Tentative $\sim$1000 km s$^{-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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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 NONorthern Extended Millimeter Array (NOEMA), we report the tentative detection of the [CII] line at $\sim 4\sigma$ significance. The integrated [CII] line emission is spatially offset $\sim 4$ kpc from the rest-frame ultraviolet (UV) emission. The total [CII] luminosity ($L_{\text{CII}} = 2.7 \times 10^8 L_\odot$) is consistent with the relation between [CII] luminosity and star formation rate observed in nearby and high-$z$ star-forming galaxies. More interestingly, the [CII] line is blueshifted by $980 \pm 10$ km s$^{-1}$ with respect to the Ly$\alpha$ line. If confirmed, this corresponds to the largest velocity offset reported to date between the Ly$\alpha$ line and a nonresonant line at $z \geq 6$. 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 of GN-108036 could be interpreted as the presence of a high column density of hydrogen gas and/or an outflow with a velocity of $v_{\text{out}} \sim 30 \text{ kpc east of GN-108036}$ at a similar systemic velocity and without counterpart rest-frame UV emission.

Key words. Galaxies: high-redshift - Galaxies: ISM - Galaxies: star formation

1. Introduction

The first galaxies most likely formed during the first $\sim 200-300$ Myr in the lifetime of the Universe (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 this early epoch ($z \gtrsim 8$), the gas in the Universe was mostly neutral, which means that the first galaxies and their increasing star formation activity are 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 multiwavelength approach that takes the interplay between stars, dust, and warm and cold gas into account.

Until recently, the study of the first galaxies was limited to the characterization of their 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 past decade, and based on the advent of the improved capabilities of the NONorthern Extended Millimeter Array (NOEMA) and the Atacama Large Millimeter/sub-millimeter Array (ALMA), we can now study 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, which is one of the main coolants of the neutral gas (e.g., Wolfire et al. 2003). One advantage of the [CII] line is that it is bright (typically $\sim 0.1-1\%$ 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 for tracing the neutral gas. This is particularly relevant at high-$z$ given the difficulties or serious limitations in observing the CO and HI transitions. At $z \gtrsim 6$, [CII] line observations of star-forming galaxies have revealed clumpy gas structure, which is typically spatially offset from the UV emission and in general follows the observed relation between the star formation rate (SFR) and the [CII] luminosity observed in nearby galaxies (e.g., Maiolino 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 that is produced by young massive stars. The Ly$\alpha$ line is resonant; therefore, it is typically offset in velocity with respect to nonresonant 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 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 $z \sim 6-8$ star-forming galaxies showed that these systems tend to have Ly$\alpha$ velocity offsets in the $\sim 100-500$ km s$^{-1}$ range, and that galaxies with the largest velocity offsets have lower Ly$\alpha$ equivalent widths and higher SFRs. Based on simple expanding

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spherical-shell models, these large velocity offsets could be interpreted to mean that the galaxy has a high neutral hydrogen column density and/or an outflow (e.g., Verhamme et al. 2006, 2015).

In this letter we focus on the combined analysis of the Lyα and [CII] line emission GN-108036, a star-forming galaxy at z = 7.213. The redshift of GN-108036 is based on the detection of the Lyα line from deep Keck/DEIMOS spectroscopy (Ono et al. 2012). This makes GN-108036 one of the most distant sources known in the northern hemisphere (dec. +62°08′07″). The stellar mass of GN-108036 is $M_\star = 10^{8.76} M_\odot$, and its SFR is in the range of 29 to 100 $M_\odot$ yr$^{-1}$ based on calculations using the rest-frame UV continuum and stellar population synthesis models, respectively (Ono et al. 2012).

This work is organized as follows. In Section 2 we describe the observations and data reduction. In Section 3 we present the results. In Section 4 we discuss the [CII] properties of the galaxy and the velocity offset with respect to the Lyα line emission. In Section 5 we present the summary and conclusions. We adopt the following cosmological parameters: $H_0 = 67.4$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.315$ and $\Omega_\Lambda = 0.685$ (Planck Collaboration et al. 2020). For a source at $z = 7.21$, this results in a physical scale of 5.24 kpc/′′.

