A tentative $\sim1000$ km s$^{-1}$ offset between the [CII] 158 $\mu$m and Ly$\alpha$ line emission in a star-forming galaxy at $z = 7.2$

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June 27, 2022

ABSTRACT

GN-108036 is a star-forming galaxy at $z = 7.21$, and one of the most distant known sources in the Northern hemisphere. Based on observations from the NOrthern Extended Millimeter Array (NOEMA), here we report the tentative detection of the [CII] line at $\approx 4\sigma$ significance. The integrated [CII] line emission is spatially offset about $\approx 4$ kpc from the rest-frame ultraviolet (UV) emission. The total [CII] luminosity ($L_{\text{[CII]}} = 2.7 \times 10^7 L_\odot$) is consistent with the relation between [CII] luminosity and star formation rate (SFR) observed in nearby and high-$z$ star forming galaxies. More interestingly, the [CII] line is blueshifted with respect to the Ly$\alpha$ line by $980 \pm 10$ km s$^{-1}$. If confirmed, this corresponds to the largest velocity offset reported to date between the Ly$\alpha$ line and a non-resonant line at $z \approx 6$. According to trends observed in other high redshift galaxies, the large Ly$\alpha$ velocity offset in GN-108036 is consistent with its low Ly$\alpha$ equivalent width and high UV absolute magnitude. Based on Ly$\alpha$ radiative transfer models of expanding shells, the large Ly$\alpha$ velocity offset in GN-108036 could be interpreted as the presence of a large column density of hydrogen gas, and/or an outflow with a velocity of $v_{\text{out}} \approx \Delta v_{\alpha}/2 \approx 500$ km s$^{-1}$. We also report the 3$\sigma$ detection of a potential galaxy companion located $\sim 30$ kpc east of GN-108036, at a similar systemic velocity, and with no counterpart rest-frame UV emission.

1. Introduction

The first galaxies most likely formed during the first $\approx 200$-300 Myr of the Universe lifetime (e.g., Bromm & Yoshida [2011] Wise et al. [2011]). These early galaxies represent the primordial building blocks of the galaxy population we observe today. During that early epoch ($z \approx 8$), the gas in the Universe was mostly neutral, which makes the first galaxies, and their increasing star formation activity, natural contributors to the reionization of the Universe (e.g., Fan et al. [2006]). To better understand the properties of these first systems, it is important to consider a multi-wavelength approach, that takes into account the interplay between stars, dust, and warm and cold gas.

Until recently, the study of the first galaxies was limited to the characterization of its nebular and stellar emission: "Hubble Space Telescope" (HST) near-infrared observations of young and massive stars, Spitzer mid-infrared observations of the bulk of the stellar population, and rest-frame ultraviolet (UV) observations from ground telescopes of the Ly$\alpha$ and higher ionization lines (e.g., Ono et al. [2012] Zitrin et al. [2015] Stark et al. [2017]). Over the last decade, and thanks to the advent of the improved capabilities of the NOrthern Extended Millimeter Array (NOEMA) and the Atacama Large Millimeter/sub-millimeter Array (ALMA), we now have access to the study of the cold and neutral gas component in these early systems.

The main tracer of the cold gas in high-$z$ galaxies is the [CII] 157.74 $\mu$m fine structure transition, one of the major coolants of the neutral gas (e.g., Wolfire et al. [2003]). One advantage of the [CII] line is that it is bright (typically $\approx 0.1$-1% of the far-infrared luminosity (e.g., Stacey et al. [1991] Herrera-Camus et al. [2018]), and remains bright in metal-poor environments (e.g., Israel & Maloney [2011] Cormier [2014] Cigan [2015] Bouwens et al. [2021]). Because the C ions can be collisionally excited by hydrogen atoms and molecules, the [CII] line represents a powerful alternative to trace the neutral gas. This is particularly relevant at high-$z$ given the difficulties or serious limitations to observe the CO and HI transitions. At $z \approx 6$, [CII] line observations of star-forming galaxies have revealed clumpy gas structure, which is typically spatially offset from the UV emission, and follows in general the observed relation between the star formation rate (SFR) and the [CII] luminosity observed in nearby galaxies (e.g., Maolino et al. [2015] Carniani et al. [2017] 2018).

