SEARCH FOR [C II] EMISSION IN z = 6.5–11 STAR-FORMING GALAXIES

Jorge González-López1,2,9, Dominik A. Riechers3, Roberto Decarli2, Fabian Walter2, Livia Vallini4, Roberto Neri3, Frank Bertoldi6, Alberto D. Bolatto7, Christopher L. Carilli8, Pierre Cox5, Elisabetta D. Cunha2, Andrea Ferrara4, Simona Gallerani4, and Leopoldo Infante1,9

1 Instituto de Astrofísica, Facultad de Física, Pontificia Universidad Católica de Chile Av. Vicuña Mackenna 4860, 782-0436 Macul, Santiago, Chile; jgonzal@astro.puc.cl, linfante@astro.puc.cl
2 Max Planck Institute für Astronomie Heidelberg Königstuhl 17, D-69117 Heidelberg, Germany; decarli@mpia.de, walter@mpia.de, cunha@mpia.de
3 Astronomy Department, Cornell University 200 Space Sciences Building, Ithaca, NY 14853, USA; reiechers@astro.cornell.edu
4 Scuola Normale Superiore Piazza dei Cavalieri 7, I-56126 Pisa, Italy; livia.vallini@sns.it, andrea.ferrara@sns.it, simona.gallerani@sns.it
5 Institut de RadioAstronomie Millimétrique 300 Rue de la Piscine, Domaine Universitaire, F-38406 Saint Martin d’Hères, France; neri@iram.fr, cox@iram.fr
6 Argelander Institute for Astronomy, University of Bonn Auf dem Hügel 71, D-53121 Bonn, Germany; bertoldi@astro.uni-bonn.de
7 Department of Astronomy, University of Maryland College Park, MD 20742, USA; bolatto@astro.umd.edu
8 National Radio Astronomy Observatory P.O. Box 0, Socorro, NM 87801, USA; ccari@nrao.edu
9 Centro de Astro-Ingeniería, Pontificia Universidad Católica de Chile, V. Mackenna 4860, Santiago, Chile.

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ABSTRACT

We present the search for the [C II] emission line in three z > 6.5 Lyα emitters (LAEs) and one J-dropout galaxy using the Combined Array for Research in Millimeter-wave Astronomy and the Plateau de Bure Interferometer. We observed bright z ~ 6.5–7 LAEs discovered in the Subaru Deep Field (SDF) and the multiple imaged lensed z ~ 11 galaxy candidate found behind the cluster MACS0646.7+7015. For the LAEs IOK-1 (z = 6.965), SDF J132415.7+273058 (z = 6.541), and SDF J132408.3+271543 (z = 6.554) we find upper limits for the [C II] line luminosity of <2.05, <4.52, and <10.56 × 10^11 L_⊙, respectively. We find upper limits to the far-IR (FIR) luminosity of the galaxies using a spectral energy distribution template of the local galaxy NGC 6946 and taking into account the effects of the cosmic microwave background on the millimeter observations. For IOK-1, SDF J132415.7+273058, and SDF J132408.3+271543 we find upper limits for the FIR luminosity of <2.33, 3.79, and 7.72 × 10^11 L_⊙, respectively. For the lensed galaxy MACS0646.7+273058, and SDF J132408.3+271543 we find upper limits for the [C II] emission in high-redshift galaxies as well as the difficulties for future observations with the Atacama Large Millimeter/submillimeter Array (ALMA) and the Cerro Chajnantor Atacama Telescope (CCAT).

Key words: galaxies: high-redshift – galaxies: individual (IOK-1, SDF J132415.7+273058, SDF J132408.3+271543, MACS0646-JD) – ISM: lines and bands

Online-only material: color figures

1. INTRODUCTION

Lyα emitters (LAEs) are galaxies selected through strong Lyα emission and are among the most studied galaxy populations at high redshift. The use of narrow-band filters over a wide area on the sky has proven to be a very effective method to find galaxies up to z ~ 7 (Iye et al. 2006; Fontana et al. 2010; Vanzella et al. 2011; Rhoads et al. 2012; Shibuya et al. 2012; Schenker et al. 2012; Ono et al. 2012). The possibility of finding LAEs from z ~ 1 to z ~ 7 shows that this type of galaxy can be used to understand galaxy evolution over cosmic time. It has been observed that the LAE fraction in UV-selected galaxies increases with redshift up to z ~ 6 (Stark et al. 2010), which is expected because of the decreasing dust content at higher redshifts. Beyond z ~ 6 it is expected that the LAE fraction decreases as the amount of neutral hydrogen (H I) increases because of the incomplete reionization of the intergalactic medium (IGM; Ota et al. 2008; Stark et al. 2010; Pentericci et al. 2011; Ono et al. 2012; Schenker et al. 2012). This is consistent with the comparatively low success rate of detection of Lyα emitters at z ≥ 7.

If Lyα photons from redshifts z ≥ 7 are absorbed by H I in the IGM (Dayal & Ferrara 2012), it will be difficult to spectroscopically confirm the candidates at high redshift, such as the candidate z ~ 12 galaxy UDFj-39546284 discovered in the Hubble Space Telescope (HST) Ultra Deep Field (Bouwens et al. 2011; Ellis et al. 2013; Brammer et al. 2013; Capak et al. 2014), and the candidates found behind galaxy clusters at z ~ 9.6, MACS1149-JD, and z ~ 10.7, MACS0647-JD (Zheng et al. 2012; Cee et al. 2013).

