ALMA [C II] 158 µm DETECTION OF A REDSHIFT 7 LENSED GALAXY BEHIND RXJ1347.1−1145

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ABSTRACT

We present the results of ALMA spectroscopic follow-up of a z = 6.766 Lyman-α emitting galaxy behind the cluster RXJ1347.1−1145. We report the detection of [C II] 158 µm line fully consistent with the Lyman-α redshift and with the peak of the optical emission. Given the magnification of μ = 5.0±0.3, the intrinsic (corrected for lensing) luminosity of the [C II] line is L_{[CII]} = 1.4^{+0.2}_{−0.1}×10^7 L_⊙, roughly ~5 times fainter than other detections of z ∼ 7 galaxies. The result indicates that low L_{[CII]} in z ∼ 7 galaxies compared to the local counterparts might be caused by their low metallicities and/or feedback. The small velocity off-set (∆v = 20^{+140}_{−40} km s^{-1}) between the Lyman-α and [C II ] line is unusual, and may be indicative of ionizing photons escaping.

Subject headings: galaxies: high-redshift — gravitational lensing: strong — galaxies: clusters: individual — dark ages, reionization, first stars

1. INTRODUCTION

The epoch of reionization, during which the Universe became transparent to UV radiation, is still poorly understood. Faint galaxies are likely responsible for this transformation, however this connection is far from con-


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a key parameter, with the [C II] luminosity decreasing with decreasing size of the [C II] emitting region in high surface density clouds. Other factors that influence total [C II] emission include (i) the relative abundances of the various gas phases composing the interstellar medium ISM (ionized, neutral and molecular), (ii) the hardness of the radiation field, and (iii) the temperature and density of the emitting gas.

In this paper we report on ALMA observations of RXJ1347:1216, a normal \((L < L^*)\) star forming galaxy with Lyman-\(\alpha\) emission at \(z_{\text{Lya}} = 6.7659_{-0.0005}^{+0.0005}\). It was first reported by Bradley et al. (2014) and Smith et al. (2014) as a photometrically selected \(z \sim 7\) galaxy from the HST and Spitzer CLASH data (Cluster Lensing And Supernova survey with Hubble, Postman et al. 2012). We have spectroscopically confirmed its redshift using Keck DEIMOS data (Huang et al. 2016) and HST grism data from GLASS (Treu et al. 2015) Schmidt et al. (2016). In Huang et al. (2016) we also measured its integrated stellar properties using deep Spitzer SURFSUP data (Spitzer UltRa Faint SUrvey Program, Bradač et al. 2014). Our magnification model shows that the massive foreground galaxy cluster RX J1347.1–1145 magnifies RXJ1347:1216 by a factor \(5.0 \pm 0.3\). Taking into account magnification, the galaxy’s intrinsic rest-frame UV luminosity is \(0.18^{+0.07}_{-0.05} L^*\) (assuming characteristic magnitude at \(z \sim 7\) of \(M_U^* = -20.87 \pm 0.26\) from Bouwens et al. 2015) making RXJ1347:1216 the first galaxy detected with ALMA at \(z \sim 7\) having a luminosity characteristic of the majority of galaxies at \(z \sim 7\).

Throughout the paper we assume a \(\Lambda\)CDM concordance cosmology with \(\Omega_m = 0.27\), \(\Omega_{\Lambda} = 0.73\), and Hubble constant \(H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1}\). Coordinates are given for the epoch J2000.0, and magnitudes in the AB system.

2. OBSERVATIONS AND DATA REDUCTION

We observed RXJ1347:1216 with ALMA on July 21 2016 in Band 6 with 38 12-m antennae on a configuration of 15-700m baselines. The precipitable water vapor stayed stable at \(\sim 0.8 \text{ mm}\) during the observations. The total time on-source was 74 minutes, with the phases centered at the HST position of the source. Out of the four spectral windows, SPW0 was set to Frequency Division Mode and its center tuned to the [C II] 158 \(\mu\)m rest-frame frequency of 1900.54GHz and a sky-frequency of 244.85GHz, in the Upper Side Band, yielding a velocity resolution of 9.5 \(\text{ km s}^{-1}\) after a spectral averaging factor of 16 was applied to reduce the data rate. The other three spectral windows were used for continuum in Time Division Mode (31.25MHz spectral resolution) at lower frequencies. We used J1337–1257 for bandpass and absolute flux scale calibrators and J1354–1041 for a phase calibrator.