In combination with the [CII] transition, another important tracer of these very high-$z$ systems is the Ly$\alpha$ line, produced by young massive stars. The Ly$\alpha$ line is resonant, therefore, it is typically offset in velocity with respect to non-resonant lines (e.g., Steidel et al. [2010] Erb et al. [2014] Hashimoto et al. [2015] Cassata et al. [2020]). The observed Ly$\alpha$ line structure offers valuable information about the interstellar medium (ISM) and it surrounding intergalactic medium (IGM). For example, blueshifted or redshifted Ly$\alpha$ emission with respect to the systemic redshift of a system could indicate the presence of inflowing or outflowing gas, respectively (e.g., Dijkstra et al. [2006] Verhamme et al. [2006] Gronke et al. [2015]). A compilation by Hashimoto et al. [2019] of Ly$\alpha$, [CII], and [O II] 88 $\mu$m line observations of $z \approx 6$ - 8 star-forming galaxies, shows that these systems tend to have Ly$\alpha$ velocity offsets in the $\approx 100 - 500$ km s$^{-1}$ range, and that galaxies with the largest velocity offsets have lower Ly$\alpha$ equivalent widths and higher star formation rates. Based on simple expanding spherical shell models, these large velocity offsets...
2. Observations and data reduction

We used NOEMA to observe GN-108036 in the [C ii] 158 μm transition and dust continuum. At the redshift of the source, the [C ii] transition is redshifted to ν(158 μm) ≈ 231.5 GHz, which falls into NOEMA Band 3. GN-108036 was first observed in March 2019 using the most compact array configuration (D) for an on-source time of 3.2 hrs. The second set of observations was taken on March 2020 using array configuration C for an on-source time of 3.7 hrs. We reduced and combined both data sets using the CLIC and MAPPING software by IRAM. For the imaging of the [C ii] cube and the dust continuum map we use natural weighting to maximize the sensitivity. The resulting synthesized beam for the D, C, and combined C+D data was θ ≈ 2.1″ × 1.5″, θ ≈ 1.2″ × 0.9″, and θ ≈ 1.4″ × 1.1″, respectively. The rms noise for the D, C, and combined C+D line cubes is 0.46, 0.35, and 0.35 mJy beam⁻¹ in 25 km s⁻¹ channels, respectively.

We also created a dust continuum map using part of the sidebands of the C+D data where we do not expect line emission from the source. The rms noise in this map is 13 mJy beam⁻¹. Assuming a characteristic dust temperature for a z ∼ 6–7 galaxy of T_dust ≈ 45 K (e.g., Schreiber et al. 2018; Faisst et al. 2020), and a dust emissivity index of β = 1.5, the expected non-detection indicates a dust mass upper limit of M_dust < 9.5 × 10^6 M_⊙. The low dust content in GN-108036 is consistent with that observed in other massive (M_∗ ≈ 10^9 M_⊙), star-forming galaxies at z ∼ 7–9, including: A2744-YD4 at z = 8.4 (M_dust ≈ 6 × 10^9 M_⊙; Laporte et al. 2017), B14-65666 at z = 7.2 (M_dust ≈ 10^9 M_⊙; Hashimoto et al. 2019), A1689-zD1 at z = 7.13 (M_dust ≈ 2 × 10^9 M_⊙; Bakx et al. 2021), and a handful of luminous Lyman-break galaxies at z ∼ 7–8 (M_dust ≤ 5 × 10^7 M_⊙ if the dust temperature is ≥ 40 K; Schouws et al. 2022).

3. Results

3.1. Tentative detection of the [C ii] 158 μm transition in GN-108036

We performed a blind search for [C ii] line emission by systematically placing apertures of the beam size across the cubes separated by a distance of a quarter of a beam size. We tentatively detected two sources with an integrated signal-to-noise (S/N) of
...in two regions of the cube: 1) in the center, and slightly offset from the spatial position of the detection of GN-108036 in the HST rest-frame UV and Lyα data, and 2) about ~30 kpc east from the HST detection of GN-108036.

The top-left panel of Fig. 1 shows the [C II] spectrum of the potential detection of GN-108036 extracted from the compact array NOEMA data. From a single Gaussian fit we find that the line is centered at ~982 ± 13 km s⁻¹ with respect to the detection of the Lyα line (Ono et al. 2012). We discuss more about this large velocity offset in Section 4.2. The curve of atmospheric transmission overplotted as a gray line shows that the tentative line detection is not a result of a strong or broad atmospheric absorption line. The integrated [C II] flux is 0.22±0.06 Jy km s⁻¹, which corresponds to a detection of the source with a S/N of 3.7. In Appendix A we also show the histogram of the peak S/N per beam in the compact array data. As expected, the distribution roughly follows a Gaussian shape, and the potential detection of GN-108036 with a peak S/N of 5.4 (magenta bin) corresponds to a high-S/N “outlier”.

