The Astrophysical Journal Supplement Series, 172:518–522, 2007 September

RADIO AND MILLIMETER PROPERTIES OF $z \sim 5.7$ Lyα EMITTERS IN THE COSMOS FIELD: LIMITS ON RADIO AGNs, SUBMILLIMETER GALAXIES, AND DUST OBSCURATION[1]

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Received 2006 September 17; accepted 2006 October 16

ABSTRACT

We present observations at 1.4 and 250 GHz of the $z \sim 5.7$ Lyα emitters (LAEs) in the COSMOS field found by Murayama et al. At 1.4 GHz there are 99 LAEs in the lower noise regions of the radio field. We do not detect any individual source down to 3 σ limits of $\sim$30 μJy beam^{-1} at 1.4 GHz, nor do we detect a source in a stacking analysis, to a 2 σ limit of 2.5 μJy beam^{-1}. At 250 GHz we do not detect any of the 10 LAEs that are located within the central regions of the COSMOS field covered by MAMBO ($20' \times 20'$) to a typical 2 σ limit of $S_{250} < 2$ mJy. The radio data imply that there are no low-luminosity radio AGNs with $L_{1.4} > 6 \times 10^{24}$ W Hz^{-1} in the LAE sample. The radio and millimeter observations also rule out any highly obscured, extreme starbursts in the sample, i.e., any galaxies with massive star formation rates >1500 $M_\odot$ yr^{-1} in the full sample (based on the radio data), or 500 $M_\odot$ yr^{-1} for the 10% of the LAE sample that falls in the central MAMBO field. The stacking analysis implies an upper limit to the mean massive star formation rate of $\sim$100 $M_\odot$ yr^{-1}.

Subject headings: galaxies: evolution — galaxies: formation — infrared: galaxies — submillimeter — surveys

1. INTRODUCTION

Numerous studies have demonstrated that using narrowband filters centered on the Lyα line is a powerful method for discovering high-redshift star-forming galaxies (Hu et al. 2004; Kodaira et al. 2003; Rhoads et al. 2003; Malhotra & Rhoads 2004; Tran et al. 2004; Kurk et al. 2004; Santos et al. 2004; Martin & Sawicki 2004; Taniguchi et al. 2005; Iye et al. 2006). Indeed, the majority of galaxies known at $z \sim 6$ have been discovered in this way. Finding galaxies at these extreme redshifts has been of paramount importance since the recent discovery of Gunn-Peterson absorption by a partially neutral IGM toward the highest z QSOs ($z \sim 6$; Fan et al. 2006b), a signature of cosmic reionization. Reionization is a key benchmark in cosmic structure formation, indicating the formation of the first luminous objects (Fan et al. 2006a).

The Cosmic Evolution Survey (COSMOS), covering 2 deg^2, is designed to probe the evolution of galaxies, AGNs, and dark matter in the context of their cosmic environment with the Very Large Array (VLA; Schinnerer et al. 2007). The COSMOS *Hubble Space Telescope* (*HST*) field has extensive supporting observations, ranging from the radio through the X-ray (Scoville et al. 2007). Part of this program entails a Subaru narrowband survey of the full field centered on Lyα at $z \sim 5.7$ (Murayama et al. 2007). This survey has revealed a large sample of galaxies at $z \sim 5.7$, with 110 candidate galaxies.

Observations of the COSMOS field have been done at 1.5″ resolution (FWHM) at 1.4 GHz down to an rms level between 8 and 10 μJy beam^{-1} (Schinnerer et al. 2007). Observations have also been done at 250 GHz at a resolution of 10.6″ of the inner $20' \times 20'$ of the COSMOS field using MAMBO at the IRAM 30 m telescope to an rms level of 0.9 mJy (Bertoldi et al. 2007), and a somewhat larger, shallower field ($30.6' \times 30.6'$) at a resolution of 31″ using BOLOCAM at the Caltech Submillimeter Observatory (Aguirre et al. 2007) to an rms level of 1.9 mJy.