Among the usual interstellar medium (ISM) tracers at optical/UV wavelengths, the only line that has been observed at z > 4 in galaxies is Lyα. The emission of Lyα is complicated by its high optical depth in the emission region and its escape through resonant scattering, by dust absorption, and by the contribution from outflows. Therefore, direct constraints on the gas properties from the Lyα line strength are difficult to derive. This motivates the exploration of alternative means to study the highest-redshift galaxies. Promising candidates include far-infrared fine-structure emission lines, e.g., [C II] (2P_{1/2} → 2P_{1/2}) at 157.74 μm, which is not affected by the increasingly neutral IGM at z ≥ 7 and can account for up to 1% of the total infrared luminosity in some galaxies, especially in those with low luminosity and metallicity (Crawford et al. 1985; Stacey et al. 1991; Israel et al. 1996; Madden et al. 1997).
Throughout this paper we use a cold dark matter cosmology ($\Omega_m = 0.3$ and $\Omega_{\Lambda} = 0.7$), with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $H_{100} = 100$ km s$^{-1}$ Mpc$^{-1}$, and $z_{max} = 0.3$. This cosmology is used throughout the paper and is assumed in Section 2. Throughout this paper we use $78.4$ km s$^{-1}$ Mpc$^{-1}$ to convert redshift into distance and $78.4$ Mpc$^{-1}$ to convert distance into redshift.

The [C ii] line traces photodissociation (also called photon-dominated) regions (PDRs), as well as diffuse H I and H II regions. In PDRs, the far-UV radiation produced by OB stars heats the surface layers of molecular clouds, which cool preferentially through [C ii] emission. It has been observed that most of the [C ii] emission in IR-bright galaxies comes from PDRs and that the PDR gas mass fraction can be up to 50% in starbursts like M82 (Crawford et al. 1985).

Modeling of far-infrared (FIR) emission lines observed in starburst galaxies showed that at least 70% of the [C ii] emission is produced in PDRs (Carral et al. 1994; Lord et al. 1996; Colbert et al. 1999). In the low-metallicity system Haro 11, on the other hand, at least 50% of the [C ii] emission arises from a more diffuse, extended ionized medium (Cormier et al. 2012). The different conditions in which the [C ii] emission is produced and the direct or indirect relation of these conditions with the star formation process suggest that [C ii] emission should be a good tracer of the global galactic star formation activity (de Looze et al. 2011), at least for galaxies with low $T_{dust}$ or low $\Sigma_{IR} = L_{IR}/\pi r^2_{mid-IR}$ (Diaz-Santos et al. 2013). [C ii] is found to be the strongest emission line, stronger than CO, and thus is the most promising tracer of the dense, star-forming regions in distant galaxies where [C ii] can be detected with ground-based telescopes because of the redshift into observable atmospheric windows.

In recent years, the [C ii] 158 $\mu$m emission line has been established as a promising observable in high-redshift galaxies (Maiolino et al. 2005, 2009; Iono et al. 2006; Walter et al. 2009, 2012a; Hailey-Dunsheath et al. 2010; Stacey et al. 2010; Ivison et al. 2010; Wagg et al. 2010, 2012; Cox et al. 2011; De Breuck et al. 2011; Valtchanov et al. 2011; Galleneri et al. 2012; Venemans et al. 2012; Carilli et al. 2013; Wang et al. 2013; Willott et al. 2013; Riechers et al. 2013). Most of the high-$z$ detections were for infrared-luminous starbursts, many of which also show signatures of active galactic nuclei. See the review by Carilli & Walter (2013) for more details.

With star formation rates of a few tens of $M_\odot$ yr$^{-1}$, based on the Ly$\alpha$ and UV continuum emission, LAEs are classified as “normal” star-forming galaxies. Different studies claim that LAEs are young, dust-free, starbursting galaxies, supported by UV observations (Gawiser et al. 2006; Finkelstein et al. 2007; Lai et al. 2008). Recent mid-IR (MIR) detection of LAEs at $z \sim 2.5$ and $z < 0.3$ shows that a significant fraction of the star formation in these galaxies is strongly obscured by dust (Oteo et al. 2012a, 2012b). Thus, LAEs are promising targets for the detection of [C ii] at high redshift.

Previous attempts to detect [C ii] in a small sample of LAEs at $z \sim 6.6$ were unsuccessful (Walter et al. 2012b; Kanekar et al. 2013; Ouchi et al. 2013).

Here we present the result of a search for [C ii] in three LAEs at $z > 6.5$ and in a lensed galaxy at $z \sim 11$. In Section 2 we describe the target selection and observations. The data are shown in Section 3 together with some implications and analysis in Section 4. A summary of the paper is presented in Section 5. Throughout this paper we use a $\Lambda$ cold dark matter cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_{\Lambda} = 0.7$, and $\Omega_m = 0.3$.

2. OBSERVATIONS

2.1. Source Selection

The three Ly$\alpha$ emitters targeted in this study were discovered in the Subaru Deep Field (SDF). Two of the LAEs observed belong to the sample of LAEs at $z \sim 6.6$ discovered by Taniguchi et al. (2005). The targets are the brightest LAEs (sources 3 and 4 in their catalog) and have a narrow and bright Ly$\alpha$ emission line. The third LAE (IOK-1) was discovered at $z \sim 7$ by Iye et al. (2006). It is one of the brightest and most distant LAEs known to date.

The fourth target, MACS0647-JD, is a lensed Lyman-break galaxy (LBG) discovered behind the galaxy cluster MACS0647.7+7015 at $z = 0.591$ (Coe et al. 2013). The galaxy was discovered as a J-dropout galaxy lensed into three magnified images as part of the Cluster Lensing and Supernova survey with Hubble (CLASH; Postman et al. 2012). The three images of the galaxy, MACS0647-JD1, MACS0647-JD2, and MACS0647-JD3, have magnifications of $\sim 8$, $\sim 7$, and $\sim 2$, respectively. The photometric redshift of the galaxy is $10.7^{+0.6}_{-0.4}$ (95% confidence limits). This is one of the highest-redshift galaxy candidates known to date.