The left panel of Fig. B.1 in the Appendix shows the spectra extracted in the same region from the extended array and combined array data. The signal is present in the ~ 2× higher angular resolution dataset at the same velocity range, but with lower significance. This could be the result of the [C II] line emission in GN-108036 to be significantly more extended than 1″ (~5 kpc), as it has been observed in other z ~ 6 ~ 7 star-forming galaxies (e.g., Carniani et al. 2020).

We constructed a [C II] integrated intensity map (or moment 0) integrating the [C II] line emission around the potential detection of the line centered at the velocity of ~982 km s⁻¹. The peak signal-to-noise in the integrated [C II] line emission map is ≈ 5.4. Fig. B.2 in the Appendix shows the [C II] moment 0 map, and the right panel of Fig. 1 shows the [C II] integrated intensity contours (at significance levels of 2.5, 3, 4 and 5σ) overplotted on the HST/WFC3 map of the field. The dotted black circle in the center indicates the position of GN-108036 as detected in the rest-frame UV and Lyα emission (Ono et al. 2012). The peak of the integrated [C II] line emission is offset with respect to the peak of the rest-frame UV and Lyα emission by ~4 kpc in the south-east direction. We checked the astrometric accuracy of the HST images using stars in the field in the GAIA catalog (Gaia Collaboration et al. 2018), and this is not the source of the observed offset. Spatial offsets between the star-forming regions and [C II] line emission have been observed in other star-forming galaxies at z ≥ 5 (e.g., Carniani et al. 2018), and could be related to difference in the ionizing state of the gas, dust obscuration, and/or the effect of stellar feedback destroying molecular gas (e.g., Vallini et al. 2015; Katz et al. 2017).

Together with the tentative detection of the [C II] line in GN-108036, we identify a potential additional system located approximately at 30 kpc in the east direction. The spectrum is shown in the lower-left panel of Fig. 1. Interestingly, the tentative detection is at a similar velocity (~910 ± 57 km s⁻¹) of the possible detection of the [C II] line in GN-108036, but the line profile is significantly wider (503 ± 134 km s⁻¹). The integrated [C II] flux is 0.47±0.15 Jy km s⁻¹, which corresponds to a tentative detection with a S/N of ~ 3. As Fig. B.2 in the Appendix shows, the signal is much weaker in the compact array data. The contours of the integrated [C II] line emission from the extended array data are shown in green in the right panel of Fig. 1.

Table 1 summarizes the [C II] line properties of the tentative detections of GN-108036 and the companion. We include the redshift of the source (Lyα and [C II]), the central velocity and SFR estimates from different indicators ranging between ~30 and 100 M⊙ yr⁻¹ (Ono et al. 2012), follows the main relation observed in other z ~ 6 ~ 8 galaxies (Schaerer et al. 2020). GN-108036, with SFR estimates from different indicators ranging between ~30 and 100 M⊙ yr⁻¹ (Ono et al. 2012), follows the main relation observed in other z ~ 6 ~ 8 galaxies, and lies in between the [C II]–SFR scaling relations for galaxies on and above the main-sequence. Regarding the potential companion of GN-108036, there is no
Fig. 3: Lyα velocity offset (Δv_{Lyα}) with respect to the [C ii] line as a function of Lyα equivalent width (left) and absolute UV magnitude (right) observed in star-forming galaxies at 5 < z < 8 (gray circles; Hashimoto et al. 2019). The tentative detection (3σ) of GN-108036 is shown in both panels with a pink diamond.

HST counterpart or SFR estimate available, so we include the [C ii] luminosity value as an horizontal green line 2.

The fact that GN-108036 follows the [C ii]–SFR relation observed in other z ≥ 6 star-forming galaxies, combined with the small spatial offset observed between the peak of the [C ii] line and the rest-frame UV and Lyα emission, argues in favor of the interpretation of the [C ii] line detection in GN-108036 as real and associated with the galaxy.