In this paper we use the data from the VLA, MAMBO, and BOLOCAM observations of the COSMOS field to constrain the centimeter and millimeter properties of the $z = 5.7$ LAEs. This study represents the deepest radio continuum study of high-z LAEs, over the largest area, as well as the most extensive study of these sources at millimeter wavelengths to date. These data allow us to set limits on any low-luminosity radio AGNs, as well as on the number of highly dust-obscured starburst galaxies in the LAE sample at $z = 5.7$. We perform a stacking analysis to set a limit to the mean UV obscuration of high-z LAEs.

2. THE SAMPLE AND THE RADIO AND MILLIMETER OBSERVATIONS

2.1. *The Sample*

The sample is taken from the narrowband Lyα survey of Murayama et al. (2007) centered on a redshift of $z = 5.7 \pm 0.05$. They cover the full COSMOS field, implying a comoving volume of 1.5×10^6 Mpc^3. They select sources that are detected in the narrowband NB816 filter at NB816 < 25.1 mag, are undetected in shorter wavelength broadband filters, and have NB816-to-broadband near-IR colors that imply Lyα (observed) equivalent widths $\mathrm{EW_{obs}} > 120$ Å [corresponding to rest-frame $\mathrm{EW_{rest}} = \mathrm{EW_{obs}}/(1+z) > 18$ Å].

[1] Based on data collected at the Subaru Telescope, which is operated by the National Astronomical Observatory of Japan; the National Radio Astronomy Observatory, which is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc.; the IRAM 30 m telescope; and the Caltech Submillimeter Observatory.

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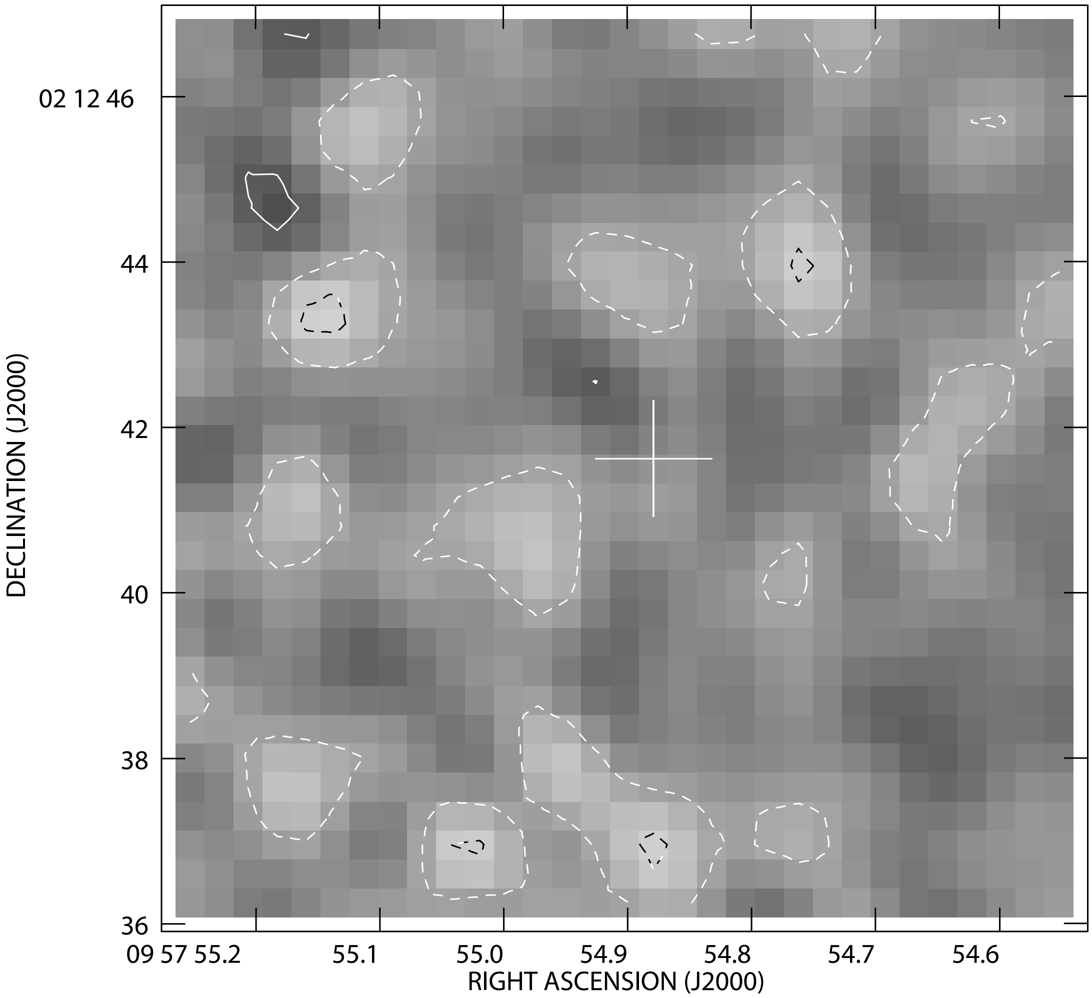