The data reduction followed the standard procedures in the Common Astronomy Software Applications (CASA) package. The data cube was cleaned using Briggs weighting and ROBUST = 0.5. The FWHM beam size of the final image is \(0.58'' \times 0.41''\) at a position angle of 288 deg. The 1\(\sigma\) noise of the [C II] 158 \(\mu\)m line image is \(\sigma_{\text{line}} = 250\mu\text{Jy beam}^{-1}\) at 244.7424GHz over a channel width of 30 \(\text{ km s}^{-1}\) (24.5MHz). The continuum image was extracted using all the line-free channels of the four spectral windows, resulting in a continuum sensitivity of \(< 15\mu\text{Jy (1\sigma)}\). Flux calibration errors (\(\sim 5\%\)) are included in all measurements.

3. RESULTS

We have detected [C II] emission in RXJ1347:1216 with Lyman-\(\alpha\) emission first reported by Huang et al. (2016) and Schmidt et al. (2016). The [C II] line is detected at 5\(\sigma\) (peak line flux \(S_{\text{line}} = 1.25 \pm 0.25\mu\text{mJy}\) using 30 \(\text{ km s}^{-1}\) resolution, Fig. 1) Due to gravitational lensing, we are able to measure [C II] luminosity in RXJ1347:1216 that is intrinsically \(\sim 5\) times fainter than other such measurements at \(z \sim 7\) to date (and similar luminosity to a \(z \sim 6\) object in Knudsen et al. 2016a). We extract the spectrum using native spectral resolution with channel width of 9.6 \(\text{ km s}^{-1}\) (7.8125MHz) and measure [C II] redshift of \(z_{\text{[CII]}} = 6.7655 \pm 0.0005\) (Fig. 2). We fit the line using a Gaussian and estimate peak flux of \(S_{\text{line}} = 0.82 \pm 0.26\mu\text{mJy}\), FWHM of 75 \(\pm 25\) km s\(^{-1}\) and the integrated line flux of \(S_{\text{line}} \Delta \nu = 67 \pm 12\mu\text{mJy km s}^{-1}\). The integrated values do not critically depend upon the assumption of a Gaussian profile within the uncertainties. The luminosity is \(L_{\text{[CII]}} = 1.5_{-0.5}^{+0.3} \times 10^7 L_{\odot}\), corrected for lensing and the errors reflect both uncertainties.

\begin{table}
\centering
\caption{Stellar population modeling results for RXJ 1347:1216 using HST and Spitzer photometry from Huang et al. (2016), spectroscopy of Lyman-\(\alpha\) from Keck DEMOS from Huang et al. (2016) and [C II] from ALMA observations.}
\begin{tabular}{ll}
\hline
ALMA & \\
\hline
R.A. & 13:47:36.214 \\
Dec. & \(-11:45:15.16\) \\
z_{\text{Lya}} & 6.7655 \pm 0.0005 \\
S_{\text{line}} & 1.25 \pm 0.25\mu\text{Jy} \\
S_{\text{line,G}} (Gauss Fit) & 0.82 \pm 0.26\mu\text{Jy} \\
S_{\text{line,AV}} (Gauss Fit) & 67 \pm 12\mu\text{mJy km s}^{-1} \\
FWHM (Gauss Fit) & 75 \pm 25\text{ km s}^{-1} \\
L_{\text{[CII]}} & 1.5_{-0.5}^{+0.3} \times 10^7 L_{\odot} \\
Continuum & < 15\mu\text{Jy (1\sigma)} \\
E(B-V)_{\text{fit}} & < 2 \times 10^8 L_{\odot} (3\sigma) \\
SFR_{\text{IR}} \times f_{\mu} & < 3 M_{\odot} \text{ yr}^{-1} (3\sigma) \\
\hline
\end{tabular}
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\begin{tabular}{ll}
\hline
ALMA & \\
\hline
R.A. & 13:47:36.207 \\
Dec. & \(-11:45:15.16\) \\
z_{\text{Lya}} & 6.7655 \pm 0.0005 \\
E(W_{\text{Lya}}) & 26 \pm 4\mu\text{Jy} \\
\Delta z_{\text{HST–ALMA}} [\text{arcsec (kpc)}] & 0.1 (0.5) \\
\Delta v_{\text{Lya–[CII]}} & 20^{+140}_{-100} \text{ km s}^{-1} \\
F_{\text{160W}} & 26.1 \pm 0.2\text{mag} \\
\mu_0 & 5.0 \pm 0.3 \\
M_{\text{stellar}} \times f_{\mu} & 8.0_{-5.9}^{+6.5} \times 10^7 M_\odot \\
SFR_{\text{SED}} \times f_{\mu} & 8.5_{-1.0}^{+0.4} \times 10^2 M_\odot \text{ yr}^{-1} \\
SFR_{\text{IR}} \times f_{\mu} & 3.2 \pm 0.4 \times 10^2 M_\odot \text{ yr}^{-1} \\
\sigma_{\text{SFR}} & \leq 15\mu\text{mJy} \\
\alpha_{\text{SFR}} & 105_{-1}^{+1} \text{ Gyr}^{-1} \\
E(B-V) & 0.1_{-0.0}^{+0.04} \\
\beta_{\text{UV}} & -2.5_{-1.6}^{+1.0} \\
\hline
\end{tabular}
\end{table}
in the flux estimates as well as magnification (Table 1).