2. Observations and data reduction

We used NOEMA to observe GN-108036 in the [CII] 158 μm transition and dust continuum. At the redshift of the source, the [CII] transition is redshifted to ν[CII]$_{obs} = 231.5$ 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 hr. The second set of observations was taken in March 2020 using array configuration C for an on-source time of 3.7 hr. We reduced and combined the two data sets using the CLIC and MAPPING software by IRAM.\footnote{CLIC and MAPPING are part of the GILDAS package (Guilloteau & Lucas 2000): http://www.iram.fr/IRAMFR/GILDAS}. For the imaging of the [CII] cube and the dust continuum map, we used natural weighting to maximize the sensitivity. The resulting synthesized beam for the D, C, and combined C+D data was $θ = 2.1″ \times 1.5″$, $θ = 1.2″ \times 0.9″$, and $θ = 1.4″ \times 1.1″$, 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 μJy beam$^{-1}$. Assuming a characteristic dust temperature for a $z \sim 6–7$ 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 nondetection indicates a dust mass upper limit of $M_{dust} < 9.5 \times 10^5 M_\odot$. The low dust content in GN-108036 is consistent with that observed in other massive ($M_\star \sim 10^9 M_\odot$) star-forming galaxies at $z \sim 7–9$, including A2744–YD4 at $z = 8.4$ ($M_{dust} \sim 6 \times 10^6 M_\odot$; Laporte et al. 2017), B14–65666 at $z = 7.2$ ($M_{dust} \sim 10^6 M_\odot$; Hashimoto et al. 2019), A1689–zD1 at $z = 7.13$ ($M_{dust} \sim 2 \times 10^6 M_\odot$; Balx et al. 2021), and a handful of luminous Lyman-break galaxies at $z \sim 7–8$ ($M_{dust} \lesssim 5 \times 10^5 M_\odot$ if the dust temperature is $≥ 40$ K; Schouws et al. 2022).

3. Results

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

We performed a blind search for [CII] line emission by systematically placing apertures of the beam size across the cubes separated by 30 kpc. The potential companion are extracted from the compact- and extended-array configuration data, respectively. Right: HST rest-frame UV map of the field of GN-108036. The dotted black circle indicates the position of the HST rest-frame UV emission from GN-108036, and the solid black circle around the center has a radius of 30 kpc. The integrated-intensity contours of the [CII] line emission in GN-108036 (2.5, 3, 4, and 5σ levels) extracted from the compact-array data are shown in magenta. In green we show the potential detection of a companion based on the [CII] line emission extracted from the extended-array data. The beam sizes are shown in the lower left corner. The atmospheric transmission curve in the frequency range covered by our observations is shown as a gray line in the upper part of the panels.
rated by a distance of a quarter of a beam size. We tentatively detected two sources with an integrated signal-to-noise ratio (S/N) of \( \gtrsim 3 \) 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 Ly\( \alpha \) data, and 2) \( \sim 30 \) kpc east of the HST detection of GN-108036.

The top left panel of Fig. 1 shows the [CII] 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 \( -982 \pm 13 \) km s\(^{-1}\) with respect to the detection of the Ly\( \alpha \) line (Ono et al. 2012). We discuss this large velocity offset in Section 4.2. The curve of atmospheric transmission overlapped as a gray line shows that the tentative line detection is not a result of a strong or broad atmospheric absorption line. The integrated [CII] flux is 0.22 \( \pm \) 0.06 Jy km s\(^{-1}\), which corresponds to a detection of the source with an 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 an outlier with a high S/N.

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 data set with the about twice higher angular resolution in the same velocity range, but with lower significance. The reason might be that the [CII] line emission in GN-108036 is significantly more extended than \( \sim 1'' \) (~~5 kpc), as has been observed in other \( z \sim 6 \)−7 star-forming galaxies (e.g., Carniani et al. 2020).