FIG. 1.—Stacked 1.4 GHz image of the LAEs in the COSMOS field (99 sources). The rms noise level is 1.25 μJy beam^{-1}. The cross marks the stacking position, centered on the LAE positions (the absolute coordinates are arbitrary). The contour levels are -6, -4, -2, 2, 4, and 6 μJy beam^{-1}, and the beam has FWHM = 1.5″.

They find 110 candidate LAEs, and they estimate that the contamination rate by low-z objects is <14%. Thirty-seven sources are also detected in longer wavelength filters (z'), corresponding to rest-frame UV emission (1250 Å). All of the sources are small, <0.5″, and a few (~5%) show evidence for two or three compact components. No large (tens of kiloparsecs or more) "Lyα blob" sources are detected (Steidel et al. 2000; Matsuda et al. 2004).

2.2. *The VLA Observations*

We have searched for radio emission from the LAEs in the COSMOS field using the data presented in Schinnerer et al. (2007). At each position we determine the flux density and the rms noise in the region. The relative astrometric accuracy between the radio and optical images is better than 0.2″ (Sanders et al. 2007), while for a 3 σ detection the positional uncertainty is given roughly by FWHM/(S/N) $\sim$ 0.5″. We have searched for radio sources within a 0.6″ radius of the LAE optical position. We exclude from the analysis 11 LAEs in higher noise regions of the field, such as those close to a bright continuum source, or near the edge of the field, leaving a sample of 99 sources total, and 33 with UV continuum detections.

We do not detect any source >3 σ at 1.4 GHz within 0.6″ of any LAE in the sample of 99. The typical 3 σ limit is 30 μJy beam^{-1} at 1.4 GHz. Note that, for the full sample of 99 sources, we expect 0.05 chance coincidences within 0.6″ at the level of 30 μJy beam^{-1}, based on faint radio source counts (Fomalont et al. 2006).

We have also performed a radio stacking analysis of the sources, summing images centered on the positions of the LAEs, weighted by the rms in each subfield. Stacking all the LAEs, we do not detect a source at the LAE position to a 2 σ limit of 2.5 μJy beam^{-1}. If we only stack the UV-detected sources (33 sources), we find a 2 σ limit of 4 μJy beam^{-1} (Fig. 1).

One LAE, J10000.51+014940.1, has a marginal (2.7 σ) 1.4 GHz source of 27 $\pm$ 10 μJy, located just 0.2″ from the optical position (Fig. 2). If real, the implied luminosity density at a rest-frame frequency of 1.4 GHz is $L_{1.4} = 6 \times 10^{24}$ W Hz^{-1}, assuming a spectral index of -0.75. We do not consider this a firm detection, but deeper radio imaging would be very interesting for this source.

We note that in the study of the GOODS-North field, Ajiki et al. (2006) found 10 LAEs at $z \sim 5.7$ using a technique similar to that employed for the COSMOS field. Comparing these sources to the deep radio survey of Richards (2000), we again find that no LAE has a radio counterpart to a 5 σ detection limit of 40 μJy.