We investigate the \( L_{\text{[CII]}} - \text{SFR} \) connection for this galaxy. The strength of the [C II] emission correlates with the SFR in local dwarf galaxies (De Looze et al. 2014), however the [C II] luminosity is not a simple function of SFR, nor is there a simple correlation between [C II] luminosity and the total mass of the ISM at higher redshifts. This is shown in Fig. 3 where we plot \( L_{\text{[CII]}} \) vs. SFR. We include results from simulations by Vallini et al. (2015) as well as results for \( z > 3 \) galaxies from the literature. We show the SFR of RXJ1347:1216 estimated by Huang et al. (2016) along with the upper limit on the \([\text{CII}]\) line with our results as it requires very low gas-phase [O iii] ratios.

The recent detection of [O II] leads to a significantly higher SFR, in line with our results as it requires very low gas-phase [O iii] ratios.

The low [C II] luminosity given SFR is consistent with predictions from the Kennicutt-Schmidt relation of SFR to gas mass ($M_{\text{gas}} = (3.5^{+2.1}_{-1.1}) \times 10^9 M_\odot$), where the error is the 1σ uncertainty. In addition, Dunlop et al. (2016) noted that the HST and ALMA astrometric uncertainty of 0′′1 (HST uncertainty is smaller). In Fig. 1, the [C II] emission overlaid on the HST color composite RGB image (optical-F110W-F160W). The contours are spaced linearly between 1−5σ (solid lines); negative contours (−1, −2σ) are given as dashed lines. A 1′′ × 1′′ zoom-in is shown in the inset, and the beam is given in bottom-left.

The [C II] line is spatially consistent (measured offset is 0′′1) with the rest-frame UV emission within the standard ALMA astrometric uncertainty of 0′′1 (HST uncertainty is smaller). In addition, Dunlop et al. (2016) noted that the HST and ALMA astrometry of the HUDF presented both a systematic shift of 0′′25 and a random offset of up to 0′′5. Similarly, Pentericci et al. (2016) notes 0′′1−0′′6 random offsets measured from serendipitous detections in the field. Unfortunately, we do not detect any other sources in our small field-of-view to perform relative astrometric calibration.

The Lyman-α line redshift of this object is also in excellent agreement with the [C II] redshift (Fig. 2). The resulting velocity offset of Lyman-α compared to [C II]...
is only $\Delta v = 20^{+140}_{-40}$ km s$^{-1}$ (68% confidence, positive $\Delta v$ indicates that Lyman-$\alpha$ is redshifted). The Lyman-$\alpha$ redshift was difficult to determine with a high accuracy given the proximity of a skyline, hence in Huang et al. (2016) we reported it only with two significant digits. We remeasure the redshift using our DEIMOS data (and improve on absolute wavelength calibration reported in Huang et al. 2016). The reasons for asymmetric errors on the measurement (Table 1) are the proximity of the skyline, lower S/N of the line ($\sim 10\sigma$), and the asymmetric nature of the line. The errors are, however, small and we do not detect significant shift of the Lyman-$\alpha$ line.

This is somewhat unexpected, as for such a low luminosity galaxy (0.18$^{+0.07}_{-0.06}$ $L_\odot$, rest-frame EW of Lyman-$\alpha$ 26 $\pm$ 4Å) the outflows are ubiquitous at lower-$z$. At $z \sim 3$, Erb et al. (2014) reported Lyman-$\alpha$ velocity shifts of $\Delta v \approx 100 - 500$ km s$^{-1}$ for low-EW (EW $\lesssim 10\AA$) LAEs and a strong anti-correlation between $\Delta v$ and EW. They concluded that $\Delta v$ is likely modulated both by galaxy continuum luminosity and by Lyman-$\alpha$ EW. At $z \sim 7$, however, Stark et al. (2015) measured an offset of $\Delta v \approx 60$ km s$^{-1}$ between Lyman-$\alpha$ and CIV for a lensed low-luminosity galaxy A1703-zd6 at $z = 7.045$ (though CIV might not trace systemic velocity). Pentericci et al. (2016) reported velocity shifts of $\sim 100$ km s$^{-1}$ between [C II] and Lyman-$\alpha$ for their 3 most significant detections. For a higher luminosity galaxy Stark et al. (2017) reported an offset between CII] and Lyman-$\alpha$ of $\sim 340$ km s$^{-1}$. Given the small velocity offset of RXJ1347:1206 (and similar other low luminosity galaxies) it seems that at $z \sim 7$, Lyman-$\alpha$ is much closer to systemic velocity than is the case for low-$z$ LAEs at similar UV-continuum luminosities.