2.2. CARMA Observations

Observations of the three $z \sim 6.5–7$ LAEs were carried out using the Combined Array for Research in Millimeter-wave Astronomy (CARMA) between 2008 July and 2010 July. The array configurations used were the most compact, D and E, to minimize phase decoherence and maximize point source sensitivity. The [C ii] line has a rest frequency of 1900.54 GHz (157.74 $\mu$m). For the redshifts of the targets, the line is shifted to the 1 mm band. The receivers were tuned to a frequency $\sim 150$ km s$^{-1}$ bluer than the expected frequency from the redshift determined by the peak of the Ly$\alpha$ line. This is to take into account the possible absorption by the IGM in the Ly$\alpha$ line. The setups provide an instantaneous bandwidth of $\sim 1.5$ GHz ($\sim 1800$ km s$^{-1}$) with a spectral resolution of 31.25 MHz ($\sim 37–39$ km s$^{-1}$).

The observations were processed using MIRIAD (Sault et al. 1995). The absolute flux calibrators used are 3C84, MWC349, 3C273, and Mars, the latter being the most used. As passband calibrators the QSOs 3C273, 3C345, and 0854+201 were used. As a gain calibrator the QSO 1310+323 was used. The time on source for IOK-1 was 58.5 hr, for SDF J132415.7+273058 it was 15.9 hr, and for SDF J132408.3+271543 it was 4.6 hr. The final cubes were made using natural weighting to maximize point source sensitivity. The observations resulted in the following beam sizes: for IOK-1, 1$''$.86 $\times$ 1$''$.33, position angle (P.A.) = $-0^\circ$.34; for SDF J132415.7+273058, 1$''$.92 $\times$ 1$''$.56, P.A. = 83$^\circ$.45; and for SDF J132408.3+271543, 2$''$.54 $\times$ 2$''$.01, P.A. = 88$^\circ$.02 (all targets are D and E configurations). For the D configuration the minimum baseline is 11 m, and the maximum is 150 m. For the E configuration the minimum baseline is 8 m, and the maximum is 66 m. Table 1 summarizes the sensitivities reached for the observations of the LAEs.

2.3. PdBI Observations

All MACS0647-JD observations were carried out in 2012 November as part of a Director’s Discretionary Time program with the Plateau de Bure Interferometer (PdBI). The target was observed with four WideX frequency setups (3.6 GHz bandwidth each), covering 80% of the photometric redshift range ($z = 10.1–11.1$). Two of the three lensed images (JD1 and JD2) are within 18$''$ of each other, and they were covered in a common 2 mm pointing. The absolute flux calibrators used are MWC349, 2200+420, 3C279, and 0716+714. As gain calibrator the QSO 0716+714 was used. The total on-source time for all tunings was 7.4 hr (six-antenna equivalent).
The two results correspond to the most sensitive and the least sensitive setups.

The observations were processed using GILDAS. The beam size of the observations is the following: for MACS0647-JD, 2′.10 × 1′.76, P.A. = 102°0′ (C configuration). For the C configuration the minimum baseline is 22 m, and the maximum is 184 m. Table 2 summarizes the sensitivity reached for the observations of MACS0647-JD.

### 3. RESULTS

#### 3.1. Line Emission

The spectra of the three $z \sim 6.5$–7 LAEs are presented in Figure 1, and the spectrum of MACS0647-JD is shown in Figure 2. No significant emission is detected at the redshifted line frequencies or close to them. The observations were sampled to a channel resolution of 50 km s$^{-1}$ similar to the expected FWHM of the [C$\text{II}$] emission line (see Section 4.1). We use our nondetections to put constraints on the luminosities of the [C$\text{II}$] lines for all targets. The results for the LAEs can be seen in Table 1, and those for MACS0647-JD are in Table 2. The upper limits were estimated assuming that the sources were unresolved. For MACS0647-JD, the spectra of the two images were corrected by the primary beam pattern before combination. The [C$\text{II}$] luminosities were estimated assuming that the velocity-integrated flux of the line is $I_{\text{line}} = S_{\text{line}} \Delta v$, with $S_{\text{line}}$ being three times the rms of the 50 km s$^{-1}$ channel and $\Delta v = 50$ km s$^{-1}$ being the range in velocity (details are given in the notes in Table 1). Using $3\sigma$ over a 50 km s$^{-1}$ channel to estimate the upper limit in the luminosities can result in a underestimation. We point out that for a more conservative estimation the luminosities should be multiplied by a factor of two (i.e., $3\sigma$ over 200 km s$^{-1}$ channel). Assuming a channel width of 200 km s$^{-1}$, our IOK-1 [C$\text{II}$] limit is $\sim 10\%$ deeper than the previous PdBI limit (Walter et al. 2012b).

#### 3.2. Continuum Emission

No continuum emission is detected in our observations of the three LAEs and the $z \sim 11$ LBG. The sensitivity reached for the continuum observations is given in the Table 1 for the LAEs, and a continuum map for the three LAEs is shown in Figure 3. The results for the MACS0647-JD are given in Table 2, and the continuum map is shown in Figure 4. In Section 4.2 we discuss how the cosmic microwave background (CMB) affects our continuum observations, and in Section 4.3 we use our continuum measurements to constrain the nature of our targets.

### Table 1

| Source     | R.A.          | Dec.         | $z^c$ | $V_{\text{obs}}^b$ (GHz) | $\sigma_{\text{cont}}^a$ (mJy beam$^{-1}$) | $\sigma_{\text{line}}^d$ (mJy beam$^{-1}$) | $L_{\text{[CII]}}^b$ ($10^8 L_\odot$) | $L_{\text{[CII]}}^b$ (10$^8 L_\odot$) | SFR$_{\text{dust}}^g$ (M$_\odot$ yr$^{-1}$) | SFR$_{\text{UV}}^h$ (M$_\odot$ yr$^{-1}$) |
|------------|---------------|--------------|-------|--------------------------|------------------------------------------|------------------------------------------|----------------------------------------|----------------------------------------|------------------------------------------|------------------------------------------|
| IOK-1      | 13:23:59.80   | +27:24:56.0  | 6.965 | 238.881                  | 0.19                                     | 1.17                                     | <2.05                                  | <6.34                                  | <109.1                                  | ~24                                     |
| SDF J132415.7 | 13:24:15.70 | +27:30:58.0  | 6.541 | 252.154                  | 0.37                                     | 2.82                                     | <4.52                                  | <10.3                                  | <177.2                                  | ~34                                     |
| SDF J132408.3 | 13:24:08.30 | +27:15:43.0  | 6.554 | 251.594                  | 0.75                                     | 5.67                                     | <10.56                                 | <21.0                                  | <360.9                                  | ~15                                     |

Notes. All luminosity upper limits are $3\sigma$.