2.3. *The MAMBO and BOLOCAM Observations*

Ten of the LAEs are located within the 20′ × 20′ field imaged with MAMBO at 250 GHz (Bertoldi et al. 2007). Given a FWHM of 10.6″, we searched for MAMBO counterparts greater than 3 σ and within 3.5″ of an LAE. None of the LAEs have a MAMBO counterpart, to a typical 3 σ upper limit of $S_{250} < 3$ mJy. A stacking analysis leads to a 2 σ limit to the mean 250 GHz flux density of $S_{250} < 0.7$ mJy. For reference, based on submillimeter

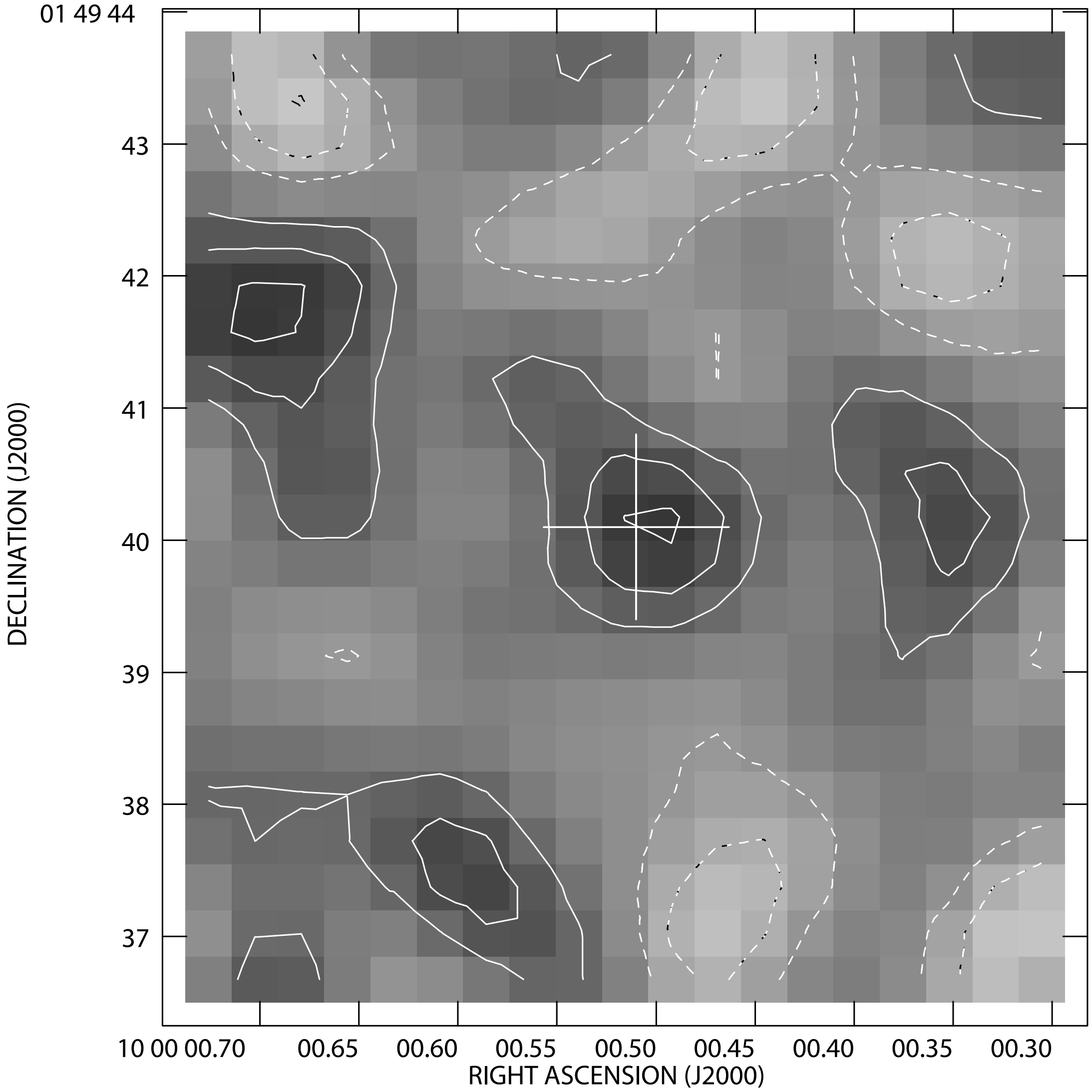

Fig. 2.—VLA 1.4 GHZ image of the field centered on the $z = 5.7$ LAE J10000.51+014940.1 in Ajiki et al. (2006). The cross marks the position of the LAE. The contour levels are -27, -18, -9, 9, 18, and 27 μJy beam^{-1}, and the beam has FWHM $= 1.5''$.

galaxy source counts (Bertoldi et al. 2007), we expect 0.01 chance coincidences within $3.5''$ with $S_{250} \geq 3$ mJy for the 10 LAEs located in the MAMBO-COSMOS field.