We constructed a [CII] integrated-intensity map (or moment 0) by integrating the [CII] line emission around the potential detection of the line centered at the velocity of \( -982 \) km s\(^{-1}\). The peak S/N in the integrated [CII] line emission map is \( \sim 5.4 \). Fig. B.2 in the Appendix shows the [CII] moment-0 map, and the right panel of Fig. 1 shows the [CII] integrated-intensity contours (at significance levels of 2.5, 3, 4, and 5\( \sigma \)) overlapped 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 Ly\( \alpha \) emission (Ono et al. 2012). The peak of the integrated [CII] line emission is offset with respect to the peak of the rest-frame UV and Ly\( \alpha \) emission by \( \sim 4 \) kpc in the southeast. We confirmed 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 [CII] line emission have been observed in other star-forming galaxies at \( z \gtrsim 5 \) (e.g., Carniani et al. 2018), and could be related to differences 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 [CII] line in GN-108036, we identify a possible additional system that is located approximately at 30 kpc in the east. The spectrum is shown in the lower left panel of Fig. 1. Interestingly, the tentative detection is at a similar velocity (\( -910 \pm 57 \) km s\(^{-1}\)) of the possible detection of the [CII] line in GN-108036, but the signal-to-noise ratio is significantly wider (503 \( \pm \) 134 km s\(^{-1}\)). The integrated [CII] flux is 0.47 \( \pm 0.15 \) Jy km s\(^{-1}\), which corresponds to a tentative detection with an S/N of \( \sim 3 \). As Fig. B.2 in the Appendix shows, the signal is much weaker in the compact-array data. The contours of the integrated [CII] line emission from the extended array data are shown in green in the right panel of Fig. 1.

Table 1 summarizes the [CII] line properties of the tentative detections of GN-108036 and the companion. We include the redshift of the source (Ly\( \alpha \) and [CII]), the central velocity, and full width at half maximum (FWHM) of the [CII] line from the best 1D Gaussian fit, the integrated [CII] flux, and the [CII] luminosity.

### 4. Analysis

#### 4.1. Relation between [CII] line emission and star formation activity

Under the assumption of an ISM in thermal equilibrium, and considering that the [CII] transition is one of the main cooling channels (e.g., Woldire et al. 2003), a tight relation is expected between the [CII] line emission and the star formation activity. This relation has been observed in nearby star-forming galaxies and high-z main-sequence systems (e.g., De Looze et al. 2014; Herrera-Camus et al. 2015; Herrera-Camus et al. 2018; Schaerer et al. 2020). Fig. 2 shows the relation of [CII] luminosity - SFR observed in \( z \gtrsim 6 \) galaxies (gray circles; Matthee et al. 2019). The solid (orange) and dot-dashed (blue) lines correspond to the scaling relations observed in star-forming galaxies on and above (\( \times 20 \sim 100 \)) the main-sequence independent of redshift (Herrera-Camus et al. 2018), and the solid red line shows the best-fitting relation based on ALPINE \((z \sim 4 \sim 5)\) and \( z \gtrsim 6 \) galaxies (Schaerer et al. 2020). The tentative detection of GN-108036 is shown with a magenta diamond. The SFR of GN-108036 ranges from \( \sim 30 \) to \( \sim 100 \) M\( \odot \) yr\(^{-1}\) depending on whether the rest-frame UV emission or SED are used, respectively (Ono et al. 2012). The solid green line indicates the [CII] luminosity for the companion, which does not have an HST counterpart or SFR estimate.

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Table 1: [C\textsc{ii}] 158 \mu m fluxes and parameters from the Gaussian fit to the tentative detections of GN-108036 and its companion

<table>
<thead>
<tr>
<th>Source</th>
<th>SFR [M_\odot yr^{-1}]</th>
<th>z_{Ly\alpha}</th>
<th>z_{[CII]}</th>
<th>Central velocity [km s^{-1}]</th>
<th>FWHM [km s^{-1}]</th>
<th>Integrated Flux [Jy km s^{-1}]</th>
<th>Luminosity 10^{6} L_\odot</th>
</tr>
</thead>
<tbody>
<tr>
<td>GN-108036</td>
<td>~ 30 - 100</td>
<td>7.213</td>
<td>7.180</td>
<td>-982.2 \pm 12.7</td>
<td>102.7 \pm 29.9</td>
<td>0.22 \pm 0.06</td>
<td>2.7</td>
</tr>
<tr>
<td>Companion</td>
<td></td>
<td>-</td>
<td>7.188</td>
<td>-910.1 \pm 57.2</td>
<td>503.5 \pm 134.7</td>
<td>0.47 \pm 0.15</td>
<td>6.0</td>
</tr>
</tbody>
</table>

Fig. 3: Ly\alpha velocity offset (\Delta v_{Ly\alpha}) with respect to the [C\textsc{ii}] line as a function of Ly\alpha equivalent width (left) and absolute UV magnitude (right) observed in star-forming galaxies at 5 < z < 8 (gray circles; Hashimoto et al. 2019), including three z > 7 galaxies from the REBELS survey (gray squares; Endsley et al. 2022). The tentative detection (3\sigma) of GN-108036 is shown in both panels with a pink diamond.