4.2. Lyα - [C ii] velocity offset

Lyα is a resonant line, thus its profile carries important information about the content, geometry and kinematics of the atomic gas. At z ≳ 2 - 3, star-forming galaxies can show significant velocity differences between Lyα and non-resonant lines (e.g., Hα, Hβ, [O iii]) that range between 100 to 1000 km s^{-1} (e.g., Hashimoto et al. [2013], Erb et al. [2014]). At z ≥ 6, Lyman Break galaxies show Lyα velocity offsets with respect to the [C ii] line that are typically between 100 to 500 km s^{-1}. The record belongs to the star-forming galaxy B14-65666 at z = 7.15, with Lyα line emission redshifted with respect to the [C ii] and [O iii] lines by Δv_{Lyα} = 772 km s^{-1} (Hashimoto et al. 2019).

In the case of GN-108036, the tentative detection of the [C ii] line is blueshifted with respect to the Lyα line by 982.2 ± 12.7 km s^{-1}, the largest velocity offset reported to date for a system at z ≥ 6. Figure 3 compares the Lyα velocity offset in GN-108036 with star-forming galaxies at z ≥ 6 compiled by Hashimoto et al. [2019]. The left panel shows the anti-correlation observed between Δv_{Lyα} and Lyα equivalent width (EW_{Lyα}), and the right panel shows the positive correlation observed between Δv_{Lyα} and the UV absolute magnitude (M_{UV}) of the system.

To first order, and based on models of Lyα radiative transfer in expanding shells, there are two scenarios that can explain the large velocity offset observed in GN-108036. In the first scenario, the presence of a large column density of atomic hydrogen implies that Lyα photons suffer from more dust attenuation due to a larger optical path length, which causes a reduction of the Lyα equivalent width and an increase in the Lyα velocity offset (e.g., Erb et al. 2014). In the second scenario, the increasing UV absolute magnitude is correlated with stronger star formation activity, which can drive outflows including atomic gas that would increase the Lyα velocity offset. In a simple approximation, it is expected that the velocity of the outflow (v_{out}) is correlated with Δv_{Lyα} as Δv_{Lyα} = 2 × v_{out} (e.g., Verhamme et al. 2006). This would imply an atomic gas outflow velocity for GN-108036 of ∼ 500 km s^{-1}. This outflow velocity is consistent with those observed in local starburst with comparable levels of star formation activity (e.g., Shapley et al. 2003, Heckman & Borthakur 2016).

5. Summary and conclusions

We report new NOEMA Band 3 observations of the [C ii] 158 μm transition and dust continuum in one of the most distant sources in the Northern hemisphere, the star-forming galaxy GN-108036 detected in Lyα emission at z = 7.12 (Ono et al. 2012). Our main results can be summarized as follows:

1. We tentatively detect GN-108036 in [C ii] line emission with a S/N ≳ 4. The peak of the integrated emission is spatially offset about 4 kpc with respect to the peak of the rest-frame UV and Lyα line detection (Ono et al. 2012). Spatial offsets of similar magnitudes are commonly observed in star-forming systems at z ≥ 6 (e.g., Carniani et al. 2018). The po-

Table 1: [C ii] 158 μm fluxes and parameters from the Gaussian fit to the tentative detections of GN-108036 and its companion

| Source          | SFR [M_{⊙} yr^{-1}] | z_{Lyα} | z_{[C ii]} | Central velocity [km s^{-1}] | FWHM [km s^{-1}] | Integrated Flux [Jy km s^{-1}] | Luminosity [10^8 L_{⊙}] |
|-----------------|----------------------|---------|------------|-----------------------------|------------------|---------------------------------|--------------------------|
| GN-108036       | ~ 30 - 100           | 7.213   | 7.180      | -982.2 ± 12.7               | 102.7 ± 29.9     | 0.22 ± 0.06                     | 2.7                      |
| Companion       | -                    | 7.188   | ∼ 910.1 ± 57.2 | -                           |                  |                                 |                          |

2 All measurements and scaling relations in Figure 2 have been scaled to the same initial mass function of Salpeter [1955] following the conversion factors listed in Madau & Dickinson [2014].
tentative [C ii] detection is blueshifted with respect to the Lyα emission by 982.2 ± 12.7 km s\(^{-1}\). If confirmed, this would be the largest Lyα velocity offset reported to date for a z ≥ 6 star-forming galaxy. GN-108036 is not detected in the dust continuum, and the 3σ dust mass upper limit is \(M_{\text{dust}} \lesssim 9.5 \times 10^6 M_{\odot}\).