There is one LAE, J100040.22+021903.8, that has a potential MAMBO source located $5''$ south of the LAE position, with a flux density of $S_{250} = 3.2 \pm 0.91$ mJy (Fig. 3). The BOLOCAM image shows a value of 1.7 ± 1.9 mJy at this position. The radio image shows a surface brightness of 15 ± 10 μJy beam^{-1} at the LAE position. This LAE is not detected in the UV continuum, and the total star formation rate based on the Lyα luminosity is only 6 $M_{\odot}$ yr^{-1} (uncorrected for obscuration). Given the positional offset and the relatively low significance of the MAMBO detection, we cannot claim either the reality of the MAMBO source or an association of the LAE and the (marginal) MAMBO source. If real, the implied FIR luminosity is $L_{\rm FIR} = 1.1 \times 10^{13}$ $L_{\odot}$, and the predicted radio flux density at 1.4 GHz is 10 μJy based on a star-forming galaxy template (Carilli & Yun 2000). Deeper observations at 250 and 1.4 GHz are required to check the reality of this source.

We also searched the wider, shallower BOLOCAM field for counterparts to the LAEs. There are 12 LAEs in the BOLOCAM field (10 are common to the MAMBO field), and again, no source is detected with BOLOCAM to a typical 3 σ limit of 5.7 mJy. A stacking analysis provides a 2 σ limit of 1 mJy.

3. DISCUSSION

We do not detect any individual source to a typical 3 σ limit of 30 μJy beam^{-1} at 1.4 GHz. A limit of 30 μJy beam^{-1} at an observing frequency of 1.4 GHz implies a limit to the radio luminosity at an emitted frequency of 1.4 GHz of $L_{1.4} < 6 \times 10^{24}$ W Hz^{-1}, assuming a spectral index of -0.75. For comparison, the nearby Fanaroff-Riley type I (i.e., low-luminosity) radio galaxy M87 has $L_{1.4} = 9 \times 10^{24}$ W Hz^{-1}. The lack of radio AGNs in the LAE sample is not surprising, since V. Taniguchi et al. (2007, in preparation) show that the narrowband search technique selects against broad-line QSOs, for which the emission lines are typically broader than the filter. Likewise, Hu et al. (1998) and Keel et al. (1999) find a relatively low fraction (between 17% and 40%) of narrow-line AGNs in lower z LAE samples, while Shapley et al. (2003) find that only 3% of the Lyman break galaxies at $z \sim 3$ show optical emission-line spectra consistent with an AGN. Overall, our nondetection of even a low-luminosity radio AGN