References: IOK-1: Iye et al. (2006); Ouchi et al. (2012)—SDF J132415.7+273058 and SDF J132408.3+271543 : Taniguchi et al. (2005)

$^a$ Observing frequencies; tuned ~125 MHz blueward of the Ly$\alpha$ redshifts for all targets.

$^b$ 1$\sigma$ continuum sensitivity at a 158 $\mu$m rest wavelength.

$^c$ $[\text{CII}]$ line sensitivity over a channel width of 50 km s$^{-1}$.

$^d$ $[\text{CII}]$ luminosity limit over a channel width of 50 km s$^{-1}$ assuming $L_{\text{line}} = 1.04 \times 10^{-3} I_{\text{line}} (1+z)^{-1} D_L^2$, where the line luminosity, $L_{\text{line}}$, is measured in $L_\odot$; the velocity integrated flux, $I_{\text{line}} = S_{\text{line}} \Delta v$, in Jy km s$^{-1}$; the rest frequency, $\nu_{\text{rest}} = \nu_{\text{obs}}(1+z)$, in GHz; and the luminosity distance, $D_L$, in Mpc (e.g., Solomon et al. 1992).

$^e$ 3$\sigma$ limit based on the SED of NGC 6946 and including the effect of the CMB.

$^f$ 3$\sigma$ limit based on $L_{\text{[CII]}}$ excluding the effect of the CMB.

$^g$ UV-based SFR from Jiang et al. (2013).

$^h$ $H_{\text{UV}}$-based SFR from Jiang et al. (2013).

### Table 2

| Parameter | MACS0647-JD1, JD2 |
|-----------|-------------------|
| Coordinates (J2000) JD1 | 06:47:55.731, +70:14:35.76 |
| Coordinates (J2000) JD2 | 06:47:53.112, +70:14:22.94 |
| $\mu$ (JD1+JD2) | ~15 |
| Redshift | 10.7$^{+0.6}_{-0.4}$ |
| UV SFR | ~1 (M$_\odot$ yr$^{-1}$) |
| $\nu$ | 156.7–171.1 (GHz) |
| $\sigma_{\text{cont}}^a$ | 0.17 mJy beam$^{-1}$ |
| $\sigma_{\text{line}}^d$ (setup A)$^b$ | 3.17 mJy beam$^{-1}$ |
| $\sigma_{\text{line}}^d$ (setup B)$^b$ | 4.12 mJy beam$^{-1}$ |
| $\sigma_{\text{line}}^d$ (setup C)$^b$ | 3.19 mJy beam$^{-1}$ |
| $\sigma_{\text{line}}^d$ (setup D)$^b$ | 6.42 mJy beam$^{-1}$ |
| $L_{\text{[CII]}}$ (setup C)$^c$ | <6.78 × 10$^{-7}$ × (15$\mu$1$^{-1}$) ($L_\odot$) |
| $L_{\text{[CII]}}$ (setup D)$^c$ | <6.36 × 10$^{-7}$ × (15$\mu$1$^{-1}$) ($L_\odot$) |
| $L_{\text{[CII]}}$ (corrected CMB)$^c$ | <1.65 × 10$^{-7}$ × (15$\mu$1$^{-1}$) ($L_\odot$) |
| SFR (L$_{\text{IR}}$) (corrected CMB)$^c$ | <28 × (15$\mu$1$^{-1}$) (M$_\odot$ yr$^{-1}$) |
| SFR (L$_{\text{[CII]}}$) (setup C)$^c$ | <5 × (15$\mu$1$^{-1}$) (M$_\odot$ yr$^{-1}$) |
| SFR (L$_{\text{[CII]}}$) (setup D)$^c$ | <9 × (15$\mu$1$^{-1}$) (M$_\odot$ yr$^{-1}$) |

Notes. All luminosity upper limits are $3\sigma$.

References: coordinates, magnification, redshift, and UV SFR from Cee et al. (2013). All the luminosities and SFR are corrected by magnification.

$^a$ 1$\sigma$ continuum sensitivity at a 158 $\mu$m rest wavelength.

$^b$ 1$\sigma$ [C$\text{II}$] line sensitivity over a channel width of 50 km s$^{-1}$.

$^c$ 3$\sigma$ [C$\text{II}$] luminosity limit over a channel width of 50 km s$^{-1}$ as in Table 1. The two results correspond to the most sensitive and the least sensitive setups.

$^d$ 3$\sigma$ limit based on the SED of NGC 6946 and including the effect of the CMB.

$^e$ 3$\sigma$ limit based on $L_{\text{[CII]}}$ excluding the effect of the CMB.

$^f$ Based on the De Looze et al. (2011) $L_{\text{[CII]}}$–SFR relation. The two results correspond to the most sensitive and the least sensitive setups.