This is important, because velocity offsets are crucial in interpreting the line visibility during the reionization epoch. The low offset is interpreted differently in the so-called shell models vs. multi phase models of LAEs. A shell model requires low neutral gas column density or a high outflow velocity (Verhamme et al. 2015). In the case of a multi-phase model (Dijkstra et al. 2016), a low velocity offset translates to a low covering fraction of neutral gas, independent of its neutral column density and outflow velocity. In both models, however, the low velocity offset is a consequence of the presence of low HI-column density escape routes for Lyman-$\alpha$ photons, which may also allow ionizing photons to escape (see Verhamme et al. 2015, Dijkstra et al. 2016, Verhamme et al. 2016 for more detailed discussions). For a more general conclusion a larger sample is needed, but if future observations systematically show smaller velocity offsets, this would imply that the observed drop in LAE fraction between $z \sim 6$ and 7 (e.g. Schenker et al. 2012, 2014, Tilvi et al. 2014, Carnana et al. 2014, Pentericci et al. 2014, Schmidt et al. 2016) is more easily explained by changes in the IGM, than in the circumgalactic medium or galactic intrinsic properties (Dijkstra 2014, Mesinger et al. 2015, Choudhury et al. 2015).

4. CONCLUSIONS

In this paper, we report a [C II] ALMA detection of a low-luminosity galaxy at $z = 6.7655$. The [C II] redshift agrees with Lyman-$\alpha$ redshift and the position agrees with the optical/UV HST counterpart of this object (within uncertainties). This indicates that the Lyman-$\alpha$
We assume a metallicity that is $Z_{2016}$, using SMC dust attenuation curve from Pei (1992). We are consistent with predictions of simulations of $Z < 0.2 Z_{\odot}$, from low-redshift low-metallicity dwarf galaxies, yet it is typical of $z \sim 7$ sub-$L^*$ galaxies. The [C II] luminosity is much lower than that expected from low-redshift low-metallicity dwarf galaxies, yet it is consistent with predictions of simulations of $Z < 0.2 Z_{\odot}$ galaxies at $z \sim 7$ by Vallini et al. (2015). The departure of high-$z$ galaxies from local relation is the most likely explanation for why several searches of [C II] emission at $z \sim 7$ have yielded non-detections, as many have assumed the $L_{\text{CII}}$-SFR relation for local dwarf galaxies. Due to gravitational lensing we reach lower intrinsic flux limits (factor of ~5) than similar observations of field galaxies, and as a result we are able to study a source that belongs to the bulk of the population at $z \sim 7$. As shown in this study, such lens-magnified observations enable studies of the ISM in the sources responsible for reionization. Future high-resolution observations with ALMA will allow us to resolve (spectrally and spatially) more galaxies at $z \sim 7$, and study in detail the kinematics and spatial distributions of [C II]-emitting gas at sub-kpc scales. Such studies will firmly establish ALMA as the premiere facility that will revolutionize the explorations of the earliest galaxies and our understanding of their place in the galaxy evolution and reionization puzzle.

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**REFERENCES**

Bertin, E. & Arnouts, S. 1996, A&AS, 117, 393

Bouwens, R. J., Illingworth, G. D., Oesch, P. A., Trenti, M., Lahbè, I., Bradley, L., Carollo, M., van Dokkum, P. G., Gonzalez, V., Holwerda, B., Franx, M., Spitler, L., Smit, R., & Magee, D. 2015, ApJ, 803, 34

Bradac, M., Ryan, R., Casertano, S., Huang, K.-H., Lemaux, B. C., Schrabback, T., Gonzalez, A. H., Allen, S., Cain, B., Gladders, M., Hall, N., Hildebrandt, H., Hinz, J., von der Linden, A., Lubin, L., Treu, T., & Zitrinsky, D. 2014, ApJ, 785, 108

Bradley, L. D., Zitrin, A., Coe, D., Bouwens, R., Postman, M., Balestra, I., Grillo, C., Monna, A., Rosati, P., Seitsa, S., Host, O., Lemze, D., Moustakas, J., Moustakas, L. A., Shu, X., Zheng, W., Broadhurst, T., Carrasco, M., Jouvel, S., Koekemoer, A., Medezinski, E., Meneghetti, M., Nonino, M., Smit, R., Umetsu, K., Bartelmann, M., Benitez, N., Donahue, M., Ford, H., Infante, L., Jimenez-Tejas, Y., Kelso, D., Lahav, O., Maoz, D., Melchior, P., Merten, J., & Molino, A. 2014, ApJ, 792, 76

Bruzual, G. & Charlot, S. 2003, MNRAS, 344, 1000

Calzetti, D., Armus, L., Bohlin, R. C., Kinney, A. L., Koornneef, J., & Storchi-Bergmann, T. 2000, ApJ, 533, 682