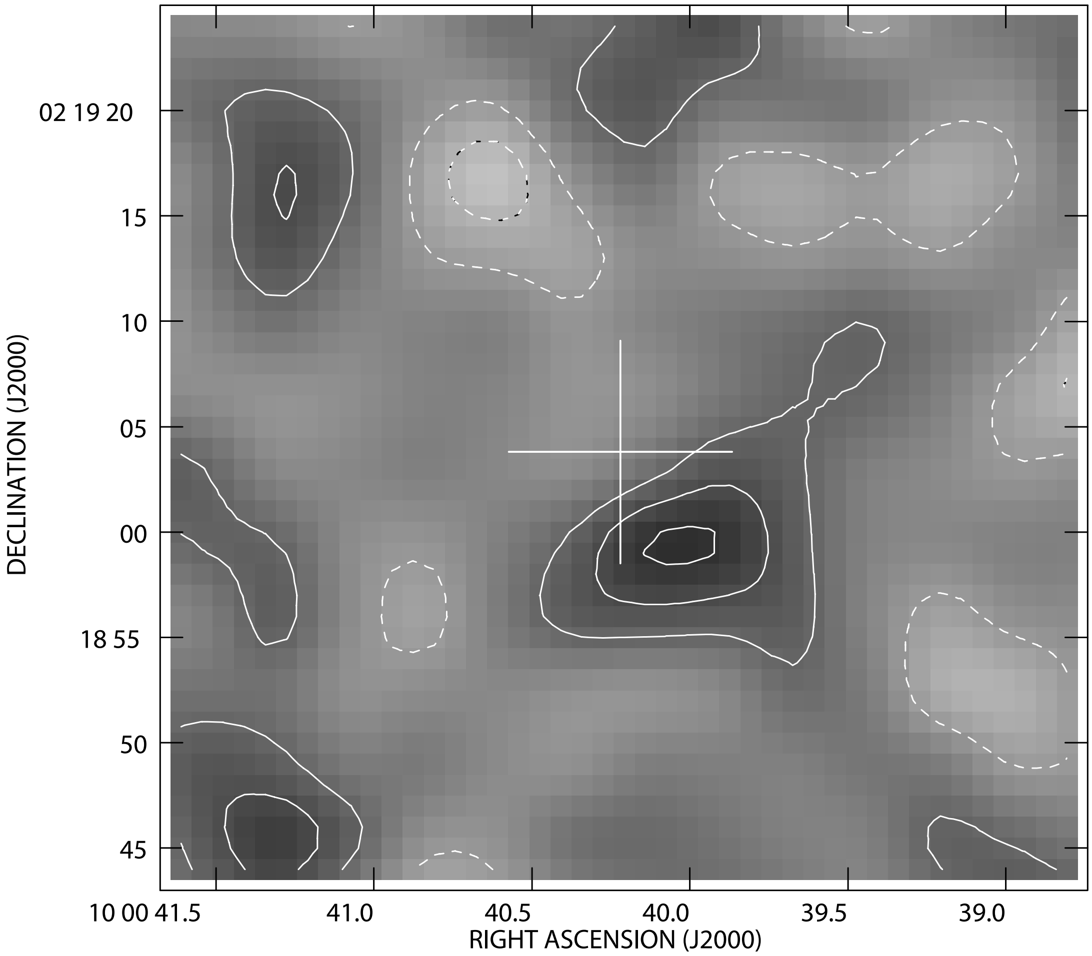

FIG. 3.—MAMBO 250 GHz image of the field centered on the $z = 5.7$ LAE J100040.22+021903.8 in Ajiki et al. (2006). The cross marks the position of the LAE, and the size of the cross corresponds to the FWHM of the MAMBO beam. The contour levels are -3, -2, -1, 1, 2, and 3 mJy beam^{-1}, and the beam has FWHM = 10.6″.

in any of the 99 COSMOS LAEs is broadly consistent with the conclusion that the narrowband Lyα search technique preferentially selects for star-forming galaxies.

We should point out that, in their extensive study of a sample of NB816-selected LAEs at $z \sim 4.5$, Malhotra & Rhoads (2002) found that a surprising fraction of the sources ($\sim$60%) had Lyα $EW_{rest} > 240$ Å. They state that such large EWs cannot arise through normal star formation, requiring either (1) a narrow-line AGN, (2) a top-heavy IMF, or (3) low metallicities. The largest measured EW_{rest} in the COSMOS LAE sample is 103 Å; however, the majority of the sources are not detected in the UV, and hence, only lower limits on the EW values can be set (see § 2.1). Murayama et al. (2007) discuss the EW distribution for the COSMOS sample in more detail.

The radio luminosity limit also corresponds to a massive (>5 $M_\odot$) star formation rate, $\sim$1500 $M_\odot$ yr^{-1} (Condon 1992). Hence, we can rule out any highly dust obscured, hyperluminous infrared starburst galaxy. Such a source would correspond to a bright submillimeter galaxy with a 250 GHz flux density of $\sim$9 mJy, assuming that the local FIR-radio correlation continues to apply to redshift $z \simeq 6$ (e.g., Blain et al. 2002; Bertoldi et al. 2007; Carilli & Yun 1999, 2000). The MAMBO image of the inner 20′ of the COSMOS field pushes this limit down to 3 mJy (500 $M_\odot$ yr^{-1}), at least for the 10% of the LAE sample that fall within this area.