The observations were performed using GILDAS. The beam size of the observations is the following: for MACS0647-JD, 2′.10 × 1′.76, P.A. = 102°0′ (C configuration). For the C configuration the minimum baseline is 22 m, and the maximum is 184 m. Table 2 summarizes the sensitivity reached for the observations of MACS0647-JD.
Carilli et al. (2013) tried to for a significant influence of the quasar on the properties of the LAE from the observations. Carilli et al. (2013) combine a high-resolution cosmological simulation with a subgrid multiphase model of the ISM to simulate the [C II] emission in a halo similar to the LAE Himiko at \( z = 6.6 \). They find that 95\% of the [C II] emission is generated in the cold neutral medium (CNM), mainly in clumps with an individual size \( \lesssim 3 \) kpc. They present a spectrum for the simulated [C II] emission, where the FWHM of the main peak is \( \sim 50 \) km s\(^{-1}\), very similar to the value of 56 km s\(^{-1}\) of the LAE at \( z = 4.7 \). This suggests that the width of the [C II] line is, to first order, determined by the gravitational potential of the clumps. The [C II] emission produced in the CNM follows the gravitational potential of the clumps, resulting in narrow emission lines associated with each clump. An ensemble of emitting clumps moving through the galaxy following the potential of the galaxy could combine and produce a broader line. Such behavior is not observed in the simulations, where just a small number of clumps dominate the [C II] emission.

We conclude that the adopted width of \( \sim 50 \) km s\(^{-1}\) for the [C II] line in LAEs agrees with recent observations and simulations. Nevertheless, we do not discard the possibility of [C II] lines being broader than our assumption, but the occurrence of unusually narrow lines in this population appears plausible.

### 4.2. CMB Effects

The CMB radiation emits as a blackbody with a temperature of \( T_{\text{CMB}} = 2.7 \) K. The temperature of the CMB increases linearly with \( (1+z) \), becoming an important factor to take into account for observations of objects at high redshift. da Cunha et al. (2013) showed the effect of the CMB on observations of high-redshift galaxies. Here we will follow the prescription formulated by da Cunha et al. (2013) to take into account the effects of the CMB in the continuum observations of galaxies at high redshift. We will apply this prescription to the spectral energy distribution (SED) of the local galaxies as if they would be observed at a given redshift \( z \).

The templates that we use are those presented by Silva et al. (1998) for the galaxies Arp 220, M82, M51, and NGC 6946. For the galaxies assume cold dust with temperature \( T_{\text{dust}} \) and an emissivity index \( \beta \). For Arp 220 we used \( T_{\text{dust}} = 66.7 \) K and \( \beta = 1.86 \) (Rangwala et al. 2011), for M82 we used \( T_{\text{dust}} = 48 \) K and \( \beta = 1 \) (Colbert et al. 1999), for M51 we used \( T_{\text{dust}} = 24.9 \) K and \( \beta = 2 \) (Mentuch Cooper et al. 2012), and for NGC 6946 we used \( T_{\text{dust}} = 26 \) K and \( \beta = 1.5 \) (Skibba et al. 2011). At a
Figure 2. Spectrum of MACS0647-JD. The spectrum shows the added fluxes measured on the positions of the two lensed images, JD1 and JD2 (combined magnification $\mu \sim 15$). The spectra of the two images were corrected by the primary beam pattern before combination. The four setups are plotted in different colors; blue, red, green, and orange are for setups A, B, C, and D respectively. The error bars correspond to the quadrature of the errors of the individual measurement of the fluxes for JD1 and JD2 in each frequency channel. For display purposes, the spectrum is sampled at a channel resolution of 200 km s$^{-1}$, but the search of the $[\text{C}\text{II}]$ line as well as the analysis was made with the spectrum sampled to 50 km s$^{-1}$.
(A color version of this figure is available in the online journal.)

Figure 3. Rest frame 158 $\mu$m continuum maps of the LAEs. Each contour level represents 1$\sigma$ steps ($\pm 1\sigma$ levels are not shown). Solid contours are positive signals, and dashed contours are negative signals. The 1$\sigma$ levels are 0.75 mJy beam$^{-1}$ for SDF J132408.3+271543, 0.37 mJy beam$^{-1}$ for SDF J132415.7+273058, and 0.19 mJy beam$^{-1}$ for IOK-1. The blue crosses represent the position of each LAE as given in Table 1.
(A color version of this figure is available in the online journal.)

Figure 4. Continuum map of the field of MACS0647-JD. Each contour level represents 1$\sigma$ steps ($\pm 1\sigma$ levels are not shown). Solid contours are positive signals, and dashed contours are negative signals. The 1$\sigma$ level is 93 $\mu$mJy beam$^{-1}$. The blue plus signs represent the positions of the two lensed images MACS0647-JD1 and MACS0647-JD2, as given in Table 2.
(A color version of this figure is available in the online journal.)

given redshift the CMB contributes to the dust heating such that the equilibrium temperature is

$$T_{\text{dust}}(z) = \left[ \left( T_{\text{dust}}^{z=0} \right)^{4+\beta} + \left( T_{\text{CMB}}^{z=0} \right)^{4+\beta} \right]^{1/(4+\beta)}. \quad (1)$$

$T_{\text{dust}}^{z=0}$ is a measurement of the mean dust temperature as determined by a modified blackbody (MBB) fit to an observed galaxy IR SED at $z = 0$, representing the total IR luminosity of the galaxy. As a representative fit, this is equally applicable to both optically thin galaxies and optically thick galaxies as in the case of Arp 220. As long as the galaxy is transparent to the CMB radiation (true for even Arp 220), Equation (1) holds. The additional heating by the CMB affects the SEDs such that the peak of the emission is shifted to a shorter wavelength and the total luminosity associated with the cold dust is higher by $T_{\text{dust}}^{z=0}[T_{\text{dust}}^{z=0}]^{4+\beta}$. We need to modify the intrinsic SED of the galaxies to include this new $T_{\text{dust}}(z)$. The flux density depends on the blackbody radiation for the given temperature,

$$F_{\nu}(1+z) \propto B_\nu(T_{\text{dust}}(z)). \quad (2)$$

To include $T_{\text{dust}}(z)$ we have to apply the following factor to convert the intrinsic SED flux density to the emission associated
with the new temperature $F^*_{\nu/(1+z)}$:

$$F^*_{\nu/(1+z)} = F^\text{int}_{\nu/(1+z)} \times \frac{B_\nu(T_{\text{dust}}(z))}{B_\nu(T_{\text{dust}}(z=0))}. \quad (3)$$