108036; therefore, we include the [C\textsc{ii}] luminosity value as an horizontal green line.\textsuperscript{2}

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

4.2. Ly\alpha - [C\textsc{ii}] velocity offset

The Ly\alpha line is a resonant line. Its profile therefore carries important information about the content, geometry, and kinematics of the atomic gas. At z \sim 2 - 3, star-forming galaxies can show significant velocity differences between Ly\alpha and nonresonant lines (e.g., H\alpha, H\beta, and [O\textsc{iii}]) that range between 100 to 1000 km s^{-1} (e.g., Hashimoto et al. 2013; Erb et al. 2014). At z \geq 6, Lyman-break galaxies show Ly\alpha velocity offsets with respect to the [C\textsc{ii}] line that are typically between 100 to 500 km s^{-1}. The star-forming galaxy B14-65666 at z = 7.15 has the highest offset. The Ly\alpha line emission is redshifted with respect to the [C\textsc{ii}] and [O\textsc{iii}] lines by \Delta v_{Ly\alpha} = 772 km s^{-1} in this galaxy (Hashimoto et al. 2019).

For GN-108036, the tentative detection of the [C\textsc{ii}] line is blueshifted with respect to the Ly\alpha line by 982.2 \pm 12.7 km s^{-1}, the largest velocity offset reported to date for a system at z \geq 6. Figure 3 compares the Ly\alpha velocity offset in GN-108036 with star-forming galaxies at z \geq 6 compiled by Hashimoto et al. (2019) and three z > 7 systems from the Reionization Era Bright Emission Line Survey (REBELS; Endsley et al. 2022). The left panel shows the observed anticorrelation between \Delta v_{Ly\alpha} and the

\textsuperscript{2} All measurements and scaling relations in Figure 2 have been scaled to the same initial mass function (Salpeter 1955) following the conversion factors listed in Madau & Dickinson (2014).

5. Summary and conclusions

We reported new NOEMA Band 3 observations of the [C\textsc{ii}] 158 \mu m transition and dust continuum in one of the most distant sources in the northern hemisphere, the star-forming galaxy GN-108036 detected in Ly\alpha emission at z = 7.12 (Ono et al. 2012). Our main results are summarized below.

1. We tentatively detect GN-108036 in [C\textsc{ii}] line emission with an S/N \sim 4. The peak of the integrated emission is spatially offset by \sim 4 kpc with respect to the peak of the rest-frame UV and Ly\alpha line detection (Ono et al. 2012). Spatial offsets of similar magnitudes are commonly observed in star-forming systems at z \geq 6 (e.g., Carniani et al. 2018). The potential [C\textsc{ii}] detection is blueshifted with respect to the Ly\alpha...
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_dust < 9.5×10⁶ M☉.

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

3. GN-108036, with an SFR that ranges between ~ 30–100 M⊙ yr⁻¹ (Ono et al. 2012), follows the relation of the [Cii] 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_{[CII]} – SFR observed in nearby and high-z main-sequence star-forming galaxies (e.g., Herrera-Camus et al. 2018; Schaerer et al. 2020). The potential [Cii] emission in GN-108036 is almost cospatial with the rest-frame UV and Lyα emission and GN-108036 follows the L_{[CII]} – SFR relation. This argues in favor of the hypothesis that the [Cii] line detection is real.

4. The Lyα velocity offset observed in GN-108036 is consistent with the positive and negative correlations observed between ∆V_{Lyα} and EW_{Lyα} (Lyα) and M_{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 EW_{Lyα} and high M_{UV} are 1) the high HI column density, and 2) the outflow with a velocity v_{out} ∼ ∆V_{Lyα}/2 ∼ 500 km s⁻¹. Certainly, deeper, higher angular resolution observations of GN-108036 are needed to confirm the [Cii] line detection, and to further explore these two scenarios.

The upgraded NOEMA capabilities, which will have 12 antennas by the end of October 2022, and has a correlator bandwidth of ~ 31 GHz, is a great opportunity to search and detect z ≥ 6 galaxies in [Cii] line emission based on robust photometric redshift estimates. The latter should become available in large numbers in the near future from the James Webb Space Telescope.

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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.

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 dotted green line indicates the respective rms noise for three different data sets. The solid red line indicates the redshift measured in the 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 correspond 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.