The mean total star formation rate (for stars of 0.1–100 $M_\odot$) for all the sources based on the Lyα luminosity is $\sim$8 $M_\odot$ yr^{-1} (Murayama et al. 2007). A similar number is found for the star formation rates derived from the Lyα luminosity for the UV-detected subsample. For comparison, the star formation rates derived from UV luminosities are systematically higher, with the mean total star formation rate derived from the UV luminosities for the UV-detected sources $\sim$12 $M_\odot$ yr^{-1}. The implied massive (5–100 $M_\odot$) star formation rates, assuming a Salpeter IMF, are a factor of 5.6 smaller, or 1.4 and 2.1 $M_\odot$ yr^{-1} for the Lyα and UV sources, respectively. The difference between the Lyα-derived and UV-luminosity-derived star formation rates is discussed in Murayama et al. (2007), and likely relates to extra attenuation of the Lyα line due to associated Lyα absorption. Note that none of these values have been corrected for dust extinction.

From the radio stacking analysis, we derive a (2 σ) upper limit to the mean massive star formation rate of 81 $M_\odot$ yr^{-1} for all the LAEs, and 130 $M_\odot$ yr^{-1} for just the UV-detected sources. These radio limits to the star formation rate are independent of the dust content. Hence, the upper limit to the mean obscuration of the LAE galaxies in either the UV continuum or the Lyα line is about a factor of 60. For comparison, the typical Lyman break galaxy is thought to have its UV emission attenuated by a factor of $\sim$5 due to intrinsic dust (Steidel et al. 1999), and the mean obscuration for galaxies selected using the Lyα narrowband technique is thought to be even smaller (Shapley et al. 2003). Hence, while our study represents the most sensitive, widest field radio and millimeter study of high-z LAEs to date, it also accentuates the relatively poor limits that can be reached in the radio and millimeter for star-forming galaxies at the highest redshifts, when compared to studies using the Lyα line.

The main result of this work is to rule out the existence of any highly obscured massive starbursts or low-luminosity radio AGNs in the COSMOS LAE sample. Clearly, to push down to normal star-forming galaxies will require the 1–2 orders of magnitude improvement in sensitivity afforded by the upcoming Expanded Very Large Array and the Atacama Large Millimeter Array (ALMA).

Note added in manuscript.—Subsequent to the acceptance of this paper, an additional nine LAEs were discovered on further investigation of the Subaru images, making a total of 119 LAEs in the COSMOS field (Murayama et al. 2007). We have searched the radio and submillimeter COSMOS images for counterparts but do not detect any source to limits similar to those presented for the original sample of 110 LAEs. The stacking analysis is effectively unaltered by these new sources.

There is one source in the new sample of nine (J095825.26+022651.32 = source 4 in the final LAE catalog; Murayama et al. 2007) which projects within 5″ northwest of a strong radio hot spot. This radio hot spot is at the end of one of the radio lobes of an arcminute-sized luminous radio galaxy. The (likely) optical identification of the radio host galaxy is an early-type galaxy with a photometric redshift of 1.1 ± 0.2, situated in a cluster of galaxies at this redshift identified by Finoguenov et al. (2007). We feel the projected proximity of the LAE and the radio hot spot is most likely just a coincidence, although it is possible that gravitational lensing by the cluster may magnify the LAE, or that the detected excess in the NB816 filter is due to broad [O II] 372.7 nm nebular emission at $z = 1.19$, associated with shocked gas preceding the radio hot spot. Spectroscopy of this object is needed to test these possibilities.

C. L. C. acknowledges partial support from the Max-Planck Society and the Alexander von Humboldt Foundation through the Max-Planck Forschungspreise 2005. We thank the referee for very useful comments. The *HST* COSMOS Treasury program was supported through NASA grant HST-GO-09822. We gratefully acknowledge the contributions of the entire COSMOS collaboration. More information on the COSMOS survey is available at http://www.astro.caltech.edu/cosmos.

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