This factor will only apply to the part of the SED that corresponds to the emission of the cold dust. To accomplish this, we scale an MBB to the peak of the FIR emission of the SED at $T_{\text{dust}}(z=0)$ and then use this MBB emission to estimate the ratio $(R_v)$ of emission associated with the cold dust at a given frequency,

$$R_v = \frac{K^\beta B_\nu(T_{\text{dust}}(z=0))}{F^\text{int}_\nu}, \quad (4)$$

where $K$ is just the scaling factor. The flux density associated with the new temperature of the cold dust will be

$$F^*_{\nu/(1+z)} = M_v \times F^\text{int}_{\nu/(1+z)} \quad (5)$$

with

$$M_v = \left[ (1 - R_v) + R_v \times \frac{B_\nu(T_{\text{dust}}(z))}{B_\nu(T_{\text{dust}}(z=0))} \right]. \quad (6)$$

Finally, following da Cunha et al. (2013), we have to take into account the effect of the CMB as an observing background. For this we have to multiply the flux associated with $T_{\text{dust}}(z)$ by $C_\nu$,

$$C_\nu = \left[ 1 - \frac{B_\nu(T_{\text{CMB}}(z))}{B_\nu(T_{\text{dust}}(z))} \right], \quad (7)$$

resulting in the observed flux of the galaxies being

$$F^\text{obs}_{\nu/(1+z)} = C_\nu \times M_v \times F^\text{int}_{\nu/(1+z)}, \quad (8)$$

with $C_\nu \times M_v$ representing the effect of the CMB in the observations at a given frequency. The same corrections are derived when an optically thick emission is assumed, as in the case of Arp 220.

As we can see in Figure 5, the effect of the CMB decreases the observable flux density at 2 mm by up to a factor of five (in the case of M51) for the galaxy at $z \sim 11$ when the temperature of the CMB is higher, as expected. Also, the effect is higher for galaxies with a lower temperature of the cold dust. Galaxies with a temperature of the order of 25–30 K are more affected than those with a temperature of 40–50 K. The CMB effects will be important for estimations of the flux densities of these types of galaxies in the continuum and for correct interpretation of the observations.

The CMB effects on the $[\text{C}\ II]$ line observations are similar to those on the continuum. The flux of an emission line observed against the CMB is

$$\frac{S^\text{obs}_{\nu/(1+z)}}{S^\text{int}_{\nu/(1+z)}} = \left[ 1 - \frac{B_\nu(T_{\text{CMB}}(z))}{B_\nu(T_{\text{exc}})} \right], \quad (9)$$

with $T_{\text{exc}}$ being the excitation temperature of the transition. For the case of local thermal equilibrium, when collisions dominate the excitation of the $[\text{C}\ II]$ line, the excitation temperature of the transition is equal to the kinetic temperature of the gas ($T_{\text{kin}}$). The kinetic temperature varies for the different $[\text{C}\ II]$ emission regions. Gas temperatures within PDRs are typically $T \sim 100–500$ K (Stacey et al. 2010), for the CNM $T \approx 250$ K, for the warm neutral medium (WNM) $T \approx 5000$ K, and for the ionized medium $T \approx 8000$ K (Vallini et al. 2013).

Since the CMB temperature at $z = 6.5–11$ is much lower than the gas temperature of the $[\text{C}\ II]$ emitting region, it will not contribute significantly to the $[\text{C}\ II]$ excitation but must be taken into account as the background against which the line flux is measured. In most of the $[\text{C}\ II]$ emission regions, the temperatures are so high that the observed flux of the line against the CMB is similar to the intrinsic flux ($S^\text{obs}_{\nu/(1+z)}/S^\text{int}_{\nu/(1+z)} \approx 1$). For the extreme case where the entire $[\text{C}\ II]$ emission is being produced in PDRs with a temperature of 100 K in a galaxy at $z = 11$, the observed flux (using Equation (9)) would be 90% of the intrinsic flux. We found this case very unlikely since in low-redshift galaxies the $[\text{C}\ II]$ emission produced in PDRs is
50%–70% of the total [C II] luminosity and the gas temperatures associated with the PDRs are higher (Crawford et al. 1985; Carrall et al. 1994; Lord et al. 1996; Colbert et al. 1999). We conclude that the CMB effects on the [C II] line observations are negligible for our observations.

4.3. Spectral Energy Distribution of the Galaxies

Using the upper limits on the continuum, we compare the targets with the SED templates of local galaxies. For the LAEs, the SEDs of the local galaxies are scaled to the flux of a near-IR filter that is not contaminated by the Lyα emission line. For MACS0647-JD, the filter used for the scaling is the one next to the Lyman break. The photometry of IOK-1 and MACS0647-JD together with the SED of local galaxies is shown in Figure 5. For SDF J132415.7+273058 and SDF J132408.3+271543 (not shown) the situation is very similar: the sources have a similar redshift, the continuum upper limits are comparable and the CMB effects are of the same order. Our upper limit for IOK-1 is comparable to the upper limit found by Walter et al. (2012b) using PdBI observations.

Using the SED of NGC 6946 as a template, we estimate the IR luminosity given the upper limit flux densities, similar to the approach shown by Walter et al. (2012b). We scale the SED of NGC 6946 to the 3σ upper limits of the millimeter observations and integrate from 8 μm to 1 mm (rest frame) to compute the IR luminosity.