2. Together with GN-108036, we tentatively detect (3σ) in [C ii] line emission one additional source at similar systemic velocity but located ≈ 30 kpc east of GN-108036. This source has no counterpart in the HST imaging of the field.

3. GN-108036, with a SFR that ranges between 30 – 100 \(M_{\odot}\) yr\(^{-1}\) (Ono et al. 2012), follows the relation between the [C ii] luminosity and the SFR observed in star-forming galaxies at z ≥ 6 (e.g., Matthee et al. 2019), and is consistent with the scaling relations of \(L_{\text{[CII]}} \sim \text{SFR}\) observed in nearby and high-z main-sequence star-forming galaxies (e.g., Herrera-Camus et al. 2018; Schaerer et al. 2020). The fact that the potential [C ii] emission in GN-108036 is almost co-spatial with the rest-frame UV and Lyα emission, and that GN-108036 follows the \(L_{\text{[CII]}} - \text{SFR}\) relation, argues in favor of the [C ii] line detection to be real.

4. The Lyα velocity offset observed in GN-108036 is consistent with the positive and negative correlations observed between \(\Delta v_{\text{Lyα}}\) and \(E_{\text{W}(\text{Lyα})}\) and \(M_{\text{UV}}\) in z ≥ 6 star-forming galaxies, respectively. If models of Lyα radiative transfer in expanding shells apply to GN-108036, the physical scenarios that could explain the observed large Lyα velocity offset, the low \(E_{\text{W}(\text{Lyα})}\) and high \(M_{\text{UV}}\) are: 1) the presence of a large HI column density, 2) the existence of an outflow with velocity \(v_{\text{out}} \sim \Delta v_{\text{Lyα}}/2 \sim 500\) km s\(^{-1}\). Certainly deeper, higher angular resolutions observations of GN-108036 are needed to confirm the [C ii] line detection, and further explore these two scenarios.

The upgraded NOEMA capabilities, which will have 12 antennas by the end of the summer of 2022, and has a correlator (PolyFiX) with a bandwidth of ~ 31 GHz, offers a great opportunity to search and detect in [C ii] line emission z ≥ 6 galaxies based on robust photometric redshifts estimates. The latter should become available in large numbers in the near future thanks to the James Webb Space Telescope.

Acknowledgements. We thank the referee for very useful comments and suggestions that improved the manuscript. R. B.-S and R.H.-C thank the Max Planck Society for support under the Partner Group project "The Baryon Cycle in Galaxies" between the Max Planck for Extragalactic Physics and the Universidad de Concepción. R.H.-C also acknowledge financial support from Millenium Nucleus NCN 19-058 (TITANs) and support by the ANID BASEL projects ACE210002 and FB210003.

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Appendix A: Significance of the potential [C\textsc{ii}] detections of GN-108036 and its companion

Fig. A.1 shows the distribution of positive and negative peak S/N values per beam of the compact array data, respectively. The tentative detection of GN-108036 is shown as a magenta bin with a peak S/N value of 5.3.

![Histogram of peak SNR values](image)

Fig. A.1: Left: Distribution of the peak S/N values (positive and negative) for the compact array data. The tentative detection of GN-108036 is shown as magenta bin.

Appendix B: NOEMA [C\textsc{ii}] line observations of GN-108036 with different array configurations

Fig. B.1 shows the [C\textsc{ii}] line spectra of GN-108036 (left) and the potential companion (right) extracted from the D, C, and combined array configuration data, respectively.

Fig. B.2 shows the [C\textsc{ii}] line integrated intensity map of GN-108036 based on the compact array (D) data. The contours correspond to 2.5, 3, 3.5, 4, 4.5, 5 and 5.5\sigma significance levels. The white cross at the center corresponds to the position of the HST rest-frame UV emission from GN-108036.
Fig. B.1: Left: NOEMA spectrum of GN-108036 with a possible new [C II] 158 µm transition detection (orange area). In all three panels, the green dotted line indicates the respective rms noise for three different data sets. Red solid line indicates the redshift measured by Lyα detection. Right: Same as the left panel but for the companion system.

Fig. B.2: Flux map of GN-108036 in [CII] emission line for the compact data set. The contours corresponds to the 2.5σ, 3σ, 3.5σ, 4σ, 4.5σ, 5σ and 5.5σ (integrated) levels. The beam size is plotted in the bottom left.