpha$ emitter galaxies and a powerful radio galaxy. Based on UV-luminous stellar mass, this system should be comparable in mass to our target region. Klammer et al. (2005) detected CO emission in the $1-0$ and $5-4$ transitions, clearly associated with the radio galaxy. While the inferred gas mass is within a factor of four of our object, the velocity structure differs: the emission line detected by Klammer et al. (2005) was twice as broad as our line emitter, possibly due to momentum input from the radio source.

We note that the CO luminosity and derived mass of our line emitter are similar to those of submillimeter galaxies (SMGs) at lower redshifts (Greve et al. 2005). These are also often associated with galaxy overdensities at high redshift (e.g., Smail et al. 2003). While some SMGs with this mass would have been detected in our deep Spitzer IRAC imaging (based on their $K$-band magnitudes at $z = 2.5$ [Smail et al. 2004] redshifted to $z = 5.12$), others would not. CO emission is not a reliable star formation rate (SFR) indicator, but is loosely correlated with far-infrared luminosity, and hence SFR. Data on this relation at high redshift is sparse, but known EMGs with comparable gas masses to our detected source have SFRs of $\sim 1000 M_\odot \text{yr}^{-1}$. By contrast, the tight limit on the H$_2$ mass in the LBGs in our field would imply obscured star formation rates of less than a few hundred solar masses per year, even given dust properties similar to those of SMGs. Our detected source likely represents a more extreme environment than that seen in LBGs at the same redshift and could be a high-redshift counterpart for the intense starbursts in SMGs.

It is becoming increasingly clear that no one survey technique can provide a complete picture of large-scale structure at high redshift. Overdensities of Lyman break galaxies are correlated with the presence of Ly$\alpha$ emitters, radio galaxies, SMGs, DLAs (Cooke et al. 2003), and now molecular emission line galaxies at this redshift. Each component of the structure may account for only a few percent of the baryonic mass and each presents observational challenges. While LBGs and DLAs probe comparable mass halos at $z = 3$ (Cooke et al. 2006), molecular line emitters may probe more massive and denser regions of the same structures.

Extensive extrapolation based on a single line from a single source is risky. Observations of this source in other emission lines will be required to confirm its redshift and luminosity. Such observations will also begin to characterize the gas temperature and density, and determine whether the CO to gas mass conversion factor for ULIRGs is appropriate for low-mass systems at early times. Additional sources must be identified and characterized to determine whether our initial detection is anomalous or typical of its population. Ultimately, more extensive millimeter surveys, based on existing deep data sets, are required to establish the molecular gas content of large-scale structures at high redshift, and to probe this early stage of galaxy formation.

6. CONCLUSIONS

Our main conclusions can be summarized as follows:

1. We have investigated the molecular gas content, as traced by low-order transitions of CO, in a large-scale structure identified in Lyman break galaxies at $z = 5.12$.

2. Neither of two known Lyman break galaxies in our survey area show associated molecular line emission, suggesting that their molecular gas content does not significantly exceed their stellar content.

3. We have identified a source with line emission at $37.642$ GHz, which we identify as emission in the CO(2–1) transition at $z = 5.1245 \pm 0.0001$. This source is currently undetected at any other wavelength.

4. The inferred gas mass in this single source is $M(H_2) = (1.9 \pm 0.2) \times 10^9 M_\odot$, comparable to the total stellar mass of UV-luminous sources in the same region.

5. Further studies of UV-faint sources at high redshift are essential to characterize such systems, and could make substantial progress toward balancing the baryon budget at early times.

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Facilities: ATCA(12mm, 7mm)

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