The IR luminosity corresponding to this intrinsic SED and the associated star formation rate (SFR, Kennicutt 1998) are given in Table 1 for the LAEs and in Table 2 for MACS0647-JD. We note that estimating the IR luminosity using NGC 6946 without taking into account the CMB results in a significant understimation of the luminosity upper limits. The IR luminosity limit corrected by the CMB of the LAEs at z ∼ 6.6 is 35% higher than without correcting by the CMB. For IOK-1 at z ∼ 7, the IR luminosity limit is 50% higher than the estimation without correcting by the CMB. For MACS0647-JD at z ∼ 10.7, the IR luminosity limit corrected for the CMB is ∼3.5 times the IR luminosity limit not corrected by the CMB. For galaxies with a cold dust temperature of ∼25 K, the effect of the CMB on the observations is very important at high redshift, and it will significantly limit the feasibility of detecting galaxies that are not extremely starbursting in the IR continuum; it will not greatly affect the detectability of [C II] emission.

4.4. Ratio L_{[CII]}/L_{FIR}

Figure 6 presents our upper limits to L_{[CII]}/L_{FIR} and L_{FIR} together with detections of [C II] in other galaxies. The arrows represent the region of possible values for L_{[CII]}/L_{FIR} and L_{FIR} (integrated from a 42.5 to 122.5 μm rest frame). If we used UV-based SFR estimates to infer L_{FIR}, our data points would move across the diagonal arrows toward the region where local galaxies are, putting our L_{[CII]}/L_{FIR} upper limits close to the average value found for the local galaxies. The ratio L_{[CII]}/L_{FIR} is a measure of how efficient the [C II] emission is in cooling the gas. The values presented for our targets, log(L_{[CII]}/L_{FIR}) ∼ −2.9, do not necessarily imply that [C II] is not efficient in cooling the gas in these galaxies; it is most likely a consequence of the galaxies having much lower FIR luminosities than our conservative upper limits. Different processes can affect the ratio L_{[CII]}/L_{FIR}. In galaxies with low extinction and low metallicity, like in Haro 11, about 50% of the [C II] emission arises from the diffuse ionized medium (Cormier et al. 2012). Variations on the fraction of [C II] emission associated with the ionized medium will also affect the ratio L_{[CII]}/L_{FIR}. In some galaxies, the internal dust extinction can affect the ratio L_{[CII]}/L_{FIR}. In Arp 220, the dust is optically thick at 158 μm and can absorb part of the [C II] emission, decreasing the ratio L_{[CII]}/L_{FIR} (Rangwala et al. 2011).

Díaz-Santos et al. (2013) present the results of a survey of [C II] in luminous infrared galaxies (LIRGs) observed with the Photodetector Array Camera and Spectrometer (PACS) instrument on board the Herschel Space Observatory. They found a tight correlation between the ratio L_{[CII]}/L_{FIR} and the far-IR S_{ν}(63 μm)/S_{ν}(158 μm) continuum color, independent of their L_{IR}. They found that the ratio decreases as the average temperature of dust increases, suggesting that the main observable linked to the variation of L_{[CII]}/L_{FIR} is the average dust temperature. For galaxies with dust temperatures ∼20 K the average ratio is log(L_{[CII]}/L_{FIR}) ∼ −2, suggesting that for galaxies like NGC 6946 with a dust temperature of ∼26 K, the ratio L_{[CII]}/L_{FIR} should be on the same order of magnitude. Díaz-Santos et al. (2013) also found a correlation between L_{[CII]}/L_{FIR} and the luminosity surface density of the mid-IR emitting region (Σ_{IR} = L_{IR}/πr_{mid-IR}^{2}). LIRGs with lower L_{[CII]}/L_{FIR} ratios are warmer and more compact. We can use this relation to find a rough estimation of L_{[CII]}/L_{FIR} for our targets. For r_{mid-IR} we use the size found in the UV observations of the targets. The half-light radius of IOK-1 is ≈0.62 kpc (Cai et al. 2011). The FWHM size of SDF
3.2 kpc, respectively (Taniguchi et al. 2005). For MACS0647-JD \( \lesssim \) found at low redshift. More observations are needed to clarify Himiko suggest that LAEs at Looze et al. (2011), with the gray area corresponding to \( 2 \sigma \) rate of galaxies. The black solid lines correspond to the relation found by de HCM-6A by Kanekar et al. (2013). The black diamond corresponds to the upper limit of the \([\text{C} \text{ii}]\) emission found for Himiko by Ouchi et al. (2013). We can also see in the emission from PDRs and should be seen as a lower limit. In Figure 9, we present the integrated flux of \([\text{C} \text{ii}]\) emission produced by the three modeled phases: CNM, WNM, and the ionized medium. Most of the \([\text{C} \text{ii}]\) emission comes from the CNM (\( \sim 50\% \)); the rest comes from the WNM (\( \sim 20\% \)) and from the ionized medium (\( \sim 30\% \)). For comparison, in Himiko, 95\% of the emission is produced in the CNM, and the rest in the WNM. No emission from the ionized medium was modeled in the simulation of Himiko (Vallini et al. 2013). We can also see in the emission that the FWHM of the main peak is \( \sim 50 \text{ km s}^{-1} \), just as expected.

4.6. IOK-1 Models

Using the same procedure as presented in Vallini et al. (2013) for the \([\text{C} \text{ii}]\) emission of Himiko, we estimate the emission of \([\text{C} \text{ii}]\) for IOK-1 at \( z \sim 7 \). For this simulation, the SFR was set to \( 20 \text{ M}_\odot \text{ yr}^{-1} \) with a stellar population age of 10 Myr. The metallicity was set to solar to have a conservative estimation of the \([\text{C} \text{ii}]\) emission. The simulation does not include the emission from PDRs and should be seen as a lower limit. In Figure 8, we show the \([\text{C} \text{ii}]\) emission produced by the three modeled phases: CNM, WNM, and the ionized medium. Most of the \([\text{C} \text{ii}]\) emission comes from the CNM (\( \sim 50\% \)); the rest comes from the WNM (\( \sim 20\% \)) and from the ionized medium (\( \sim 30\% \)). For comparison, in Himiko, 95\% of the emission is produced in the CNM, and the rest in the WNM. No emission from the ionized medium was modeled in the simulation of Himiko (Vallini et al. 2013). We can also see in the emission that the FWHM of the main peak is \( \sim 50 \text{ km s}^{-1} \), just as expected.

In Figure 9, we present the integrated flux of \([\text{C} \text{ii}]\) for a different combination of metallicities and stellar population ages. This shows a strong dependency on the metallicity, which is expected since it is treated linearly with the abundance of \([\text{C} \text{ii}]\) in the gas. The second main feature of this result is the dependency on the stellar population age. Here we assumed a continuum SFR of \( 20 \text{ M}_\odot \text{ yr}^{-1} \); for the older stellar populations a higher number of heating photons come from the UV part of the
The only molecular gas masses measured in high-redshift UV-selected star-forming galaxies come from the detection of CO transition lines in lensed LBGs. The measured values are \( \sim 4 \times 10^8 M_\odot \), \( \sim 9 \times 10^8 M_\odot \), and \( \sim 1 \times 10^9 M_\odot \) for MS 1512-cB58 (\( z = 2.73 \)), the cosmic eye (\( z = 3.07 \)), and MS1358-arc (\( z = 4.9 \)), respectively (Coppi et al. 2007; Riechers et al. 2010; Livermore et al. 2012). Our upper limits for the LAEs are similar to the values estimated for the observed LBGs. For MACS0647-JD our upper limit for the molecular mass is at least eight times lower than in the observed LBGs.

Using the UV–SFR relation, we can estimate the gas depletion timescales for our targets, assuming \( \tau_{\text{dep}} = \frac{M_{\text{gas}}}{\Sigma_{\text{SFR}}} \).

We estimate upper limits for the depletion time of \( \lesssim 8, \lesssim 11, \) and \( \lesssim 66 \) Myr for IOK-1, SDF J132415.7+273058, and SDF J132408.3+271543, respectively. For MACS0647-JD the depletion time is \( \lesssim 60 \) Myr. The estimated depletion times for the observed lower-redshift lensed LBGs are within the range of \( \sim 7–24 \) Myr, similar to our upper limits. The depletion times for the LAEs are consistent with the ages of \( \lesssim 15 \) Myr estimated for the young population of LAEs at \( z \sim 4.5 \) found by Finkelstein et al. (2009) and to the simulated LAEs at \( z \sim 3.1 \) with ages \( <100 \) Myr (Shimizu et al. 2011). The depletion times of the LBGs are consistent with the LBG phase predicted duration of 20–60 Myr (González et al. 2012).

Saintonge et al. (2013) presented molecular gas masses and depletion timescales for a sample of lensed star-forming galaxies at \( z = 1.4–3.1 \). The range of measured molecular gas masses is \( 5.6 \times 10^8–4 \times 10^{11} M_\odot \), and that of depletion timescales is 127–1089 Myr. The longer depletion timescales measured for the lower-\( z \) sources could indicate that they experience less “extreme” bursts of star formation in comparison to our \( z > 6.5 \) sample. However, assuming a higher molecular-to-atomic gas ratio (of at least 5) would put our upper limits within the values measured by Saintonge et al. (2013).

5. SUMMARY AND OUTLOOK

We have presented a search for [C\( \text{ii} \)] emission in three LAEs at \( z \sim 7 \) and in a LBG at \( z \sim 11 \) using CARMA and the PdBI. We summarize our results and conclusions as follows.

1. We have not detected the [C\( \text{ii} \)] emission line of any of our targets. Given the recent observational results and simulations of the [C\( \text{ii} \)] emission in high-redshift LAE, we adopt a line width of 50 km s\(^{-1}\) for the [C\( \text{ii} \)] emission. We put constraints on the luminosity of the line for the targets. For the LAEs the 3\( \sigma \) \( L_{[\text{C}\text{ii}]} \) upper limits are \( < 2.05, < 4.52, \) and \( < 10.56 \times 10^6 L_\odot \) for IOK-1, SDF J132415.7+273058, and SDF J132408.3+271543, respectively. Our [C\( \text{ii} \)] upper limits are consistent with the relation of SFR to \( L_{[\text{C}\text{ii}]} \) found by de Looze et al. (2011). The 3\( \sigma \) upper limit in the [C\( \text{ii} \)] luminosity of MACS0647-JD is \( < 5.27 \times 10^7 \) (\( \mu/15 \))^\( -1 \) \( L_\odot \) (assuming that the redshift of the galaxy is within the most sensitive setup).

2. No detection of the FIR continuum is found at a wavelength of 158 \( \mu \text{m} \) rest frame for any of the four targets. Assuming an SED template for the local galaxy NGC 6946 as a template for the high-redshift galaxies observed here, we present conservatives upper limits for the FIR luminosity. We find \( < 2.33, 3.79, \) and \( 7.72 \times 10^{11} L_\odot \) as upper limits for IOK-1, SDF J132415.7+273058, and SDF J132408.3+271543, respectively; these values account for the effect of the CMB on the observations. For MACS0647-JD, the upper limit in the FIR luminosity is...
3. We present the results of simulations supporting the brightest component of the \( [\text{C}\ II] \) line having a width of the order of 50 km s\(^{-1}\). Here we want to emphasize the necessity of resolving such emission lines in future ALMA observations to not lose signal-to-noise ratio by selecting a channel resolution that is too low.

4. The effect of the CMB must be taken into account in the FIR luminosities for the targets. The CMB-corrected FIR luminosity limits are 35% higher than those without CMB correction at \( z \approx 6.6, 50\% \) higher at \( z \approx 7, \) and 350% higher at \( z \approx 11 \) for \( T = 26 \) K. We thank the referee for useful comments and suggestions, which significantly improved the quality of this paper. We acknowledge support from FONDAP “Centro de Astrofísica” 15010003. L.I. is thankful for the collaboration of the CLASH team.

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